BS 7777-3:
1993

Flat-bottomed, vertical, cylindrical storage tanks for low temperature service —

Part 3: Recommendations for the design and construction of prestressed and reinforced concrete tanks and tank foundations, and for the design and installation of tank insulation, tank liners and tank coatings

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Pressure Vessel Standards Policy Committee (PVE/-) to Technical Committee PVE/15, upon which the following bodies were represented:

British Chemical Engineering Contractors' Association
British Compressed Gases Association
British Gas plc
Concrete Society
Energy Industries Council
Engineering Equipment and Materials Users' Association
Institution of Gas Engineers
Institution of Mechanical Engineers
Process Plant Association
Thermal Insulations Contractors' Association
Welding Institute

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Contents

Foreword

This Part of BS 7777 has been prepared under the direction of the Pressure Vessels Standards Policy Committee.

Flat-bottomed, vertical, cylindrical storage tanks for refrigerated liquefied gases have traditionally been of the single containment design where the liquid is contained in a single shell surrounded by a conventional low bund wall at a considerable distance. Where a double shell construction was used, the outer shell was mainly there to contain the insulation.

These tanks were built in accordance with two British Standards:

BS 4741:1971, *Specification for vertical cylindrical welded steel storage tanks for low temperature service: single wall tanks for temperatures down to – 50 °C.*

BS 5387:1976, *Specification for vertical cylindrical welded storage tanks for low-temperature service: double-wall tanks for temperatures down to – 196 °C.*

Until the 1970s, it was normal practice to store all refrigerated products in single containment tanks. Since that time it has increasingly become the practice for the inner tank for hydrocarbons and ammonia to be surrounded by an outer tank or wall. It is still the practice to store liquid oxygen, liquid nitrogen or liquid argon in single containment tanks. This outer tank or wall is intended to prevent the release of the liquefied products into the surrounding area in case of leakage from or damage to the inner tank. This philosophy results in increased safety for the surrounding area. Such constructions are known as double containment tanks and full containment tanks.

Depending on the lowest service temperature, the inner tank may be made from carbon-manganese steel, low nickel steel, 9 % nickel steel, aluminium or stainless steel. The double containment tanks and full containment tanks generally have outer tanks or walls made from prestressed concrete, reinforced concrete with an earth embankment or one of the metals specified for the inner tank. BS 4741 and BS 5387 specified the requirements for single containment tanks only and consequently did not include the requirements for material selection, design, construction, loading cases, etc. that are necessary for double and full containment tanks.

To redress this situation, the Storage Tank Committee of The Engineering Equipment and Materials Users' Association (EEMUA) published in 1986 *Recommendations for the design and construction of refrigerated liquefied gas storage tanks*, Publication No. 147[1]. The intention of EEMUA was that this document would form the basis of a British Standard to be published a few years later. Together, BS 7777-1 to BS 7777-4 supersede BS 4741:1971 and BS 5387:1976, which are withdrawn.

Although experience has demonstrated that the risk of failure of a single containment tank designed and fabricated in accordance with British Standards is very low, this can be further reduced by more stringent requirements for material selection, design, construction, inspection and testing. For certain stored products, however, the consequences of failure may be considered so great that an outer tank or wall is deemed necessary. Thus a further reduction of risk of failure can be achieved through the use of a double or full containment storage concept. The definitions of single, double and full containment tanks are given in **3.1** of BS 7777-1:1993.

The selection of the storage concept should take into account the location, the operational conditions and the environmental conditions. This standard covers only flat-bottomed, cylindrical, stand-alone, storage tanks. However, it is not intended to exclude the use of other concepts and designs which have been proven in service.

This British Standard comprises four Parts:

— *Part 1: Guide to the general provisions applying for design, construction, installation and operation*;

— *Part 2: Specification for the design and construction of single, double and full containment metal tanks for the storage of liquefied gas at temperatures down to – 165 °C*;

— *Part 3: Recommendations for the design and construction of prestressed and reinforced concrete tanks and tank foundations, and for the design and installation of tank insulation, tank liners and tank coatings*;

— *Part 4: Specification for the design and construction of single containment tanks for the storage of liquid oxygen, liquid nitrogen or liquid argon*.

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 26, 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.

1 Scope

This Part of BS 7777 provides recommendations for the design and construction of prestressed concrete components, reinforced concrete components, foundations, insulation, linings and coatings. The recommendations are applicable to single, double or full containment tanks for above ground installation at service temperatures down to – 165 °C, and single containment tanks down to – 196 °C. Guidance on design criteria for concrete structures, prestressed concrete and prestressing losses for concrete members is given in Annex A, Annex B and Annex C.

NOTE A bibliography is included as Annex D.

2 References

2.1 Normative references

This Part of BS 7777 incorporates, by reference, provisions from specific editions of other publications. These normative references are cited at the appropriate points in the text and the publications are listed on page 26. Subsequent amendments to, or revisions of, any of these publications apply to this Part of BS 7777 only when incorporated in it by updating or revision.

2.2 Informative references

This Part of BS 7777 refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on page 26, but reference should be made to the latest editions.

3 Definitions

For the purposes of this Part of BS 7777, the definitions given in BS 7777-1:1993 apply.

4 Design conditions

Tanks should be designed to suit the pressures that are met in service. Unless otherwise agreed between the purchaser and the manufacturer the internal positive pressure should be not greater than 140 mbar[1)] (gauge), and the internal negative pressure should be not greater than 6 mbar (gauge).

NOTE 1 The internal positive pressure of 140 mbar (gauge) may be exceeded subject to agreement between the purchaser and contractor, but for large diameter tanks the design of the roof to shell joint and anchorage might be limiting (see BS 7777-4).

NOTE 2 For tanks with concrete roofs the internal positive pressure of 140 mbar (gauge) may be exceeded because of increased dead weight.

The lowest service temperature permitted is – 165 °C for tanks conforming to BS 7777-2 and – 196 °C for tanks conforming to BS 7777-4.

5 Information to be exchanged between the purchaser and the contractor

Information to be exchanged between the purchaser and contractor should be as given in clause **5** of BS 7777-1:1993.

6 Materials

6.1 General

All materials utilized should be in accordance with the recommendations of this Part of BS 7777. If alternative materials are utilized, they should conform to written standards and have at least the minimum properties given in the British Standards referred to in **6.2** to **6.7**. The use of alternative materials should be agreed between the purchaser and the contractor.

6.2 Materials for prestressing steel and anchors

NOTE Prestressed concrete is a form of reinforced concrete, which is a heterogeneous material, that is maintained in a state of compression as a result of the tensile forces applied to the prestressing steel tendons within the concrete structure. Residual compression of the concrete is necessary under service load conditions.

The greatest load to the concrete structure occurs during construction, when the tensile load is applied to the prestressing steel tendons or bars. The jacking stress in the steel tendon is normally 65 % to 75 % of the ultimate tensile strength. Thereafter the applied stress to the steel tendons reduces due to lock-off, transfer, relaxation and creep.

The prestressing losses are calculated to determine the residual stress in the tendon (see Annex C).

Normally prestressed concrete for refrigerated liquid gas (RLG) containments utilizes a fully bonded system between the tendons and the concrete. This takes the form of either cementitious grouting of ducts after stressing the tendons or applying a sprayed or pneumatic concrete coating to an externally wire wound prestressing system. It is essential that a reliable system of bonding is utilized and that no likelihood of slippage of the tendon, or any part of it, is envisaged at the design temperature.

From test results it is seen that considerable ductility is retained in prestressing tendons at low temperature. Notch toughness can be reduced but there is no risk of a failure being propagated to adjacent bars or strands of a tendon. Furthermore, within a short distance of a failed bar or strand, full strength is regained because of the bond between the steel and the concrete.

Unlike reinforcing steel for cryogenic use, prestressing steel undergoes maximum tensile stress at ambient temperature during the tensioning process.

The notch ductility of the strand or wire is assumed to be acceptable since the action of cooling a stressed bar or wire with inherent crack-like defects caused by mechanical damage, or by the rolling process, does not induce the probability of brittle fracture. Local yielding of defects during the prestress operation at ambient temperature exceeds the strain for failure at low temperature.

Since the prestress relaxes as a result of prestrain and transfer losses, the critical strain for fracture cannot be achieved for a crack at low temperature. Thus toughness tests on prestressing steel strands or tendons at the design temperature are not necessary.

1) 1 mbar = 10^{-3} bar = 100 N/m^2 = 100 Pa.

6.2.1 ***Tendons***

Prestressing steel in the form of wire, strand or bar should conform to BS 4486:1980 or BS 5896:1980.

With a seven wire strand system, tests should be carried out to the satisfaction of the purchaser to demonstrate that centre wire slippage cannot occur at minimum service temperature.

6.2.2 ***Anchorages***

Anchors for prestressing steel should be in accordance with BS 4447:1973, together with the following.

a) The material from which the anchors are made should be suitable for the temperatures to which they are subject.

NOTE Cast iron is not regarded as suitable for use below – 20 °C.

b) The suitability of the anchors for use at the intended temperatures should be demonstrated to the satisfaction of the purchaser by means of appropriate tests.

c) An anchor system, such as wedge anchors for strand, which involves "pull-in" can result in indentations and thus should be employed only when the purchaser is satisfied, through additional tests, that the strength and toughness properties are not impaired and that the full load-elongation characteristic can be developed.

6.3 Reinforcing steels for concrete

6.3.1 ***Service at ambient temperatures***

Steel bar, wire or mesh for reinforcing concrete which is designed for use at ambient temperature should be in accordance with BS 4449:1988, BS 4482:1985 or BS 4483:1985, as appropriate.

NOTE 1 These specifications include requirements for ductility (elongation) in the tensile test. Purchasers should utilize the available options to ensure that these requirements are met (see **6.3.2**).

NOTE 2 Recommendations are also given in BS 8110-1.

6.3.2 ***Service at temperatures down to* – 20 °C**

For the design of reinforced concrete structure or elements where the design temperature during a normal operating or emergency condition does not fall below – 20 °C, reinforcing bar should conform to **6.3.1** as a minimum.

NOTE BS 4449, BS 4482 and BS 4483 do not include requirements for insuring against the risk of brittle fracture at low temperatures. However, reinforced concrete is a heterogeneous material and the reinforcing elements are separate items. Fracture of one element entails a redistribution of its load over adjacent elements without propagating its failure to those elements.

6.3.3 ***Service at temperatures below* – 20 °C**

For the design of reinforced concrete structure or elements where the design temperature during a normal operating or emergency condition falls below – 20 °C, steel reinforcement should conform to **6.3.1**, and in addition one of the following alternatives should be adopted.

a) Steel that meets the ductility and toughness recommended in **6.3.4**.

NOTE 1 This may be carbon manganese steel, 9 % nickel steel or austenitic stainless steel.

b) Reinforcing or prestressing steel with reduced allowable tensile stress.

NOTE 2 ANSI/NFPA 59A:1990[2] recommends a maximum allowable tensile stress for reinforcement for service temperatures down to – 165 °C. This is significantly lower than the stress permitted for ambient temperature, and may result in an uneconomic design, but can be justified where special steel is not available.

NOTE 3 Whilst the design temperature for the tank is deemed to be the product temperature, the design temperature for the embedded bar may be calculated assuming the temperature gradient that is present in the concrete component.

Table 1 lists the materials that should be used and their allowable tensile stresses in non-tensioned reinforcement for service at temperatures down to – 165 °C.

Table 1 — Allowable tensile stresses in non-tensioned reinforcement for service at temperatures down to – 165 °C

Reinforcing steel (conforming to BS 4449, BS 4482 or BS 4483)	
Diameter (d) mm	**Allowable tensile stress** N/mm^2
$d \leq 12$	82.7
$12 < d \leq 25$	68.9
$d > 25$	55.2
Prestressing steel (conforming to BS 4486 or BS 5896)	
Crack control applications	206.8
Other applications	552

6.3.4 ***Toughness and ductility***

6.3.4.1 *General*

The ductility and toughness of carbon steel, carbon-manganese steel or ferritic alloy steel for reinforcing bars should be determined for applications where the design is for service below – 20 °C. Tests for ductility and toughness should be in accordance with **6.3.4.2**.

NOTE Reinforcing steel undergoes a decrease in ductility with decreasing temperature, whilst experiencing an increase in both yield strength and ultimate tensile strength.

Where reinforcement is required for serviceability or loading conditions at above – 20 °C only, and is not required to meet performance criteria when the concrete is subjected to the product temperature, the steel need not conform to the recommendations for toughness given in **6.3.4.1**. This would include reinforcement required for conditions such as shrinkage control, fire resistance, etc.

Fully-finished bar should be sampled from two production heats, from the maximum and minimum sample size for the order and from all strength grades to be used.

6.3.4.2 *Testing*

The manufacturing procedure for reinforcing bar should be approved by the purchaser and qualified in respect of toughness (see **6.3.4.3**). The supplier should not deviate from the qualified procedure without the prior approval of the purchaser. During the test, the specimen temperature should be as uniform as possible. The difference between the temperature at any two points of the specimen or the difference between the temperature at any point and the design temperature should not exceed 5 °C.

The steel manufacturer should be given full details of the temperature operating range including test temperature.

Tensile tests in accordance with **C.1.2** to **C.1.4** of BS 4449:1988 and as stated below should be conducted on unnotched and notched bar specimens at the design temperature supplied by the purchaser. Tensile tests on notched bar specimens should be carried out and compared with the results on unnotched bar specimens to establish the notch sensitivity at the design temperature.

NOTE 1 The purchaser may require a temperature/notch sensitivity transition graph for which the notch sensitivity ratio can be determined at sufficient intervals to accurately plot the transition curve. The results should be submitted to the purchaser to demonstrate that the requirements of **6.3.4.2** have been met.

Test pieces cut from a length of reinforcing bar for testing in a cooling chamber should be between 500 mm and 1 000 mm, depending on diameter, but should be not less than 15 × diameter. The test temperature should be the lowest design temperature that the reinforcement bar would be subjected to under abnormal loading conditions.

Tensile tests should be carried out at the design temperature to establish the strain during a tensile load test. For an unnotched bar the tensile test should establish the lower yield stress (for hot rolled bars) or the 0.2 % proof stress (for cold rolled bars). The percentage plastic elongation should be measured over a minimum gauge length (L_o) of 100 mm taken at a position at least $2d$ away from the point of subsequent fracture, where d is the diameter of the bar. (This is to avoid the possibility of measuring at a point at the onset of constriction of the test piece. See Figure 1 a).)

Each specimen should demonstrate a percentage plastic elongation of at least 3 %.

The notch sensitivity ratio (NSR) should be determined where:

$$\text{NSR} = \frac{\text{Tensile strength of notched bar}}{\text{0.2 \% proof stress of unnotched bar}} \text{ or } \frac{\text{Tensile strength of notched bar}}{\text{Lower yield stress of unnotched bar}}$$

The test specimens should be taken from adjacent positions in the same bar. NSR ≥ 1 should be achieved for acceptable specimen toughness.

The test specimen for notched bar tests should be notched at the half length position between the machine grips. A V-notch should be used that has an internal angle of 45° and a radius at the base of 0.25 mm. Machining techniques and tolerances should be in accordance with BS EN 10045-1:1990. For longitudinal ribbed bars the notch should be placed across the rib and penetrate 1 mm into the underlying bar. For transverse ribbed bars the notch should be placed on the crown (see Figure 2). The percentage plastic elongation over a section with a minimum gauge length (L_o) of 100 mm separated from the notch by a minimum distance of $2d$, should be not less than 1 % [see Figure 1 b)].

NOTE 2 The above tests apply to straight unbent bars only.

Retests should be in accordance with clause **12** of BS 4449:1988. The loading rate on the specimen is limited such that the maximum stress increase rate is 180 N/mm^2 per minute in the elastic range and the maximum strain rate is 0.15 % per minute in the plastic range.

The percentage plastic elongation is the permanent percentile increase of the original gauge length (L_o) corresponding to tensile strength R_m.

6.3.4.3 *Certification of reinforcing steel*

For reinforcing steel the manufacturer should certify the following information:

a) the steelmaking process;

b) the chemical composition and range for C, Si, Mn, Ni, P, S, Nb, V, Ti, and Al;

c) typical residual levels of Cr, Mo and Cu from recent production records;

d) the billet reheating temperature;

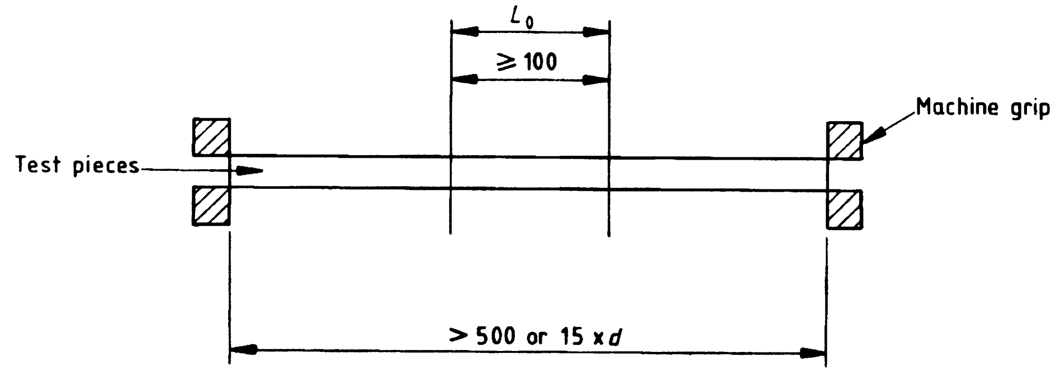
e) the finish rolling temperature;

f) the controlled cooling conditions, if applicable.

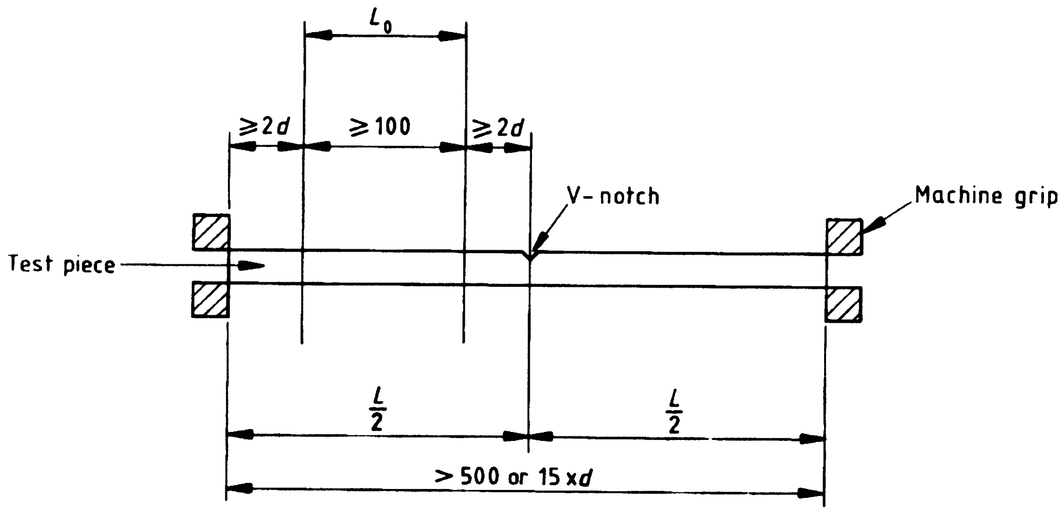
6.4 Concrete

Prestressed concrete should conform to at least grade C40 of BS 5328-1:1991.

NOTE 1 The enhanced properties that are known to exist for concrete as a material of construction at low temperature should not be used in determining the material safety factors. However, the reduced expansion coefficient should be utilized. Recommendations for concrete and its constituents are given in BS 5328-1.



a) Unnotched bar



b) Notched bar

Figure 1 — Reinforcement bar specimen dimensions for testing at the design temperature in a cooling chamber

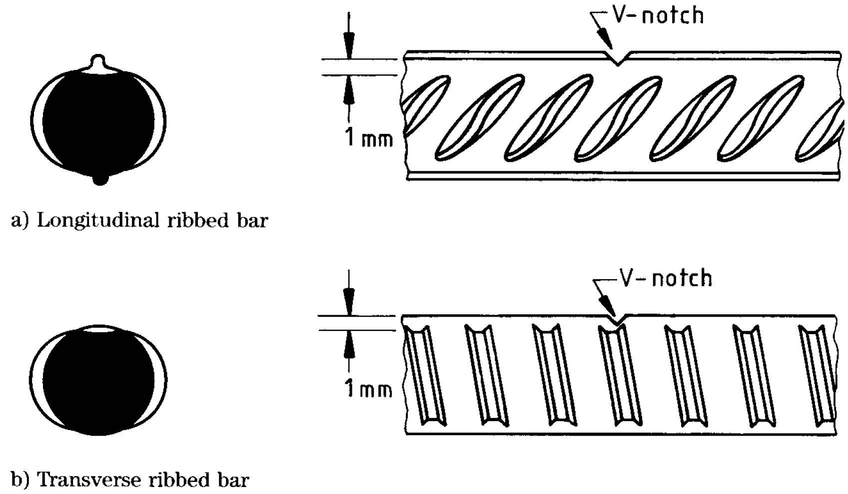


Figure 2 — Notch on reinforcement bar

The concrete mix should be such that the concrete has acceptable properties with respect to the following:

a) impermeability;

b) freedom from cracks;

c) fire resistance;

d) behaviour at low temperature;

e) durability;

f) resistance to sulphate and chloride attack.

The mix should be designed to reduce the bulk water content such that internal ice formation, and hence internal cracking, is minimized. The water/cement ratio should not exceed 0.5. The use of plasticizers is permissible to obtain adequate workability.

NOTE 2 A low water/cement ratio reduces the pore water within the concrete matrix. The freezing of pore water causes an expansion of about 9 %. Some of this expansion is taken up within existing air voids but, if there is excessive water, internal cracking of the concrete can result.

The concrete mix may contain up to 5 % entrained air. Where the concrete can be subject to freeze/thaw cycles, tests should be carried out to demonstrate the suitability of the selected concrete mix.

Mixing, transportation, placing, curing and testing should be undertaken in accordance with BS 8110-1:1985 and BS 5328-1:1991, BS 5328-2:1991, BS 5328-3:1990 and BS 5328-4:1990.

NOTE 3 Ground granulated blast furnace slag (g.g.b.s.) or pulverised fuel ash (p.f.a.) may be used with conventional Portland cement.

NOTE 4 The use of g.g.b.s. or p.f.a. assists in reducing the heat of hydration of thick concrete sections and thus reducing the early thermal shrinkage. Natural uncrushed aggregates of high strength and low porosity are preferred to ensure maximum frost resistance.

6.5 Earth fill

The fill for the embankment should consist of selected material which is not sensitive to excessive consolidation.

Materials with a compacted density higher than 1 750 kg/m^3 and an angle of internal friction of at least 30° are preferred, e.g. sands and gravels.

NOTE 1 Granular soils placed and compacted in layers form high quality fill material. For compaction it is preferred that the material is not single-sized, but contains variation in grain size.

The permeability of the fill should be determined so that pore water pressure cannot develop during construction of the embankment.

NOTE 2 Significant settlement of an embankment may damage the slope protection and the roads located on the embankment. In addition it produces a downward loading on the wall due to friction between soil and the concrete of the wall.

Weak rock, such as mudstone, shales, marl and chalk, should not be used for heavily loaded embankments.

Soil with 35 % or more material by volume finer than 0.06 mm, organic soil or peat should not be used for embankment filling.

NOTE 3 Cohesive soils have a low permeability and this may result in very little consolidation during the construction of the embankment. It is essential that careful examination of the predicted consolidation settlement be made with cohesive soils. The installation of adequate drainage to prevent hydraulic pressure build up is recommended.

Material for the drainage layer should be selected to consist of rock or coarse fill with a silt and clay content limited to 4 % (*V*/*V*).

NOTE 4 At some locations the subsoil consists of impermeable material and a bottom drainage layer under the tank and the embankment may be required.

NOTE 5 Limiting the silt and clay content prevents clogging of the drainage system.

The drainage layer should be protected by a filter layer so that fine material from the embankment fill cannot penetrate into the coarse material.

NOTE 6 As an alternative to natural filter layers various geotextile materials can be used.

6.6 Insulation materials

6.6.1 *General*

The base insulation material should be capable of supporting the tank contents through the base plates.

A suitable filling arrangement for the annular space insulation should be used, such that the filling densities specified by the manufacturer are achieved. Provision should be made to allow for the replenishment of the system.

The insulation materials may be divided into the following categories:

- — tank base insulation;
- — tank shell internal insulation;
- — tank shell exterior insulation;
- — roof insulation;
- — suspended deck insulation.

The material selected for the base insulation should provide the necessary load bearing capacity as well as the required thermal characteristics.

Table 2 gives an overview of insulation materials used for various purposes.

6.6.2 *Chemical properties of insulation materials*

The resistance to liquefied gases of the insulation material should be determined. The chemical properties of the insulation material should be checked to ensure that there is no chemical reaction with the stored product.

NOTE If water penetrates some insulation materials, such as polyurethane, polyisocyanurate or phenolic, an acidic condition may be set up. This may corrode unprotected steel and is a reason for ensuring that water is eliminated.

Table 2 — Insulation materials for refrigerated storage

Typical examples of insulation materials	Location in tank						
	Tank base	Single tank outside of shell	Double tank inside of outer shell	Double tank outside of inner shell	Double tank inner/outer shell interspace	Suspended deck	Single tank roof
Cellular glass	×	×		×			×
Perlite concrete	×						
Foamed or aerated concrete	×						
Plastics foam (e.g. polystyrene) concrete	×						
Timber	×						
Polyvinyl chloride foam		×	×	×			×
Polyisocyanurate foam		×	×	×			×
Phenolic foam		×	×	×			×
Polystyrene foam		×	×	×			×
Polyurethane foam		×	×	×			×
Glass reinforced polyurethane foam		×	×	×			
Mineral wool or glass fibre blankets				×[a]		×	
Loose fill insulants; expanded perlite or vermiculite					×	×[b]	

[a] Used in combination with loose fill insulants normally for its mechanical properties.
[b] Normally used in bagged form.

6.6.3 ***Mechanical properties of insulation materials***

Insulation material located beneath a tank bottom should be able to withstand the load imposed upon it. The allowable compressive stress for service and test conditions for cellular glass should be either 0.33 times the guaranteed average compressive strength or 0.5 times the guaranteed minimum strength of the grade selected, whichever is less.

NOTE 1 Other materials can be used in the same manner but the guaranteed minimum compressive strength values should be used rather than average values.

Insulation materials should be suitable for use over the thermal range envisaged. The mechanical properties of the insulants should withstand the forces induced during cool-down, and any thermal cycling during service.

NOTE 2 Cool-down should be as gradual as possible.

NOTE 3 Most plastic foams have a coefficient of linear expansion 6 to 20 times that of steel. This effect should be taken into account in the design.

Where insulation materials, especially plastic foams, have properties which vary according to the direction of foaming during manufacture, i.e. the properties are anisotropic, such variations should be taken into account in design and during installation.

NOTE 4 It is possible to apply some grades of polyurethane foam by spraying, rather than by laying blocks. This application is a specialist operation and requires experienced contractors.

Blocks should be statistically sampled and checked for conformity with properties specified in the design.

Differential movement between blocks and substrate, caused by the thermal gradient, should be considered.

6.6.4 ***Fire***

The possibility of fire in an adjacent tank should be taken into account when insulation is designed for refrigerated storage tanks. Smoke and toxic fume generation during a fire should also be considered.

NOTE 1 Tank spacing, water deluge systems, quantity, flammability, locality, vulnerability and the implications of potential loss of product are factors which should be considered when specifying insulating materials, particularly where it is proposed to use a plastic foam insulant.

NOTE 2 Unmodified polyurethane has a high flammability constant. The most convenient way of determining fire resistance on a small scale is to use the limiting oxygen index test given in ASTM D2863[3]. The test measures the quantity of oxygen necessary to sustain burning of a small sample of the plastic foam, but it does not simulate what might happen in a real-life situation. Materials which require a higher percentage of oxygen to burn than the 21 % present in the atmosphere have some fire retarding capability.

6.7 Liners and membranes

6.7.1 ***Steel liners and membranes not exposed to refrigerated liquid***

The materials for liners and membranes for concrete outer tanks, where the liner is not exposed to the refrigerated temperature, should be in accordance with Table 6 of BS 7777-2:1993.

6.7.2 ***Steel liners and membranes exposed to refrigerated liquid***

Where contact with a product occurs as a result of spillage and/or leakage, the material of liners and membranes should be selected to withstand the product temperature. (See the material types listed for double or full containment in Table 2 of BS 7777-2:1993.)

Where contact with the product is not likely to occur, materials in accordance with Table 6 of BS 7777-2:1993 may be used, by agreement between the purchaser and the contractor. Typically, liners considered to have a low risk of contact with the product are either those covered with insulation, or that part of the liner above the agreed height necessary to cope with a minor spillage or leakage.

6.7.3 ***Non-metallic liner materials***

Non-metallic liner materials such as epoxy coatings should be subject to testing to ensure leak resistance and durability.

7 Foundations

7.1 General

The foundations of refrigerated storage tanks should support the design loadings and ensure structural integrity.

Foundation design should be in accordance with BS 8004:1986.

NOTE Because of the wide variety of soils, surface and subsurface, climatic conditions and the concept for storage, it is not practicable to cover all situations. The allowable soil loading and foundation system can only be decided for each individual case.

The design of the foundations for liquefied gas storage tanks should take into account the following aspects:

a) imposed loads represent a major proportion of the total gravity load;

b) imposed loads are frequently fully attained, but can also vary frequently as the contained liquid level is changed;

c) the contents of a liquefied gas storage system represent a high concentration of energy where accidental release could have severe consequences;

d) the low temperature of the tank contents could, unless protective measures are adopted in the foundation system, cause problems of ground freezing and frost heave for certain types of soil and rock.

7.2 Soil investigation

7.2.1 *General*

Prior to the design and construction of the foundation, a geotechnical investigation should be conducted by a qualified geotechnical engineer. This should determine the stratigraphy and the physical properties of the soils underlying the site.

The soils investigation should be carried out in accordance with BS 5930:1981. The soil thermal conductivity and electrical conductivity for earthing requirements should be determined.

Information should be obtained from a review of the regional geology and subsurface conditions, and the history of similar structures in the vicinity.

7.2.2 *Ground water investigation*

Full details, including seasonal variations, of the depth of the ground water table, including any perched water tables and subsurface water flows, should be obtained for the area of planned storage.

Data on the permeability of the soils and the susceptibility to frost heave should be identified.

Consideration should be given to possible changes in the ground water regime from construction works.

7.3 Seismic investigation

A seismic investigation should be carried out for an RLG storage system, in view of potential hazards arising from leakage.

The extent of the investigation required should depend on the assessment of seismic intensity for the site and the recurrence interval, consistent with the risk level assumed in the design.

NOTE No country is entirely free from earth tremors, though their effects may be insignificant in the design of conventional structures. Reference should be made to Annex B of BS 7777-1:1993.

7.4 Site selection

The following sites should be avoided, where economic considerations permit the selection of alternative areas:

a) sites where part of a tank is on rock or other firm undisturbed ground, and part is on fill, sites where the depth of required fill is variable, and sites where ground under part of the tank area has been pre-consolidated;

b) sites on swamps or where layers of highly compressible material are below the surface;

c) sites where stability of the ground is questionable, e.g. adjacent to deep water courses, mining operations, excavations or steeply sloping hillsides, karst topography or gypsiferous materials which could include weak lenses subject to dilution;

d) sites where tanks may be exposed to flood waters, resulting in possible uplift, displacement or scour, or conversely sites where any subsequent lowering of the groundwater table could lead to additional differential settlement;

e) sites near to active faults or on soils susceptible to liquefaction in areas subject to earthquakes.

7.5 Foundation design

7.5.1 *General*

The tank base and foundation of the containment system should be designed to transmit all loads to suitable load bearing strata. The tank base and foundation should be impermeable to the stored product in the event of leakage and should be able to withstand the anticipated differential and total settlement.

The design should conform to BS 8004:1986 and take account of the nature of the soil/structure interaction, the definition of the liquid loads and tank foundation settlement, frost heave of underlying soil and of earthquake loading.

7.5.2 *Loading conditions*

The different stages of the life of the structure, i.e construction, testing, commissioning, service and maintenance, should be considered in the design. Any abnormal events, e.g. earthquake, fire, etc., should be considered.

Normal service loads and the abnormal loads that should be taken into account are given in BS 7777-1:1993.

7.5.3 *Allowable soil loading*

The allowable bearing pressure of the soil should be determined.

NOTE This is determined from a geotechnical investigation, in which there is consideration of the extent, reliability and confidence in predictions of the ultimate bearing capacity and settlement. Advantage may be taken of modern computer techniques to investigate soil/structure interaction, in addition to traditional analysis.

7.5.4 *Settlement*

The maximum total and/or differential settlement during the life of the tank should be within the permissible settlement limit.

The permissible settlement limit should be the maximum for the deformation of the tank, after allowance has been made for construction tolerances. The limit should be agreed between the foundation designer and tank designer for the maximum total and/or differential settlement.

The differential settlement limits given in Table 3 may be used for guidance. The total settlement of the foundation may be large when the foundation is in a cohesive soil, due to consolidation of the resultant large stressed zone. The above settlement limits may be modified to suit the specific details of the design of the tank and ancillary equipment and should be agreed with the purchaser and contractor(s). Although much of the settlement will occur before commissioning, it should be ensured that connections to adjacent plant, pipework, etc., will accept any residual, relative, settlements.

NOTE Considerations affecting the permissible settlement limit include, but are not limited to, the following:

a) the dimensions and aspect ratio of the tank;

b) the stiffness of the foundation;

c) the stiffness of the tank and its components;

d) the reliability of the investigation;

e) the possibility of interactive effects with adjacent tanks and integral earth embankments.

Table 3 — Differential settlement limits

Type of settlement	Differential settlement limit
Tilt of the tank	1 : 500
Tank floor settlement along a radial line from the periphery to the tank centre	1 : 300
Settlement around the periphery of the tank	1 : 500 but not exceeding the maximum settlement limit calculated for tilt of the tank

Settlement should be monitored during the various phases in the life of the installation, including construction, hydrostatic testing, commissioning and operation. Special conduits buried in the foundation should be provided for instrumentation. The location and number of conduits provided should be commensurate with the accuracy required for the assessment of total and differential settlement in the critical areas. The monitoring frequency should be commensurate with the predicted time, and load dependent rate of change of settlement.

The accuracy and repeatability of instruments should be compatible with the sensitivity of the structure. Redundancy should be built into the instrumentation system to allow for instrumentation failures.

Where the subsoil supporting the foundation is unable to carry the load of a full tank without excessive settlement, the following methods of improvement should be considered:

a) removal and replacement of unsatisfactory material by suitable compacted granular fill that is not frost susceptible;

b) improvement of soft or loose material by vibration or dynamic compaction;

c) pre-loading with a temporary overburden;

d) enhanced subsoil drainage with pre-loading;

e) stabilization by chemical or grout injection;

f) piling.

7.5.5 *Frost heave*

Frost heave should be avoided.

NOTE The ground beneath a refrigerated tank loses heat to the tank, although the tank floor construction incorporates insulation. This loss of heat from the soil could lead to frost heave.

Common means of avoiding frost heave are as follows:

a) the use of electrical heating elements within ducts or warm-water circulating systems, located within the subgrade or more usually within the concrete base slab where such systems are readily serviceable and replaceable;

b) elevation of the base slab above ground level so as to allow circulation of air below the tank.

The foundation designer should define the minimum control temperature assumed for the foundation design. The temperature of the supporting soil or concrete, during normal operation, should be not less than 4 °C.

Where the soil of a foundation is sensitive to drying and shrinkage a maximum foundation temperature should be defined.

If a heating system is used it should be designed to minimize excessive temperatures that could lead to high boil-off rates, and to permit functional and performance monitoring. The arrangement should take account of any variations in the heat transfer characteristics of the materials of construction, particularly around the tank perimeter or around a bottom entry, if applicable.

The heating system should be installed so that any heating element or temperature sensor used for control is readily replaceable. The design of the system should be such as to permit the regular monitoring of its performance.

7.5.6 *Drainage*

Areas around storage tanks should be drained away from the tank to prevent water accumulation around the foundations. This should include firewater run-off, where applicable.

Control systems should be provided to prevent the product contaminating the drainage system in the event of spillage.

For single containment and double containment concepts the sealing arrangements around the base of the tank and the insulation cladding should be detailed to eliminate the possibility of water migration to the cold tank surfaces and foundations.

7.5.7 ***Resistance to uplift***

Steel tanks will require anchorages to resist uplift of the shell due to the effects of internal tank vapour pressure, wind load or earthquake. Straps should be located uniformly around the perimeter of the tank and anchored into the concrete base and be adequately protected from corrosion.

7.6 Types of foundation and tank base

7.6.1 ***General***

Four types of foundation should be considered for use in refrigerated storage schemes:

a) ring beam;

b) surface raft;

c) pile supported base;

d) elevated slab.

7.6.2 ***Ring beam foundations***

Where the surface and subsurface soil can support applied loads from the tank and contents, an earth mound foundation should be considered.

A concrete ring beam should resist uplift of the shell of a single containment tank or the inner shell of a double containment tank, due to internal vapour pressure. The ring beam should also resist the vertical loads of the shell and ensure that differential settlement to the earth mound foundation is limited.

Particular attention should be given to the ring beam to earth mound interface to avoid a sharp change in bearing medium. A transition support should be provided.

The ring beam should be designed to withstand horizontal pressures from the contained earth mound including all surcharge effects from the tank and contents.

7.6.3 ***Surface raft foundations***

Where subsurface soils have the necessary properties to support designated loadings, a soil supported reinforced concrete surface raft should be considered.

NOTE 1 This raft or slab normally incorporates an increased thickness as necessary under the shell of single containment tanks or the inner and outer walls of double or full containment tank, depending on the loads that apply.

In the design of the slab, provision should be made for the effects of local differential settlement, drying shrinkage, creep and thermal strain during service or under upset conditions.

Where an outer concrete tank with an earth embankment is used, the high concentration of load from the outer wall combined with vertical load from the embankment may require a separate foundation for the wall at a level below the underside of the base slab. Either a design with part of the base slab integral with the wall or a design with a vertical slip joint between base slab and wall may be considered.

NOTE 2 The use of a bitumen slip layer on the external face of the wall minimizes the friction downdrag from the embankment. Special measures may still be necessary to minimize differential settlement between the wall and base slab so that the integrity of the membrane and heating conduits is not impaired.

7.6.4 ***Pile supported base***

Where subsoil conditions do not permit a near-surface soil supported foundation, the base should be supported on piles. Pile design and installation should be in accordance with BS 8004:1986.

Where a displacement pile system is adopted ground heave and/or pile heave due to frost should be considered.

The base design should take account of variations in pile stiffness. The integrity of the piles should be checked and tested on completion of installation. Unless the design of the piling system is such that it is possible to prove the integrity of each pile by field test, consideration should be given to designing the base and pile system to accommodate a redistribution of load in the event of failure of an individual pile.

NOTE 1 Drying shrinkage, creep, thermal changes and cold spots due to small leaks cause horizontal deformations in the base. The amount of this deformation decays towards the centre of the base.

NOTE 2 Vertical thermal gradients in the base induce moments in the base and rigidly connected piles. In a double or full containment tank, horizontal forces and moments from upset conditions or abnormal loads on the storage tank may also be transferred to the base slab.

NOTE 3 Consideration should be given to the joint between pile supports and the base. If the subsoil characteristics are suitable, closely spaced slender piles can be rigidly connected to the base. Where large diameter in-situ formed piles are used it is possible to use rigid connections for the piles near the centre of the tank, but to provide a sliding joint for the remainder.

7.6.5 ***Elevated slab foundation***

The use of an elevated slab should be considered where it is undesirable or uneconomic to install and maintain heating elements.

NOTE 1 The concrete slab of the tank floor enables free circulation of air beneath. Heat loss from the ground to the tank via the support columns is thus minimized.

NOTE 2 The concrete slab is supported by closely spaced columns. These may be extensions of piles or based on shallow foundations, depending upon the type of subsoil.

The clear space beneath the concrete slab should be not less than 1.5 m above ground level to permit access for inspection and maintenance.

The ground beneath the tank should be graded to prevent liquid pooling beneath the tank.

The clear space beneath an elevated slab foundation should be provided with gas detection equipment.

NOTE 3 The ventilation may be insufficient to prevent the formation of gas pockets emanating from leaks in the storage system or associated piping.

The recommendations given in **7.6.4** should apply to elevated slabs, whether the columns are supported by piled foundations or shallow foundations.

Where there is a possibility of a spill that would be sufficient to flood the underlying clear space with refrigerated liquid gas, consideration should be given to the thermal effect on the elevated slab and the adjacent ground.

7.7 Level tolerances

Tank base surfaces under the shell plates should be laid to a level tolerance of ± 6 mm in 10 m and ± 12 mm between any two points around the perimeter.

8 Prestressed concrete outer tank

8.1 General

Prestressed concrete tanks are normally selected rather than reinforced concrete tanks for economic reasons.

NOTE A brief description of prestressing methods and systems is given in Annex B.

Prestressed concrete outer container loadings should be in accordance with clause **7** of BS 7777-1:1993.

NOTE The principle upon which prestressed concrete is founded is that a predetermined compressive force is applied to a member or structure, to achieve a controlled change in its behavioural properties.

8.2 Prestressing system

Circumferential prestress to circular tanks should be provided by means of the following techniques:

a) horizontal tendons positioned in ducts within the concrete wall of the tank, extending between the buttresses formed on the outer face of the tank wall; or

b) an aggregation of tendons formed by winding wire or strand around the outer face of the wall.

NOTE 1 Winding systems tension prestressing wire by drawing it through a die or by using a differential system which releases wire onto the face of the tank at a rate less than the rate of movement of the stressing carriage and thereby subjects it to tensile strain. The stressing carriage is suspended from a top cradle and propels itself around the tank by means of a continuous chain.

In recent practice, the wires have been concentrated in a number of separate bands, rather than spread over the whole exterior of the tank. A band may include several hundred wires, in multiple layers, with each layer embedded in sprayed concrete or mortar, and each completed band protected by a further layer of protective mortar.

NOTE 2 Where linear prestressing techniques are used, the tendons are embedded within the concrete, and are anchored at stressing piers.

Cylindrical walls can be prestressed both vertically and circumferentially. The vertical prestress is applied before the horizontal prestress. This gives the wall capacity to accommodate vertical bending, induced during the circumferential prestressing, induced by the liquid load and/or induced by thermal gradients that might otherwise cause horizontal cracking.

Non-tensioned reinforcement is often used in addition to control cracking.

8.3 Loss of prestress

NOTE 1 The total loss of stress in prestressing steel is the sum of the individual losses calculated from transfer, creep, shrinkage, friction, curvature and relaxation.

Losses should be calculated in accordance with BS 8110-1:1985. Guidance on calculating losses is given in Annex C.

NOTE 2 The prestress in the steel, and thus in the concrete, reduces over a period of time from various losses. These are principally due to shrinkage and creep of the concrete and relaxation of the steel. In the case of post-tensioning by means of tendons, there is also pull-in at the anchorages and friction between tendon and duct from the stressing operation.

NOTE 3 It is necessary to use high strength steels and high initial stress levels to ensure an adequate level of stress after the losses have occurred. It is also necessary to use concrete with a high quality level, with a strength of 40 N/mm^2 or more.

NOTE 4 Long tendon layouts are generally preferred since, when fewer tendons are used, congestion at the stressing buttresses is reduced.

8.4 Design of tendons

The design of the prestressed tendons should be in accordance with BS 8110-1:1985.

NOTE 1 Bonded tendons are normally used as a means of applying prestress to the tank walls.

Where linear tendons are employed, a choice can be made between bonded tendons, which are placed within metal ducts and subsequently grouted, and non-bonded tendons which comprise strands or bars individually greased and sleeved in polyethylene or polypropylene, before delivery. Those are cast directly into the concrete without ducts, and no subsequent grouting is needed.

Both types of tendons have a similar performance under normal service conditions, but their behaviour differs under abnormal conditions. With bonded tendons, a large number of narrow cracks are developed in the concrete. With non-bonded tendons a small number of wide cracks tend to appear and it may be necessary to use additional non-tensioned reinforcement for crack control purposes.

Non-bonded tendons rely solely for their performance on the integrity of the anchors. Bonded tendons, on the other hand, derive additional security from the grout.

Transfer and residual stresses should be taken into account. The amount of prestress should be calculated taking into account all losses.

NOTE 2 Although not considered for design purposes (except at transfer), concrete exhibits some tensile strength. At low temperature the tensile strength increases.

The total tensile load capacity of the tendons, including any non-stressed reinforcement, should be greater than the tensile load capacity of the concrete tank wall at the design temperature.

NOTE 3 This is to ensure that, in the event of overloading, sudden failure or bursting of the tank in a brittle manner is a non-credible event.

The layout of tendons, particularly adjacent to the stressing buttresses, should be considered early in the design process to ensure that practical details are attainable and that the anchorages and all necessary end-block reinforcement are accommodated.

NOTE 4 This is necessary so that the subsequent placing and consolidation of the concrete is not prejudiced.

8.5 Position of tendons

When horizontal tendons are positioned both stress distribution and fire resistance should be taken into account.

Circumferential prestressing steel should be placed on the outside of the vertical tendons at the centre of the wall.

8.6 Protection of tendons

Tendons should be protected from corrosion during the life of the tank. The adequacy of the corrosion protection system should be demonstrable.

Protection of tendons should be in accordance with BS 8110-1:1985.

NOTE 1 For non-bonded tendons reference should be made to FIP Recommendation 91[4].

NOTE 2 Precautions need to be stringent in the case of wire winding systems where the tendons are placed on the outer surface of the wall and obtain their protection from sprayed mortar. Materials and workmanship both require a high level of control.

8.7 Design of concrete structure

8.7.1 *General*

Design of the concrete structure should be in accordance with BS 8110-1:1985 and BS 8110-2:1985 and BS 8007:1987 (see also ANSI/NFPA 59 A [2].

The loading combinations which could occur during the construction and operational lifetime of the tank should be determined.

NOTE BS 8110-1 provides load and material factors for construction and normal operation. For emergency load combinations, such as fires, earthquakes and inner tank leakages, no factors are provided, but reduced factors may be used due to the low probability of such an event (see Annex A).

8.7.2 *Stress*

Under maximum design loading conditions, including the liquid and the temperature loading due to inner tank leakage, the minimum residual average compressive stress of 1.0 N/mm^2 should be provided in the principal direction(s) of the prestress.

NOTE 1 Allowance should be made for all losses.

NOTE 2 The purchaser may also specify other stress requirements for abnormal loads and conditions.

Thermal stresses caused by either transient or steady state conditions should be calculated and combined with other externally and internally induced stresses to assess whether the residual compression zone is adequate to maintain liquid tightness of the concrete section.

8.7.3 *Base*

The tank base should be either prestressed or reinforced concrete.

NOTE With prestressed concrete the base is conventionally a continuous slab. If piles are employed, provision should be made to allow the slab to slide relative to the piles. Otherwise, the amount of prestress transferred to the piles, due to shear at the interface of piles and slab, may be excessive.

With reinforced concrete the base may be cast as a continuous slab or may be divided into a number of relatively small bays with the junctions bridged by cryogenic expansion/contraction joints.

The base design should take into account, where applicable, the interaction with a liner or membrane. The base design should ensure that all strains from tank loading, shrinkage, etc., are compatible with the type and material of the liner used.

8.7.4 *Wall*

The application of prestressed concrete walls should relate to components which are not subject to product temperature during normal service conditions.

NOTE 1 The design and construction of walls for concrete refrigerated storage tanks follow the same principles as for similar cylindrical prestressed structures, for which other structural codes and standards have been developed, e.g. BS 8007.

NOTE 2 Circumferential prestress is used to maintain concrete walls in compression when subjected to an internal hydrostatic load generated by the accidental release of the contents of the inner tank.

NOTE 3 Vertical prestress is commonly used to enable the wall to accommodate the differential stresses generated in the event of inner tank leakage.

8.7.5 *Wall to base junction*

For the design of the wall to base junction, the following should be taken into account:

a) liquid tightness for double containment and liquid and gas tightness for full containment;

b) differential radial compressive movement or strain;

c) radial thermal contraction or expansion, either at the service condition or abnormal conditions specified in the design philosophy;

d) resistance to any abnormal loads specified in the design philosophy;

e) liner and insulation displacements at the junctions.

The method of construction and the position of the wall membrane, whether internal, external or embedded, and its ability to resist low temperature should also be considered.

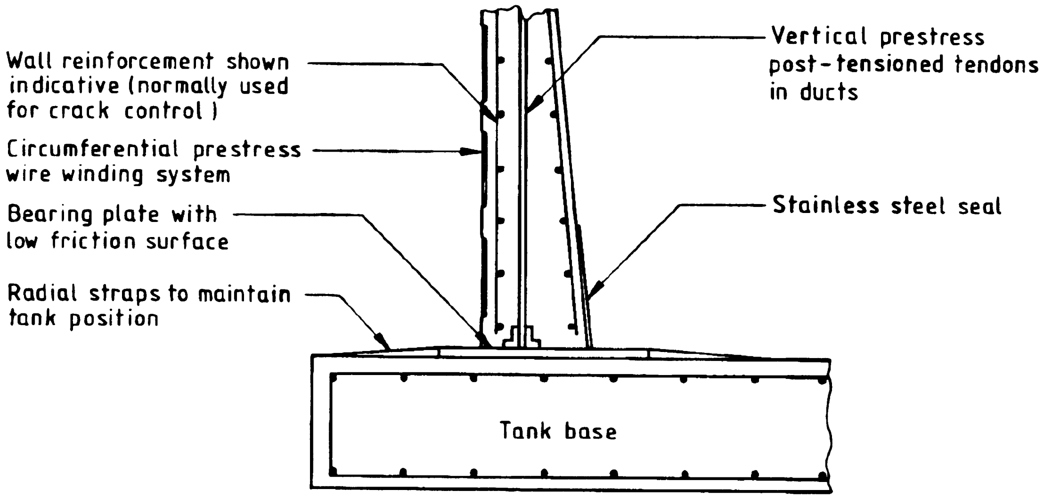
NOTE 1 The design of the junction of the wall and base is crucial for the integrity of the whole outer tank.

NOTE 2 When circumferential prestress is applied the containment wall tends to contract. If under emergency conditions the wall is loaded by internal pressure from a cryogenic liquid, it tends first to expand, by an amount slightly less than the previous compression, due to the pressure of liquid. Thereafter this expansion is reduced over a period of hours by shrinkage due to thermal effects.

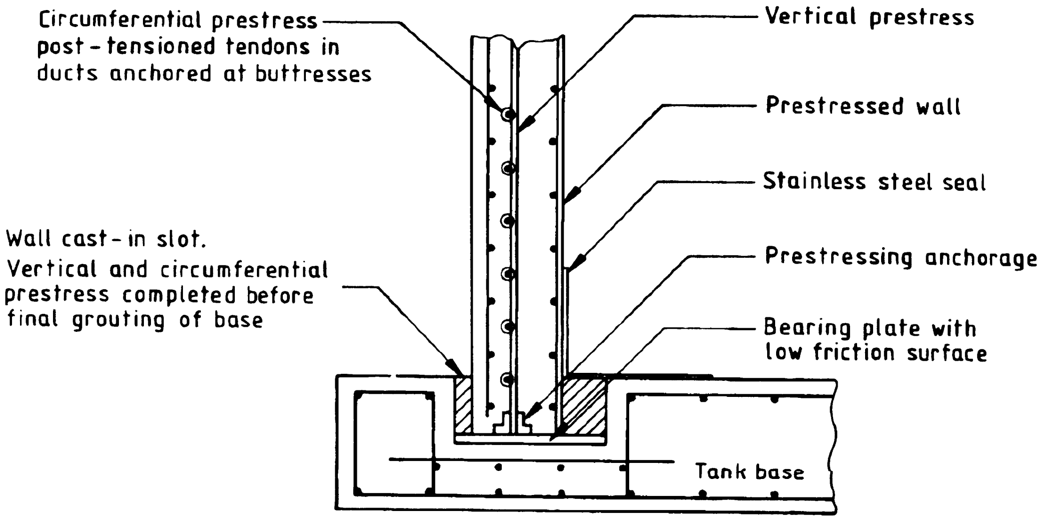
NOTE 3 Radial thermal contraction or expansion may be caused by thermal shock.

NOTE 4 Typical abnormal loads that should be specified are blast, fire or seismic.

Three designs of joint should be considered: sliding, pinned or fixed (see Figure 3).

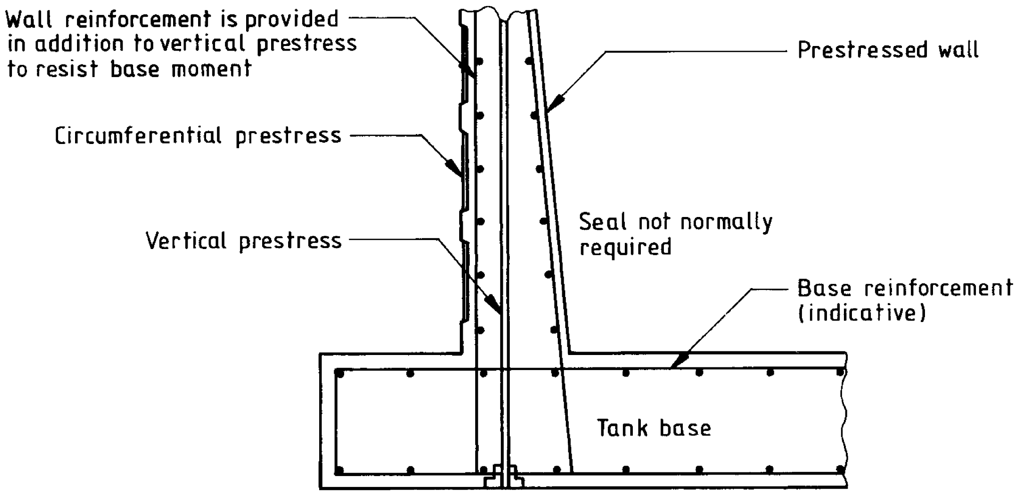


a) Sliding joint



b) Pinned joint

Figure 3 — Typical joints for prestress wall to base junction



c) Fixed joint

Figure 3 — Typical joints for prestress wall to base junction *(concluded)*

Table 4 — Summary of the advantages and disadvantages of joints in the wall to base junction

System	Advantages	Disadvantages
Sliding joint	Stresses are predicted with good reliability Secondary stresses are relatively small	Dependent on adequacy of joint seal Some uncertainty over degree of sliding obtained
Pinned joint	Prestress is predicted with good reliability Maximum moment occurs in wall away from the joints, at level where "end effects" from vertical tendons are largely smoothed out	Subsequent secondary stresses are less reliable Large shears and fairly large moments
Fixed joint	Robust form of construction	Prediction of stresses is uncertain Large moments and shears Prestressed walls necessitate the use of continuous prestressed base (a special thermal protection at the joint may be introduced to reduce additional stresses due to thermal loading Maximum moment occurs at the joint

NOTE 5 For the sliding joint, the wall is free to move horizontally. It is supported by the base slab. Generally it is necessary to ensure that the outer tank cannot move laterally. Radial guides should be provided to ensure that the movement is concentric with the base slab. A flexible seal, commonly in the form of a stainless steel strip, should be provided to prevent leakage of liquid or gas.

For the pinned joint, substantial shear is transferred from wall to base slab, but the joint is not required to transmit bending moments. The custom is to allow the wall to slide while it is being prestressed. Thereafter it is pinned in position, by one of several devices, but not prevented from vertical rotation.

For the fixed joint, the movement of the wall, relative to the base slab, is prevented. The joint is designed to accept the relatively large moments and shears which arise as a consequence.

A summary of the advantages and disadvantages of each type of joint in the wall to base junction is given in Table 4.

8.7.6 *Wall to roof junction*

For the design of the wall to roof or wall to upper shell junction for full containment tanks, the following should be considered:

a) gas tightness;

b) radial and vertical loadings applied by the roof, where vertical loadings are both downwards and upwards;

c) radial thermal loading due to interaction of roof and wall;

d) abnormal loads, such as blast, fire or seismic, specified in the philosophy.

Where a steel dome is adopted, a cylindrical steel element between the top of the concrete wall and the edge of the dome should be used.

NOTE 1 The steel to concrete junction is usually a pinned connection.

NOTE 2 Where a concrete dome is adopted, a monolithic connection between wall and dome is commonly used.

8.8 Fire resistance

In an emergency situation the prestressed wall may be required to give resistance to the radiated heat from an adjacent tank or plant fire. The design parameters should be specified by the purchaser to establish the hazard and will normally be in the form of heat flux for a specified period from each credible event.

The purchaser should also specify the hazard scenario, e.g. a fire from an adjacent tank with a pool of liquid in the bunded area. Calculations should demonstrate the effects of temperature gradient, heat build-up, burn-out rate, etc.

Concrete is inherently a good material to resist the effects of high temperature, but certain precautions should be taken to prevent excessive spalling or cracking.

Protection of prestressing anchors should be provided especially if unbonded tendons are used.

Factors governing the performance of concrete at high temperature are given in BS 8110-2:1985.

The residual strength, at elevated temperatures, of the concrete wall should be assessed to ensure collapse cannot occur if it is required to maintain its structural integrity and thus liquid contents.

For prestressed concrete tank walls subject to fire effects, the most critical factor is usually the rate of temperature increase on an exposed surface. The use of intumescent coatings, or a sacrificial layer with mesh reinforcement, should be considered where excessive spalling could occur.

Sliding wall to base junctions should be checked for their thermal properties.

Where an elevated slab is used, the piers supporting the tank base exposed to radiation should be checked for their load bearing capacity.

9 Reinforced concrete outer tank with earth embankment

9.1 General

Where site conditions or economic factors are advantageous a reinforced concrete outer tank with an earth embankment should be used as the secondary liquid container for a double containment or full containment tank.

NOTE This standard does not consider the use of a reinforced concrete outer tank without an earth embankment since there is no experience of this type of construction. Figure 4 shows a typical example of a tank with an earth embankment. Insulation is present under the inner tank bottom, on the inside of the outer wall and on the suspended deck. A concrete roof can be used as an alternative.

9.2 Loading

Reinforced concrete outer tank loadings should be in accordance with Table 1 of BS 7777-1:1993.

The design of a reinforced concrete outer tank should be in accordance with BS 8110-1:1985, BS 8007:1987 and with **8.7** of this Part of BS 7777.

9.3 Concrete properties at low temperatures

For design purposes the values for compressive strength, Poisson's ratio and elastic modulus should be in accordance with BS 8110-1:1985 and BS 8110-2:1985 for normal temperature conditions.

NOTE Under cryogenic conditions most concrete properties are not affected by the low temperature. Some properties are frequently enhanced.

The thermal expansion coefficient reduces at low temperature. This reduction should be taken into account in the design.

9.4 Reinforcing steel

Reinforcing steel should be in accordance with **6.3**.

NOTE Concrete has significant compressive strength but its tensile strength is relatively low. The failure mode under tensile loading is brittle. Reinforcing bars are incorporated within the concrete to form a composite section, where the concrete or concrete and reinforcement bar take the compressive stress and the steel reinforcement bar takes the tensile stress. The concrete in the tensile stressed area can crack and the section should be designed so that both the spacing and width of cracks are controlled.

9.5 Earth embankment

The earth embankment should be in accordance with **6.5**.

9.6 Wall heating

Wall heating should be in accordance with clause **12**.

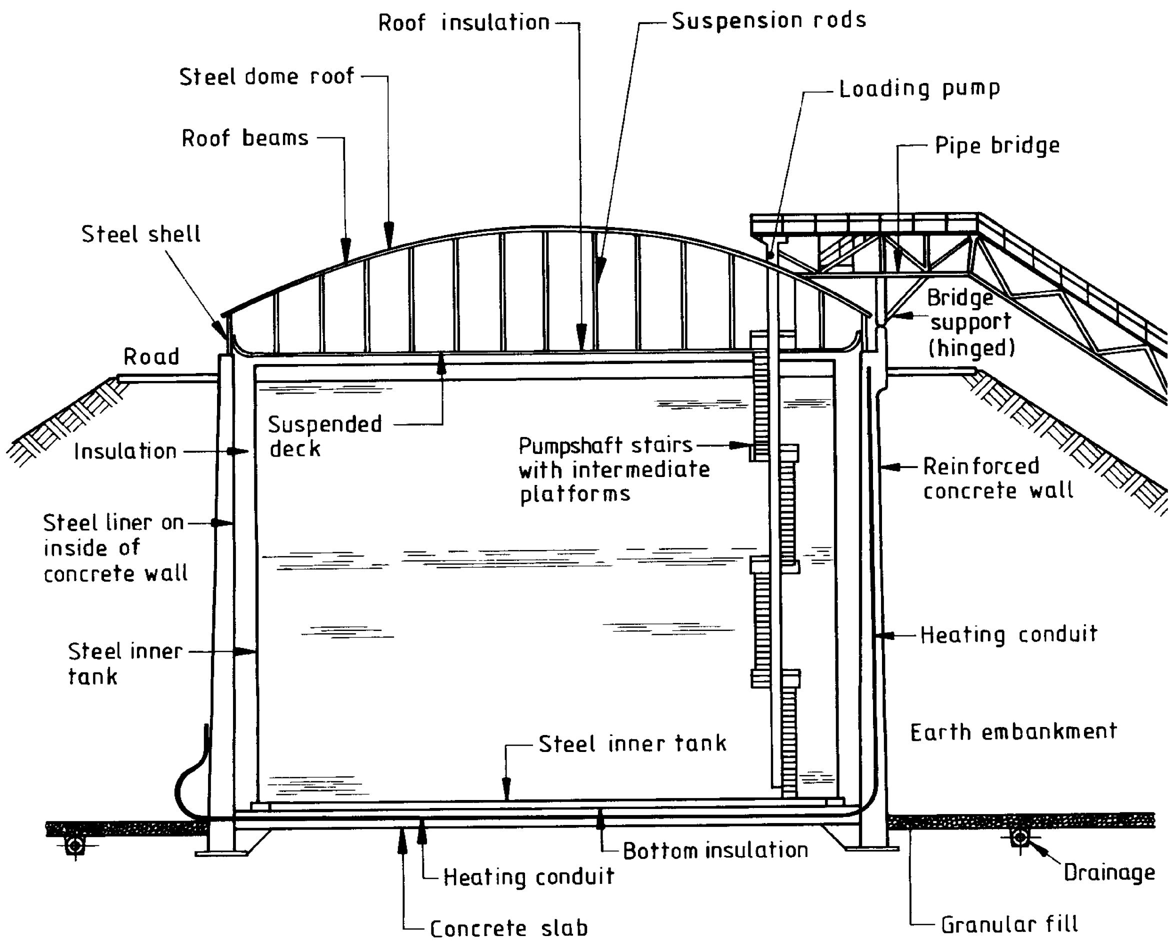


Figure 4 — Typical section of tank with a reinforced concrete outer tank with earth embankment

10 Insulation

10.1 General

Low temperature storage tanks should be insulated.

The base insulation and the tank foundation should be designed as an entity.

NOTE 1 Where foundations are constructed at ground level, without a clear space, the need for foundation heating should be considered for the prevention of ground heave due to frost.

NOTE 2 The effect of the insulation is to minimize heat gain to the tank, maintain the outer tank at approximately ambient temperature and minimize condensation and ice formation.

10.2 Design

To establish the type and level of insulation for both operating and emergency conditions, the following should be taken into account:

a) maximum acceptable rate of boil-off of the contents;

b) outer tank temperature is maintained at or above the outer tank design temperature;

c) permissible load bearing characteristics of the base insulation;

d) compatibility of structural design of the inner with the outer tank;

e) suitability of use in contact with the stored product, and in contact with the purge gas, where applicable;

f) anticipated differential settlement of tank foundation;

g) pressure exerted by the insulation on the inner and outer tanks.

The design of the insulation should allow for the contraction or expansion of the inner tank. The inner tank should remain centrally located in the outer container under all design conditions.

The insulation system, which includes any system applied to the outer tank, should incorporate, or inherently be, a vapour barrier and should also be fire resistant.

Attachments welded to the inner tank shell and roof, for the purpose of supporting insulation materials, should be in accordance with **7.2.7.8** of BS 7777-2:1993.

10.3 Water vapour barrier

Water vapour penetration of the insulation should be excluded by the installation or application of a vapour barrier to the insulation.

NOTE Below ambient temperature the reduced vapour pressure causes an imbalance which attracts water vapour to the colder surface. Once the water is below 0 °C icing occurs. This produces cracks in most insulation materials due to the expansion from the liquid to solid state.

For temperature cycles, the freeze-thaw effect induces the degeneration of the insulant which ultimately results in ice forming at the cold metal surface and eventually at the warm side of the insulation.

10.4 Compatibility

Insulation material types should be compatible with the tank components and with each other (see **6.6**).

11 Liners and membranes

11.1 General

NOTE 1 Liners or membranes are applied primarily as a vapour barrier. Full containment concrete outer tanks will normally be required to inhibit the passage of both product vapour and water vapour. Unless specified by the purchaser it is not normally required to provide liners or membranes to double containment walls, base slabs or interspaces.

A membrane should be provided below and around the insulation surrounding the tank. For the selection of the membrane material, account should be taken of the temperature and stress to which it is subject in service conditions and under upset conditions.

Materials that have been proved capable of retaining their impermeability in these conditions should be used.

Where the membrane is a coating applied to a concrete surface, its coefficient of thermal expansion should be compatible with that of the concrete throughout the relevant temperature range.

NOTE 2 Prolonged contact with hydrocarbon products has no significant detrimental effect on the properties or useful life of concrete, even at ambient temperatures. Chemical and physical activity progressively diminishes as the temperature is reduced.

NOTE 3 Liner and coating systems are commonly included in the design of concrete components for refrigerated storage systems for the following reasons:

a) to make the component gas tight and/or liquid tight;

b) to prevent the ingress of water vapour into the tank.

NOTE 4 A liner is generally an impervious barrier which is in contact with, and usually acts compositely with, the concrete. Coatings are conventionally applied directly to the concrete surface.

The duty of a liner depends upon the following:

a) the design philosophy;

b) its location, whether on the internal face, external face or embedded;

c) its temperature; and

d) its initial state of stress.

Liners are normally made of steel.

NOTE 5 For bottom or floor membrane or vapour barriers, reference may be made to FIP Guide to good practice 912/134[5].

11.2 Design

For a liner or membrane system, the following operational and abnormal loading conditions should be considered:

a) degree of resistance to permeation and diffusion of liquids and/or gases;

b) service temperature;

c) strain compatibility requirements;

d) limiting thermal gradients.

Abnormal loadings conditions can include the following:

1) thermal shock;

2) degree of resistance to permeation and diffusion under various emergency conditions;

3) temperatures lower than the service temperature;

4) liquid loading;

5) mechanical loading;

6) additional gas pressure;

7) strain compatibility requirements, perhaps under transient thermal conditions;

8) bridging capability of cracks in concrete;

9) resistance to fire;

10) resistance to blast, flying objects and impact effects;

11) resistance to earthquake conditions.

NOTE 1 A liner may be located on the outer face of a concrete tank. In practice this option is available for wall components only. Floor and roof liners are constrained by construction considerations to be located on the inner face. Hence at wall to floor and wall to roof junctions the liner has to pass through the concrete to form a continuous seal. A liner applied to the outer face of the wall is only suitable for use with wire winding prestressing systems. The wire is applied to the outside face of the lining which is thus placed in ring compression. The close spacing of the wires eliminates any possibility of buckling of the liner. When used on the outer wall of a storage system it is more vulnerable under some upset conditions, like external fire or impact, than an inner liner but is more easily repaired if damaged. It is protected from thermal shock, which arises from internal leaks, by the thickness of the concrete. An outer wall liner is not suited for use with embedded tendons.

NOTE 2 A liner may be located on the inner face of a reinforced concrete tank with an earth embankment. It may also be applied to prestressed concrete tanks with embedded tendons or with wire winding. Where it is designed to act compositely with the concrete it should be designed to resist buckling during and after prestressing. This includes the effects of creep and shrinkage of the concrete wall. If leaks occur from the inner tank the liner may experience contraction and thermal shock. In addition to considering the principal strain in the liner, consideration should also be given to the rate of strain under these conditions. A more expensive metal suitable for the lower temperature may be needed. The effects of thermal shock on any anchors or shear studs connecting the liner with the concrete should be considered.

NOTE 3 At the junctions with the floor and roof, there is no need for the liner to penetrate the concrete. However, the wall to floor junction is subject to circumferential and radial strains, due to the effects of prestress, creep, long term shrinkage and temperature changes after construction, under both service and upset conditions. These dimensional changes can be accommodated through overall straining, by means of flexible zones at the junction, or by other means. The design of the liner at the floor to wall junction requires special examination when a sliding joint is used.

NOTE 4 Prestressed concrete tanks are designed to be liquid tight. Thus for containment structures no additional membrane is necessary to ensure liquid tightness. A liner or membrane may therefore be selected to provide a vapour barrier only. Its selection should be based on comprehensive tests, showing acceptable results.

Vapour permeability (water and gas), chemical resistance and application techniques should be tested and shown to be acceptable.

12 Base and wall heating

12.1 General

Where the tank base and wall are not exposed to the supply of heat from the atmosphere, heating should be provided to maintain the tank walls and base at a temperature which prevents ice formation.

12.2 Design

The heat output and physical positioning of the heating elements should be designed on the basis of heat transfer calculations using finite element or finite difference methods.

To ensure that the recommendations of **7.5.5** are followed, the factor of safety on heat input should be 1.3.

For tank bases, where a two-dimensional model is necessary, two options should be considered:

a) a section across a base radius perpendicular to the direction of the heater element;

b) axisymmetric segments, with the assumption that the heater elements are circular.

Material heat transfer properties should be incorporated in the model for the ring beams, insulation, bitumen sand, levelling concrete, subsoil and air around the ground surface. Two sets of boundary conditions should be considered:

1) at the tank base, which is the design temperature for the product;

2) the soil at a depth below the tank.

NOTE For a depth of 20 m the assumption of a fixed temperature of 7 °C should be adequate for the purposes of base heating design in normal soil conditions.

12.3 Heating control

The heating circuit output should be controlled by temperature controllers.

NOTE The temperature controller sensors should be strategically located throughout shell and base. They should also be close to any thermal discontinuity. The temperature controllers should be so connected that if any temperature sensor reaches the lowest set temperature, then all heaters are switched on until all sensors reach the maximum set temperature.

12.4 Temperature sensors

All temperature controllers should have spare temperature sensors, permanently installed and available for connection to the controller circuits. It is recommended that the connection procedure ensures rapid changeover.

12.5 Electrical failure of individual circuits

Electrical heating should consist of a number of independent parallel circuits designed so that electrical failure of any one circuit does not decrease power supply to the remaining circuits.

Heaters are to be located so that the heating deficiency caused by the failure of any one heating circuit is spread evenly throughout the heated area.

12.6 Electrical failure of main power supply

Electrical heating should be designed so that in the event of electrical failure of a main power supply cable, or a power transformer:

a) sufficient time is available to repair the above equipment before damage occurs due to excessive cooling;

b) provision for connecting a stand-by heating power source is made.

12.7 Heater elements

Heater elements should be designed and installed to facilitate any maintenance that may be necessary and the replacement of failed units.

13 Prestressed and reinforced concrete construction

13.1 Foundations

Construction activities and control should be in accordance with BS 8004:1986 and BS 8110-1:1985.

Construction procedures should specify the method of carrying out the works to enable the construction to conform to the design requirements with respect to differential and/or total settlement limits.

NOTE This is particularly important where large slabs are constructed on compressible material and special techniques such as pre-consolidation may be required.

13.2 Prestressed concrete

Materials, mix design, mixing technique and construction of prestressed concrete, and of ducting and grouting post-tensioned tendons should be in accordance with BS 5328-1:1991 and BS 5328-2:1991 and BS 8110-1:1985.

NOTE Reference can be made to FIP guide to good practice 912/134[5].

A method statement for the casting, curing and stressing should be agreed between the designer and contractor.
A comprehensive record of stressing operations should be retained by the contractor.

13.3 Reinforced concrete

Materials, mix design, mixing techniques and construction of reinforced concrete should be in accordance with BS 5328-1:1991 and BS 5328-2:1991 and BS 8110-1:1985.

14 Installation of insulation

14.1 General

Construction activities should be under the control of a competent engineer.

14.2 Base insulation

Corrosion protection of the inside bottom plates and the lower rings of the shell plates of the outer tank should be applied before the installation of the base insulation. Damage to applied protection should be avoided during construction.

Before the base insulation is laid, the level of the bottom plates of the outer tank should be checked to ensure that they rest firmly on the foundation.

Insulating materials should be maintained clean and dry. They should be laid on a clean and dry surface. The upper surface should be protected against mechanical damage.

NOTE A vapour seal applied to the upper surface of the base insulation prevents ingress of moisture to the insulation during construction.

Openings in the base insulation for tank anchorages should be sealed.

Where the base insulation consists of blocks, a screed should be laid over the top of the outer tank bottom to form a level bed for installation. This screed should be covered with a moisture-proof layer. The vertical joints between the blocks should be staggered.

Where loose fill insulation materials are to be used they should be compacted as necessary during installation to ensure that the loads from the inner tank are supported.

14.3 Shell and roof insulation

Before the shell and roof insulation is applied the inner and outer tanks should have been fully tested and the tank should be clean and dry.

Insulation materials should be maintained in a clean and dry condition.

The ingress of moisture to the space between the inner and outer tanks during construction should be prevented.

When powder insulation is used excessive packing of the powder should not take place as a result of movement of the inner tank. The powder should be installed to the designated level. Where an expansion space is provided for the inner tank shell, powder should not enter this space.

Filling points above the annular space should be provided to allow for the topping up of insulation where settlement occurs.

15 Earth embankment

Before construction, the designer should specify materials and workmanship. Details of site preparation, dewatering or watering, fill and compaction should be included.

During construction wall loadings should not be exceeded by the action of traffic movement, material stockpiling or overfilling.

NOTE For details about the fill work, reference may be made to BS 6031.

Annex A (informative) Guidance on design criteria for concrete structures

A.1 General

BS 8110-1 and BS 8110-2 cover the design of concrete structures utilizing limit state methods. Partial safety factors are applied to characteristic material strengths and loads, to provide design strengths and design loads used for the analysis of sections at relevant limit states.

All relevant limit states should be considered in the design analysis to ensure adequate degrees of safety and serviceability. The normal approach is to design initially on the basis of the most critical limit state, which is frequently the ultimate limit state, and then to check against the serviceability limit states, which are mainly those imposed by deflection and cracking limitations.

Structures are subject to different types of loading simultaneously, i.e. there will be various combinations of loads to be considered in the design. Critical conditions can apply when one load is at its maximum value whilst another combined load is at its minimum value. Hence two values are used for the partial safety factors, depending on whether they have an adverse or beneficial effect on the section being analysed. This produces the most onerous combination of ultimate loads.

A.2 Load cases to be considered

In general the tank purchaser specifies the load cases to be considered by the tank designer. However, it is the responsibility of the tank designer to check that all appropriate load cases and combinations are incorporated and ensure an adequate safe design.

As part of this responsibility the designer should prepare a detailed loading summary table, to cover all phases of the tank operational life. Abnormal or emergency loads as listed in clause **7** of BS 7777-1 should be evaluated and included as necessary. Table A.1 shows a typical loading summary for a prestressed concrete outer tank, and Table A.2 shows a typical loading summary for a reinforced tank with earth embankment.

A.3 Partial safety factors

Adverse and beneficial partial safety factors to be applied to loads and materials for the ultimate limit state (ULS) and serviceability limit state (SLS), for normal loading cases, are given in BS 8110-1. Values of factors for abnormal loading cases are shown in Table A.3.

Table A.1 — Summary of design loads for prestressed concrete containment

Loading conditions	Normal loads										Emergency loads							
	Construction		Test		Cool down		Operation		Maintenance		Leakage		Blast		Earthquake		Fire	
	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base
Dead weight of concrete	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Dead weight of steel tank		×		×		×		×		×		×		×		×		×
Live load	(×)	×					×	×		×								
Design pressure				×		×		×		×	×	×	×	×	×	×	×	×
Wind load	×		×		×		×		×		×		(×)		(×)		×	
Prestressing	×	(×)	×	(×)	×	(×)	×	(×)	×	(×)	×	(×)	×	(×)	×	(×)	×	(×)
Shrinkage	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Creep	×	×	×	×	×	×	×	×	×	×								
Temperature differential					(×)	×	(×)	×			×	×		×		×	×	×
Leakage											×	×						
Blast													×	(×)				
Earthquake															×	×		
Fire																	×	

Key

×, applicable;

(×), not always applicable, or not required for adverse loading.

Table A.2 — Summary of design loads for reinforced concrete containment

Loading conditions	Normal loads										Emergency loads							
	Construction		Test		Cool down		Operation		Maintenance		Leakage		Blast		Earthquake		Fire	
	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base	Wall	Base
Dead weight of concrete	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Dead weight of steel tank		×		×		×		×		×		×		×		×		×
Live load	(×)	×					(×)	×		×								
Design pressure				×		×		×		×	×	×	×	×	×	×	×	×
Wind load	×		(×)		(×)		×		×		×		(×)		(×)		(×)	
Embankment soil pressure	×		×		×		×		×		×		×		×	×	×	
Shrinkage	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Creep	×	×	×	×	×	×	×	×	×	×								
Temperature differential					×	×	×	×			×	×	×	×	×	×	×	×
Leakage											×	×						
Blast													×	(×)				
Earthquake															×	×		
Fire																	×	

Key

×, applicable;

(×), not always applicable, or not required for adverse loading.

Table A.3 — Partial load factors for abnormal loading cases

Load combinations	Load factors					
	Dead		Imposed		Abnormal load	Wind
	Adverse	Beneficial	Adverse	Beneficial		
Operational loads plus an abnormal load case, i.e. earthquake, blast overpressure, external impact, fire, leakage from inner tank	1.05	1.0	1.05	0	1.05	0.3[a]

NOTE 1 Values of material partial load factors to be used when considering abnormal loading cases are in accordance with BS 8110-1.

NOTE 2 It is assumed that earthquake, blast overpressure, external impact and fire do not occur simultaneously. Leakage from the inner tank and fire could be considered together. Also, leakage from inner tank may occur in combination with an earthquake load, e.g. after-shock from a main event may be a realistic scenario.

[a] Applied in combination with fire or earthquake only.

Annex B (informative) Prestressed concrete

Prestressing modifies the behaviour of concrete in several ways as follows.

a) *Improvement in its ability to resist subsequently applied loads which give rise to tensile stress.* The tensile strength of concrete is relatively small (between one-tenth and one-fifth of the compressive strength). It is also unreliable. Prestressing is applied to create pre-compression in a member or structure, or those parts of a member or structure, which will subsequently be subjected to loads which give rise to tensile stresses. The magnitude of this pre-compression is designed to equal or exceed the subsequent tension. The behaviour of concrete in shear is improved in the same way. The critical principal tensile stresses, which determine the shear strength, are counteracted by the pre-compression.

b) *Change in the mode of tensile failure.* In plain concrete, failure in tension takes place in a brittle manner. In reinforced concrete, cracking is controlled by the reinforcement but cracks due to overload remain open when the overload has been removed. In prestressed concrete with bonded steel, overload can cause cracks, as in reinforced concrete, but the continuing presence of the prestressing force ensures that the cracks close again when the overload has been removed. In prestressed concrete with non-bonded steel the behaviour is different in that a small number of wide cracks develop. Nevertheless, they close again on removal of the overload. The use of bonded non-stressed reinforcement in combination with non-bonded pre-stressing tendons allows crack widths and spacings to be controlled.

c) *Response to movement.* All structural concrete, whether reinforced or prestressed, is subject to dimensional change, due to shrinkage or creep. In the case of prestressed concrete, in addition to any creep due to the applied loads, the prestressing forces cause movements which should be considered in the design.

NOTE The two main methods of prestressing are known as pre-tensioning and post-tensioning. The terms relate to the time at which the tension is applied to the prestressing steel, relative to the casting of the concrete.

Pre-tensioning is employed mainly for precast factory made units. The tendons are tensioned against independent supports and concrete is cast around the tendons, to which it becomes bonded. When the tension is removed from the ends of the tendons it is transferred to the precast units.

Post-tensioning is usually a site technique. The concrete is placed around untensioned sheathed tendons, or around sheaths or ducts into which tendons are subsequently threaded. When the concrete has attained adequate strength, the tendons are tensioned using hydraulic jacks where the concrete acts as the stressing abutment. The tensioned tendons are locked into anchors and the jacks are depressurized and removed.

The tendons are finally protected by pumping cement grout into the ducts. In addition to providing protection to the tendons the cement grout influences the subsequent behaviour of the structure, particularly crack formation under overload, by providing a bond between tendons and concrete structure.

Annex C (informative) Guidance on the calculation of prestressing losses for concrete members

C.1 Shrinkage strain of concrete

The prestress loss from the shrinkage of concrete is obtained by multiplying the shrinkage per unit length of concrete by the modulus of elasticity of the steel. In lieu of experimental evidence, the shrinkage per unit length of concrete may be taken as 100×10^{-6}.

C.2 Specific creep strain of concrete

Specific creep strain of concrete (creep per unit length per unit of applied stress) is based on transfer and assumed when the concrete has achieved its 28 day characteristic strength. In lieu of more accurate data a creep coefficient of 1.4 may be used.

Values of Young's modulus (E_c) vary depending on the original water content, effective age at transfer, section thickness, ambient relative humidity and ambient temperature (see Table C.1).

The specific creep strain is obtained by dividing the creep coefficient by the appropriate value of E_c. The loss of prestress is obtained by multiplying the specific creep strain by the concrete stress at transfer and by the modulus of elasticity of the tendons.

Table C.1 — Creep strain of concrete

Characteristic strength f_{cu}	**Young's modulus E_c**	
	Mean	**Typical range**
N/mm²	kN/mm²	kN/mm²
40	28	22 to 34
50	30	24 to 36
60	32	26 to 38

C.3 Elastic deformation

The loss of force from the elastic deformation of the concrete should be calculated on the basis of half the product of the modular ratio and the stress in the concrete adjacent to the tendons averaged along their length. Alternatively the loss of prestress may be exactly computed on the basis of the sequence of tensioning.

C.4 Relaxation of prestressing steel

The losses due to relaxation of the steel are calculated by multiplying the 1 000 h relaxation value, given by the manufacturer on a certificate of approval, by 2.0 for class 1 high tensile wire, strand or bar, or by 1.5 for class 2 wire or strand.

The relaxation class is in accordance with BS 5896.

If no certificate of approval is available showing the appropriate relaxation value then the assumed value should be the maximum stated for the appropriate load condition given in accordance with BS 5896 for high tensile wire or strand, or BS 4486 for high tensile bar.

C.5 Friction in ducts

The losses due to friction for the curvature of the duct are assessed using the following equation:

$$P_x = P_o e^{-ux/r_{ps}}$$

and the losses due to friction due to the unintentional variation of the duct profile are assessed using the following equation:

$$P_x = P_o e^{-Kx}$$

where

- P_o is the prestressing force in the tendon at the jacking end (in kN);
- P_x is the prestressing force at any distance x from the jack, or stressing point (in kN);
- e is the base of Napierian logarithms (2.718);
- x is the distance from the stressing point or tangent point on a curved duct (in m);
- u is the coefficient of friction;
- r_{ps} is the radius of curvature (in m);
- K is the coefficient per metre length depending on the type of duct, its inside surface and the method of forming and maintaining its position within the concrete section during concrete placement.

Unless more exact information is available the following values for the friction constants are recommended:

a) for steel tendons in ducts

$u = 0.3$

$K = 33 \times 10^{-4}$

b) for greased, strand in polythene or polypropylene ducts

$u = 0.12$

$K = 25 \times 10^{-4}$.

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