

EEMUA Publication 207 - Double concrete tanks for liquefied gas – guide to design, construction and operation

PUBLICATION 207

Edition 1

Released by IHS. NOT FOR RESALE

THE ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION

Double concrete tanks for liquefied gas

Guide to design, construction and operation

PUBLICATION 207

Edition 1

Copyright © 2009 The Engineering Equipment and Materials Users Association.
A company limited by guarantee. Registered in England. Company number 477838.

ISBN 978 0 85931 152 6

Imprint reference 05-2015
First published 12-2009

Registered and Trading Address
63 Mark Lane London EC3R 7NQ
Telephone: +44 (0)20 7488 0801
Fax: +44 (0)20 7488 3499
E-mail: sales@eemua.org
Website: www.eemua.org



ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION

About EEMUA

The Engineering Equipment and Materials Users Association is usually known by its initials, EEMUA. EEMUA is an Association established by the owners and operators of industrial assets. Any organisation that is a substantial user or substantial purchaser of engineering products may apply to become a member of EEMUA. Membership is subject to the approval of Council.

EEMUA aims

EEMUA aims to improve the safety, environmental and operating performance of industrial facilities in the most cost-effective way, pursuing and promoting leadership in industrial asset management by sharing engineering experiences and expertise, and by the active, enlightened promotion of the distinct interests of users of engineering products. These aims are achieved by various means, including:

- Providing the organisation within which networking, information sharing and collaboration among users on non-competitive technical matters can take place
- Influencing the way written regulations are interpreted and applied in practice
- Promoting and presenting members' views, and encouraging the application of good sound engineering practices
- Developing user guides, specifications, training and competency schemes
- Facilitating members' participation in national and international standards making
- Influencing relevant national and European legislation and regulation.

The income and resources of EEMUA are applied solely towards the promotion of the aims of the Association. No profit is transferred by way of dividend, bonus or otherwise to members. The work of the Association is mainly carried out by members' representatives on EEMUA Technical Committees, Working Groups, and Forums, supported by EEMUA staff.

Incorporation, membership and other information

For the purposes of conducting its business, EEMUA is incorporated in England and Wales as a company, limited by guarantee, not having share capital. All usual aspects of company management and business administration are dealt with through the EEMUA Chief Executive, including policy implementation and leadership of the Executive team (the staff).

A list of EEMUA publications for sale is given at the end of this Publication. The full list is also on the Association's website, including details of on-line shopping facilities.

To enquire about corporate Membership, write to ask@eemua.org or call +44 (0)20 7488 0801.

ABOUT THIS PUBLICATION

Legal aspects

All rights, title and interest in this Publication belong to EEMUA. All rights are reserved. No part of this Publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means: electronic, mechanical, photocopying, recording or other, without the express prior written agreement of the EEMUA Chief Executive. Infringement of copyright is illegal and also reduces the Association's income thereby jeopardising its ability to fund the production of future publications.

It has been assumed in the preparation of this Publication that: the user ensures selection of those parts of its contents appropriate to the intended application; and that such selection and application is correctly carried out by appropriately qualified and competent persons for whose guidance this Publication has been prepared. EEMUA and the individual members of the Work Group that prepared this EEMUA Publication do not, and indeed cannot, make any representation or give any warranty or guarantee in connection with material contained herein. EEMUA and the individual members of the Work Group that prepared this EEMUA Publication expressly disclaim any liability or responsibility for damage or loss resulting from the use or reliance on this Publication. Any recommendations contained herein are based on the most authoritative information available at the time of writing and on current good engineering practice, but it is essential for the user to take account of pertinent subsequent developments and/or legislation.

Any person who encounters an inaccuracy or ambiguity when making use of this Publication is asked to notify EEMUA without delay so that the matter may be investigated and appropriate action taken.

Consultation and feedback

EEMUA encourages constructive comments on this Publication from both Members of the Association and others.

Comments should be sent on the standard feedback form, a copy of which is provided towards the end of this Publication. An electronic version of the feedback form is available from EEMUA - e-mail your request for a copy to ask@eemua.org, telephone your request to +44 (0)20 7488 0801, or download the form from the EEMUA website at www.eemua.org. Submit comments by e-mail (preferred) or post.

Comments are considered by the relevant EEMUA Technical Committees and may be incorporated in future editions of this Publication. New editions are publicised on the EEMUA website.

Contents

1. Introduction and Scope	1
2. Qualification	3
2.1 Introduction	3
2.2 Objectives of the Qualification Roadmap	3
3. Materials	7
3.1 Introduction	7
3.2 Concrete	7
3.3 Shotcrete	10
3.4 Cementitious Materials	11
3.5 Aggregates	11
3.6 Water	11
3.7 Admixtures	11
3.8 Fibres	11
3.9 Reinforcement	11
3.10 Post-tensioning Ducts	13
3.11 Grout	13
3.12 Insulation	13
3.13 Metallic Components	14
3.14 Structural Non-metallic Components	14
3.15 Coatings	14
4. Design	17
4.1 Introduction	17
4.2 General Design Requirements	17
4.3 Design Actions	19
4.4 Foundations	26
4.5 Primary Pre-stressed Concrete Tanks	27
4.6 Secondary Concrete Tank	35
4.7 Insulation Systems	40
4.8 Membranes and Linings	41
4.9 Instrumentation Systems	42
4.10 Electrical Systems	42
4.11 Pressure and Vacuum Relief Systems	44
4.12 Piping Systems	44
4.13 Roof Platforms	45
5. Construction	47
5.1 Introduction	47
5.2 Documentation	47
5.3 Work Organisation	48
5.4 Testing and Quality Control during Construction	49
5.5 Concrete Construction	52
5.6 Steel Structure	54
5.7 Installation of Insulation	55
5.8 Mechanical Outfitting	55
6. Inspection and Testing of the Completed Works	57
6.1 Introduction	57
6.2 Objectives	57

6.3 Organisation	58
6.4 Double Concrete Tank without Liner to Primary Tank	58
6.5 Double Concrete Tank with Steel Lined Primary Tank	64
7. Tank Commissioning	69
7.1 Introduction	69
7.2 Status of Tank at Start of Commissioning	69
7.3 Preparation for Commissioning	70
7.4 Drying of Tank	71
7.5 Purging	72
7.6 Commissioning of the Tank Heating System.....	74
7.7 Cool-down	74
7.8 Commissioning of the Submerged Pumps	76
7.9 Completion of Commissioning	76
8. Operations	77
8.1 Introduction	77
8.2 Prevention of an Overfill	77
8.3 Prevention of Overpressure	77
8.4 Prevention of Vacuum.....	77
8.5 Tank Heating System	78
8.6 Liquid in Annulus	78
8.7 Prevention of Rollover	78
8.8 Refilling after Maintenance	78
9. Maintenance.....	79
9.1 Introduction	79
9.2 Safety	79
9.3 Maintenance Planning	79
9.4 Review of Tank Performance.....	79
9.5 Foundations	79
9.6 Wall	81
9.7 Concrete Roof	81
9.8 Equipment Items	82
9.9 Inspection Check List and Suggested Inspection Frequency.....	83
10. Tank Decommissioning.....	85
10.1 Introduction	85
10.2 Decommissioning Procedure	88
11. Demolition.....	95
11.1 Introduction	95
11.2 Responsibilities of the Owner and Contractor.....	95
11.3 Documentation and Planning	96
11.4 Methods of Demolition	97
11.5 Demolition Procedures and Methods.....	97
12. Definitions and Abbreviations	101
13. References	103
13.1 Standards, Codes and Directives	103
13.2 EEMUA Publications	107
13.3 References in this Publication.....	107
14. Bibliography	111

Tables

Table 1 Estimation of dynamic modulus.....	8
Table 2 Effectiveness of sieve aperture size	14
Table 3 Recommended partial action factors for combinations of actions	24
Table 4 Partial factors for materials for ultimate limit states to EN 1992-1-1	25
Table 5 Critical damping values	26
Table 6 Differential settlement limits.....	27
Table 7 Acceptance criteria for liquid tightness in primary tanks except at SSE .	30
Table 8 Secondary tank allowable stresses in concrete and steel reinforcement for normal conditions.....	36
Table 9 Secondary tank principal acceptance criteria under "spill" conditions	37
Table 10 Tests to metallic vapour barrier elements in secondary tank	60
Table 11 Leak classification and repair criteria.....	63
Table 12 Tests on steel liners.....	65
Table 13 Oxygen concentration end-points for purging from air	73
Table 14 Minimum temperature reached.....	73
Table 15 Summary of inspections	83
Table 16 Combustible gas and points for purging	88

Figures

Figure 1 Levels for tank sizing and alarms	32
Figure 2 Prevention of an overfill	77

Acknowledgements

This Publication has been developed by a Work Group consisting of members of the Storage Tanks Technical Committee (STC) of EEMUA. In addition, the STC acknowledges and is grateful for the help and advice provided by personnel from:

- Arup;
- CryoTank (a wholly owned subsidiary of Statoil);
- Lloyd's Register;
- Technip;
- Whessoe Oil and Gas Ltd

all of whom were also members of the EEMUA STC Work Group.

Cover photograph courtesy of NCC Construction AS.

Notes for Users of this Publication

Standards

This Publication refers throughout to International, European and British Standards. Standards are prepared to ensure that only proven techniques are used and that materials employed are suitable for the purpose. Through the adoption and use of standards, the requirements for essential safety should be met. The use of standards is not a legal requirement in some countries in Europe and around the world. However it is stressed that, where a contract is placed which states that manufacture is to be in accordance with specified standards, then this may be determined as a legal requirement. Manufacturers or suppliers of equipment may offer equipment not conforming to standards, but, in such cases, they should have to be able to prove that all legislation concerning essential safety has been complied with. This could be a time consuming and expensive task.

Users' Responsibility

Users of this Publication should satisfy themselves that the sections of this Publication they are using are relevant to the application being considered, that they are correctly applied and that, to the best of their knowledge, no legislative changes have taken place affecting this Publication's content subsequent to the date of publication.

Users of this Publication are also referred to the Section on Legal Aspects, page iii.

Nomenclature

In this Publication, "Section" refers to a part of this Publication, "Clause" refers to a part of a third-party document, such as a standard.

1. Introduction and Scope

Double concrete storage tanks are a recognised method for storing liquefied natural gas (LNG). However, until recent times they have been rarely used. In the main, tanks have been constructed from 9% nickel steel and the guidance given in EEMUA Publication 147 has been widely used when designing and building these types of tanks. However, the soaring price of 9% nickel steel in the first decade of the 21st century has meant an increasing interest in the use of double-walled concrete tanks and a number of contractors have started to offer designs to the market place.

Research into the use of concrete for liquefied gas applications dates back to the 1950s. Commercial application for LNG storage began in the late 1960s and tanks constructed then are still in operation today. These tanks were designed and constructed without having established codes and guidelines for concrete in refrigerated conditions. In the intervening years, all tanks have become subject to greater scrutiny and this has, in turn, meant that codified guidance has been required to ensure that levels of safety and reliability expected today can be properly specified and tested.

Interest in concrete tanks has been rekindled following a 25 year hiatus. In part, this has been a response to a perceived need for tanks to be built more swiftly and economically. In recent years, a number of tank designs have been proposed to meet this need.

Some of the concrete tank designs now being proposed are direct descendants of the tanks still in service. These generally use concrete for strength and metallic liners to meet liquid tightness requirements (however, unlined tanks have been used for the storage of liquid oxygen). For concrete tank designs, the owner should pay attention to those details that are novel, to the means of ensuring the liner is designed and constructed to work well in refrigerated conditions and to the integrity of the interface between the concrete and steel elements.

Other designs have aimed to exploit further the inherently good performance of concrete at cryogenic temperatures by eliminating metallic liners on the primary container. Codes of practice acknowledge that well-constructed concrete which is maintained in compression can be considered liquid tight. However, to ensure that this level of liquid-tightness is delivered, the owner should recognise that more stringent steps should be taken to ensure that good workmanship coupled with a thorough quality assurance and testing regime are provided. Unlined primary containers may not completely prevent small amounts of product reaching the outside surface of the primary container as liquid. In these circumstances, the owner may either decide that the quantities of liquid involved have negligible impact on the reliable operation of the tank or may ask for additional measures to be implemented to reduce permeation. These might include the provision of a stripping pump in the annular space or the introduction of a liner.

The adoption of concrete for primary containment also increases the chance of alternative technologies being employed for vapour barriers and thermal protection systems. Such systems are permissible under established codes of practice so, by implication, are satisfactory within this guidance.

It is believed that the current codes for refrigerated liquefied gas, EN 1473 and EN 14620, do not give sufficient specific recommendations in all areas to address double concrete storage tanks. In the USA, ACI 376, a code for designing LNG tanks, is in preparation (at the time of writing) by the American Concrete Institute. However, while this code covers double concrete tanks, it may not fully complement existing and future European codes and standards. Further guidance is also required for the operation, maintenance, decommissioning and demolition of such tanks.

Against the background detailed in the preceding paragraphs, this Publication (EEMUA 207) has been written to provide a framework of guidance in the use of concrete for both the primary and secondary containment of liquefied gases. Its aims are to describe the methods and steps to design, construct, operate and finally decommission concrete tanks used for liquefied gas storage. An owner who follows this Publication should have the expectation that a tank delivered using them should meet or exceed the levels of safety and reliability that have been exhibited by more established tank technologies.

It is often the case that tanks of this type are constructed using local suppliers, sub-contractors and labour in parts of the world where the stringent quality requirements may not be the norm. Reference to this document provides a basis for helping to ensure that quality is achieved and that consistency in design and construction is maintained.

The concrete secondary containers currently proposed for liquefied gas concrete tanks follow established practice. The guidance included in this Publication, being more comprehensive in its treatment of concrete design and construction, should prove a useful adjunct to existing codes and standards for any tank secondary container.

All construction should be in accordance with the relevant statutory requirements and safety regulations. Reference to these should be made before a design is finally adopted. The materials used, as well as the design and workmanship, should also comply with the appropriate International, European and British standards.

2. Qualification

2.1 Introduction

The fundamental aim of the qualification procedure for a new solution is to imbue the required confidence in all stakeholders that the new solution is fit for purpose in the field. Qualification confirms the fitness of the new solution through documented examination and provision of evidence that the new solution meets the specified requirements for the intended use.

This Section defines a qualification procedure for liquefied gas containment systems to ensure that a systematic and consistent qualification process is used for all such systems in future applications. The qualification roadmap framed herein is a defined process based on Det Norske Veritas Recommended Practice DNV-RP-A203 ⁽¹⁾. This document serves as a robust industry standard in the management of the qualification of new technology.

2.2 Objectives of the Qualification Roadmap

The objective of the qualification roadmap is to lay down a framework for the qualification of a new technology that serves the interests of all stakeholders involved:

- the manufacturer, who offers the new technology to the market and therefore needs to display a proof of fitness for purpose;
- the company that integrates the new technology into a larger system and hence needs to evaluate the total system reliability;
- the end-user of the new technology, who has to optimise the benefits of their investment through selection between competing technologies.

The qualification roadmap lists the logical steps and milestones that should be achieved in order to satisfy all stakeholders involved in the new solution.

2.2.1 Non-Disclosure Agreements and Contracts

Confidentiality between all parties in regards to the exchange of information needs to be arranged by contracts for that purpose. With regards to an external Classification Society charged with the qualification of the new technology, such as DNV or Lloyd's Register, information made available should not be limited.

2.2.2 Qualification Roadmap

The detailed roadmap is to be approved and agreed by the Classification Society, contractor and client. At the appropriate phase, a detailed plan is drawn up which identifies the methods to be used to assure the intended reliability and margin towards each failure mode. The detailed roadmap that is agreed upon should adhere to the overall process flow listed:

- qualification basis;
- ranking of failure modes;
- maintenance and modification effects;
- data collection, planning and execution;
- reliability analysis;
- qualified technology.

The qualification roadmap should be revised at each phase of the development project. Feedback loops between steps should always be in operation as design, specification or maintenance modifications are inherently plausible in any qualification roadmap.

2.2.3 Design and Materials

All design details and materials should be defined, with the respective corresponding requirements of functionality, safety, limiting parameters, constructability and other relevant expectations being summarised and defined in a Table of Functional Requirements.

2.2.4 Applicable Standards

All relevant standards and procedures are to be listed in order to comprehensively define the statutory requirements of the new technology in the Statutory Requirements Table. For technology where there are no standards available, standards describing comparable technologies should be considered, in which case only the relevant parts that are applicable are used.

2.2.5 Service Life Phases

All service life phases are to be defined and listed, together with the respective duration and service class during each phase, in a Service Life Table.

2.2.6 Functional Requirements Factors

All operational and external factors that may influence the functional requirements are to be defined and listed in a Functional Requirement Factors checklist.

2.2.7 Design Nodes

All the elements of the design are to be defined and listed in a Nodes Table. In cases of proven technologies, all references and certificates are to be listed. For those elements involving new technological aspects, the key challenges and uncertainties are to be identified.

2.2.8 System Loads (Actions)

All design loads (actions) acting on the design system under consideration, such as functional loads and accidental loads, are to be defined and listed in a System Loads Table. As a minimum, the actions as stipulated in EN14620 should be taken into account.

2.2.9 Environmental Loads (Actions)

All environmental loads (actions) acting on the design system under consideration, both natural and functional, are to be defined and listed in an Environmental Loads Table. As a minimum, the actions as stipulated in EN14620 should be taken into account.

2.2.10 Failure Mode Identification (FMI) and Risk Ranking (RR)

A failure mode assessment identifies all possible failure modes with underlying failure mechanisms for both the nodes and overall system design. The evaluation should take into account each of the phases of the new technologies service life. All failure modes and their corresponding failure mechanisms should be listed in a Failure Mode Identification (FMI) Table. The failure modes and failure mechanisms should be ranked based on their risk and the resultant information should be incorporated into a Risk Ranking (RR) Table.

2.2.11 Reiterative Step to ensure Completeness

All changes to assumptions, risk categories, categories of new technology, probability of occurrence and safety margins to failure used in the construction of the FMI and RR tables should be continuously updated throughout each stage of the qualification process. This reiterative feedback loop is a mandatory process that ensures the robustness and completeness of the overall system design and ultimately drives the qualification of the new technology by highlighting go/no go decision points.

2.2.12 Critical Service Matrix

The Critical Service Matrix should be constructed through the integration of the previously identified failure modes, failure mechanisms and functional requirements. The Critical Service Matrix lists the nodes, critical phases and critical loads (actions).

2.2.13 Critical Parameters

Key issues such as dimensioning loads (actions), failure modes and functional requirements from the qualification basis should be summarised in a Critical Parameters Report. This ensures that the relevant input parameters for analyses and tests are used and updated with possible changes in design during the qualification process.

2.2.14 Analysis and Testing Plan

The Critical Parameter Report forms the basis and input, including definition of the limits, to the qualification activities. The qualification activities should include the compilation of Analysis Plan and Testing Plan. The Analysis Plan should include the planned numerical and/or analytical analysis of the design system. The Testing Plan should include the method to be used to obtain the data, qualify the data and compare with the target.

2.2.15 Evaluation of Probability of Success (PoS)

The Probability of Success (PoS) of the remaining qualification program is to be calculated. If the resultant PoS is deemed satisfactorily high, the remaining phases listed below should be followed. The PoS of the project represents a major go/no-go decision point.

2.2.16 Analysis and Testing Report

The aforementioned Analysis Plan and Testing Plan are implemented with the resultant outputs of the tests compiled in the Analysis and Testing Report.

2.2.17 Reliability Analysis Report

In order to establish the reliability of the functionality of the new technology, the functional and reliability requirements are checked against the results from the Analysis and Testing Report and recorded in the Reliability Analysis Report. Common methods for estimation of the overall system reliability include the reliability block diagram technique (RBD) or a fault tree analysis (FTA).

2.2.18 Qualification Report

The final Qualification Report is a confirmation by examination and provision of evidence that the new technology meets the specified requirements for the intended use. The Qualification Report summarises all information deriving from the qualification activities and should demonstrate that all identified uncertainties are minimised to an acceptable level.

3. Materials

3.1 Introduction

This Chapter discusses the material selection, testing and pre-qualification requirements for design and construction of double concrete storage tanks. Details of the required characteristics of the concrete are explained, together with guidance on other materials used in construction of the tank, including shotcrete, cementitious materials, aggregates, water, reinforcement and coatings.

General references regarding material properties and testing are included in Chapter 14 of this Publication.

3.2 Concrete

The class of concrete for pre-stressed construction should be at least $f_{ck}40$ in accordance with EN 1992-1-1 Table 3.1 (i.e. C40/50).

Concrete should conform to the requirements of EN 206-1 regarding constituents, testing, durability, concrete quality, mixing and placing.

The concrete should be designed to have acceptable properties for the following:

- impermeability;
- fire resistance;
- behaviour at cryogenic temperature;
- durability.

Durability aspects of the secondary container should be evaluated against EN 1992-1-1 Clause 4. The exposure class of the primary container can be taken as XC3 of EN 1992-1-1 Clause 4.

3.2.1 Cryogenic Response of Concrete

The behaviour of concrete at cryogenic temperature may be different from that at ambient temperature and, hence, should be considered in the determination of the performance of the structure. It is permissible to incorporate temperature-dependent properties in structural analysis models. The strengths to be used in design should not take account of enhanced properties that may be present at cryogenic temperatures.

Cast concrete specimens should be tested in an approved concrete testing laboratory with the capabilities to test concrete to temperatures below -170°C . Separate specimens should be tested for elastic modulus and compressive strength. The dynamic modulus of the concrete should be assessed in accordance with BS 1881-209 or by measurement of direct ultrasonic pulse velocity in accordance with EN 12504-4 at a frequency of 54 kHz. The pulse velocity measurement can then be used to estimate the dynamic modulus of the concrete in accordance with Table 1. Compressive strength should be determined in accordance with EN 12390-3.

Table 1 Estimation of dynamic modulus

Ultrasonic pulse velocity km/s	Dynamic modulus MN/m ²
3.6	24000
3.8	26000
4.0	29000
4.2	32000
4.4	36000
4.6	42000
4.8	49000
5.0	52000

The following criteria should be satisfied:

- it should be demonstrated that the characteristic compressive strength has been achieved through statistical analysis of tests performed on specimens that have not been immersed in liquid nitrogen;
- the mean compressive strength of specimens immersed in the liquid nitrogen should be within the range +90% to +110% of the mean strength of the non-immersed specimens;
- no individual compressive strength measurement of an immersed specimen should be below 80% of the characteristic concrete strength;
- the mean tensile splitting strength of the specimens immersed in liquid nitrogen should be within the range +90% to +110% of the mean tensile splitting strength of the non-immersed specimens.

3.2.2 Moisture Content of Concrete

The influence of moisture content of the concrete should be considered in the assessment of thermal conductivity, thermal deformation, permeability, specific heat, moisture migration and risk of freeze-thaw attack.

3.2.3 Thermal Deformation

The value for coefficient of thermal expansion of concrete for use in design should be the value which is appropriate for the temperature range and moisture content range to be expected in service.

Note that water cement ratios for the primary container concrete should preferably be maintained below 0.4 to avoid expansive freezing of water within the concrete matrix, although water cement ratios up to 0.45 may be shown to be acceptable. Depending on aggregate type, coefficients of thermal expansion may vary from $4\text{--}12 \times 10^{-6}/^{\circ}\text{C}$ (see FIP Report 1982 ⁽²⁾).

3.2.4 Thermal Conductivity and Specific Heat

The influence of moisture on the thermal conductivity, K , and specific heat, c , of the concrete should be established for use in design, to consider hazard and other transient conditions that result in thermally induced stresses.

3.2.5 Creep

The value of concrete creep coefficient for use in the design should be that for ambient temperature determined by calculation in accordance with EN 1992-1-1

Clause 3.1.4 and Annex B, or measured in accordance with ASTM C-512 or relevant national standard.

3.2.6 Elastic Modulus

The value of concrete elastic modulus for use in the design should be that for ambient temperature given in EN 1992-1-1 Clause 3.1.3, or determined in accordance with a relevant national standard or national provisions in accordance with EN 206-1 Clause 5.1, except under conditions where underestimation of elastic modulus may adversely affect the design.

3.2.7 Strength

Concrete strength for use in design should be as determined at ambient temperature in accordance with EN 1992-1-1 Clause 3.1.2.

Where uncracked concrete properties are to be adopted, the strain history of the concrete needs to be tracked from first placement. The potential for early-age thermal cracking, drying shrinkage and internal cracking due to heat of hydration effects, should be included in this assessment.

The cement heat of hydration should be assessed according to the semi-adiabatic method given in EN 196-9 when uncracked concrete properties are to be adopted in design. An upper limit of 270 J/g is suggested where a low heat concrete is targeted due to warm weather working. This can typically be achieved by using either 50% ground-granulated blast furnace slag or 30% pulverised fuel ash as the cement replacement.

3.2.8 Concrete Mix Design Thermal Requirements

The contractor should document, by work procedures and planning calculations of temperature-stress-strength development, that he can comply with the following:

- the maximum permissible temperature of the concrete, within any section, should be 70°C;
- the maximum permissible difference between the centre and the surface temperature of a structural component should be 20°C, unless it can be demonstrated that a higher value, depending on the type of coarse aggregate, can be used without risk of early thermal cracking;
- the maximum permissible difference between the average temperature of a newly cast structural component and the average temperature of a hardened structural component (restraining the movements of the newly cast component) should be determined by the contractor. This determination should be carried out for each type of component and should be based on temperature-stress-strength development calculations. The maximum temperature differences should correspond to a maximum crack risk of 0.65 (defined as the ratio between the actual tensile strength of the concrete divided by the actual stress);
- if use of a cooling system is required to comply with the above requirements, the effects of this system should be included.

3.2.9 Poisson's Ratio

The value of Poisson's ratio for concrete for use in the design should be that for ambient temperature given in EN 1992-1-1 Clause 3.1.3, or determined in accordance with a relevant national standard, or national provisions in accordance with EN 206-1 Clause 5.1.

3.2.10 Permeability

Where concrete is to be used for primary containment without a liner, it should be designed to have an intrinsic permeability to cryogenic fluids of not greater than 10^{-18} m² unless it is demonstrated in the design of the structure that a greater value can be accommodated without exceeding tank performance limits. Pooling of liquid product within the secondary container, or degradation of insulation as a result of excessive liquid permeation, are examples of unacceptable performance.

It should be noted that earlier permeability test apparatus may have had some deficiencies, such as incomplete sealing of test specimens, micro-cracking and geometrically-induced inaccuracies. Most of these deficiencies resulted in apparently higher reported permeability.

Testing methods and procedures are required to demonstrate that the concrete exhibits adequate permeability performance. Some guidance is given in References ⁽³⁾ to ⁽⁵⁾ on testing methods.

The testing technique, acceptance criteria and method should be approved by the owner. It should be noted that the testing described in this Section is material acceptance testing. Permeability testing and acceptance criteria for construction features such as construction joints should be in accordance with Chapter 6.

If a transition from liquid to gaseous product was present within the thickness of a test sample, the gaseous product may have inhibited liquid flow and resulted in an artificially low intrinsic permeability.

3.2.11 Durability

The concrete should be designed to be durable for its intended working life in the environment to which it is to be exposed in accordance with EN 1992-1-1 Clause 4.

3.2.12 Fire Resistance

The concrete should be designed to have high resistance to spalling in fire in accordance with EN 1992-1-2 Clause 4.5.

3.3 Shotcrete

Shotcrete applied to wire-wound pre-stressing should be in accordance with EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems) specification for sprayed concrete ⁽⁶⁾.

3.4 Cementitious Materials

Cement and fly ash should conform to EN 206-1 Clause 5.1. Ground granulated blast furnace slag should conform to EN 15167-1. Silica fume should conform to EN 13263-1.

3.5 Aggregates

Aggregates, including lightweight aggregates, used in making concrete should conform to EN 206-1 Clause 5.1 and should not be adversely affected by exposure to cryogenic temperatures.

3.6 Water

Water used in mixing concrete should conform to EN 206-1 Clause 5.1.

3.7 Admixtures

Admixtures for concrete should conform to EN 206-1 Clause 5.1. Where two or more admixtures are used in concrete their compatibility should be checked and documented.

Where fly ash, ground granulated blast furnace slag or silica fume is used as an admixture, it should comply with the requirements of EN 206-1 Clause 2.3.

3.8 Fibres

Polypropylene or other synthetic fibre used to improve resistance to spalling of concrete in fire should have documented evidence from the producer of satisfactory performance in conditions appropriate to the structure.

Steel fibres and their storage should conform to an appropriate European Technical Approval, a relevant national standard, or national provisions in accordance with EN 206-1 Clause 5.1.

3.9 Reinforcement

3.9.1 Reinforcing Steel

For the design of reinforced concrete structure where the design temperature during a normal operating or emergency condition does not fall below -20°C, the reinforcing steel should comply with EN 1992-1-1.

3.9.2 Cryogenic Grade Reinforcing Steel

For the design of reinforced concrete components exposed to either service or accidental cryogenic conditions, the selection of the steel reinforcement should be based on ductility and toughness and should comply with one of the following:

- the resulting stresses should not exceed the allowable stress values specified in Clause 7.4.1.4 of NFPA 59A;
- steel that satisfies the notch sensitivity ratio (NSR), plastic elongation and yield strength when tested in accordance with the requirements of EN 14620-3 Annex A;

- fully austenitic stainless steel high-yield deformed bar conforming to the requirements of BS 6744 grade 500, with a yield strength or 0.2 proof strength not less than 415 N/mm².

All testing should be conducted by an agency acceptable to the designer.

3.9.3 Reinforcement Connectors

It should be demonstrated that reinforcement connectors, used at ambient temperature, are suitable for the intended application.

For low temperature, the connectors should be subjected to the same tests at design metal temperature and the results of these tests should be compared to those at ambient temperature. The connectors should be considered suitable if the low temperature results are within 5% of those specified at ambient temperature. The contractor should carry out appropriate tests, which should include, as a minimum, tests for tensile strength and ductility. The results of these tests should meet appropriate criteria set by the designer.

3.9.4 Pre-stressing Steel

Pre-stressing steel, anchors and ducts should be in accordance with EN 1992-1-1.

Strand for pre-stressing systems should comply with FIP recommendations for the approval, supply and acceptance of steels for pre-stressing tendons ⁽⁷⁾. Stress relaxation of the strands should be Class "very low", i.e. not more than 2.5% of failure after 1,000 hours at ambient temperature from an initial stress 70% of failure. Mechanical properties should be assessed in accordance with FIP assessment of mechanical properties of structural materials for cryogenic applications ⁽⁸⁾.

All post-tensioning tendons should be stored and handled to protect them from mechanical, electro-chemical, heat or other damage. Cutting or trimming of the ends of post-tensioning tendons using a torch or oxy-acetylene cutting flame should not take place.

The tendon assembly should comply with FIP Recommendations on acceptance and application of post-tensioning systems ⁽⁹⁾ the tendons and anchorage assemblies should be grouted after post-tensioning.

Post-tensioning anchorage systems should be demonstrated to have been qualified by testing at the design cryogenic temperatures. ETAG 013 ⁽¹⁰⁾ contains guidelines for the technical approval of post-tensioning systems, including at cryogenic temperatures.

Steel for wirewound pre-stressing should conform to BS 4486, BS 5896 or ASTM A821, or equivalent national standard.

3.9.5 Pre-stressing Anchorage Materials

Any pre-stressing anchorages that may be subjected to low temperatures should be fabricated from alloy steels that retain a high degree of toughness at cryogenic temperatures.

The suitability of such materials should be demonstrated to the satisfaction of the designer by means of appropriate tests. ETAG 013 ⁽¹⁰⁾ contains guidelines for the technical approval of post-tensioning system anchorages, including at cryogenic temperatures.

3.10 Post-tensioning Ducts

Post-tensioning ducts should be in accordance with the requirements of EN 1992-1-1.

3.11 Grout

Grout for bonded tendons should be in accordance with the requirements of EN 1992-1-1.

3.12 Insulation

Insulation material should meet the requirements of EN 14620-4. Timber may be used both as an insulation material and a structural member, in accordance with EN 14620-4.

3.12.1 Perlite Ore

Prior to shipment to site the perlite ore should be prepared according to Perlite Institute specifications PI-111 ⁽¹¹⁾ or PI-112 ⁽¹²⁾ and then subject to the following acceptance tests:

- samples should be taken for sieve analysis at a rate of 100 to 200 g for every 150 tonnes (minimum) of ore. The contractor should nominate his basis of grading the ore in respect of the sieve size for approval (see PI-115 ⁽¹³⁾);
- samples should be taken for water content at a rate of 25 g for every 150 tonnes (minimum) of ore. The total water content of the ore should be 2% to 4% by weight (see PI-118 ⁽¹⁴⁾);
- samples should be taken for spectrographic analysis by X-ray fluorescence methods generally in accordance with BS 1902-9 techniques (or other equivalent standards) at a rate of 50 g for every 300 tonnes of ore. The analysis should demonstrate the consistency of the ore and the absence of matter which could prove detrimental to the production of perlite for cryogenic use;
- samples should be taken to check on expandability of the perlite ore in accordance with PI-307 ⁽¹⁵⁾. Alternatively if the contractor can provide previous records from the same ore supply that confirms expanded perlite results, then this requirement may be waived with agreement.

3.12.2 Expanded Perlite

The contractor should demonstrate for approval, either by tests on the proposed ore or by previous records of such tests, that the expanded perlite can achieve the following properties:

- thermal conductivity, measured in accordance with ASTM C-177 or C-518 specifications, should be in accordance with the values used in the boil-off calculations. Adjustments to the thermal conductivity should be made for

testing temperature and interstitial gas. Moisture content should be checked, as a minimum, once per day and should be measured at the bottom and top section of the tank, regardless of machine breakdown;

- sieve analysis, tested in accordance with PI-115 ⁽¹³⁾ should conform to Table 2.
- water content tested in accordance with PI-118 ⁽¹⁴⁾ should not exceed 0.5% by weight;
- uncompacted density (as produced density) should be measured in accordance with PI-200 ⁽¹⁶⁾ and ASTM C-520 at least every eight hours of production. The range of uncompacted density necessary to achieve the specified compacted density should be determined by demonstration. If the density specified varies outside the agreed limits, then additional density checks should be taken on a continuous basis and action taken to return the density to the correct range;
- compacted density should be measured in accordance with PI 201 ⁽¹⁷⁾ and should show a compacted density of between 48.0 and 65.6 kg/m³.

Table 2 Effectiveness of sieve aperture size

Sieve Aperture Size (mm)		% Retained	
Passing	Retained	Min.	Max.
	1.18	0	10
1.18	0.850	0	25
0.850	0.600	5	35
0.600	0.300	15	50
0.300	0.150	10	40
0.150		0	30

3.13 Metallic Components

Metallic components, including liners, should meet the requirements of EN 14620-2.

Structural aluminium should meet the requirements of BS 8118-1 or national equivalent.

3.14 Structural Non-metallic Components

Where non-metallic components are specified which have to display adequate strength and toughness at cryogenic temperatures, the performance of the proposed materials should be demonstrated by representative testing at both ambient and cryogenic temperatures.

Non-metallic components include, for example, low-friction materials such as polytetrafluoroethylene in sliding joints and polyester films used as part of the thermal protection system.

3.15 Coatings

Adequate durability of the concrete should be achieved through suitable mix design and concrete detailing. There is no requirement for painting to meet tank performance requirements.

Polymeric or mastic water vapour barriers, where employed in place of a metallic liner on the inside surface of the secondary container, should meet the requirements of EN 14620-4 and EN 14620-3.

4. Design

4.1 Introduction

This Section gives design guidance for double concrete storage tanks. Double concrete tanks described here have a concrete outer secondary tank and concrete inner primary tank. Properly designed and constructed, they should provide a similar in level of performance to that of double tanks with a pre-stressed concrete secondary tank and a metallic primary tank, designed in accordance with EN 14620. The design guidance given here has been specifically prepared for full containment type tanks, but may also be used for double and single containment tanks.

This Section covers the following aspects of the design of double concrete tanks:

- general design requirements;
- specific design requirements;
- foundations;
- design of the primary pre-stressed concrete tank;
- design of the secondary concrete tank;
- insulation systems;
- membranes and linings;
- instrumentation systems;
- electrical systems;
- pressure and vacuum relief systems;
- piping systems;
- roof platforms.

4.2 General Design Requirements

4.2.1 Performance Requirements

The double concrete full containment tank should consist of a circular primary container and a secondary container, which together form an integrated storage tank. The primary container should be a self-standing container holding the liquid product.

Tanks can be placed on the ground, or partly buried, or in a pit in the ground. The raft can be supported on raised piles. The type of foundation required depends on the result of the soil report and seismic study.

The design life should be specified by the owner but should not be taken as less than 25 years for design purposes.

The primary container should either be open at the top, in which case it does not contain product vapours, or it should be equipped with a dome roof so that the vapours are contained. It should have concrete walls, a concrete base or a metallic bottom and, where required, a concrete or metallic dome. The primary container may incorporate a continuous metallic or non-metallic coating or barrier, suitable for refrigerated service, to satisfy the leak tightness provisions of EN 14620. In normal tank service, the primary container should be designed to provide liquid containment and limit ingress of product (which, if occurring, should preferably be in gaseous form) into the interspace between the primary and secondary containers.

The secondary container should be a self-supporting concrete tank equipped with a dome roof of concrete or metal and designed to combine the following functions:

- in normal tank service to provide, in the case of an open top primary container, the primary vapour containment of the tank and to hold the thermal insulation of the primary container;
- in the case of leakage of the primary container, to contain all liquid product and to remain structurally vapour tight. Venting is acceptable but it should be controlled by a pressure relief system.

The tank should be designed so that:

- under normal operating conditions, the liquid and vapour are contained;
- it can be filled and emptied at specified rates;
- the boil-off is controlled and can be relieved by flaring or venting;
- the pressure operating range specified is maintained;
- the ingress of air and moisture is prevented or minimised consistent with the permeability performance specified for the secondary container, except in exceptional cases when the pressure or vacuum relief valves have to be used;
- the boil-off is as specified and condensation and/or frost on the external surface is minimised;
- frost heave of the foundation is prevented;
- damage due to specified accidental actions is limited and does not result in the loss of liquid.

For designing tanks to resist earthquakes, the tank system should be designed to maintain structural integrity during and after operational basis earthquake (OBE) and safe shutdown earthquake (SSE) events. There should be no loss of containment capability, other than the small amount of product permeation permitted and defined in Section 3.2.10 and water vapour and product vapour permeability as defined in EN 14620-3 Clause 10.3. The primary tank should be sized so that there is sufficient freeboard space to accommodate liquid sloshing during OBE and SSE events. Damage should be prevented to access ways into the tank on and above the suspended deck.

The tank should be designed in accordance with the specific requirements of EN 1473, this Publication and EN 14620. Where conflict exists, the precedence should be given to the specific requirements of EN 1473, this Publication, then EN 14620.

4.2.2 Safety and Environmental Requirements

The tank design should enable the tank to be operated in a prudent and safe manner taking into consideration all anticipated significant faults that may occur.

The design of the tanks should take into account any special requirements concerning the nature, handling and storage of gases and chemicals. All equipment should be designed to ensure the safety and security of all plant personnel.

A hazard identification study should be carried out in accordance with the recommendations of EN 14620-1.

The contractor should prepare a Health, Safety and Environment (HSE) plan for the design, construction and commissioning of the tank in accordance with the recommendations of EN 14620-1.

4.2.3 Information Required for Design

The owner should specify design data and agree information with the contractor in accordance with Annex B of EN 14620-1.

A site-specific ground and seismic investigation should be carried out by the owner in accordance with the recommendations of EN 1473, EN 14620-1 and EN 1998-5 in order to evaluate the potential of earthquake activity and to determine the characteristics of seismic ground motion for design purposes.

In order to provide sufficient geotechnical information for the tank design a minimum of four explorations (borings/cone penetration tests) should be performed under each tank, with at least one exploration located beneath the centre of the tank and the remainder around the periphery. Seismic testing should be undertaken and shear wave velocities obtained for the strata beneath each tank. The depth of the exploration beneath the underside of the tank base should be at least equivalent to the tank foundation's external diameter at the periphery and one and a half times the diameter beneath the tank's centre or into structurally acceptable bedrock if encountered.

4.3 Design Actions

Design actions should be in accordance with EN 1473 and EN 14620 and as listed below. The secondary container should be designed in accordance with the requirements of EN 1473 and EN 14620-3.

For the avoidance of doubt, the earthquake return periods should be in accordance with EN 14620.

The word "action" is used here in line with the definition given in EN 1990. According to this definition, an action can be direct: a set of forces (loads) applied to a structure, or indirect: a set of imposed deformations or accelerations such as by temperature effects or earthquakes. For a full definition see Chapter 12.

4.3.1 Normal Actions

4.3.1.1 Permanent Actions

Actions which are due to the self-weight of materials, components and fixed equipment.

The global and local effects from pre-stressing should be considered at all stages of construction, testing, commissioning, service and decommissioning. The consequences of early life and late life pre-stressing actions should be considered.

4.3.1.2 Variable Actions

4.3.1.2.1 Product Actions

Effects of the product should be considered, including hydrostatic and hydrodynamic pressures, gas and/or vapour pressure and product weight.

4.3.1.2.2 Imposed Actions

Imposed actions on the roof according to EN 14620-1.

4.3.1.3 Wind Actions

Design to withstand the effects of wind actions and atmospheric pressure distribution should be applied in accordance with EN 1991-1-4. Wind velocity should be taken as having a 10-minute mean wind velocity taken 10 m above the ground, with an annual chance of exceedance of 0.01 or less. The Basic Wind Velocity should be established from historic data or meteorological modelling and should not be less than 25 m/s, unless a lower wind velocity can be justified by adequate data.

4.3.1.4 Snow Actions

Design to withstand the effects of snow actions should be applied in accordance with EN 1991-1-3.

4.3.1.5 Insulation Pressure

Both primary and secondary containers should be designed for the pressure exerted by the insulation system, including perlite powder and, where included, a resilient blanket.

4.3.1.6 Design Internal Pressures

Effects of both positive and negative internal pressures should be considered. The owner should specify the maximum positive and negative (vacuum) design internal pressures.

4.3.1.7 Settlement Actions

The storage tank and its foundation should be designed to take account of the maximum total and differential foundation settlements predicted to occur during the life of the tanks. Settlement actions should consider the likely variability of soil profiles and also consider the long-term (creep) behaviour of the soil, sub-soil and rock strata. The range of acceptable soil properties should be selected so as to adequately account for the potential range of soil stiffness and early and late life settlement profiles.

4.3.1.8 Shrinkage, Creep and Early-age Thermally Induced Actions

Shrinkage and creep induced actions should be considered in accordance with EN 1992-1. Deformations arising from shrinkage and creep should be considered for both Ultimate and Serviceability Limit States.

Concrete shrinkage and creep are affected by a number of criteria, but primarily by relative humidity. Effects may be assessed at ambient temperature conditions, but adverse effects due to conditions at the upper and lower range of temperatures and levels of humidity should be considered.

The sequence of construction should be agreed with the contractor when considering cracking due to restraint. Where some degree of autogenous healing

is to be relied upon during hydrostatic testing, crack widths due to shrinkage and restraint should be limited to the values given in EN 1992-3. CIRIA Guide C660 ⁽¹⁸⁾ also provides guidance on early-age thermal crack control.

4.3.1.9 Construction Actions

All possible significant design issues caused as a consequence of construction should be considered according to EN 1991-1-6.

Effects of the sequence of construction stages on the secondary tank wall and base should be assessed for all significant action combinations, due to the construction of the roof, part erection stages and actions from temporary works. In cases when the upper part of the wall or ringbeam (if present in the design) is either not fully constructed and/or pre-stressed prior to roof erection, then its partly constructed capacity should be used in the assessment.

4.3.1.10 Testing and Commissioning Actions

The tanks should be designed for hydrostatic and pneumatic testing and cool-down in accordance with Chapters 6 and 7 and EN 14620-5.

4.3.1.11 Thermal Actions

Thermal effects during testing, cool-down, normal and abnormal operation and warming should be considered.

The minimum design temperature for the primary container components should be the product temperature.

Temperature design actions include both transient thermal actions resulting from the differential rates of cooling between different materials, including concrete elements, metallic embedments and liners and steady state temperature actions should be assessed throughout the structure. Concrete and metallic coefficients of thermal expansion at ambient and cryogenic temperatures should be used where appropriate. The coefficient of expansion of the concrete is sensitive to the aggregate type, concrete moisture content and temperature. The coefficient of expansion of a dry to moderately moist concrete mix at ambient and cryogenic temperatures is usually within the range $4\text{--}12 \times 10^{-6}/^{\circ}\text{C}$ (see FIP Report 1982 ⁽²⁾). Concretes with high moisture contents should be avoided. In the absence of test data, a minimum/maximum moisture range should be adopted for the design. Actual values for the design concrete mix should be confirmed by testing.

Effects of both highest and lowest temperature variations and the effects of solar gain should be considered. Either the owner's supplied temperature design data, or the 95th and 5th percentile of the maximum/minimum average daily temperatures, should be taken as the design temperature(s). The stress-free temperature for concrete should be included within the assessment and may be taken as 21°C, or a regional annual average temperature, in the absence of site specific information.

Convective heat transfer to the surrounding ambient air affects the surface temperature of the concrete. Convective film coefficients may be used to represent this heating or cooling effect of the surrounding air. These coefficients are a function of the air movement around the tank, solar radiation and the

temperature differential between the surrounding air and the concrete surface and shape.

4.3.1.12 OBE-type Earthquake

The tank should be designed to withstand the OBE-type earthquake as defined in EN 14620-1.

The primary container should be filled to the normal operating level, as defined in Section 4.5.3.1, for OBE action combinations.

4.3.2 Abnormal Actions

4.3.2.1 Leakage of the Primary Container

The secondary container should be designed so that it can contain the maximum liquid content of the primary container. The secondary container should be checked for intermediate filling conditions on the basis of steady-state temperature distribution. Besides major product spills from the primary tank into the interspace, the consequences of a minor product spill covering the floor of the interspace between the inner and outer tanks but below the top of the thermal protection system (TPS), if present, should also be investigated.

In addition the effects of a local cold spot within the interspace upon the tank walls, secondary liner and TPS, if present, should be investigated. Where the owner has not defined the size of the cold spot, it should be assumed to be equivalent to a circle 1.0 m in diameter on the secondary tank floor and walls.

Consideration should be given to possible leakage of pipe flanges and valves and their effect on the secondary tank roof and walls. Areas where spillage may occur should be designed for contact with liquid product temperatures or protected by provision of product catchment and drainage.

4.3.2.2 SSE-type Earthquake

The tank should be designed to withstand the SSE-type earthquake as defined in EN 14620-1.

The primary container should be filled to the normal operating level, as defined in 3.5.3.1, for SSE action combinations.

The effects of SSE need only be considered at the Ultimate Limit State.

4.3.2.3 External Fires and Explosions

The owner should specify the likely extent of external fires and explosions. External fire effects can include a pressure-relief tailpipe fire, adjacent tank fire, impoundment fire or process equipment fire.

For concrete and pre-stressed concrete tanks subject to fire, the most important factor is usually the rate of increase in temperature on the surface exposed to the radiation. Where excessive spalling may occur, a sacrificial layer of concrete with mesh reinforcement, intumescent coatings or a deluge cooling system should be considered. A sliding wall base connection should be checked for its thermal

response, as should exposed piers for an elevated tank. Where a metallic liner provides composite structural support, the effect of elevated temperatures should be considered on its performance.

4.3.2.4 Impact

Unless specified otherwise by the owner, the secondary tank walls and roof should be designed to withstand, without cracking or spalling on the internal face, the impact of a flying object weighing 50kg, travelling at 45 m/s, impacting perpendicular to the surface, with an impact area equal to a circle with a 100 mm diameter.

The effects of missile impact may be analysed using the Winfrith Model as described by Bangash ⁽¹⁹⁾. This method was developed by the UK Atomic Energy Authority and is based on the method developed by the French Atomic Energy Commission (Commissariat à l'Énergie Atomique, CEA).

The concrete element under consideration should be at least 20% thicker than the minimum thickness required to prevent perforation or scabbing, in order to account for uncertainty.

4.3.3 Combinations of Actions

The tank should be designed for the Ultimate Limit State (ULS) and Serviceability Limit State (SLS) combination of actions.

- ULS - includes all action conditions. This design state should be assessed to determine concrete section adequacy in accordance with the strength requirements of EN 1992 using appropriate material strength partial safety factors and partial action factors (see Table 3 and Table 4);
- SLS - includes construction, normal operating, and spill conditions. This design state should be assessed to determine structure displacements and crack widths for durability and liquid tightness of the concrete wall for the spill condition.

The normal actions referred to above should be combined in accordance with EN 1990, such that all possible combinations which can occur during construction, testing, cool-down, normal operation and warming-up of the tanks, are incorporated in the design. Only one accidental action should be combined with the appropriate combination of normal actions in any individual case.

All relevant action combinations should be considered including, but not limited to, those listed in Table 3.

Partial action factors should be applied in accordance with EN 1992 and in accordance with Table 1 of EN 14620-3 for abnormal actions (accidental and abnormal actions are the same) as shown in Table 4.

The effects of the range of differential settlements, creep, shrinkage and maximum and minimum ambient temperatures should be included in the analyses. However, where a ductile mode of failure is assured and where second order effects are negligible, deformation actions may normally be neglected for strength demonstration. Where these actions are included, only the deformation strain need be incorporated in the strength assessment.

Table 3 Recommended partial action factors for combinations of actions

	Permanent Actions				Pre-stress		Variable Actions										Abnormal Actions		
	Dead	Diff. Settle ment	Shrinkage & Creep		Early	Late	Product (liquid)		Design Gas Pressure			Wind	Hydro Test Water	Live Actions	OBE	Temp (Product & Ambient)	Liquid Spill & Gas Pressure	Blast, Impact & Fire	SSE
			Early	Late			Max	Min	Test	Max	Min								
Construction																			
ULS																			
Adverse	1.35	x	1.0	x	1.2	x	x	x	x	x	x	1.35 ⁽¹⁾	x	1.35 ⁽²⁾	x	x	x	x	x
Beneficial	1.0	x	1.0	x	0.9	x	x	x	x	x	x	0.0	x	0.0	x	x	x	x	x
SLS																			
Adverse	1.0	x	1.0	x	1.0	x	x	x	x	x	x	1.0 ⁽¹⁾	x	1.0 ⁽²⁾	x	x	x	x	x
Beneficial	1.0	x	0.0	x	1.0	x	x	x	x	x	x	0.0	x	0.0	x	x	x	x	x
Test																			
ULS																			
Adverse	1.35	1.35	1.0	x	1.2	x	x	x	1.2	x	x	1.35	1.2	1.35	x	x	x	x	x
Beneficial	1.0	1.0	1.0	x	0.9	x	x	x	0.0	x	x	0.0	0.0	0.0	x	x	x	x	x
SLS																			
Adverse	1.0	1.0	1.0	x	1.0	x	x	x	1.0	x	x	x	1.0	1.0	x	x	x	x	x
Beneficial	1.0	1.0	0.0	x	1.0	x	x	x	0.0	x	x	x	0.0	0.0	x	x	x	x	x
Operation																			
ULS																			
Adverse	1.35	1.35	1.0		1.2		1.2	x	x	1.2		1.35 ⁽¹⁾	x	1.35 ⁽²⁾	1.2	x	x	x	x
Beneficial	1.00	1.00	1.0		0.9		0.0	1.0	x	x		x	x	x	x	x	x	x	x
SLS																			
Adverse	1.0	1.0	1.0		1.0		1.0	x	x	1.0		1.0 ⁽¹⁾	x	1.0 ⁽²⁾	1.0 ⁽³⁾	1.0 ⁽⁴⁾	x	x	x
Beneficial	1.0	1.0	1.0		1.0		0.0	1.0	x	x		x	x	x	x	x	x	x	x
Abnormal																			
ULS																			
Adverse	1.05	1.05	x		x	1.2	1.00	x	x	1.05		0.3 ⁽⁵⁾	x	x	1.0 ⁽⁶⁾	1.05 ⁽⁷⁾	1.0 ⁽⁸⁾	1.0 ⁽⁹⁾	1.0 ⁽¹⁰⁾
Beneficial	1.0	0.0	x		x	0.9	x	x	x	x		x	x	x	x	x	x	x	x

Notes

x: action case not considered in combinations

(1), (2), (3), (5) or (6): only one of these actions to be present in any combination

(3) & (4): do not act in the same combination, except for the spill condition on the secondary container

(10): not to be combined with any of (5), (6), (7), (8) or (9)

Table 4 Partial factors for materials for ultimate limit states to EN 1992-1-1

Design situations	γ_c for concrete	γ_s for steel	γ_s for pre-stressing steel
Persistent & Transient	1.5	1.15	1.15
Accidental	1.2	1.0	1.0

4.3.4 Tank Analysis Model

4.3.4.1 General Aspects

The tank should be analysed as an integrated structure that includes the primary tank and secondary tank, including the foundation. The analyses should demonstrate that the performance and acceptance requirements described in Sections 4.5.1, 4.5.2, 4.6.1 and 4.6.2 are achieved for the worst combination of actions anticipated. Consideration should also be given to the potential for movement at the interface of soil layers as well as within layers.

For actions that do not vary significantly in the circumferential direction, a two-dimensional axi-symmetric model can be used for the analysis. For actions that do vary in the circumferential direction, a three-dimensional model is recommended, unless it can be demonstrated that a two-dimensional analysis provides conservative results. The effects of structural discontinuities should be considered and, where it is deemed necessary, they should be allowed for in the models. The three-dimensional model should include significant features such as wall thickenings, outstands, buttresses and ringbeams, if present.

The theory of linear elastic analysis may be used to determine the effects for each component action on the tank structure. The effect of combinations of actions should be assessed using superposition of the component action results. The component results should be multiplied by the appropriate SLS and ULS action factors and summed to obtain the various internal design forces and displacements for each action combination.

Non-linear transient analysis may be used for severe thermal action conditions including fire and spill scenarios. The analysis should be based on ambient temperature properties and characteristic material strengths, but the effects of temperature and time dependent properties should be examined where relevant. The analysis should consider the full temperature time history up to steady-state conditions. Where the structure has cracked, the effects of reduced stiffness and in-elastic deformations should be taken into account.

4.3.4.2 Seismic Aspects

The seismic design and analysis of the primary containment tank should be in accordance with the provisions of EN 1998-4. Where decoupled horizontal and vertical lumped mass models are used, the representation of tank-fluid behaviour in the vertical model should comply with the requirements of ACI 350.3. The response spectra or time history analysis method should be used for calculating the seismic responses of the tank-fluid-foundation system. The time-histories should satisfy the amplitude, frequency and duration requirements for the site OBE and SSE events. Both horizontal and vertical ground motions should be

accounted for in the seismic analysis. Procedures for applying time history analysis should follow those recommended in EN 1998-1 Clause 3.2.3.

Material damping values as expressed as a percentage of critical damping are required for the tank-fluid-foundation system in lumped mass models. Damping values in Table 5 should be considered as maxima unless higher values can be justified.

Table 5 Critical damping values

Component for design	Damping factors	
	OBE	SSE
Steel	2.0%	4.0%
Fluid - Horizontal Impulsive	2.0%	5.0%
Fluid - Horizontal Convective	0.5%	0.5%
Fluid - Vertical Flexible	2.0%	5.0%
Fluid - Vertical Rigid*	0.0%	0.0%
Pre-stressed Concrete	2.0%	5.0%
Reinforced concrete	4.0%	7.0%

* The vertical rigid component is the motion of the liquid which moves vertically in phase with the ground. It is assumed to be at a frequency of 33 Hz and, for practical purposes, it is taken to be equivalent to the zero period response (refer to ASCE 4-98).

Soil damping values should be verified in the geotechnical investigation. The maximum damping limits recommended by EN 14620-1 Clauses 7.3.2.2.13 and 7.3.3.3 should be adhered to. The viscous damping ratio of the structure expressed as a percentage for any vibration modes should not exceed 15% for OBE and 20% for SSE.

During an SSE event, the secondary tank is permitted to sustain localised and limited non-linear behaviour (e.g. yielding in steel, tensile cracking in concrete). Therefore the SSE design check should allow non-linear methods of analysis in accordance with EN ISO 19901-2 Clause 6.2.3, where the design depends on a combination of static reserve strength, ductility and energy dissipation to resist SSE actions.

Where uplift is permitted during seismic events, in accordance with Sections 4.5.1 and 4.6.1 and anticipated for the primary or secondary tanks, then a full 3D transient dynamic non-linear finite element analysis, incorporating the effects of soil-fluid-structure interaction, should be undertaken to assess resultant forces upon the foundation, stresses within the tank components and to confirm that the performance and acceptance requirements are met.

4.4 Foundations

4.4.1 General

The foundations should be designed to support the design actions and ensure structural integrity in accordance with the requirements of EN 14620. Foundations should be designed in accordance with EN 1997.

4.4.2 Soil Investigation

To account for variation in soil and rock parameters, the soil profile should be studied as part of the geotechnical investigation, to determine the design soil profile and the range of variation of design parameters.

4.4.3 Performance Requirements

The foundations should meet the requirements of EN 14620.

The maximum total and/or differential settlement during the life of the tank should be within the permissible settlement limits. The latter should be agreed with the owner and contractor(s). In the absence of further information, the differential settlement limits in Table 6 may be used for guidance. Where the designer departs from the values given in Table 6 it should be demonstrated that all load bearing elements, including insulation, can withstand the imposed deformation.

Table 6 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 calculate for tilt of the tank

4.4.4 Foundation Design

The effects of soil structure interaction (SSI) and settlement should be analysed and foundations, including piles if used, should be designed, using a range of design soil profile parameters as detailed in ASCE 4-98.

An acceptable method to account for uncertainties in SSI analysis is to vary the low strain soil shear modulus. Low strain soil shear modulus should be varied between the best estimate value times $(1 + C_v)$ and the best estimate value divided by $(1 + C_v)$, where C_v is a factor that accounts for the uncertainties in the analysis and soil properties. If sufficient and adequate soil investigation data are available, the mean and standard deviation of the low strain shear modulus should be established for every soil layer. The C_v should then be established so that it covers the mean $\pm$ one standard deviation for every layer. The minimum value of C_v should be 0.5. When insufficient data are available to address uncertainties in soil properties, C_v should be taken as no less than 1.0.

4.5 Primary Pre-stressed Concrete Tanks

4.5.1 Performance Requirements

The primary container should be designed in accordance with EN 1992.

The primary container should have concrete walls, be open at the top, with a concrete or a metallic base.

In normal tank service, the primary container provides liquid containment and remains liquid tight as defined below, thus limiting ingress of product into the interspace between the primary and secondary containers.

Key performance requirements are to prevent product spilling into the interspace and minimising permeation through the wall or base of the primary container. The tank should be designed so that where small volumes of liquid are allowed to permeate through the primary tank, in accordance with the limits defined in Section 3.2.10, deterioration of the insulation in the interspace is prevented. The primary container should be considered to be Tightness Class 3 to EN 1992-3, for considerations of liquid tightness.

Liquid tightness of concrete elements, without a liquid tight liner, may be ensured by using a well proportioned, well consolidated concrete mix appropriate for cryogenic temperatures. The concrete should be free from honeycombing and unplanned cold joints. A concrete primary container can be constructed using either slipforming, jumpforming, conventional shuttering or pre-cast with sealed jointing. A significant advantage of slipforming is that, if performed correctly, it minimises construction joints in the cylindrical wall, thereby enhancing the liquid tight behaviour of the tank. Jumpforming and conventional formwork, which are simpler methods and more commonly used, introduce a large number of horizontal and often vertical joints. Although it is possible to produce joints that behave continuously, it is very difficult to achieve this in practice. Crack widths and depths should be minimised by design, and the provision of adequately detailed reinforcement and joints properly designed and constructed. Where permeability requirements of a concrete element alone cannot be guaranteed by design and testing, then a continuous impervious coating or barrier appropriate to the service conditions should be incorporated.

The liquid tightness of a continuous metallic liner, placed within the concrete section and maintained in compression at cryogenic temperatures, can be assumed. The liquid tightness of concrete elements, without a liquid tight liner, should be defined by the minimum compression zone in the concrete structure. An unlined primary container should be considered to be Tightness Class 3 to EN 1992-3 and pre-stress reinforcement should be designed to ensure liquid tightness.

For primary containers without a continuous impervious coating or barrier a process simulation analysis should be performed to demonstrate and quantify the volume and behaviour of liquid as it permeates through the primary container.

The analysis should consider the following features:

- the full range of constituent gases in the liquid product held in the tank and their different characteristics including but not limited to boiling points and viscosities;
- pressures generated by phase transition of liquid to vapour;
- permeability characteristics of the concrete, both inherent and crack induced;
- temperature profile of the stored product external environment and structure and insulation;
- the filling and emptying cycles.

In the event that liquid product is shown to reach the annular space, measures should be taken to demonstrate that the thermal and structural properties of the

insulation material are not compromised. A reasonable factor of safety should be established on the volume in order to size any collection system and on the life expectancy of the insulation.

Product tightness and crack control in the wall may be provided by circumferentially pre-stressing a shotcrete, precast or cast-in-place concrete core wall containing a liquid-tight steel barrier, or by a cast-in-place wall with both circumferential and vertical pre-stress reinforcement. For a tank without a liquid tight liner both horizontal and vertical construction joints should be avoided.

The primary container should remain product tight under empty conditions after undertaking the following: post-tensioning, hydrostatic test, cool-down, operational action combinations and OBE combinations. There should be no permanent deformation during or after an OBE event.

The primary container should not collapse or rupture in a brittle manner during an SSE event, it should retain its integrity.

The primary tank should be designed to have sufficient free-board, to prevent both spillage and any contact with the suspended deck due to sloshing waves during an OBE or SSE event.

For primary containers with metallic bottoms, uplift should be prevented for an OBE event, or restricted where anchorages are used, but maybe permitted as agreed with the owner, subject to analysis and design for an SSE event providing the performance and acceptance requirements of the tank are maintained. Anchorage straps slacken because the primary tank cools down more than the straps which pass through warmer zones before being anchored in the secondary foundation. Uplift can thus occur where anchorage straps are used, but only to the point where slack in the straps is eliminated.

For primary containers with monolithic concrete bottoms, uplift is acceptable provided that primary container concrete performance criteria are met in the tank wall and tank bottom.

Sufficient frictional resistance or anchorage should be provided to restrict sliding during seismic events, so that it is controlled and the effects are not detrimental to the design. Horizontal sliding of the tank should not be allowed for an OBE event. Sliding should not be allowed for an SSE event, unless it can be demonstrated that there can be no detrimental performance to the tank systems and that the possible movements for an SSE event are acceptable to the owner. Friction factors should be based on existing design guidance or testing. A factor of safety against sliding of 1.5 should be applied for an OBE event and 1.0 for an SSE event unless possible movements are acceptable to the owner. When sliding resistance is provided by specific anchorage, the bottom plate and bottom insulation and other relevant parts should be designed to withstand the actions resulting from anchorage.

4.5.2 Acceptance Criteria

The primary container should have a Seismic Classification B in accordance with EN 1473 Clause 4.5.2.2. The primary container should remain operational after an OBE event and should keep its containment capability in the case of an SSE event.

Unless an impermeable membrane or liner has been used, minimum requirements for product tightness are:

- under empty conditions and operation action conditions in the concrete wall and in the concrete base:
 - the net resultant force in a section should be compressive; and
 - a compressive zone, in both perpendicular directions, of either 50% of the section thickness or 200 mm, whichever is greater, should be maintained;
- under the combination of operational conditions plus OBE event in both the concrete wall and the concrete base, a compressive zone of either 50% of the section thickness or 200 mm, whichever is greater, should be maintained. Maximum design stresses in materials should comply with the requirements of EN 1992 for ULS and SLS conditions;
- tensile capacity of concrete should not be used when calculating the size of the uncracked zone.

For primary tanks with a metallic liquid liner it is the performance of the metallic liner in terms of its liquid tightness, rather than that of the concrete components that is of primary interest. Where a carbon steel liner is to be used then it should be designed to remain in compression at low temperatures in order to avoid low temperature cracking.

Alternatively, for tanks using liners with steel Classification IV or V to EN 14620-2 Clause 4.3.1.2.1, then the allowable stress in service for the liner should meet the requirements of Table 4 of EN 14620-2, i.e. the lesser of $0.43f_u$ or $0.67 f_y$ for Type IV steel or $0.4f_u$ or $0.67 f_y$ for Type V steel.

Table 7 Acceptance criteria for liquid tightness in primary tanks except at SSE

Acceptance Criteria	Primary Tank - with metallic liner	Primary Tank - without a metallic liner
Minimum depth of concrete compression zone	Not required	50% of wall thickness or 200 mm whichever is the greater
Minimum residual average concrete compressive stress (in the compressive zone)	Compressive	Compressive
Limiting stress and strain in the reinforcement	Characteristic yield stress (i.e. does not result in a permanent set)	Characteristic yield stress (i.e. does not result in a permanent set)
Limiting maximum compressive (and bearing) stress in the concrete	$\alpha_{cc}f_{ck}/\gamma_C$, to EN 1992-1-1	$\alpha_{cc}f_{ck}/\gamma_C$, to EN 1992-1-1
Surface crack widths in concrete	In accordance with EN1992-1 Clause 7.3.1	In accordance with EN1992-1 Clause 7.3.1
Stress in carbon steel liner	The stress should be compressive at temperatures less than -20°C	Not applicable