

DEP SPECIFICATION

MEMBRANE TYPE REFRIGERATED LNG TANKS

DEP 34.51.01.37-Gen.

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DESIGN AND ENGINEERING PRACTICE

DEM1



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1. INTRODUCTION

1.1 SCOPE

This new DEP specifies requirements and gives recommendations for the design, supply, fabrication, construction, inspection and testing of LNG tanks with membrane type primary container and reinforced/pre-stressed concrete outer container. The capacity, number and salient data pertaining to the tanks are presented in (Appendix E).

The primary membrane together with thermal insulation and a concrete tank jointly form an integrated composite structure. This composite structure provides the liquid containment. The primary membrane, secondary barrier (Thermal Corner Protection - TCP) and load bearing insulation behind the membrane are to be in accordance with EN 14620-2 as a minimum. Local codes and standards may also apply.

This DEP addresses all components of the tanks including the primary membrane, the bottom and lower part of the wall secondary barrier (TCP), the suspended deck, the outer concrete tank and the outer tank vapour/moisture barrier.

This DEP contains mandatory requirements to mitigate process safety risks in accordance with Design Engineering Manual (DEM) 1 - Application of Technical Standards.

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by Shell GSI, the distribution of this DEP is confined to Shell companies and, where necessary, to Contractors and Manufacturers/Suppliers nominated by them. Any authorised access to DEPs does not for that reason constitute an authorisation to any documents, data or information to which the DEPs may refer.

This DEP is intended for use in facilities related to oil and gas production, gas handling, oil refining, chemical processing, gasification, distribution and supply/marketing. This DEP may also be applied in other similar facilities.

When DEPs are applied, a Management of Change (MOC) process shall be implemented; this is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements could be more stringent than in this DEP, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable with regards to the safety, environmental, economic and legal aspects. In all cases, the Contractor shall inform the Principal of any deviation from the requirements of this DEP which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned, the objective being to obtain agreement to follow this DEP as closely as possible.

1.3 DEFINITIONS

1.3.1 General definitions

The **Contractor** is the party that carries out all or part of the design, engineering, procurement, construction, commissioning or management of a project or operation of a facility. The Principal may undertake all or part of the duties of the Contractor.

The **Manufacturer/Supplier** is the party that manufactures or supplies equipment and services to perform the duties specified by the Contractor.

The **Principal** is the party that initiates the project and ultimately pays for it. The Principal may also include an agent or consultant authorised to act for, and on behalf of, the Principal.

The word **shall** indicates a requirement.

The capitalised term **SHALL [PS]** indicates a process safety requirement.

The word **should** indicates a recommendation.

1.3.2 Abbreviations

Term	Definition
AGA	American Gas Association
ALARP	As Low As Reasonably Practical
CCR	Central Control Room
CCTV	Closed Circuit Television
CQCE	Concrete Quality Control Engineer
DCS	Distributed Control System
DLF	Dynamic Load Magnification Factor
DSSI	Dynamic Soil Structure Interaction
EDRS	Equipment Data Requisition Sheet
FEA	Finite Element Analysis
FEM	Finite Element Modelling
IBS	Primary insulation space
IPS	Instrumented Protective System
IS	Secondary insulation space (behind secondary barrier)
LEL	Lower Explosion Limit
LNG	Liquefied Natural Gas
LTD	Level Temperature Density
MaxNOL	Maximum Normal Operating Level
MCR	Main Control Room
MDLL	Maximum Design Liquid Level
MDR	Master Document Register
MinNOL	Minimum Normal Operating Level
MT	Magnetic Particle Examination
OBE	Operating Basis Earthquake
P&IDs	Process and Instrument Diagram
PEFS	Process Engineering Flow Scheme
PLC	Programmable Logic Controller
PLD	Permissible Compressive Load
PLDF	Permissible load factor
PMI	Positive Material Identification
PRV	Pressure Relief Valve
PT	Dye Penetrant Test
PUF	Polyurethane Foam
PVC	Polyvinyl Chloride
RCRV	Reserve Capacity Relief Valves
RTD	Resistance Thermal Detectors
RPUF	Reinforced polyurethane foam

Term	Definition
SIL	Safety Integrity Level
SLS	Serviceability Limit State
SSE	Safe Shutdown Earthquake
SSI	Soil Structure Interaction
TCP	Thermal Corner Protection (Secondary Barrier)
ULS	Ultimate Limit State
XLPE	Cross-Linked Polyethylene

1.4 CROSS-REFERENCES

Where cross-references to other parts of this DEP are made, the referenced section or clause number is shown in brackets (). Other documents referenced by this DEP are listed in (24).

1.5 SUMMARY OF MAIN CHANGES

This is a new DEP.

1.6 COMMENTS ON THIS DEP

Comments on this DEP may be submitted to the Administrator using one of the following options:

Shell DEPs Online (Users with access to Shell DEPs Online)	Enter the Shell DEPs Online system at https://www.shelldeps.com Select a DEP and then go to the details screen for that DEP. Click on the "Give feedback" link, fill in the online form and submit.
DEP Feedback System (Users with access to Shell Wide Web)	Enter comments directly in the DEP Feedback System which is accessible from the Technical Standards Portal http://www.shell.com/standards . Select "Submit DEP Feedback", fill in the online form and submit.
DEP Standard Form (Other users)	Use DEP Standard Form 00.00.05.80-Gen. to record feedback and email the form to the Administrator at standards@shell.com .

Feedback that has been registered in the DEP Feedback System by using one of the above options will be reviewed by the DEP Custodian for potential improvements to the DEP.

1.7 DUAL UNITS

This DEP contains both the International System (SI) units, as well as the corresponding US Customary (USC) units, which are given following the SI units in brackets. When agreed by the Principal, the indicated USC values/units may be used.

1.8 NON NORMATIVE TEXT (COMMENTARY)

Text shown in italic style in this DEP indicates text that is non-normative and is provided as explanation or background information only.

Non-normative text is normally indented slightly to the right of the relevant DEP clause.

2. GENERAL

2.1 DESCRIPTION OF THE TANK(S)

1. The tank(s) SHALL [PS] be in accordance with the "Membrane" concept as specified in EN 14620 and EN 1473.
2. The tanks shall meet the requirements of the codes and standards referenced herein unless specifically modified by this DEP.
3. Materials, inspection and testing for the tank may be carried out to the relevant codes and standards provided that the specific requirements of this DEP are maintained.
4. The membrane type primary containment system shall consist of an open top container comprising a flexible corrugated stainless steel membrane supported by load bearing insulation and outer concrete tank.
5. A suspended deck with insulation shall be located above the primary open top liquid container. The primary membrane container and load bearing insulation is surrounded by a monolithic concrete outer tank consisting of a post tensioned concrete wall, a reinforced concrete base slab and a reinforced concrete dome roof.
5. The primary membrane shall be as per EN 14620 Part 2 and the requirements of this DEP and associated datasheets.
6. The load bearing insulation design shall be in accordance with EN 14620 Part 4 and the requirements of this DEP and associated datasheets.
7. The outer tank shall be as per EN 14620 Part 3 and the requirements of this DEP and associated datasheets. The roof and base of the outer tank shall be of reinforced concrete whilst the walls shall be post tensioned in both the horizontal direction and vertical direction.
8. The tanks SHALL [PS] be designed and constructed so that:
 - a. In normal service:
 - i. Primary membrane is liquid and vapour tight. No product liquid or vapour shall enter the insulation space behind the membrane.
 - ii. Moisture ingress in insulation space is prevented by a polymeric moisture barrier applied to the concrete slab and wall inside surfaces. Both vapour and moisture tightness of the roof and top part of the outer wall above the insulation is provided through the incorporation of a metallic vapour barrier.
 - b. In upset or emergency conditions where product accumulates in the inter-space:
 - i. The outer tank wall and the secondary liquid and vapour barrier contain the liquid product and prevent leakage.
 - ii. Product losses due to container permeability are acceptable (under these conditions and determination of absolute rates is not required).
 - iii. Controlled venting of the product vapour is permitted.

2.2 TECHNICAL SCOPE INCLUSIONS

1. Design and construction of the foundation, including soil improvement, deep foundations (or otherwise) is by the Contractor;
2. A reinforced concrete base slab with under tank heating system designed to prevent frost heave and support the tank and appurtenances;
3. A primary open top liquid containment system made from a stainless steel (or invar) membrane corrugated in two directions and supported by a load bearing insulation system. The membrane and insulation system are to be designed by the Contractor;

4. A concrete outer tank, consisting of a post tensioned concrete wall rigidly connected to a reinforced concrete bottom slab and a reinforced concrete dome roof. All concrete surfaces directly exposed to the product vapour shall be lined with a carbon steel vapour barrier. All concrete surfaces behind the membrane and not directly exposed to the product vapour shall be lined with a polymeric moisture barrier;
5. A "Thermal Corner Protection (TCP)" (Secondary Barrier) covering the entire bottom and the lower part of the wall. The top of the TCP shall be anchored into the post tensioned concrete wall approximately 5 m (16.4 ft) above the base slab. The TCP material shall be sandwiched between two layers of load bearing insulation.
6. A carbon steel roof liner which is integrally connected to the reinforced concrete roof with studs and forms an integral structure with the reinforced concrete roof.
7. A flat plate suspended inner deck, supported by stainless steel rod hangers from the concrete roof shall be constructed from aluminium, stainless steel or 9 % nickel steel.
8. A tank insulation system composed of glass fibre blankets on the suspended deck for the tank roof, nozzle insulation and a load bearing insulation system for the tank bottom and wall;
9. Submerged pump risers including pumps lifting mechanisms, cables from the top of the tube to the pump, and junction boxes, internal piping, etc. Spare pump to be fit tested and checked for all applicable tanks;
10. Submerged pumps shall be designed, supplied and installed by the tank Contractor and will conform to DEP requirements.
11. For the pump power cables, the Contractor will supply and install the cables from grade to a Junction Box (JB or JBs) at the top of the pump wells. For other electrical items, Contractor will supply, detail, locate and install all electrical components or equipment in or on the tank, and between the tank and the nearest JB, substation or auxiliary room as designated for each component.
12. Platforms, walkways, stairs, caged ladders, hoists, monorails, hand railing and accessories;
13. Insulation space purge and monitoring system;
14. Instrumentation for level, density and temperature measurement (all in one unit), temperature, settlement monitoring, gas/leak detection, cool down control, and any other instrumentation specified on project PEFSSs, or deemed necessary for the safe operation of the LNG tank is to be supplied, detailed, located and installed by the Contractor. Also, all associated wiring and electrical components required that are within the tank battery limits to the JB or designated termination point for each component;
15. Valves for pressure and vacuum protection, including first isolating valves and vent stacks;
16. An active fire protection system consisting of fire detection and control system including nitrogen snuffing system for the pressure relief valves;
17. Firewater system for roof platform and all equipment;
18. Design, installation, NDE and testing of all pipe work and pipe work insulation associated with the tank to the Battery Limit;
19. The Contractor shall model and design the piping systems within the scope of the tank and determine loads that the pipe supports shall accommodate. The Contractor shall consult with Principal on surge and slug design considerations when establishing piping system anchor point requirements within the battery limit. Battery limit shall be defined in the contract documentation. The Contractor shall also comply with the following:

- a. All piping within the tank, on the tank roof and wall is within the Contractor's battery limit. Piping termination points and battery limits shall be identified within interface documentation.
- 20. The Contractor shall design, supply and install;
 - b. The base slab heating system including all associated control and protective devices.
 - c. Lighting, earthing and lightning protection systems on and around the tank area.
 - d. Electrical equipment and devices for MOVs, hoists and cranes.
 - e. Aircraft warning lights if required by local regulations.
- 21. Lifting equipment (either slewing jib or gantry crane) on the main pump platform for component handling including in-tank pump removal and replacement. The Contractor shall also design, supply and install all electrical equipment and devices for MOV's hoists and cranes;
- 22. All trays, racks, supports for the electrical and instrumentation on the tank shall be within the scope of the Contractor when in the tank or on the tank wall, but for cabling exiting the tank area, the Contractor (if required) will utilise cabling trays supplied and installed by others;
- 23. The Contractor shall also design, furnish and install all external pipe work and Insulation materials for external pipe work within the Contractor's battery limit and any special support components and any non-standard insulation materials required at any pipe supports or guides.
- 24. All Inspection work by an independent subcontracted inspection agency may be used for all shop fabricated sub-components as applicable providing that the qualifications of all inspectors shall satisfy the requirements of API 620, section 7.2.1.

2.3 CODES AND INDUSTRY STANDARDS

Detailed list of applicable codes and standards is included in (24) of this document.

- 1. All codes and standards unless noted otherwise shall be the latest edition, including revision, addenda, supplements or others at the time of Invitation to Tender.

3. FOUNDATIONS, PAVING AND DRAINAGE

3.1 SOIL INVESTIGATIONS

- 1. Soil investigations for the tank site shall be conducted by the Principal to establish ground characteristics and variability of the underlying strata. Both factual and interpretive investigation data and reports for the LNG tank site shall be made available to the Contractor upon completion.
 - a. The available data shall be reviewed and verified by the Contractor that it is sufficient for the design and construction of the LNG Tank.
 - b. If the Contractor requires additional information on ground conditions, including ground improvement, then the Contractor shall carry out the additional work at its own expense.
- 2. The final interpretation of the factual data provided to the Contractor and the factual data obtained by the Contractor shall be the Contractor's sole responsibility.
- 3. If Contractor identifies additional required information, then the Contractor is to bring to the attention of the Principal proposed requirements for a complementary soil investigation.
 - a. The Contractor shall carry out an assessment of the scope of the additional work and communicate this to the Principal at tender stage.

- b. Detailed information pertaining to the Contractor's proposed foundation/ground improvement methodology shall be provided for evaluation/agreement of the Principal at the tender stage.
4. The minimum total number of exploratory holes shall be 13 configured in a 1,4,8 pattern, i.e., 1 at centre, 4 evenly round circle of half diameter, plus 8 evenly distributed round the perimeter.
5. The Contractor shall within the Tender submission nominate the preferred ground improvement technology required and include a comprehensive level 3 schedule for the geotechnical works.
 - a. Specific milestones shall be included for site investigation, ground improvement activities, testing and handover of foundation for start of construction activities.

3.2 FOUNDATIONS

1. The Contractor shall ensure that the LNG tank foundations are designed and constructed in such a way that, during all stages of the tanks' lifetime, including construction phases, hydro-test, operation phases and all emergency situations:
 - a. All credible combinations of loads are safely transferred to the subsoil;
 - b. Deformations including differential along any line in radial or circumferential direction are within acceptable limits from a structural and tank operational point of view;
 - c. The tank foundation is to be designed in such a way that all ground and rainwater are drained away from the LNG tank.
2. The following limiting criteria for settlement can be used by the Contractor as guidelines:
 - a. The actual settlement criteria shall be established based on the site specific geotechnical information, tank design requirements and requirements of ancillary equipment.
 - b. The predicted foundation non-uniform settlements shall not exceed the limits set out in Table 3.1.

Table 3.1 Guidelines for settlement

Type of settlement	Settlement limits
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 the tilt of the tank)

3. The Contractor shall select and optimise the foundation concept based on the content of the interpretive Geotechnical report.
 - a. Due consideration shall be given to the potential liquefaction of the soil in accordance with the requirements of DEP 34.11.00.12-Gen.
 - b. The allowable bearing pressure of the soil shall be determined and subject to agreement with the Principal.

4. DESIGN ACTIONS

4.1 GENERAL

1. The LNG tank shall be designed for all specified loading conditions/combinations which may occur during construction, testing, commissioning, operations, decommissioning and maintenance of the tank.
2. The LNG tank shall consist of both a primary and secondary containment system:

The purpose of the primary membrane is to contain the liquid product, preventing cold liquid and gas penetration into the insulation system and subsequently contacting with the load carrying outer container.

 - a. The primary containment system shall be made from a thin liquid and gas tight, double corrugated austenitic stainless steel membrane, which is to be capable of storing the net LNG capacity plus the bottom ullage below the Minimum Normal Operating Liquid Level (MinNOLL) as well as additional volume above Maximum Normal Operating Liquid Level (MaxNOLL) associated with the tank overfill protection, the seismic sloshing wave height and freeboard.
 - b. The bottom ullage and overfill protection levels shall be defined in the project specific tank datasheets.
 - c. The membrane shall be able to accommodate thermal contraction and expansion during commissioning/decommissioning and operating cycles.
3. The primary membrane system shall be supported by a concrete outer container via suitable load bearing insulation. The reinforced concrete outer container is the main load carrying element of the tank.
 - a. The primary containment system shall resist hydrostatic and internal pressure loads by transferring all loads to the load bearing insulation system.
 - b. The outer reinforced concrete container shall be designed to resist all loads transferred by the load bearing insulation system, product vapour for both normal and accidental load cases
 - c. The outer reinforced concrete container shall contain the gross capacity of the inner tank under certain accidental load conditions.
4. Specific design requirements for the inner primary steel membrane, the outer load carrying concrete container and other containment components are defined in (5) to (11) of this DEP.
5. The following specific factors shall be taken into account:
 - a. Hydrotesting of the outer tank. This is to be of a height based on the hydrotest pressure at the base of the inner tank being 1.25 times the Maximum Design Liquid Level (MDLL);
 - b. Normal operation of the tank containing LNG Maximum and Minimum Design Liquid Levels (MDLL, MinNOLL);
 - c. Maximum and minimum internal pressure.
 - d. Pneumatic test of the outer tank to a pressure equal to 1.25 times the pressure for which the vapour space is designed.
 - e. OBE and SSE Earthquakes as per (Appendix E.5);
 - f. Predicted maximum differential centre to edge settlements of the concrete bottom slab based on interpretation of the geo-technical data. The design shall allow for total differential settlement through construction, hydro-testing and operational lifetime;
 - g. Post-tensioning loads and concrete creep/shrinkage effects;

- h. Loading condition specific to the primary membrane and load bearing insulation design including thermal effect and cyclic loading.
- 6. Where piles are included in the design, the tank aspect ratio shall be selected so as to avoid tension in all piles under normal, OBE and SSE conditions.
- 7. The Contractor shall be responsible for all purging, cool-down, and commissioning procedures.

4.2 CONSTRUCTION LOADING

- 1. All loading conditions occurring during construction including loads from equipment, personnel and due to construction sequences shall be considered in the LNG tank design.
- 2. The roof liner may be used as formwork for the construction of the concrete roof. Internal air pressure may be utilized to offset the structural demands of fresh concrete during temporary load combinations. Load and material variability factors shall reflect the temporary nature of the load and ability to control the placement and thickness of the concrete.

4.3 LIVE LOADS

- 1. Live loads shall, in general, be as per EN 1991-1-1. However, the following minimum live loads shall be considered in the design of structures to account for maintenance and erection.
 - a. Roof during Erection 1.5 kNm^{-2} (0.217 psi)
 - b. Corridors, passageways and staircases 4.0 kNm^{-2} (0.580 psi)
 - c. Other live load shall be as per the requirements given in EN 1991-1-1.

4.4 PRESTRESS AND DIFFERENTIAL SHRINKAGE LOADS

- 1. Both short-term and long-term pre-stress loads imposed by post-tensioning shall be considered. Short-term pre-stress means pre-stress immediately after post-tensioning and long-term pre-stress means pre-stress loads after all time dependent losses such as concrete creep and shrinkage and tendon relaxation take place.
- 2. Short term and long term concrete differential shrinkage loads occurring due to difference in time of concrete placement for various tank components shall be considered.

4.5 WIND LOADS AND SNOW LOADS

- 1. The outer tank and associated structural components shall be designed to withstand the effects of:
 - a. Basic wind speed as per the (Appendix E.4.2) and local codes
 - b. Snow Loads as per (Appendix E.4.4)

4.6 EARTHQUAKES (OBE and SSE)

- 1. Seismic design of the primary membrane container and the outer tank shall be in accordance with the requirements of API 620 Appendix L and EN 14620 and as amended herein.
- 2. The primary membrane container and the reinforced concrete outer tank shall be designed for two levels of seismic ground motion, OBE and SSE. Return periods for OBE and SSE events and spectral construction shall be as per requirements of EN 14620-1 (§7.3.2.2.13, §7.3.3.3) and as stated in (Appendix E).

- a. The OBE ground motion shall be the motion represented by 5 % damped response spectra having a 10 % probability of being exceeded within a 50 year return period (mean recurrence interval of 475 years).
 - b. The SSE ground motion shall be the motion represented by a 5 % damped acceleration response spectrum having a 2 % probability of exceedance within a 50 year period (mean recurrence interval of 2475 years).
 - c. In accordance with EN 14620-1 §7.3.3.3 the spectral acceleration of the SSE response spectrum shall not exceed twice the corresponding OBE spectral accelerations.
3. The complete tank system shall be designed so as to:
- a. Be re-operable after an OBE event and all components including piping, structures, attachments and appurtenances shall be designed so as to remain essentially elastic. In this regard force reduction (ductility) shall not be permitted under the OBE event.
 - b. Survive the SSE event. In this regard, ductility shall be permitted as per code requirements based on the structural classification for all structural and non-structural components and attachments. Where ductility is adopted for the outer tank design including roof, wall and (where provided) piles, a detailed pushover analysis shall be undertaken to demonstrate/validate the force reduction factor selected.
4. The complete tank system including the primary membrane, load bearing insulation and outer concrete tank shall be designed for
- a. The OBE whilst filled with LNG to the Maximum Design Liquid Level (MDLL), and
 - b. SSE conditions whilst filled with LNG to the Maximum Normal Operating Liquid Level (MaxNOLL)
5. It shall be clearly demonstrated that under the predicted pressures for the OBE and SSE events, "pull away" of the membrane from the insulation does not occur.
6. The tank system shall be designed using dynamic lateral force procedures with due consideration of the effects of the various components (membrane, insulation and concrete tank) and foundation interaction. Specific combinations of components may be modelled and analysed separately.
7. For structural appendages such as platforms an appropriate analysis shall be undertaken to assess the amplification/attenuation of motion under seismic action.
8. Fixed period damping ratios for the tank structure and fluid contents shall be as per Table 4.1.

Table 4.1 Damping ratios

Component	Damping Factors in %	
	OBE	SSE
Steel	2.0	4.0
Horizontal Impulsive	2.0	5.0
Horizontal Convective	0.5	0.5
Vertical Flexible	2.0	5.0
Vertical Rigid	0.0	0.0
Prestressed Concrete	2.0	5.0
Reinforced Concrete	4.0	7.0

9. The vertical rigid component (in Table 4.1) is the motion portion of the liquid that moves in phase with the ground. It shall be assumed to be at the zero period acceleration, for the purposes of the analysis it shall be taken as 33 Hz.
10. Dynamic soil structure interaction (DSSI) effects shall be considered for all tanks not supported by a rock or rock like foundation (shear wave velocity $V_s > 750$ ms⁻¹ (2460.63 ft/s)).
 - a. Impedance function methods (where used) shall conform to the requirements of EN 1998-4 A7.
 - b. Maximum modal damping shall be limited to 15 % and 20 % respectively, for the OBE and SSE horizontal modes.
 - c. The Contractor shall provide a comprehensive DSSI design basis clearly identifying the analysis methodology, (i.e., impedance (frequency domain) or direct methods (time domain) along with ranges of dynamic impedances, soil constitutive models and methodology for including far and near field effects commensurate with the requirements of (5.3.2)).
11. For frequency domain methods the horizontal and vertical response spectra for both the OBE and SSE shall be input to the model as acceleration spectra. The responses of the composite tank structure for each mode shape shall be determined from the appropriate response spectrum, modal frequency and composite damping.
12. For the outer tank individual modes (for a given excitation direction) shall be combined using the Square Root Sum of the Squares (SRSS) method. The total seismic demand shall be determined using a 40 % spatial combination and be the maximum of:
 - a. 100 % horizontal + 40 % vertical
 - b. 40 % horizontal + 100 % vertical
13. All impulsive and convective components shall be combined using the absolute sum methods for a given excitation direction. The total seismic demand shall be determined using a 40 % spatial combination as per the above.
14. Liquid levels shall be determined in accordance with (Appendix E), so as to avoid wave impact against the suspended deck during OBE and SSE events. Sloshing wave height shall be calculated in accordance with API 620, Appendix L.

4.7 HEAT LEAK

1. The total heat-in leak shall be such that the boil-off rate per day by volume of the gross tank contents per day based on pure methane shall not exceed the percentage, shown in (Appendix E). Boil-off calculations shall be based on the following information listed in (Appendix E).
 - a. 95th percentile ambient air temperature
 - b. 5th percentile wind speed
 - c. 90 % relative humidity
 - d. Solar radiation as per (Appendix E)
2. The Contractor shall make allowances for heat gain from pumps, stilling wells and appurtenances and provide calculations during the detailed engineering phase demonstrating that the insulation fulfils the heat in-leak requirements.
3. For exposed surfaces during a period of 12 hours the daily global solar radiation shall be included. Thermal inertia of the concrete outer tank may be considered for the effect of solar radiation on boil-off rate. Calculations shall be prepared and submitted during the detailed engineering phase demonstrating that the insulation fulfils the heat in-leak requirements.

4.8 HAZARD DESIGN CONDITIONS

4.8.1 LNG spill protection

1. LNG spill collection/diversion shall be in accordance with the relevant local codes and standards.

4.8.2 Fire exposure and cold splash protection

1. In the event of fire, the tank shall be designed to remain fully functional and continue in service with the minimum of repair.
2. The outer tank roof and side walls shall be capable of withstanding fire exposure and heat radiation from the following relief valve discharge fires:
 - a. A single pressure relief valve (PRV) fire may occur by ignition of vapour relieved as a result of a failed pilot system. It is assumed that remedial action to stop a single PRV fire can be taken within 2 hours. The heat radiation shall be determined based on the total design flow rate of a single PRV discharging through the tail pipe.
 - b. Multiple PRV fires may occur by ignition of vapour relieved as a result of upsets in operation. It is assumed that the fire can be stopped by operational action within 10 minutes.
3. Main steel structural members, located on the LNG tank roof, which are supporting vital equipment, shall be protected both for fire.
4. Requirements for the fire cases are included in (Appendix B).

4.8.3 LNG major leak

1. The post-tensioned concrete tank wall and its connection to the base slab shall be designed to withstand the thermal effects of LNG in the insulation space. An appropriate number of intermediate liquid levels sufficient to demonstrate integrity of the wall shall be considered in-conjunction with maximum design internal pressure to ensure the most severe design conditions are considered.
2. The Contractor shall pay particular attention to spills in the vicinity of the TCP Embedment and in no instance shall the number of spill levels selected for analysis be less than 6.
3. It shall be demonstrated that any irreversible deformations occurring on the secondary container during the major leak or major leak + OBE shall not impact the containers ability to meet the acceptance criterion of (5.5.4).

4.8.4 Local cold spot

1. A local cold spot of 1 m (3.2 ft.) diameter at the product temperature shall be considered as acting on the walls, secondary liner and TCP. The carbon steel vapour barrier is permitted to fail under this condition.

4.8.5 High velocity Impact - Flying Valve

1. The outer tank walls and roof shall be designed to withstand the impact of a 110 kg (220 lb) projectile travelling with a velocity 45 ms^{-1} (150 fps) impacting perpendicular to surface with an impact diameter 100 mm (4 in).
2. The perforation thickness shall be determined using the modified CEA-EDF formula as presented in CEB 187 as follows;

$$V_p^2 = 1.9 f_c \rho^{1/3} \left(\frac{de^2}{M} \right)^{4/3} N^2 \left[0.35 \left(\frac{M_a}{M_{a0}} \right)^{\gamma} + 0.65 \right] \left(\frac{f_c}{f_{c0}} \right)^{-1/2}$$

- a. The maximum ratio of e/d and M_a in the above equation shall be limited to 4 kgm^{-3} and 300 kgm^{-3} respectively.
- b. N shall be taken as 1.0 commensurate with a flat nosed object.

- c. In order to account for uncertainty, the concrete elements shall be at least 20 % thicker than the minimum thickness required to reduce the projectile velocity to zero.
 - d. For walls with thickness smaller than twice the perforation thickness, the minimum percentage of reinforcement shall be 0.2% in each principle direction and on each member face.
2. The penetration depth shall be determined using the UKAEA formula as presented in CEB 187 follows;

$$G = 3.8 \times 10^{-5} N m V_i^{1.8} / (f_{cy}^{0.5} d^{2.8})$$

- a. Maximum values of m/d^3 and f_{cy} in the above equation shall be limited to 200,000kgm⁻³ and 44MPa respectively as per CEB 187.
 - b. N shall be taken as 1.0 commensurate with a flat nosed object.
 - c. In order to account for uncertainty, the concrete elements shall be at least 20 % thicker than the penetration depth when $z > 0.75$ and 50% thicker than the penetration depth when $z \leq 0.75$.
 - d. Where horizontal tendons are located within the penetration depth of the proximal face (with due allowance for uncertainty i.e. increasing penetration depth by 20% or 50% as required by (4.8.5.2 c)) the outer tank wall shall be designed with additional tendon redundancy to allow for a single tendon failure at any horizontal location without impairment of functional requirements.
3. The minimum depth to resist scabbing shall be determined using the UKAEA formula as presented in CEB 187 follows:

$$\frac{t_s}{d} = 5.3 (G)^{1/3}$$

Where G is determined in accordance with (4.8.5.2) above.

- a. Within the range $0.18 < d/t_s < 0.5$ the concrete elements shall be at least 40 % thicker than the minimum depth to resist scabbing.
- b. Where metallic liners are provided on the distal face the effects of scabbing need not be considered.

4.8.6 Low velocity Impact loads – Dropping objects

1. The concrete tank roof shall be designed to withstand impacts of dropped objects of maximum 900 mm (3 ft) diameter weighing up to a maximum of 1000 kgs (2204.62 lbs) falling from a height of 10 m (33 ft).
2. Scabbing
 - a. The conditions for scabbing or through-wall cracking to occur have been correlated by defining a scabbing number defined as presented in CEB 187 follows;

$$N_{scab} = \frac{m^{0.5} V_i d_e^{0.5}}{d_0 e (1 + e/d)} \frac{E_c^{0.5}}{f_r}$$

- b. The minimum thickness to resist scabbing shall be determined from the above equation with N_{scab} equal to 50.
- c. No account should be taken of increases in compressive strength occurring after 28 days, unless corresponding increases in the tensile strength can be demonstrated.

- d. Where metallic liners are provided on the distal face the effects of scabbing need not be considered.

4.8.7 Blast loads

1. The tanks shall be designed to safely resist the effects of the blast loading specified in (Appendix E).
2. Escalation of an explosion incident shall be prevented by ensuring structures maintain their integrity when subject to specified blast wave loading.
3. Container-associated piping up to and including the first container shutoff valve in LNG lines, and fire protection systems shall remain operational after explosion event.
4. Blast loading shall be commensurate with the 10-4 overpressure as documented in (Appendix E.6).

4.8.7 Design load conditions specifics for primary membrane

1. As a minimum loading conditions stated in (4.2) to (4.4) and (4.6) be considered in the design of the concrete outer tank. Product hydrostatic load and internal pressure inside of the primary membrane shall be transferred to the outer tank and considered in the outer tank wall design. Similarly, hydrodynamic seismic loads due to liquid acceleration at seismic events shall be accounted for in the outer tank design. Sloshing wave height shall be calculated in accordance with API 620, Appendix L.
2. The considered in the design of the primary membrane shall be as per Table 4.2:

Table 4.2 Loading conditions

Loading Condition	Static and Dynamic Loads	Cyclic Load (Fatigue Considerations)
Dead Load	X	
Construction Loads	X	
Product Load	X	X
Internal Pressure	X	X
Overpressure	X	
Internal Vacuum	X	X
Thermal Loads	X	X

3. The primary membrane shall be able to accommodate deformations imposed by post-tensioning, concrete creep and shrinkage, insulation creep, thermal expansion/contraction and foundation settlements.
4. As a minimum the following liquid and thermal cyclic actions shall be considered for the primary membrane fatigue evaluation:
 - a. Loading/Unloading - once per week
 - b. Commissioning/Decommissioning - once every two years
5. Contractor is to confirm with the Principal project specific loading/unloading requirements as it may be more onerous than specified above.

5. DESIGN CONSIDERATIONS - CONCRETE COMPONENTS

5.1 GENERAL

1. Thicknesses of the bottom slab, wall, and roof shall be selected by the Contractor to meet the performance requirements documented herein. The thickness of the wall shall be selected so that in normal operating conditions the shear forces are absorbed by the wall without the need for shear reinforcement.

2. All horizontal surfaces (including plinths) that are permanently exposed to the elements shall be laid to a grade of 1:40 to generate free draining surface.
3. Design life of the concrete components shall be 50 years. It is noted that certain national codes use the design life in order to ascertain/determine design return periods for wind and earthquake. When such codes are used checks shall be carried out to ensure that probabilities of failure are not eroded due to selection of lower 'unconventional' return periods.

5.1.1 Tank base slab

1. The tank concrete base slab/foundation design shall incorporate the recommendations of the Geotechnical report.
2. Where temporary construction joints are provided in the slab to allow for differential movement during construction the same shall be closed after partial post-tensioning of the wall.
3. For the base slab to wall junction 'kicker-less' construction shall be permitted provided the Contractor can demonstrate the ability to restrain and control the wall forms during pouring. Under no circumstances shall 'pockets' or 'box outs' be used in the base to provide securing for the formwork. Acceptable methods for securing formwork to the base slab include 'drill and fix anchors' or 'cast in place' fixings.
4. The storage tank and its foundation shall be designed to account for the maximum total and differential settlements predicted to occur during the life of the tank.
5. The bottom slab shall be of sufficient thickness to allow placement of top and bottom reinforcing mats each containing reinforcing bars in orthogonal directions, conduits for foundation heating system cables and sensors, and two inclinometer tubes embedded in the slab in orthogonal direction.
6. Heating conduits and inclinometer tubes shall maintain a minimum slope of 1/500 from the centre to the outside for water drainage. The inclinometer casings shall be cast into the slab and located at the upper most layer of the base slab. Chairs or other devices shall be used to ensure correct vertical position is maintained during pouring.

5.1.2 Tank wall

1. The wall shall be designed with monolithic connections between the base slab and wall, and wall to roof.
2. The wall outside perimeter can be circular or polygonal. The wall inside perimeter shall have a polygonal shape. The wall inside face may be provided with 28 or 56 flat facets depending on the membrane system. This arrangement simplifies installation of the insulation system and the membrane design. Contractor shall determine required number of facets.
3. The wall shall have a minimum thickness to be able to accommodate inside and outside layers of reinforcement in orthogonal directions as well as post tensioning ducts. Wall thickness may need to be significantly greater close to the base slab.
4. Minimum actual concrete clear cover for wall inside face reinforcement shall not be less than 65 mm. Contractor shall take into account in the design clear cover tolerances.
5. The wall shall be post-tensioned horizontally and vertically.
 - a. Post-tensioning shall be accomplished with an impermeable duct and tendon system.
 - b. Tank design shall account for effects due to the post-tensioning sequence during construction.
 - c. The outer tank shall be post-tensioned prior to hydrostatic and pneumatic testing. The minimum horizontal and vertical post-tensioning to be applied before the hydrostatic test of the outer tank shall be determined.

- d. Pre-stressing requirements shall also be accomplished with an impermeable duct and tendon system. All pre-stressing shall occur prior to hydrostatic and pneumatic testing.
 - e. Contractor shall use 'moveable stressing platforms' for horizontal post tensioning, i.e. use of scaffolding is not permitted as temporary works for stressing activities.
6. All openings used for construction purposes shall be considered within the design and limited to a height of 4 m (13.12 ft) measured above the top of the base slab.
- a. Determination shall be made of the post-tensioning arrangements and requirements for the location of temporary openings taking into account hydrostatic and pneumatic testing of the outer tank as well as the method used to seal the openings for hydrostatic testing and after the tank is complete.
 - b. The centre of the Thermal Protection Secondary barrier (TCP) embedment shall be located a minimum of one metre above the top of any construction openings.
 - c. Openings are provided mainly for material transport and emergency escape. Generally two temporary access openings are arranged in the wall, opposite to each other.
7. The embedment design shall consider the transient conditions under the spill condition in particular the effects of a 'cold' embed and 'warm' wall.
8. Vertical construction joints in the outer tank wall are not permitted above an elevation equal to the centreline of the TCP - 1 meter, i.e., the outer tank wall above this level be cast by complete 360° pours. Vertical construction joints including those required to form the temporary construction opening(s) are permitted below this level.
9. The post-tensioning requirements, stressing sequence, location of temporary openings and methodology used to permanently seal the openings prior to pneumatic test of the outer tank shall be submitted to Principal for review.
- d. The analysis and design of the wall shall reflect the effects of reduced axial demands due to the construction sequence in the vicinity of the access opening.
 - e. Pre-stressing of the wall shall be achieved with an impermeable duct and tendon system.
10. Horizontal ducts shall be constructed from 'thick plastic', i.e., polyethylene or polypropylene as provided by Manufacturer. Vertical ducts shall be constructed from welded CHS sections.
11. Mechanical couplers used to connect reinforcement in the construction opening areas on inside face affected by the cryogenic temperature at product leak shall be qualified for LNG service temperatures. Those located on the outside face shall be qualified for the anticipated service temperatures during normal and emergency operating conditions.

5.1.3 Tank roof

- 1. The roof shall be spherical in shape, and made of reinforced concrete with an interior carbon steel vapour barrier (liner). The roof radius shall be selected so as to enable concrete compaction without the use of a top shutter.
- 2. The roof liner including the compression ring shall be anchored into the concrete.
 - a. The steel liner located on the inside of the roof may be used as formwork for concrete placement.
 - b. The concrete may be poured in two layers to limit structural demands on the roof liner. Shear links shall be provided across layers if a two layer construction method is selected.

- c. The Contractor shall demonstrate by analysis that the roof plates and framing are adequately designed for any temporary loading scenario, including non-symmetrical loading due to wind, post-tensioning sequence and concrete pouring sequence.
3. Detail information on proposed method for checking of metallic roof design under concrete pouring condition shall be provided for evaluation/agreement of Principal at the tender stage. Minimum requirements shall be as follows:
 - a. The critical compressive state of steel roof will be assessed through 3D finite element modelling (FEM).
 - b. A minimum buckling safety factor will be maintained.
4. Offsetting of the reinforcement in the roof is not permitted through consideration of composite action between the roof plates and concrete. As a composite member, full transfer of horizontal shear shall be provided using properly anchored ties or headed studs. The maximum spacing of the ties or studs shall not exceed 0.6 m.
5. All roof penetrations and plinths for structural steelwork and appurtenances shall be provided with a concrete up-stand terminating a minimum height of 30 cm (0.98 ft) above the top of the roof uppermost surface. Specific details shall be included to prevent shrinkage of concrete from sleeves and maintain an adequate rainwater seal.
6. All the loads on the roof and those suspended from the steel structure (the deck and insulation) have to be supported by the concrete dome roof structure.
 - a. The roof structure shall also support the pump wells which are suspended from the roof.
 - b. The roof shall be designed to withstand a blanket loading of 1.2 kNm-2 (0.174 psi) projected across the whole roof area, a point load (non-concurrent) of 5 kN (1124.04 lbf) distributed over an area of 0.1 m² (1 ft²); a uniformly distributed load considered acting on the platforms and walkways as per (4.3).

5.2 DESIGN CODE

1. The reinforced and pre-stressed concrete elements of the tank wall shall be designed in accordance with the limit state philosophy of EN 1992-1-1. All applicable sections of the latest edition of the design code, including supplements and chapters describing precast and pre-stressed concrete, shall be followed except when supplemented or modified by provisions of this DEP.

5.3 ANALYSIS REQUIREMENTS

5.3.1 General

1. Normal and abnormal loads structural demands shall be determined using a combination of 2D and 3D FEM techniques. Local models shall be used to determine the structural demands at all structural discontinuities.
2. Both linear and non-linear (cracking) analyses are permitted for the determination of structural demands for Serviceability Limit State (SLS) and Ultimate Limit State (ULS) combinations. Where cracked analyses are adopted by the Contractor a full verification (of software/method) shall be provided to Principal for review.
3. For combinations including the major spill a non-linear analysis shall be undertaken using an axi-symmetric model. Concrete, reinforcement and pre-stress constitutive models used in non-linear analysis shall be in accordance with the requirements of EN 1992-1-1.
4. In the absence of a defined spillage rate, the Contractor shall examine the Concrete outer tank full with product to the maximum level along with intermediate levels to capture maximum structural demands. Particular attention shall be paid to spills in the immediate vicinity of the embedment.

5. The model(s) shall include thermal affects arising from steady state heat transfer conditions. In addition, transient thermo-mechanical analyses shall be carried out where appropriate (e.g., for liquid spill) to ensure maximum structural demands are captured prior to the establishment of steady state conditions.

Steady state conditions are defined as the thermal profiles commensurate with $t=\infty$ for any applied thermal loading.

6. The Contractor shall select soil models as necessary to determine structural demands and displacements. Loads due to pre-stressing may be simulated by axi-symmetrical loads acting perpendicular to the tank wall. Local stress concentrations occurring at structural discontinuities such as buttresses shall be considered within the design.
7. Short-term and long-term loading conditions shall be considered including the effects of concrete creep and shrinkage along with pre-stress losses, relaxation and foundation stiffness.
8. The finite element software used for modelling the tank shall be demonstrated to produce reliable results by comparison with a set of benchmark problems, i.e., those published by the UK National Agency for finite element methods and standards.
9. Where proprietary software is used by the Contractor full validation and verification shall be provided for Principal review and approval.

5.3.2 Foundation stiffness

1. In order to generate a robust design the Contractor shall carry out a bounded analysis of the tank using upper and lower bound soil profiles, taking into account the variation in soil behaviour over the design life of the tank. This philosophy shall apply irrespective of the foundation type and method of construction.
2. All load combinations with the exception of Blast, SSE, major leak and major leak + OBE shall include for uncertainty in the Soil Structure Interaction (SSI) and Dynamic Soil Structure Interaction (DSSI) analyses.
3. Uncertainty in the SSI and DSSI analyses shall be included by considering upper and lower bound stiffness considering possible variations due to the strain rate (undrained/drained), strain magnitude and load history.
4. Lower bound and upper bound estimates of the soil stiffness 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.
5. Where sufficient/adequate soil investigation data is available, the mean and standard deviation of the low strain shear modulus should be established for each and every soil layer. The C_v shall be determined so that it covers the mean ± 1 standard deviation for every layer with a minimum value of 0.5. Where insufficient data is available to address the uncertainties in soil properties C_v shall be taken as 1.0.
6. For load combinations including Blast, SSE, major leak and major leak + OBE, the foundation stiffness shall be based on 'best estimate' shear moduli commensurate the strain rate (undrained/drained) and strain magnitude with possible variations due to the load history.
7. For all other loading combinations, the foundation stiffness shall be based on lower bound/upper bound shear moduli commensurate the strain rate (undrained/drained) and strain magnitude with possible variations due to the load history.
8. Geotechnical finite element software with an established track record shall be used to determine the time dependent settlement over the lifetime of the tank. To account for soil structure interaction, 100 % of the tank base and a minimum of 50 % of the wall shall be explicitly modelled. Where necessary, 3D models shall be used to assess non-uniform settlement and tilting of the tank due to the spatial variation of soil.

9. As a minimum, spring elements shall be used to represent the sub-soil. Contractor shall clearly document methodology for linearization/determination of soil springs for use in the structural analysis. Contractor shall clearly demonstrate consistency of settlements between the geotechnical and structural analysis.
10. The static and seismic design of pile groups shall be in accordance with DEP 34.11.00.12-Gen:

5.3.3 Thermal analysis

5.3.3.1 Normal and emergency conditions

1. Structural demands due to temperature affects shall be determined from semi coupled thermo-mechanical finite element analyses using 2D axi-symmetric solid or 2D Fourier models.
2. Surface temperatures shall be determined from a heat transfer analysis. Film coefficients shall be correlated to the surface temperatures, object size and flow characteristics. For the purpose of analysis the tank shell shall be considered as a cylinder in cross flow.
3. In addition the analysis shall consider the following:
 - a. Summer and winter conditions in accordance with Table 5.1. Refer to (Appendix E) for corresponding values.
 - b. Where included, solar gain shall be determined using the Solar Radiation data contained in (Appendix E). Where appropriate, solar distribution shall be scaled from ASHRAE (2009 ASHRAE Handbook – Fundamentals) or other recognised standards to determine the total gain on horizontal and vertical surfaces.
 - c. Base heating demands shall be commensurate with the condition under consideration;
 - d. The initial temperature (stress free) T_0 should be taken as the temperature of a structural element at the relevant stage of its restraint (completion).
 - i. Where necessary upper and lower bound T_0 's shall be selected so as to maximise the differentials for 'summer' and 'winter cases'.
 - ii. Due to the construction schedule period T_0 for the base, wall and roof may adopt different values.
 - iii. Such temperature differences shall be included within construction and test load cases.

Table 5.1 Summer and winter design cases

	Temperature	Wind	Solar Gain
Summer	95 th percentile	5 th percentile	Yes
Winter	5 th percentile	5 th percentile	No

5.3.4 Blast analysis

1. The Contractor shall consider the interaction between the incident blast wave and the dynamic response of the walls and roof which could lead to structural amplification. For quasi-static approaches the Contractor shall explicitly determine the Dynamic Load Factor (DLF) using the blast profile(s) presented in (Appendix E.6).
2. Time domain analysis may also be adopted using the blast profile(s) presented in (Appendix E.6).

5.3.5 Heat of hydration analysis

1. The Contractor shall demonstrate by analysis, using test data from the proposed concrete mix that the construction sequence and environmental condition will not cause restraint cracking in the base, wall, or roof during construction.

2. Contractor shall measure and record the adiabatic temperature rise of the concrete mix for use in the hydration analysis. The Contractor shall provide the analysis methodology in order to minimise cracking during construction and maintain the crack widths within the limits of (5.5.2).

5.4 LIMIT STATE CHECK AND MINIMUM REQUIREMENTS

5.4.1 General

1. The concrete structures shall be designed for ULS and SLS for all normal situations.
2. The SLS shall be utilized to limit concrete crack widths and/or limit stresses for all load conditions including construction, testing and normal operation.
3. The ULS shall be utilized to verify the strength capacity for all load conditions with the exception of those containing spill cases for which specific analysis and acceptance criterion are stated herein.
4. Material partial safety factors for SLS and ULS conditions shall be in accordance with EN 1992-1-1.

5.4.2 Serviceability limit state (SLS)

1. SLS checks shall be in accordance with the requirements of EN 1992-1-1.
2. For normal operation, and construction and testing, the following shall apply:
 - a. Crack widths on inside and outside faces of pre-stressed concrete members shall be limited to $w_k < 0.2 \text{ mm}$ (0.007 in).
 - b. Crack widths on inside and outside faces of reinforced concrete members shall be limited to $w_k < 0.3 \text{ mm}$ (0.012 in).
 - c. Concrete members shall be 'directionally classified', i.e., walls pre-stressed only in the circumferential direction shall be designed to limit the crack widths to $w_k < 0.2 \text{ mm}$ (0.007 in) and 0.3 mm (0.012 in) in the circumferential and vertical directions respectively. Members pre-stressed both circumferentially and vertically shall be designed to limit crack widths to $w_k < 0.2 \text{ mm}$ (0.007 in).
3. For the OBE condition, crack width control is not required on inside and outside faces of pre-stressed concrete and reinforced concrete members provided the tensile reinforcement stresses for crack controlling members is $\leq 300 \text{ MPa}$.
4. For the cold spot condition, crack widths on inside and outside faces of pre-stressed concrete members shall be limited to $w_k < 0.3 \text{ mm}$ (0.012 in).

5.4.3 Ultimate limit state (ULS)

1. ULS checks shall be in accordance with the requirements of EN 1992-1-1.
2. For load caused by a relief vent fire, stresses in the pre-stressing tendons and in the reinforcing bars shall remain elastic < yield stress.
3. In addition, the compressive strain in the concrete shall be limited to $\leq \epsilon_{c1}$ to avoid crushing and spalling of the concrete. (Explosive spalling of the concrete shall be avoided).

5.4.4 Spillage acceptance criterion

1. The acceptance criterion for all spillage conditions shall be as follows:
 - a. The Residual Compression Zone (RCZ), i.e., the distance between the compressive face and the position of zero stress shall be $\geq 100 \text{ mm}$ (4 in).
 - b. The average compressive stress (RCZ_{avg}) in the RCZ shall be $\geq 1.5 \text{ MPa}$.
 - c. The characteristic crack width (w_k) calculated in accordance with EN 1992-1-1 on the inside face of the concrete in contact with product shall be $\leq 0.2 \text{ mm}$. This criterion shall be applied between elevations h_1 and h_2 where

$h_1 = \text{TCP centre} - x$

$h_2 = \text{TCP centre} + x$

Where x is the greater of 1 m (3.3 ft) or 2 x the wall thickness measured at the TCP elevation.

- d. Tensile strain in the reinforcing bars calculated on the basis of a cracked section shall be less than 1 %.
 - e. Tensile strain in the pre-stressed reinforcement calculated on the basis of a cracked section shall be $\leq f_{p0,1k}/(E_p \cdot \gamma_s)$. Where γ_s is commensurate with the accidental loading conditions (EN 1992-1-1 Table 2.1N).
 - f. Extreme compressive stress in the concrete cracked section shall be $\leq 0.85f_{ck}$.
 - g. Constitutive models for concrete and steel shall comply with the requirements of EN 1992-1-1 §3.1.5. Where tensile capacities are incorporated in the concrete constitutive model upper and lower bound values pertaining to $f_{ck0,05}$ and $f_{ck0,95}$ shall be used to demonstrate compliance with the requirements of this clause.
 - h. Spillage assessments shall be carried out for short term and long term load cases using combinations of upper and lower bound soils properties.
2. Shear capacities under spillage conditions shall be verified against the requirements of EN 1992-1-1 ULS criterion using material variability factors commensurate with the abnormal (accidental) nature of the loading.
 3. Shear links shall be permitted to resist the shear demands under the spillage cases and where provided, shall be of cryogenic grade.

5.5 LOAD COMBINATIONS

5.5.1 General

1. All appropriate load cases and combinations shall be incorporated in the design of the concrete outer tank.
2. The Contractor shall prepare a detailed loading summary table, to cover all phases of the tank lifetime. Favourable and unfavourable effects of all permanent, pre-stress, creep and shrinkage, temperature, hydrostatic and pressure actions shall be considered for all normal conditions including construction, normal operation and maintenance.
3. In all cases the design shall take into account the effects of the action, shrinkage strains, and pre-stressing forces during and after tensioning with due consideration of edge restraint at the wall junctions with the base slab and roof.

5.5.2 Serviceability limit state combinations

1. Load factors for normal conditions shall be in accordance with EN 1990 and country specific National Annexes, pertaining to reversible limit states except as modified herein. Shrinkage, creep and temperature shall be included within all SLS cases including locked in stresses arising from construction and loading history.
2. For frequent combination:

$$E_d = \sum_{j \geq 1} G_{kj} + P + Q_{sc} + Q_t + Q_f + \varphi_{1,1} Q_{k,1} + \sum_{(i > 1)} \varphi_{2,i} Q_{k,i}$$

3. Factors for $\varphi_{1,1}$ and $\varphi_{2,i}$ are presented in Table 5.2; $\varphi_{1,1}$ shall be taken as 1.0 for the OBE condition.
4. For quasi-permanent combination:

$$E_d = \sum_{j \geq 1} G_{kj} + P + Q_{sc} + Q_t + Q_f + \sum_{(i > 1)} \varphi_{2,i} Q_{k,i}$$

5. Quasi-permanent combination is normally used for long-term effects (e.g., shrinkage, creep).

Table 5.2 SLS load factors

Variable actions		G_k, P, Q_{sc}, Q_T and Q_F	Leading/Main Variable factor	Accompanying Variable factor
			$\varphi_{1,1} / \varphi_{2,1}$	$\varphi_{2,i}$
Imposed load				
Frequent	Unfavourable/F avourable	1.0	0	0
Quasi – permanent	Unfavourable/F avourable	1.0	0	0
Snow load				
Frequent	Unfavourable/F avourable	1.0	0.2	0
Quasi – permanent	Unfavourable/F avourable	1.0	0	0
Wind load				
Frequent	Unfavourable/F avourable	1.0	0.2	0
Quasi – permanent	Unfavourable/F avourable	1.0	0	0

5.5.3 Ultimate limit state combinations

- Load factors for normal conditions shall be in accordance with EN 1990 and country specific National Annexes, except where modified herein. Shrinkage, creep and temperature need not be included within ULS combinations provided that they are included at Serviceability Limit State.
- For design situations with one variable action:

$$E_d = \sum_{j \geq 1} \gamma_{Gj} G_{kj} + \gamma_P P + \gamma_{sc} Q_{sc} + \gamma_t Q_t + \gamma_f Q_f + \gamma_{Q,1} Q_{k,1}$$

- For design situations with two or more variable actions, load factors shall be designed for the less favourable of the following:

Equation 1 (Eq. 1)

$$E_d = \sum_{j \geq 1} \gamma_{Gj} G_{kj} + \gamma_P P + \gamma_{sc} Q_{sc} + \gamma_t Q_t + \gamma_f Q_f + \gamma_{obe} Q_{obe} + \gamma_{Q,1} \varphi_{0,1} Q_{k,1} + \sum_{(i > 1)} \gamma_{Q,i} \varphi_{0,i} Q_{k,i}$$

Equation 2 (Eq. 2)

$$E_d = \sum_{j \geq 1} \varepsilon \gamma_{Gj} G_{kj} + \gamma_P P + \gamma_{sc} Q_{sc} + \gamma_t Q_t + \gamma_f Q_f + \gamma_{obe} Q_{obe} + \gamma_{Q,1} Q_{k,1} + \sum_{(i > 1)} \gamma_{Q,i} \varphi_{0,i} Q_{k,i}$$

4. Factors for the above combinations, including permanent, leading, accompanying load factors are given in Table 5.3 and Table 5.4. The given factors are based on Annexes to EN 1990. For country specific load factors, refer to relevant annexes of EN 1990.

Table 5.3 ULS partial load factors for G_k , P , Q_{sc} , Q_t and Q_f actions

Action	Description of action	Factor	Unfavourable	Favourable
Permanent actions				
G_k	For (STR) limit state	γ_{Gj}	1.35	1.0
Variable Actions				
P	Pre-stressing actions	γ_P	1.2	0.9
Q_{sc}	Shrinkage and creep actions	γ_{sh}	1.2	0.0
Q_T	Temperature actions	γ_T	1.2	1.0
Q_F	Fluid actions	γ_f	1.2	1.0
$Q_{k,1}$	Leading variable action	$\gamma_{Q,1}$	See Table 5.4 for leading and accompanying variables.	
$Q_{k,i}$	Accompanying variable(s) action	$\gamma_{Q,i}$		
Q_{obe}	OBE Earthquake	γ_{obe}	1.2	0.0

Table 5.4 ULS Leading and accompanying load factors

Variable Action $Q_{k,i}$		Unfavourable permanent action factor ϵ	Leading/Main Variable factor		Accompanying Variable factor	
			$\gamma_{Q,1}$	$\phi_{0,1}$	$\gamma_{Q,i}$	$\phi_{0,i}$
Imposed Loads	Eq.1	1.0	1.5	0	1.5	0
	Eq.2	0.85	1.5	-	1.5	0
Snow Loads	Eq.1	1.0	1.5	0.5	1.5	0.5
	Eq.2	0.85	1.5	-	1.5	0.5
Wind Loads	Eq.1	1.0	1.5	0.6	1.5	0.6
	Eq.2	0.85	1.5	-	1.5	0.6

5. All variable actions should generally be present within a load combination, unless they have a favourable influence, in which case they are assigned a partial safety factor $\gamma_{Q,1}$ of zero. In general, unless it is clearly not a critical combination, each variable action should be considered as the leading variable action, in turn.

5.5.4 Accidental load combinations

1. For design situations with two or more variable actions, load factors shall be in accordance with EN 1990 and country specific National Annexes, except where modified herein:

$$E_d = \sum_{j \geq 1} G_{kj} + P + Q_{sc} + Q_t + Q_f + A_d + (\phi_{1,1} \text{ or } \phi_{2,1}) Q_{k,1} + \sum_{i > 1} \phi_{2,i} G_{k,i}$$

Where,

A_d – Accidental load

2. Load factors and load combinations for accidental conditions shall be in accordance with Table 5.5.

Table 5.5 Accidental load combinations - Load factors

Permanent Load Factor	Leading Accidental Load Factor A_d			Accompanying Variable Load Factors, $\phi_1, \phi_2,$		
G_k, P, Q_{sc}, Q_T, Q_F (ε)	SSE Spill, Impact, Blast	Spill + OBE	Fire	Imposed	Snow	Wind
Unfavourable 1.05 Favourable 1.0	1.05			0	0	0
	1.05			0	0.3	0
	1.05			0	0	0.3
		1.05		0	0	0
		1.05		0	0.3	0
		1.05		0	0	0.3
			1.05	0	0	0
			1.05	0	0.3	0
			1.05	0	0	0.3

3. Multiple 'accidental loads' shall not occur in the same combination, i.e., SSE or Spill or blast, etc.
4. Operational loads shall be combined into a single variable load and a single accidental load (as shown).

6. DESIGN CONSIDERATIONS - PRIMARY MEMBRANE

6.1 GENERAL

1. The primary membrane shall be in accordance with EN 14620-2.
2. The membrane shall be designed for the load combinations specified in Table 6.1.
3. Double corrugated membrane shall have sufficient flexibility to accommodate thermal expansion and contraction, as well as deformations due to outer tank post tensioning, concrete creep and shrinkage, insulation movements and differential settlements.

6.2 LOAD COMBINATIONS FOR PRIMARY MEMBRANE AND LOAD BEARING INSULATION

1. As a minimum, the combinations of loads indicated in Table 6.1 shall be included in the design of the membrane.

Table 6.1 Load combinations for design of membrane

LOAD COMBINATION	LOAD TYPE													
	Dead	Construction	Product	Internal Pressure	External Pressure or in-tank	Overpressure	OBE	SSE	Thermal	Outer Tank Post-Tension	Creep and Shrinkage	Insulation Deformations (Thermal and Creep)	Settlement	Fatigue
CON	X	X	-	-	-	-	-	-	-	-	-	-	-	-
MAIN	X	-	-	-	-	-	-	-	-	X	X	X	X	-
TEST	X	-	-	-	-	X	-	-	-	-	-	-	-	-
OP	X	-	X	X	X	-	-	-	X	X	X	X	X	X
OBE	X	-	X	X	-	-	X	-	X	X	X	X	X	-
SSE	X	-	X	X	X	-	-	X	X	X	X	X	X	-

- Actual load combinations used in the design shall be determined by permutation of the indicated load components.
- The load bearing insulation system including membrane attachments to insulation and insulation to the outer tank shall be able to transmit to the outer concrete tank the most unfavourable combination of load applied to the membrane.

6.3 CORRUGATED MEMBRANE CONFIGURATION

- The membrane shall be made of austenitic stainless steel plate with a minimum thickness of 1.2 mm (0.05 in).
- The membrane shall be fully supported by the insulation system.
- The membrane shall have a two directional corrugation system.
The main purpose of the corrugation system is to compensate the thermal contractions occurring during cool-down of the tank, as well as temperature fluctuations during tank operations without creating excessive stresses and strains in the membrane components.
- The system shall have larger and smaller corrugations running in orthogonal directions and crossing each other in the form of a "knot". The large and small corrugation pitches shall be designed according to the membrane flexibility requirements and constraints of the project. Double corrugated rectangular membrane sheets can be used for the wall and majority of the bottom area. The makeup sections of trapezoidal shape can be used on the bottom. The open ends of corrugations are to be covered by end caps to provide a sealed enclosure.
- The corrugations shall be made without reduction in membrane thickness.
- The membrane shall be able to transfer all mechanical loads to the outer tank through the load bearing insulation system. It shall be attached by welding to the load bearing insulation system using stainless steel insert strips, or isolated pads.

7. The membrane system shall be continuously lap welded and completely sealed. No gas or liquid shall penetrate into the insulation space during tank operation. At the top of the annular space a closure system, connecting the membrane to the outer tank metallic vapour barrier attached to the outer wall, shall be provided to ensure no gas penetration into the insulation from the dome space above suspended deck.
8. Temporary attachment welding to the membrane is not allowed.
9. No penetrations through the membrane are allowed. All inner tank connections shall be provided through the outer roof and suspended deck.

6.4 CORRUGATED MEMBRANE ANALYSIS AND DESIGN

1. As a minimum, the membrane system design shall meet requirements of EN 14620, Part 2, §5.2.2, and Annex A and Annex B.
2. All components of the membrane system shall keep the form of the membrane through smooth deformation and displacement.
3. The following shall be demonstrated:
 - a. Buckling/collapse of the corrugations is prevented;
 - b. There is no progressive deformation under cyclic loading;
 - c. There is no fatigue failure.
 - i. Fatigue evaluation applies to all components of the primary membrane including main membrane sheets, make-up angle sections and caps. Effects due to various cyclic loading shall be combined using Miner's linear damage hypothesis. The accumulated fatigue damage factor shall be less than 1.0.
 - ii. The design of the metallic membrane shall be carried out either through model testing and/or numerical analysis as required by EN 14620, Part 2, §5.2.2. The numerical analysis method shall be a non-linear FEA elasto-plastic/large displacement method and shall consider the following:
 - 1) Possible asymmetrical behaviour of the membrane under thermal loads due to the insulation anchorage system;
 - 2) Equivalent stresses shall be evaluated by either the Tresca or the Von Mises theories for both static and fatigue design;
 - 3) Where appropriate, deformation due to thermal load shall be applied as boundary conditions;
 - 4) Principle maximum stresses shall be calculated;
 - 5) Attention shall be paid to modelling (i.e., element sizing) of all membrane elements;
 - 6) It shall be demonstrated that the model used for the analysis produces good correlation with actual behaviour.
4. Stress-strain curves used for elasto-plastic analysis shall be specific for materials selected. The portion of the stress-strain curve where section reduction takes place (necking range) shall not be used.
5. Different Poisson's ratios shall be used for the elastic and plastic ranges. Poisson ratio of 0.3 can be used in the elastic range and 0.5 in the plastic range.
6. Under specified static loads, the membrane shall keep its form through smooth deformation. A liquid pressure shall be applied with a safety factor of 1.25. Principle stresses shall be used for evaluation.
7. Analysis shall demonstrate that there is no collapse or buckling of membrane corrugations under any loading. The factor of safety against buckling shall be either