

Specification for

Prestressed concrete pressure vessels for nuclear engineering

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- Electricity Supply Industry in England and Wales
- Health and Safety Executive
- Institution of Civil Engineers
- Institution of Nuclear Engineers
- Institution of Structural Engineers
- Power Plant Association
- Power Plant Contractors' Association
- South of Scotland Electricity Board
- United Kingdom Atomic Energy Authority

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Foreword

This revision of BS 4975 has been prepared under the direction of the Nuclear Energy Standards Policy Committee. It supersedes BS 4975:1973 and includes the following significant changes.

References to other British Standards have been brought up to date. This applies particularly to BS 8110-1 and BS 5500 which supersede the “Unified Code”, CP 110 and BS 3915 respectively.

In keeping with current practice elsewhere, prestressing material properties are specified in terms of characteristic rather than guaranteed values.

Additional informative appendices have been included, as follows.

- a) Appendix K on fatigue assessment of liners combines the methods of BS 5500 for strain ranges up to twice yield, with the simplified elastic-plastic method of BS 3915 for higher strain ranges, thus avoiding an excessive reliance on fatigue testing or plastic analysis, which might result from a reference to BS 5500 alone.
- b) Appendix J on the effects of irradiation on steel properties provides guidance based on a review of published data.
- c) Appendix L on the construction of control charts for testing wire, strand and bar gives detailed requirements for quality control of prestressing materials.
- d) Appendix M on optional documentation for supply with the vessel lists some of the documentation that a manufacturer may be required to supply to the purchaser for permanent record purposes.
- e) Appendix N gives an up-to-date bibliography.

There have been numerous alterations or additions to the specification which derive from 15 years to 20 years experience in the UK of the design, construction and operation of prestressed concrete pressure vessels (PCPV). For example, the inclusion of fault conditions and hazards; the deletion of the option of limit state design methods; and expansion of the section on in-service surveillance.

Sections have been added defining the responsibilities of the purchaser, manufacturer and inspecting authority and those requirements to be agreed and documented. These sections follow the principles of BS 5500.

Although the standard is not intended to cover the detailed design of the insulation and the cooling system, some expansion of this section has been considered desirable as a result of construction, commissioning and operating experience.

The format of the specification has been modified to conform to BS 0, and more clearly to separate specific requirements from guidance and informative text.

The standard specifies the design, construction, inspection and testing of single cavity and multi-cavity prestressed concrete pressure vessels (PCPVs) for nuclear reactors and makes recommendations for their surveillance. Such vessels have been used for the dual purpose of shielding and containing gas-cooled nuclear reactors and are a form of civil engineering structure requiring particularly high integrity.

Concrete is weak in tension and is prestressed to counteract tensile stresses induced by applied loadings.

When a PCPV is pressurized and heated the compressive stresses, established during prestressing, are in general reduced, but under normal operating conditions, the concrete stresses remain predominantly compressive.

Prestressing tendons may be placed around the exterior of the vessel structure or passed through ducts inside the concrete. They are usually fabricated from numerous wires or strands and may be anchored by wedge friction grips, by nail heading or by swaged sleeves, which form part of an anchor assembly, bearing on the vessel structure. A circumferential tendon may be formed by winding a single wire or strand under tension many times around the structure or by radially jacking an initially untensioned circumferential tendon away from the vessel. Very large tendons have been bonded into concrete anchors, the extension on stressing being maintained by placing packing under the anchor blocks. After tensioning, a tendon in a duct may be left with no treatment other than corrosion protection so that the tension in it can be verified at any time. Detensioning, inspection and, if necessary, renewal of tendons may then be possible. Although the practice is not recommended, the tendon ducts may be grouted. This may have structural benefits but precludes the possibility of inspection, retensioning or renewal of tendons.

Reinforcement may be incorporated in the concrete to cater for local stresses or to reduce and control the effect of any cracking that may occur. Reinforcement may also be used to increase the ultimate strength of the vessel.

The inside surfaces of the vessel are lined to prevent leakage of the reactor coolant. The lining will normally be mild steel, anchored, as necessary, to the concrete structure to limit inward buckling and control local accumulations of strain. The liner is normally used as internal shuttering for the vessel during construction.

Numerous penetrations through the concrete and liner are necessary for reactor fuelling, control and other requirements. In designs where the pressure vessel contains the boilers as well as the reactor, penetrations are required for boiler feed and steam pipes. Such vessels may have apertures giving access to the boilers for installation, inspection and removal, or separate cavities housing the boiler units. Large penetrations may be required for the circulators in gas-cooled reactors. The vessel liner is extended into the penetrations, which are sealed by steel closures or concrete plugs and may be provided with restrictors or other flow limiting devices.

If the high temperature of the reactor coolant were applied directly to the liner it could have deleterious effects on the liner and concrete and would induce high thermal stresses in the structure. Acceptable temperatures are maintained by a cooling system, normally attached to the concrete side of the liner, in conjunction with thermal insulation applied to the internal surface of the liner.

Although this standard does not cover decommissioning of the PCPV, the eventual demolition of the structure should be borne in mind at the design stage if simple measures can be introduced to ease the problems of demolition.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for their correct application.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 56, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. General

1.1 Scope

1.1.1 This British Standard specifies the design, construction, inspection and testing of prestressed concrete pressure vessels (PCPV) for nuclear reactors, including components that are necessary to maintain the structural integrity and leaktightness of the vessels. However, such concrete pressure vessels are often closely integrated with the operation of the nuclear reactor and its auxiliary plant, and the various parts of the vessel may need to perform functions additional to the structural requirements of this standard.

1.1.2 The safety of concrete pressure vessels depends, firstly, on a correct assessment of the loadings likely to be applied to the vessel and, secondly, on the proper design of the vessel to accept these loadings. This standard covers only the second aspect, the first being the responsibility of the purchaser who has to meet any statutory or other regulations¹⁾.

1.1.3 The safety of concrete pressure vessels throughout their service lives also depends on proper operational procedures being adopted and adequate monitoring and inspection of the vessels during service life being carried out. As operational procedures are the responsibility of the operator they are not included in this standard. Monitoring and inspection are dealt with in 9.4.

1.1.4 Other components of the reactor pressure circuits, including those parts of the ancillary circuits that, for inspection, can be isolated from the primary circuit at any time without having to shut down the reactor, shall comply with the relevant British Standards and any additional requirements specified by the purchaser (see 1.5).

1.1.5 In addition to the definitive requirements, this standard also requires the items detailed in 1.5 to be documented. For compliance with this standard both the definitive requirements and the documented items need to be satisfied.

NOTE 1 Where the words “purchaser” and “manufacturer” occur in the text they should be taken to include representatives of the purchaser and manufacturer or inspectors mutually agreed upon.

NOTE 2 While this standard is based on current British practice which uses PCPVs in association with gas-cooled reactors, it is not intended to limit its use solely to reactors of this type. It is proposed to keep the standard under review, but it is realized that some of the requirements might be inapplicable to new developments and in such cases revised requirements should be specified by the purchaser.

NOTE 3 The titles of the publications referred to in this standard are listed on the inside back cover.

NOTE 4 Bibliographic references are identified by a letter and number in square brackets, e.g. [K4], and will be found either at the end of the relevant appendix or in Appendix N.

1.2 Definitions

For the purposes of this British Standard the following definitions apply.

1.2.1

prestressed concrete pressure vessel (PCPV)

a structure, enclosing a nuclear reactor, that contains the pressurized primary coolant during the operation of the plant

1.2.2

vessel structure

the concrete vessel complete with tendons, anchorages and reinforcement, together with any integral part of the foundations

1.2.3

tendon

a steel element, consisting of one or more wires, strands or bars, used to impart prestress to the concrete

1.2.4

anchorage

a mechanical device or assembly that retains the load in a stressed tendon and transmits it to the concrete of the vessel structure

1.2.5

grip

a component that secures the wire, strand or bar within an anchorage

1.2.6

prestressing system

an assembly of tendons and anchorages used to impart predetermined loads to the concrete

1.2.7

reinforcement

steel elements consisting of wires, strands or bars contained within and bonded to the vessel concrete, but not used to impart prestress to the concrete

1.2.8

liner

a membrane, supported by the vessel concrete and enclosing the pressure circuit, to prevent reactor coolant leakage

1.2.9

supported penetration

that part of a penetration of the vessel structure whose liner is effectively supported by the vessel concrete

¹⁾ In the UK nuclear installations are required to be licensed under the Nuclear Installations Act 1965 and 1969. The licensee will be the ultimate purchaser and operator of the plant, including the concrete vessel. The license may, in the interests of safety, have conditions attached to it relating to the design, construction and operation of the plant.

1.2.10**unsupported penetration**

that part of a penetration of the vessel structure whose liner resists the reactor coolant pressure without effective support from the vessel concrete

1.2.11**closure**

a member providing a leaktight boundary to a penetration

1.2.12**restrictor**

a component that, in the event of a failure of a penetration or closure, limits the coolant leakage

1.2.13**tie**

a member tying the liner to the vessel concrete to limit bowing of the liner away from the concrete

1.2.14**shear connector**

a member that transmits shear loads between the liner and the concrete

1.2.15**working pressure**

the reactor coolant pressure (gauge) acting on any part of the PCPV under normal full load operating conditions

1.2.16**design pressure**

the pressure (gauge), adopted for design purposes, on any part of the PCPV when allowance is made for normal operating transients, for tolerances in the control and instrumentation systems, and the determination of pressure

1.2.17**safety valve relieving pressure**

the pressure (gauge) at which the safety relief valves achieve their rated discharge flow

NOTE This should not exceed 1.1 times the lowest design pressure; see section 8.

1.2.18**test pressure**

a selected internal pressure (gauge) applied to the PCPV at ambient temperature for test purposes

1.2.19**ultimate pressure**

the minimum internal pressure (gauge) at ambient temperature that would theoretically cause the structural failure of a significant part of the vessel structure

1.2.20**design temperature distribution**

the levels and distribution of temperatures throughout the vessel structure, caused by normal reactor operation, that give rise to the most adverse circumstances for the particular conditions and components under examination

1.2.21**start-up and shut-down**

the periods of reactor operation that give rise to changes of pressure and temperature loading on the vessel structure during the raising and lowering of power to and from normal operation respectively

1.2.22**fault conditions**

conditions that are not part of the planned operation of the reactor (i.e. not normal or test conditions)

NOTE The categories of fault conditions are defined in 1.2.23, 1.2.24 and 1.2.25.

1.2.23**frequent fault**

a plant operating condition that is expected to occur one or more times during the life of the reactor

1.2.24**infrequent fault**

a plant operating condition that is expected to occur only once, if at all, during several plant lifetimes but for which the design has to assume a once-per-lifetime basis at least, without curtailing plant life

1.2.25**limiting fault**

a plant operating condition that is not expected to occur but is considered in the design because the consequences could include the release of significant radioactivity

NOTE These conditions may require extensive remedial action or even plant write-off.

1.2.26**hazards**

low probability events specified by the purchaser that may be internal or external to the site

NOTE Internal hazards include plant fires, hot or cold gas and steam releases, pipe ruptures, missiles and dropped loads. External hazards include flooding, high wind, seismic events, gas cloud explosions and aircraft crash.

1.2.27**specified characteristic tensile strength (SCTS)**

the value of the ultimate tensile strength of a prestressing steel below which 5 % of all possible test results would be expected to fall

NOTE The precise statistical definition from BS 5896 is used in Appendix L for quality control purposes.

1.2.28**minimum design prestress**

the level of prestress that has to be maintained to ensure that the maximum permissible design stresses are not exceeded at any point in the vessel structure during its life

1.2.29**anchorage efficiency**

the percentage ratio, as determined by test, of the ultimate load of a tendon and anchorage in combination to the total SCTS of the individual wires, strands or bars comprising that tendon

1.2.30**field stresses**

stresses induced in the vessel structure by the loadings specified in **3.2.2.1**, ignoring the local effects of geometrical discontinuities, penetrations, embedments and concentrated loads

1.2.31**local stresses**

stresses induced in the vessel structure close to, for example, discontinuities, penetrations, embedments or concentrated loads

NOTE Local stresses are limited in their geometrical extent and may exceed the permissible stresses specified in **3.2.3.1.2**.

1.2.32**purchaser**

the organization that buys the finished pressure vessel for its own use or as an agent for the owner

1.2.33**manufacturer**

the organization that designs, constructs and tests the pressure vessel in accordance with the purchaser's specification. By agreement, the design function may be carried out by the purchaser or his agent, independently from the organization that constructs and tests the vessel (see **1.4.2**).

1.2.34**inspecting authority**

the body or association that verifies that the design, materials and construction comply with this standard²⁾.

1.2.35**regulating authority**

the authority in the country of installation that is legally charged with the enforcement of the requirements of the law and regulations of that country relating to pressure vessels for nuclear reactors

1.3 Basic considerations**1.3.1 General philosophy**

It is the responsibility of the purchaser to specify the loadings for which the PCPV is to be designed together with any changes or additions to the requirements of this standard that may be necessary in order to cater for the reactor system. This standard does not cover the derivation of such loadings (see **1.4.1**).

This standard adopts a number of principles that express the practice followed in the United Kingdom for the design of PCPVs for gas-cooled thermal reactors (see [18], [19] and [20] in Appendix N). The more important of these are described in **1.3.2** to **1.3.10** and are expressed in greater detail in the clauses to which reference is made.

1.3.2 Pressure limitation

Safeguards, including pressure relief valves, shall be provided. These ensure that the probability of any foreseeable fault conditions arising, which would cause the pressure inside the vessel to exceed the safety valve relieving pressure, is so small as to be negligible; the possibility of structural failure at the vessel is therefore reduced to a level that may be disregarded.

1.3.3 Temperature limitation

The thermal insulation and the cooling systems control the temperatures of the liner and structural concrete to levels at which no significant deterioration will occur.

²⁾ The purchaser may, subject to any requirements of the Regulating Authority, appoint different Inspecting Authorities for the concrete pressure vessel, the liner and penetrations, the insulation and cooling systems. The purchaser may, with the agreement of the Regulating Authority, undertake the duties of the Inspecting Authority for the concrete pressure vessel.

1.3.4 Liner

The vessel incorporates a steel liner, suitably insulated and cooled, and designed and constructed so as to remain intact and essentially leaktight to well beyond design pressure. In general, apart from those penetration liners that have been specifically designed either to reinforce the vessel structure or as unsupported penetrations, the liner will contribute very little structural strength to the vessel. Due to this small strength or stiffness contribution the liner's behaviour will be dictated almost entirely by the behaviour of the structure, and strains will be induced in the liner by deformation of the vessel structure and from restrained thermal expansion of the liner. Liner stresses are therefore strain controlled. Thus, gross cracking of the concrete or extensive overheating of the liner accompanied by high strain cycles would have to occur before any serious cracking in the liner could develop. Such cracking of the concrete could arise through large losses of prestress or severe over-pressurization, whilst overheating could arise from a gross insulation breakdown or cooling system failure. Large losses of prestress may be avoided by periodic tendon inspection. Severe over-pressurization is prevented by appropriate reactor safeguards coupled with the provision of pressure relief devices. Gross insulation breakdown or cooling system failure are avoided by appropriate redundancy and attention to detailed design assisted by temperature monitoring.

NOTE Nevertheless, the effect of faults specified by the purchaser should be investigated (see 7.2).

The presence of penetrations shall not impair the overall integrity of the structure. The liners and closures for these penetrations have to be designed to ensure adequate integrity.

1.3.5 Pressure vessel integrity

The structural integrity of a PCPV depends on the joint action of the concrete, the prestressing system, and bonded reinforcement if present. The ultimate load is reached when the structure reaches a condition at which it can no longer transmit the forces required for equilibrium. In existing designs of gas-cooled reactors the ultimate load capacity is primarily dependent on the integrity of the prestressing system. When this system consists of a large number of tendons, the premature failure of a small number of these is unlikely to reduce significantly the strength of the vessel. The capacity of the tendons for additional extension beyond that imposed by prestressing provides assurance that the transition from elastic behaviour to the collapse mechanism is progressive and clearly established.

NOTE 1 Designs in which the ultimate load depends on the integrity of the concrete, and in which the transition from elastic behaviour to failure is abrupt, should be avoided (see 3.2.4.4).

Although it may be preferable for the tendons not to require retensioning during their lifetime, in vessels with ungrouted tendons it is possible to check the load in the tendons and, if necessary, retension them. Additionally, it is possible to remove, examine and replace ungrouted tendons to assess their continuing integrity.

NOTE 2 To provide continuing assurance of vessel serviceability throughout its life, full advantage has to be taken of these facilities to carry out periodic checks of anchorages and ungrouted tendons, as well as the external face of the concrete, the penetrations and their closures.

1.3.6 Permissible stresses

Permissible stresses for concrete, bonded reinforcement and prestressing steels are chosen so that the PCPV will exhibit essentially elastic behaviour for all specified loading conditions. The loading on a PCPV differs from that on normal prestressed concrete structures because thermal loading has a special significance with regard to the creep strain experienced and this leads to redistribution of the stresses throughout the structure. The stress analyses for design conditions are required to take account of such redistribution, and to ensure that the stresses remain within specified values for all specified loading conditions.

1.3.7 Safety margins

To ensure an adequate safety margin over the design pressure an ultimate load analysis is required to demonstrate that at ambient temperature the vessel can withstand a substantially greater pressure (normally 2.5 times design pressure). In this analysis the liner is assumed to remain intact and it is not intended to demonstrate a precise margin against a realistic accident condition.

To demonstrate the tolerance of the vessel to liner leakage, a further calculation is required to cover the case of a failed liner where gas pressurization of cracks in the concrete is assumed, but without any heating of the tendons. In this hypothetical situation an ultimate pressure of 1.5 times design pressure is normally required (see 3.2.4.3 and Appendix E). It is not to be assumed that a PCPV is capable of relieving excessive internal pressure by a partial structural failure leading to venting. Periodic monitoring is required to enable any liner leakage to be detected.

1.3.8 Design requirements

Design reports for the PCPV, liner, penetrations and their closures shall be approved on behalf of the manufacturer by suitably experienced Chartered Engineers (see 1.5.1). Section 3 of this standard therefore lays down general requirements that are to be met, but does not stipulate how these are achieved, although in some instances guidance is given in the form of appendices. The quality of materials and construction is specified in some detail, particularly where the requirements differ from those of relevant standards.

1.3.9 Proof test

At the completion of construction, the vessel shall be proof-tested and vessel deflections and strains shall be monitored for correlation with predicted values (see 9.1). At proof test pressure and under any service load conditions, the vessel shall have a net compression in the concrete across any section (see 3.2.3.1).

1.3.10 In-service surveillance

The continued integrity of the PCPV shall be monitored throughout its service life by inspection of important functional and structural features at appropriate time intervals (see 1.3.5, 3.2.1.16 and 9.4).

1.4 Responsibilities

1.4.1 Responsibilities of the purchaser

The purchaser shall be responsible for furnishing the manufacturer with the information required by 1.5.2.

The purchaser shall be responsible for the completeness of the design specification and for ensuring that all the information contained in it, or agreed modifications to it, complies with this standard. The purchaser shall also be responsible for the accuracy of all calculations associated with the preparation of the design specification.

Where the Inspecting Authority is nominated by the purchaser, the purchaser shall be responsible for ensuring that any information that the manufacturer is required to supply, as specified in this standard, is made available to the Inspecting Authority.

Where necessary, it shall be the responsibility of the purchaser to ensure that the Inspecting Authority is acceptable to the Regulating Authority. This shall be done at the time of the order.

1.4.2 Responsibilities of the manufacturer

The manufacturer shall be responsible for the completeness and accuracy of all design calculations and for compliance with all applicable requirements of this standard for the whole vessel. During fabrication, unexpected factors may arise which require deviations from the specified requirements but which do not affect the safety as intended by this standard. Such deviations shall be submitted to the purchaser for approval and shall be recorded in accordance with 1.5.3 f).

Where a purchaser elects to perform the design function for the vessel or other associated components covered by this standard, the manufacturer shall be responsible for ensuring that all the design information he requires for construction and test purposes is included in the design specification and for ensuring that all construction and testing is carried out in compliance with this standard. The manufacturer shall also be responsible for the accuracy of any information he provides to the purchaser for inclusion in the design specification.

The manufacturer may subcontract specific activities to other organizations provided it satisfies the Inspecting Authority that it is competent to ensure by appropriate control or surveillance of its subcontractors that all relevant requirements of the standard are met.

The organization that discharges the manufacturer's responsibilities for construction and testing shall assume overall responsibility for compliance with this standard during all related activities including parts' manufacture and subsequent fabrication to completion at works and/or site.

The manufacturer shall furnish to the purchaser any information which, as specified by this standard, requires the approval of the purchaser, together with drawings, specifications, schedules and other documentation in sufficient detail to enable the compliance of the vessel with this standard, and with the purchaser's other requirements listed in 1.4.1.

Examinations carried out by the Inspecting Authority do not absolve the manufacturer from his responsibility for compliance with the applicable requirements of this standard.

1.4.3 Responsibilities of the Inspecting Authority

The Inspecting Authority shall be responsible for verifying that the design, materials and construction of the vessel comply with this standard.

1.5 Information and requirements to be agreed and to be documented

1.5.1 Authenticated design reports and certification

The following authenticated documentation shall be provided for retention by the purchaser.

- a) Design reports showing that the design of the PCPV and associated steel components is in accordance with this standard. Each design report shall be approved by a Chartered Engineer with adequate experience of the PCPV or associated component covered by the report [see 1.5.3 g)].

NOTE Adequacy of experience is to be verified by reference to the period of employment in a responsible position concerned with the design of PCPV or associated components, which should be for a minimum of five years. Qualifications, training and experience should be reviewed by the purchaser.

- b) Following proof test (see 9.1), and at appropriate stages of testing of the PCPV, reports and certificates shall be prepared and duly authenticated by the manufacturer, Inspecting Authority and the purchaser. These reports and certificates shall show that the standards of materials and construction comply with the agreed specification and that the intentions of the design reports have been met.

- c) Certification for all unsupported penetrations and closures shall be provided in accordance with 1.4.4 of BS 5500:1988.

1.5.2 Information to be supplied by the purchaser

The following information shall be supplied by the purchaser and shall be fully documented [see 1.5.3 h)]. Both the definitive requirements specified throughout this standard and the documented items shall be satisfied before a claim of compliance with the standard can be made and verified.

- a) A specification, which shall include the functional requirements of the vessel, together with the design pressure, normal operating conditions, normal operating transients, fault conditions and hazards that have to be considered, any minimum temperature requirement, the basis for design of the safety valves including redundancy requirements, and any special regulations or requirements for in-service inspection.

Where a purchaser elects to perform the design function for the vessel, the insulation, cooling, penetrations, primary and secondary closures or secondary restrictors, the design specification furnished by the purchaser shall contain all the information (whether provided by the purchaser or by the manufacturer) that the manufacturer would otherwise be required to submit before commencing manufacture.

- b) The name of the Inspecting Authority to be commissioned by the purchaser (see footnote to 1.2.34).
- c) Any requirements in addition to those of this standard, including details of additional criteria to be met during the design, construction, inspection and test.
- d) Any statutory or other regulations with which the finished vessel is required to comply (see footnote to 1.1.2).
- e) Information to be provided by the manufacturer in his tender and thereafter.
- f) Records to be compiled of the vessel as built, and which are to be retained by the purchaser (see 1.5.1 and 1.5.3).
- g) The name of the Regulating Authority.
- h) Quality assurance requirements.

1.5.3 Documentation to be provided by the manufacturer for record purposes

The manufacturer shall supply to the purchaser for record purposes a copy of the following documentation, as finally approved, for each vessel.

- a) A fully dimensioned drawing of the vessel as built, together with any relevant supporting information not covered by items b) to h).
- b) A list of materials (including welding consumables) used in the construction, with details of any special heat treatments carried out by the material supplier.

NOTE 1 For materials complying with a British Standard the date of the standard will be given. Where other materials are used the full specification is to be supplied.

- c) The non-destructive testing specification for all steel components.
- d) The welding procedures used during manufacture of steel components.
- e) The procedures used for radiography, ultrasonic inspection and/or crack detection of welds.
- f) Records of authorized deviations or concessions as permitted in 1.4.2.
- g) Certification and reports as required by 1.5.1, 3.3.3, 6.3, 7.2 and 9.1.
- h) Information supplied by the purchaser (see 1.5.2).

NOTE 2 The duration for which a manufacturer will retain all records he is required to generate during the design and construction of a vessel is influenced by a number of considerations which are outside the scope of this standard. If a purchaser wishes to retain permanent copies of any such records other than those listed in a) to h), e.g. design calculations, material certificates, subsequent heat treatment and manufacturing procedures, inspection and test reports, he should define his requirements in the purchase specification. To facilitate the identification of any such requirement a checklist of optional documentation is given in Appendix M.

1.5.4 Requirements to be agreed and documented

1.5.4.1 General. The items listed in **1.5.4.2** and **1.5.4.3** to be agreed, as appropriate, between the parties concerned and which are specified in the clauses referred to, shall be fully documented. Both the definitive requirements specified throughout this standard and the documented items shall be satisfied before a claim of compliance with this standard can be made and verified.

NOTE Users of this standard should appreciate that a number of items of agreement, i.e. those listed under **1.5.4.3**, cannot be agreed/documented at the time of placing the contract or order for the vessel and do not necessarily apply in every case; they make provisions for individual agreements that may be necessary during the manufacturer's operations to deal with certain practical eventualities (see **1.4.2**). It is important to distinguish these items (**1.5.4.3**) from those listed under **1.5.4.2** which do need to be agreed and documented when the contract or order is placed.

1.5.4.2 Requirements to be agreed and documented at the contract or order stage. The following items, as appropriate, shall be agreed and documented (see **1.5.3**).

- a) The manner in which the manufacturer's responsibilities are to be discharged in cases where the design, fabrication and erection functions are carried out by separate organizations (see **1.4.2**).
- b) Materials for concrete (**2.1.2**), type of concrete mix (**2.1.3** and **2.1.5**), concrete properties (**2.1.6**) and reinforcement (**2.2.2**).
- c) Prestressing system materials (**2.3.2**).
- d) Liner materials (**2.4.2**).
- e) Design pressure (**3.2.1.2**) and design temperature distribution (**3.2.1.3**), seismic loadings (**3.2.1.7**), wind loadings (**3.2.1.8**), specified fault conditions and hazards (**1.2.25**, **1.2.26**, **3.2.2.1**), extent of tendon replacement during service life (**3.2.1.16**), methods of analysis (**3.2.2.2.1**), and the ultimate load factor with leaking liner (**3.2.4.3**).
- f) Corrosion protection of tendons (**4.3.8** and Appendix F).

- g) Design proving tests of prestressing system (**5.3.1.1** and **5.3.1.2**), inspection and quality control procedures for manufacture of tendon and anchorage components (**5.3.2.1** and **5.3.2.2.1**).
- h) Procedures for ultrasonic examination of forgings and pipes (**5.4.1**).
- i) Additional requirements for unsupported penetrations, closures and restrictors (**6.4**).
- j) Arrangements for monitoring and inspection of closures and unsupported penetrations (**6.5**).
- k) Design, manufacture and inspection standards for secondary restrictors (**6.6**).
- l) Thermal and mechanical design of the insulation and cooling systems (**7.1.1**).
- m) Cooling system redundancy, corrosion treatment system and use of seam welded tube (**7.1.3**).
- n) Operational limits for fault analysis of insulation and cooling system (**7.2**).
- o) Basis for sizing relief valves and the redundancy requirements (**8.1**).
- p) Instrumentation for vacuum test (if any) (**9.3**).
- q) The nature and extent of in-service surveillance of the vessel, the arrangements for internal and external access to the vessel and the provision of equipment (**9.4.1**); the instrumentation and monitoring requirements for the concrete structure (**9.4.2**); the instrumentation and monitoring requirements for the liner, insulation and cooling systems (**9.4.3**); facilities for inspection of the liner, insulation and cooling systems (**9.4.3**).
- r) Standard deviation of tensile strength and the characteristic tensile strength of wire, strand or bar (**L.1**); the number of results required for control purposes (**L.3**).
- s) Requirements for records of optional documentation (**M.1**); quality control test intervals for cube strength results [**M.3 d**) 2)].

1.5.4.3 Requirements to be agreed and documented during the manufacturer's operations. The following items, as appropriate, shall be agreed and documented (see also **1.4.2**, **1.5.2** and **1.5.3**).

- a) Materials for concrete (**2.1.2**) and special considerations for massive structures (**2.1.5**).
- b) Use of reinforcement material not complying with specified standards (**2.2.2**).
- c) Selection of prestressing materials (**2.3.2**).
- d) Experimental evidence of suitability of tendon anchorage support [**3.2.3.1.6 a**)].
- e) Acceptance of higher stresses local to liner anchorages [**3.2.3.1.6 b**)].

- f) Need for higher ultimate load factor than 2.5 and/or for model tests (3.2.4.2).
- g) The sequence of prestressing (4.3.4).
- h) Procedures for, and records of, the location, plugging and subsequent testing of temporary holes in the liner (4.4.4).
- i) Tests for concrete materials (5.1.1 and 5.1.4).
- j) The number of production control tests for tendon anchorage assemblies (5.3.2.2.1).
- k) Additional evidence of acceptability of prestressing wire, strand or bar [note to 5.3.2.4 c)] and reporting of results falling outside acceptance limits (L.3).
- l) Alternative testing arrangements for site closing welds (6.4).
- m) The procedure for welding runs of cooling system pipework to the liner (7.1.4).
- n) The vessel proof pressure test procedures (9.1).

1.6 Interpretation

If any ambiguity is found or doubt arises as to the meaning or effect of any part of this standard, or as to whether anything ought to be done or omitted to be done, in order that this standard shall be complied with in full, the question shall be referred to the Power Reactor Technology Technical Committee of the British Standards Institution whose interpretation of the requirements of this standard upon the matter at issue shall be given free of charge and shall be final and conclusive. Parties adopting this standard for the purpose of any contract shall be deemed to adopt this provision, unless by their contract they either expressly exclude it or else import an arbitration provision in terms extending to the interpretation of this standard. However, this provision is limited to questions of interpretation and does not confer on the Committee any power or jurisdiction to adjudicate upon the contractual rights or duties of any person under a contract except so far as they may necessarily be affected by the interpretation arrived at by the Committee.

Findings or rulings of the Committee upon matters of interpretation may be incorporated as “addenda” to this standard and if so incorporated shall be treated as amendments thereto.

Section 2. Materials

2.1 Concrete

2.1.1 General

The materials to be used in the concrete and the methods of selecting and specifying the concrete mix to be used shall be in accordance with 6.1 of BS 8110-1:1985.

2.1.2 Materials for concrete

Materials for concrete shall be selected bearing in mind the special requirements of the structure, e.g. the avoidance of excessive temperature rise due to cement hydration, the avoidance of corrosion risks, etc. They shall be in accordance with 6.1 of BS 8110-1:1985, with the following exceptions.

- a) Cement shall be ordinary Portland cement complying with BS 12 or low heat Portland cement complying with BS 1370 except as may otherwise be approved by the purchaser.
- b) Aggregates shall comply with BS 882 except as may otherwise be specified or approved by the purchaser. Aggregates subject to excessive drying shrinkage or alkali-aggregate reaction shall not be used.
- c) Admixtures shall not be used except with the approval of the purchaser. Calcium chloride shall not be used.

2.1.3 Type of concrete mix

The mix used in the vessel structure shall be a “designed mix” as defined in 3.6 of BS 5328:1981 except as may otherwise be approved by the purchaser.

2.1.4 Specification of “designed” concrete mix

The mix shall be specified in accordance with 12.2 and 12.3 of BS 5328:1981.

2.1.5 Special considerations for massive structures

In selecting the concrete mix consideration shall be given, as with other massive concrete construction, to minimizing the potential temperature rise in the concrete due to the heat of hydration of the cement.

NOTE This can be accomplished by a suitable choice of cement, by the addition or partial substitution of pozzalana for cement where permissible and by using a cement content in the concrete mix no greater than strictly necessary. Where high early strengths are required precautions should be taken to ensure that the associated temperature rises are acceptable.

2.1.6 Information on concrete properties

In addition to the information on the concrete mix required by 2.1.4, the manufacturer shall also provide information on the properties of the hardened concrete that are relevant to the behaviour of the vessel.

This information shall include an evaluation of the following properties:

- a) compressive strength;
- b) tensile strength;
- c) modulus of elasticity;
- d) Poisson’s ratio;
- e) creep;
- f) shrinkage;
- g) coefficient of thermal expansion;
- h) coefficient of thermal conductivity.

Whenever possible the properties shall be determined under test conditions conforming to those expected in the vessel structure during service.

Where features of the design or construction require information on additional properties, the manufacturer shall provide the information.

The manufacturer shall justify his treatment of other factors in the design or construction of the vessel structure that may significantly affect the behaviour of the concrete, including nuclear heating, irradiation, moisture state and moisture migration in the concrete, local heating effects and heat of hydration.

When the difficulties of placing and compacting concrete may affect the resulting concrete properties, or the behaviour of the vessel structure in service, appropriate concreting trials shall be carried out under conditions and configurations simulating the actual structure.

2.2 Reinforcement

2.2.1 General

Where reinforcement is used in the vessel structure it shall be suitable with regard to the yield strength or proof stress, ductility, tensile strength and other essential properties.

2.2.2 Selection of materials

Steel reinforcement shall comply with the following British Standards:

- a) BS 4449, for carbon steel bars for the reinforcement of concrete;
- b) BS 4482, for hard drawn mild steel wire for the reinforcement of concrete;
- c) BS 4483, for steel fabric for the reinforcement of concrete.

Where a material that does not comply with any of these standards is proposed, the manufacturer shall demonstrate its suitability fully to the purchaser before it may be brought on site.

2.3 Prestressing system

2.3.1 General

The materials to be used for prestressing shall be suitable with regard to the ultimate strength, proof stress, Young's modulus and other essential properties.

2.3.2 Selection of materials

The prestressing steel shall comply with the following British Standards:

- a) BS 5896, for high tensile steel wire and strand for the prestressing of concrete;
- b) BS 4486, for hot rolled and hot rolled and processed high tensile alloy steel bars for prestressed concrete.

Where it is proposed to use materials other than those specified above this shall be subject to agreement between the manufacturer and the purchaser. The manufacturer shall demonstrate fully by suitable tests that the alternative material to be used in the construction of the PCPV qualifies in all respects before such a material is introduced to site.

2.3.3 Relaxation

A low relaxation material shall be used. The values of relaxation loss in the design shall be extrapolated from tests of not less than 1 000 h duration, carried out under representative conditions of temperature and rate of application of initial load for the make, type and size of prestressing tendon material to be used in the construction.

2.3.4 Anchorage system and tensioning systems

The components of the systems shall be selected to ensure that the required anchorage efficiency is obtained. In addition, in gripping the wire, bar or strand, the components shall not inflict surface damage that may, with time, result in a reduction in the tendon strength.

2.3.5 Ducts

Ducts and joints shall be watertight and sufficiently robust not to be damaged by the placing and compaction of concrete and other normal construction activities.

2.3.6 Tendon elasticity

The values of modulus of elasticity and the stress/strain relationship of prestressing tendons to be used in the design shall be evaluated by testing full-scale tendons of suitable length. This length shall be sufficient to ensure a uniform loading of each of the bars, wires or strands forming the tendon.

2.4 Liners (including supported penetration liners)

2.4.1 General

The manufacturer shall give particulars of the materials he proposes to use for the liner, together with a statement of the properties required which are relevant to the design, fabrication and life of the liner taking account of the operational environment.

2.4.2 Selection of materials

All materials used in the manufacture of liners shall be fully-killed carbon or fully-killed carbon manganese steels in accordance with the appropriate material specifications listed in Table 2.3 of BS 5500:1988, unless otherwise agreed between the purchaser and manufacturer. The suitability of materials not covered by Table 2.3 of BS 5500:1988 shall be fully demonstrated before liner manufacture may commence.

2.4.3 Welding materials

All materials to be used in welding shall comply with section 4 of BS 5500:1988.

Section 3. Design

3.1 General

A reactor system, its controls and protective mechanisms shall be designed to ensure that foreseeable faults in the system or its operation do not cause the pressure and temperature in the vessel to exceed the stipulated design conditions. However, because of the high degree of integrity required of a nuclear reactor system, the suitability of the PCPV shall be substantiated for all possible conditions of reactor operation. For normal operating and frequent fault conditions the permissible stresses and other criteria shall be as specified in 3.2.3 and these can be amplified in the purchaser's specification.

In addition to the normal and frequent fault loadings arising during construction, commissioning and operation of the reactor, the effects of infrequent and limiting fault conditions and specified hazards shall be examined. Because of the severe consequences of failure of the vessel the integrity of the structure shall be assessed, thereby ensuring that adequate margins of strength over the design pressure are available.

NOTE It is present practice to assess the reserve of strength of a PCPV by performing ultimate load analyses, as specified in 3.2.4.1.

3.2 PCPV structure

3.2.1 Design considerations

3.2.1.1 General. The vessel shall be designed to comply with this standard under the loading conditions specified in 3.2.2.1 and 3.2.4.1.

NOTE In Appendix A a simplified qualitative description is given of the effects of a typical sequence of loadings on the vessel structure. This appendix emphasizes the unusual significance of thermal loadings which, together with the effects of irradiation and the high integrity required, differentiate PCPVs for nuclear reactors from the great majority of prestressed concrete structures and lead to specification requirements unique to this form of structure. Such requirements are grouped together in this clause.

3.2.1.2 Design pressure and the determination of pressure. The design pressure on any part of the PCPV shall be specified by the purchaser and shall make allowance for all normal operating transients and for tolerances in the control and instrumentation systems and the determination of pressure.

NOTE 1 Attention is drawn to 1.3.2.

NOTE 2 The design pressure is usually chosen to be 1.1 times the working pressure.

3.2.1.3 Design temperature distribution. In determining the design temperature distribution of the vessel an adequate allowance shall be made for uncertainties in the thermal calculations for all normal operating transients and for any minimum liner temperature requirement as specified by the purchaser.

3.2.1.4 Foundation movements and vessel

deflections. The design shall take into account the effects of any foreseeable tilting or settlement of the foundations and of vessel deflections on plant operations. The design of the vessel shall also take account of any redistribution of foundation loadings.

3.2.1.5 Effects of shrinkage and moisture migration.

Account shall be taken in the design of the effects of moisture migration, which can cause significant variations in concrete properties.

NOTE At ambient temperatures, the migration of water in massive concrete sections and the eventual drying from exposed surfaces are likely to be extremely slow. The migration will, however, be accelerated by the temperature gradient through the thickness of the concrete of the vessel, leading to some loss of water, e.g. in the concrete immediately behind the steel liner.

3.2.1.6 Liner leakage. The possibility of slow leakage of reactor coolant through the liner during normal operation shall be considered in relation to the effects that this might have on material properties and on the integrity of the PCPV.

3.2.1.7 Seismic loadings. Consideration shall be given to the effects of seismic loads and their combination with other loads.

NOTE 1 Special attention will need to be directed towards the design of the support for the vessel to ensure that horizontal shears and overturning moments may be transmitted into the foundation and to reduce ground motion amplification as far as possible. It will also be necessary to determine the lateral forces imposed upon the vessel by equipment contained within or supported by the vessel to ensure that excessive stresses are not developed.

NOTE 2 Specific rules have not been included in this British Standard as the provisions to be made will depend upon the specification supplied by the purchaser.

3.2.1.8 Wind loadings. Wind load is not normally significant in its effects, but shall be considered when checking temporary conditions of the vessel and liner during construction.

NOTE In certain countries it is necessary to consider the effects of extremely high winds, tornadoes and any "missiles" carried by them.

3.2.1.9 Concrete ageing. The design shall be based on the 28-day characteristic cube strength except where there is justification for the use of a higher strength. The use of higher strengths shall be justified experimentally by the manufacturer. Allowance shall be made for the effect of the hydration cycle which the concrete experiences.

3.2.1.10 Concrete temperature effects. If the normal operating temperature of any section of the vessel structure is such that the failure strength of the concrete at this temperature is significantly less than at ambient temperature, this shall be taken into account in the design. Some concrete mixes, subjected to temperature above 100 °C, will suffer a reduction in compressive strength and changes in their properties. Concrete with certain aggregates, particularly limestone, may suffer significant losses below 100 °C.

3.2.1.11 Concrete irradiation effects. The effects of irradiation on concrete properties shall be taken into account in the design.

NOTE In PCPVs, total neutron doses of the order of 10^{22} neutrons/m² to 10^{23} neutrons/m² (equivalent Herald Nickel Flux, see Appendix H) can be expected to occur in local areas of the liner and attachments, depending upon the design, in regions where provision has been made for access, the dose is more likely to be of the order of 10^{21} neutrons/m².

The associated total gamma doses in PCPVs are of the order of 10^7 Gy to 10^9 Gy.

The maximum permissible neutron dose is controlled by the irradiation effects on concrete. These effects are considered to be insignificant for doses up to 0.5×10^{22} neutrons/m² (equivalent Herald Nickel Flux). At higher values it is to be shown that the overall integrity of the vessel and its components will not be unacceptably affected by the resulting changes in the concrete properties. (Appendix H discusses the effects of irradiation on concrete properties.)

3.2.1.12 Thermal relaxation of tendons. In designing the vessel structure the effects of any temperature to which tendons and/or anchorages may be exposed during normal operation shall be considered.

Tendon materials having relatively low relaxation characteristics at temperatures below 100 °C shall be used.

NOTE Tendons exposed to temperatures above that level may introduce the need for an unacceptable amount of tendon restressing during vessel service. To avoid possible strength reductions, tendon temperatures above 200 °C are not advisable.

3.2.1.13 Tendon irradiation effects. The design shall be such that tendons are not placed in positions where they will receive irradiation doses that could significantly affect their material properties (including corrosion), or demand special precautions during inspection.

NOTE No information is available on the effects of irradiation on the types of steel used for tendons, but it is likely that changes due to irradiation will be similar to those for mild steels (see Appendix J). Changes in the mechanical properties for neutron doses up to 10^{21} neutrons/m² (minimum energy 1 MeV) should therefore be negligible.

3.2.1.14 Provision of bonded reinforcement.

Reinforcement shall be provided where required:

- a) to resist tensile forces where the tensile stresses in the concrete exceed the limits specified in 3.2.3.1.4;
- b) to control and distribute cracking;
- c) to increase the ultimate load capacity of the pressure vessel.

When the tensile stresses in the concrete exceed the limits specified in 3.2.3.1.4 reinforcement shall be provided to accept the entire tensile force induced in the adjacent concrete, based on the uncracked section and calculated at stress levels not exceeding $0.87 f_y$, where f_y is the characteristic strength of the reinforcement as defined in 3.1.7.4 of BS 8110-1:1985.

NOTE 1 This procedure may lead to the provision of large quantities of reinforcement, the influence of which on the vessel behaviour will need to be investigated. Alternatively, structural strength may be justified by analysis of the structure, assuming that the concrete is cracked where unacceptable tensile stresses occur. If this should prove the integrity of the vessel, sufficient reinforcement need be provided only to control surface cracking.

Where it is considered necessary to control and distribute cracking, consideration shall be given to providing reinforcement.

NOTE 2 The use of reinforcement to distribute the type of cracking that is likely to emanate from major geometrical discontinuities in the vessel structure will probably be found not to be effective. Any such unacceptable tendencies are normally countered more efficiently by modifications to the distribution of prestress.

Elsewhere, when tensile stresses are within the limits specified in 3.2.3.1.4 no reinforcement need be provided unless it is necessary to control and distribute surface cracking local to built-in items, for example, or to limit corrosion of tendons or reinforcement near the surface.

In such cases the reinforcement provision shall be such that the maximum crack width does not exceed 0.3 mm.

NOTE 3 In some cases the environmental conditions may be such that a smaller crack width limit is deemed prudent.

Where the ultimate capacity of the pressure vessel is to be increased by the use of bonded reinforcement, account shall be taken in the ultimate load analysis (see 3.2.4) of the effects of such bonded reinforcement, and compatibility of strains (see 3.2.4.5).

3.2.1.15 Composite action of vessel structure and liner. In the design of the vessel structure, account shall be taken of the interaction between the liner, other components, and the vessel concrete.

NOTE Detailed design and other aspects of liners, closures and unsupported penetrations are dealt with in 3.3 and clause 6.

3.2.1.16 Retensioning and replacement of tendons. It shall be possible before and during service to check the prestressing loads and to maintain them so that they do not fall below the minimum acceptable value defined for the design. The minimum acceptable value shall be agreed and documented at the time of order or placing of the contract.

It shall also be possible to carry out a visual examination for corrosion or other deterioration of representative samples of tendons taken from all parts of the vessel.

The extent to which replacement of tendons is possible during service life shall be specified by the purchaser.

3.2.1.17 Spare tendon ducts. Consideration shall be given to the desirability of providing spare tendon ducts as a contingency.

3.2.2 Analysis for service load conditions

3.2.2.1 Loading conditions. Stresses and deformations in the vessel structure shall be analysed for all relevant combinations of mechanical and thermal loads which can arise under normal operating conditions throughout the life of the vessel. As a minimum, stress analyses shall be carried out for the following loadings.

- a) Prestressing forces and dead loads at completion of construction.
- b) Test pressure, relevant prestressing forces and dead loads.
- c) Design pressure, relevant prestressing forces, dead loads and design temperature distribution; both initially and at the end of the vessel life.
- d) Start-up and shut-down conditions, relevant prestressing forces and dead loads, both initially and at the end of the vessel life.

NOTE The details of start-up and shut-down conditions depend on the procedures of reactor operation that are adopted. Transient states arising in the vessel during these operations should be examined.

- e) Specified fault conditions and hazards.

In addition to the service loading conditions considered, the stresses induced in the structure at all stages of construction, including the prestressing period, shall comply with the relevant subclauses of 3.2.3 for temporary stresses during construction.

3.2.2.2 Analysis

3.2.2.2.1 General. The method of analysis selected for each loading condition shall take appropriate account of time and temperature-dependent characteristics of the concrete and tendons shall be approved by the purchaser, having due regard for the complexity of the design and loading conditions and the accuracy required (see Appendix A and Appendix B).

The validity and accuracy of any method or computer program shall be demonstrated using known solutions or alternative methods of calculation. If necessary, they shall also be checked against measurements from models or previously completed vessels in order to establish confidence in the analytical technique (see Appendix N[21]).

The tendon forces adopted in each analysis shall include allowances for the most onerous effects of loss of prestress, including tendon relaxation, and the effects of friction at the anchorage and along the length of the tendon. Account shall be taken of all significant loadings applied to the vessel structure, including stresses arising as a result of construction procedures.

Any significant effects of penetrations on the vessel structure shall be taken into consideration.

Each analysis shall provide sufficient details of the stresses and deformations induced in the concrete and any bonded reinforcement to enable the acceptability of the design to be assessed.

The deformation of the prestressed concrete pressure vessel is important in considering the continued integrity of the vessel liner and also the alignment of critical plant components; particular attention shall, therefore, be paid to the computation of vessel deformations under the action of the various loading conditions given in 3.2.2.1.

3.2.2.2.2 Analysis for loading conditions a) and b) of 3.2.2.1. For the purpose of analyses carried out under loading conditions a) and b) the concrete can be assumed to be a linear elastic material.

3.2.2.2.3 Analysis for loading condition c) of 3.2.2.1. These analyses shall be carried out under loading condition c) on the assumption that the vessel has reached steady conditions of temperature distribution. The stress-strain characteristics used for the concrete shall take account of the age, temperature and time under load.

3.2.2.2.4 Analysis for loading condition d) of 3.2.2.1. The analyses carried out under load condition c) shall be extended for loading condition d) by elastic or more refined creep calculations to indicate how the stress values obtained under condition c) will be affected by shut-down and start-up. When elastic calculations are made, some qualitative indication of how the situation would be affected by the period of shut-down shall be given.

3.2.2.2.5 Analysis for loading condition e) of 3.2.2.1. The methods of analysis under loading condition e) and acceptance criteria shall take into account the nature of the loading considered.

3.2.3 Permissible stresses in concrete and reinforcement

3.2.3.1 Concrete

3.2.3.1.1 General. Under each of the loading conditions a) to d) of 3.2.2.1 the principal stresses induced in the concrete of the vessel structure shall comply with the rules set out in 3.2.3.1.2 to 3.2.3.1.6. Sufficient prestress shall be provided to ensure that the concrete on any plane that passes through any pressurized cavity or cavities is maintained under a net compressive force. This shall be calculated using the minimum design prestress in association with a pressure equal to at least the test pressure.

3.2.3.1.2 Principal compressive field stresses in concrete. The principal compressive field stresses in concrete shall comply with Table 1.

Table 1 — Principal compressive field stresses in concrete

Loading	Permissible compressive stresses, f_{cu}^a
(a) Temporary stresses during construction	0.4
(b) Stresses under the conditions specified in 3.2.2.1 a) and b)	0.4
(c) Stresses under the conditions specified in 3.2.2.1 c) and d)	0.33
NOTE 1 For allowances for concrete ageing, temperature and irradiations, see 3.2.1.9, 3.2.1.10 and 3.2.1.11 respectively. NOTE 2 Condition e) of 3.2.2.1 is covered by 3.2.2.2.5. ^a Where f_{cu} is the characteristic cube strength of the concrete at 28 days, as defined in 2.4.2.1 of BS 8110-1:1985.	

3.2.3.1.3 Multiaxial compressive stresses in concrete. Where any principal compressive stress of a set of three simultaneously induced principal compressive stresses exceeds the values given in 3.2.3.1.2, its acceptability shall be assessed.

NOTE A method is given in Appendix D.

3.2.3.1.4 Principal tensile field stresses in concrete. Tensile field stresses shall be permitted within the outer region of the vessel concrete thickness providing that they diminish with the distance inwards from the outer surface, but shall be avoided in the vicinity of the vessel liner or supported penetration liners that are subjected to reactor coolant pressure. Under loading conditions a) and b) of 3.2.2.1 these tensile stresses shall not exceed 1.4 N/mm² and under loading conditions c) and d) of 3.2.2.1 shall not exceed 2.8 N/mm².

3.2.3.1.5 Local stresses in concrete. In examining local stresses the designer shall take account of the complexity of the prevailing stresses and the local geometry of the structure. Under some applied loadings, mechanical and/or thermal, local high stresses will be generated in the concrete that:

- will not be accurately determined by the general methods of analysis adopted, and
- will be in excess of the allowable stress levels specified in 3.2.3.1.2 to 3.2.3.1.4.

NOTE Local stress peaks are usually associated with steep stress gradients and may be generated by any of the following:

- single or multiple penetrations;
- sharp changes of geometry or stiffness;
- significant embedments in the concrete such as large liner anchorages, heavy shear connectors and ties;
- highly concentrated mechanical loads such as prestressing anchors and internal support columns;
- changes of pressure and temperature in the reactor system during start-up and shut-down that cause high transient compressive and/or tensile stresses adjacent to the vessel liners;
- local hot-spots caused by known insulation or cooling water system shortcomings.

Each such effect will require particular examination by the designer, and local stresses may be permitted to exceed the allowable levels given in 3.2.3.1.2 to 3.2.3.1.4, providing that it can be demonstrated that:

- they are not detrimental to the long-term behaviour of the PCPV;
- they will not jeopardize the safe performance of vessel components by degradation of the concrete;
- consequent local vessel structure and liner movements and strains can be adequately predicted and are within acceptable limits.

Where concrete is contained or is restrained from deformation by its shape, or where triaxial compressive stress states exist, account may be taken of these factors in assessing the acceptability of the stresses. Higher local stresses may also be acceptable if they can be shown to be either transient or notional. For example, thermal stresses may reduce in a short period because of creep, or stresses may never achieve the predicted values because of non-linear stress redistribution.

Since each local stress condition will demand individual consideration, no specific recommendation can be made. The designer will be expected to support his adopted approach with adequate analytical and/or experimental evidence and where applicable make reference to current research information. Further guidance on the treatment of local stresses is given in Appendix C.

3.2.3.1.6 Bearing stresses in concrete. The following bearing stresses shall apply.

- Tendon anchorages.** Concrete that supports tendon anchorages shall either be reinforced in accordance with 4.11 of BS 8110-1:1985 or, alternatively, the suitability of an anchorage system shall be proved experimentally to the satisfaction of the purchaser.