6.4 TYPICAL FAILURE MODES

The likelihood of occurrence of various failure modes is dependent on operating conditions and material behaviour. Review/assessment of the different failure modes will contribute to enhancement/optimisation of the inspection plan. Consideration of the consequences of the potential failure modes in the areas of safety, environment, economics and operations, should provide input for assessing the remaining risk related to the current operating period.

Examples of failure modes are given below.

Failure Mode	Likelihood of Occurrence	Comments
Internal corrosion, vessel	Low	Normally very low. Depends on LPG quality and levels of trace H_2S and water content.
External corrosion, vessel	Negligible	Vessel is externally coated and also has an impressed current CP system in case the coating starts to fail.
External corrosion, piping (between vessel and emergency shutdown valve)	Low	Fully coated piping systems should have low corrosion rates depending on paint maintenance schedules.
Erosion	Negligible	Product does not contain solid particles.
Cavitation	Negligible	Available NPSH determines (operational) minimum liquid level in the vessel.
Thermal fatigue	Negligible	Possible when pressurised import takes place via refrigerated ships
Vibration/fatigue	Low	In principle low, unless there are small-bore connections close to pumps.
Stress Corrosion Cracking (SCC)	Negligible	Unless LPG quality is off-spec.
Embrittlement	Negligible	Provided material selection is in accordance with 4.2 and Appendix D
Cold cracking	Low	Provided correct construction and fabrication procedures applied.

6.5 RECOMMENDATIONS FOR PLANNING OF INSPECTION

Based on the risk assessment, which includes the judgement of the inspection engineer with regards to his confidence in the inspection history, the data collected may be used to carry out a remaining life calculation. The level of risk should be used to evaluate the urgency for performing the next inspection.

An optimised inspection interval can then be determined for the next period of operation.

The inspection activities will need to be carried out at this interval to ensure that the degradations are monitored and assessed. This should be laid down in the inspection plan, which should include:

- inspection interval (to be assessed from remaining life calculation)

- scope of inspection
- inspection techniques to be used
- coverage of the inspection measurements/visual inspections.

The likelihood that a mounded storage vessel will suffer from material degradation either internally or externally, from various causes, is summarised in 6.4. However it should be realised that the assigned levels of likelihood of failure are only valid if the given/agreed design and operating conditions are adhered to. The inspection plan should take this into account. Any change in the pre-set conditions will warrant a re-evaluation of the likelihood of failure, and consequently a risk re-assessment.

7 REFERENCES

In this Guide, reference is made to various codes and standards which are listed in 7.1 to 7.4 below. Unless a particular issue designated by date is specifically referenced in the text, the latest issue of each publication should be consulted (together with any amendments thereto).

7.5 consists of a list of technical publications recommended for further reading.

7.1 AMERICAN STANDARDS

ASME VIII	Boiler and Pressure Vessel Code, Sec. VIII, Div. 1: Rules for Construction of Pressure Vessels
ASTM A 333	Specification for Seamless and Welded Steel Pipe for Low-Temperature Service
ASTM A 350	Specification for Carbon and Low Alloy Steel Forgings, Requiring Notch Toughness Testing for Piping Components
ASTM A 516	Specification for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service
ASTM D 1557	Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort
ASTM D 2167	Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method
NACE RP0274	High Voltage Electrical Inspection of Pipeline Coatings

7.2 BRITISH STANDARDS (including transposed ENs)

BS 3923 Pt 2[1]	Methods for Ultrasonic Examination of Welds. Pt 2: Automatic Examination of Fusion Welded Butt Joints in Ferritic Steels
BS 5400 Pt 3	Steel Concrete and Composite Bridges. Pt 3: Code of Practice for Design of Steel Bridges
BS 6072[2]	Method for Magnetic Particle Flaw Detection
BS 6651	Code of Practice for Protection of Structures against Lightning
BS 7777[3]	Flat-bottomed, Vertical, Cylindrical Storage Tanks for Low Temperature Service
EN 287-1	Qualification Test of Welders. Fusion Welding. Steels
EN 1043-1	Destructive Tests on Welds in Metallic Materials. Hardness Testing. Pt 1: Hardness Test on Arc Welded Joints
EN 1435	Non-destructive Examination of Welds. Radiographic Examination of Welded Joints
EN 1714	Non-destructive Examination of Welded Joints. Ultrasonic Examination of Welded Joints

[1] Note on BSI website: 'This standard is declared obsolescent as it is significantly out of date and it is hoped that a future European Standard will cover this topic.'

[2] Obsolescent. Replaced by EN ISO 9934-1: Non-destructive Testing. Magnetic Particle Testing. Pt 1 General Principles (information from BSI website).

[3] BS 7777 will be withdrawn when prEN 14620 (Design and Manufacture of Site Built, Vertical, Cylindrical, Flat-bottomed Steel Tanks for the Storage of Refrigerated, Liquefied Gases with Operating Temperatures between –5°C and –165°C) is published.

EN 10028-3	Flat Products Made of Steels for Pressure Purposes. Pt 3: Weldable Fine Grain Steels, Normalized
EN 10160	Ultrasonic Testing of Steel Flat Product of Thickness Equal [to] or Greater than 6 mm (Reflection Method)
EN 10164	Steel Products with Improved Deformation Properties Perpendicular to the Surface of the Product. Technical Delivery Conditions
EN 10222-4	Steel Forgings for Pressure Purposes. Pt 4: Weldable Fine-grain Steels with High Proof Strength
EN 13445	Unfired Pressure Vessels
PD 5500	Specification for Unfired Fusion Welded Pressure Vessels

7.3 INTERNATIONAL STANDARDS

IEC 60146	Semiconductor Convertors
IEC 60529	Classification of Degrees of Protection Provided by Enclosures (Ingress Protection Code)
ISO 2808*	Paints and Varnishes. Determination of Film Thickness
ISO 4624*	Paints and Varnishes. Pull-off Test for Adhesion
ISO 8501-1*	Preparation of Steel Substrates before Application of Paints and Related Products—Visual Assessment of Surface Cleanliness. Part 1: Rust Grades and Preparation Grades of Uncoated Steel Substrates and of Steel Substrates after Overall Removal of Previous Coatings
ISO 8503-1*	Preparation of Steel Substrates before Application of Paints and Related Products—Surface Roughness Characteristics of Blast-Cleaned Steel Substrates. Part 1: Specifications and Definitions for ISO Surface Profile Comparators for the Assessment of Abrasive Blast-cleaned Surfaces
ISO 9329-3	Seamless Steel Tubes for Pressure Purposes—Technical Delivery Conditions—Part 3: Unalloyed and Alloyed Steels with Specified Low Temperature Properties

* Also available as a EN ISO bearing the same number.

7.4 MISCELLANEOUS CODES AND STANDARDS

CODAP-95	French Pressure Vessel Code
EEMUA Pub 147	Recommendations for the Design and Construction of Liquefied Gas Storage Tanks
EEMUA Pub 159	Users' Guide to the Inspection, Maintenance and Repair of Aboveground Vertical Cylindrical Steel Storage Tanks
Eurocode 3	Design of Steel Structures. Pt 1-1: General Rules and Rules for Buildings

7.5 RECOMMENDED FURTHER READING

Mang, F	*Berechnung und Konstruktion ringversteifter Druckrohrleitungen*— Springer-Verlag, Berlin/Heidelberg/ New York 1966.
Mang, F	*Groszrohre und Stahlbehälter, Festigkeits und Konstruktionsprobleme*—

Verlag für angewandte Wissenschaften GmbH, Baden-Baden, 1971.

Timoshenko, S.P., Woinowsky-Krieger, S.: *Theory of Plates and Shells*—McGraw-Hill, New York/Toronto/London

Timoshenko, S.P., Gere, J.M.: *Theory of Elastic Stability*— McGraw-Hill, New York/Toronto/London

8 GLOSSARY OF ABBREVIATIONS

The following is a comprehensive list of abbreviations used in the main text of and Appendices to this document.

ABP	atmospheric boiling point
AC	alternating current
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BLEVE	boiling liquid expanding vapour explosion
BH	borehole
BS	British Standard
BSI	British Standards Institution
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CODAP	Code Français de Construction des Appareils à Pression (French Pressure Vessel Code)
CP	cathodic protection
CPT	cone penetration test
DC	direct current
DCT	deep conductivity test
EEA	European Economic Area (European Union + Iceland, Liechtenstein and Norway)
EN	CEN standard
HAZ	heat affected zone
HAZOP	hazard and operability (study)
HTS	high tensile steel
Hv	Vickers hardness (number)
IEC	International Electrotechnical Commission
IP	ingress protection
ISO	International Organization for Standardization
LPG	liquefied petroleum gas
MPI	magnetic particle inspection
MS	mild steel
NACE	National Association of Corrosion Engineers (US)
NPSH	net positive suction head
PED	(European) Pressure Equipment Directive (97/23/EC)
PER	Pressure Equipment Regulations (the transposition of the PED into UK law)
PM	piezometer
PWHT	post-weld heat treatment
RP	Recommended Practice
RT	radiographic test(ing)
SAW	submerged arc welding
SCC	stress corrosion cracking
SCT	surface conductivity test
SMAW	shielded metal arc welding
SPT	standard penetration test
USS	undisturbed soil sampling
UT	ultrasonic test(ing)

APPENDIX A
STRESS ANALYSIS OF MOUNDED STORAGE VESSELS

A.1 INTRODUCTION

The difference between the stress analysis for a mounded storage vessel and that for a conventional pressure vessel is due to the mound and the method of support. The mound and the support cause bending moments, normal forces and shear forces in the wall of the cylinder.

This appendix sets out a calculation method, which may be used for the design of mounded storage vessels. Emphasis is placed on those aspects where mounded storage vessels differ from conventional pressure vessels. Only mounded storage vessels on a continuous sand bed are considered in this calculation.

A.2 CIRCUMFERENTIAL BENDING

Several loads, such as dead weight, weight of liquid, mound loads, etc. cause circumferential bending moments in the wall of the cylinder (in addition to in-plane stresses). The relatively thin shell plates of the cylinder cannot carry these bending moments.

A.2.1 Unstiffened Cylinders

In vessels without stiffening rings, the circumferential bending moments will be transmitted to the domed ends by shear stresses in the shell. The domed ends are, in comparison with the cylindrical shell, quite rigid and may be capable of carrying these bending moments provided the length of the vessel is relatively short.

For diameters over approximately 3.5 metres, the required plate thickness of an unstiffened cylinder tends to become uneconomically heavy (due to negative internal pressure and/or external pressure) and it is therefore usually more economic to use cylinders provided with stiffening rings at regular intervals.

The analysis of the domed ends of unstiffened vessels, subjected to loads 1 through 10 (see A.4.2) is best carried out by using a finite element method.

A.2.2 Stiffened Cylinders

When stiffening rings are used, the circumferential bending moments in the shell plates are transmitted to the stiffening rings by shear forces.

If the distance between two stiffeners is L, the bending moment due to all the loads on a part of the cylinder with a length L needs to be allocated to one stiffening ring.

The domed ends are very rigid in a radial direction when welded to the cylindrical shell, and will also act as stiffeners. Torispherical heads are more rigid stiffeners than hemispherical heads. A stiffening ring just next to a torispherical head is therefore unnecessary, and the first stiffener need not be located close to the transition from dome to shell. However, irrespective of the chosen spacing between stiffeners, it is recommended that the stiffeners nearest to the domed ends be located at a distance from the domed head-to-shell weld of half the diameter of the vessel.

The domes will carry part of the non-axisymmetrical loads, which will cause stresses in the ends. The table below gives an indication of the stress increase.

Table 5 Stress increase percentages for domed ends

product	diameter D_o	hemispherical heads	torispherical heads with stiffener next to dome	torispherical heads without stiffener next to dome
propane	≤ 3600 mm	11	4	6
	3600 mm < D_o ≤ 4500 mm	11.6	4.3	6.3
	4500 mm < D_o ≤ 6000 mm	12.3	4.9	6.9
	6000 mm < D_o ≤ 7200 mm	15.2	5.7	7.7
	> 7200 mm	16	6	8
butane	≤ 3600 mm	12.1	4.4	6.6
	3600 mm < Do ≤ 4500 mm	12.8	4.7	6.9
	4500 mm < Do ≤ 6000 mm	14.6	5.4	7.6
	6000 mm < Do ≤ 7200 mm	16.7	6.2	8.4
	> 7200 mm	17.6	6.6	8.8

Regarding restrictions to stiffener placement, see previous paragraphs.

The plate thickness of the domed ends needs to be increased by the relevant percentage as shown in above table in order not to exceed the maximum design stress. This may add to the cost of the vessel, but because of uneven external soil pressure the plate thickness of hemispherical ends is usually more than required for internal pressure only (see A.5.3).

A.3 NORMAL FORCES AND SHEAR FORCES

The shear forces acting in the plane of the stiffening rings will cause bending moments and also normal and shear stresses in the rings. It should be noted that the presence of the stiffening rings, whilst greatly reducing the bending moments in the shell plates, does not eliminate the normal tensile and compressive stresses in the shell plates.

A.4 CALCULATION METHOD FOR STIFFENED CYLINDERS

A.4.1 Nomenclature

Symbols used in the calculation formulae are listed below. Where subscripted, the symbols have the particular meaning separately defined in the text.

A	=	section area	(m^2)
C	=	soil pressure coefficient	(–)
E	=	Young's modulus	(kN/m^2)
F	=	force (load)	(kN)
F′	=	force (load) per unit length	(kN/m)
H	=	distance from vessel equator to top of mound	(m)
I	=	moment of inertia (second moment of area)	(m^4)

K	=	coefficient for calculation of forces and moments in stiffeners	(–)
L	=	distance between stiffening rings	(m)
M	=	moment	(kNm)
N	=	normal force	(kN)
P, Q	=	loads on vessel	(kN)
P′, Q′	=	loads per metre length of vessel (unit loads)	(kN/m)
R	=	mean radius of cylinder	(m)
S	=	shear force	(kN)
W	=	estimated weight of stiffening ring	(kN)
c	=	parameter in buckling analysis	(–)
d	=	depth of web	(m)
f	=	allowable stress; design stress	(kN/m^2)
f_1, f_2	=	principal stresses	(kN/m^2)
h	=	depth below top of mound	(m)
k	=	parameter in buckling analysis	(–)
p, q	=	pressures	(kN/m^2)
r	=	mean radius of compression flange	(m)
s	=	primary circumferential hoop stress	(kN/m^2)
s′	=	secondary bending stress	(kN/m^2)
t	=	thickness	(m)
w	=	shell working width	(m)
y	=	deflection of cylinder with respect to the ends	(m)
β	=	parameter in buckling analysis	(–)
γ	=	weight per m^3	(kN/m^3)
σ	=	stress	(kN/m^2)
τ	=	shear stress	(kN/m^2)
χ	=	parameter in buckling analysis	(–)
ψ	=	circumferential angle between top of cylinder and point under consideration	(°, rad)

A.4.2 Loads

A.4.2.1 Dead Weight (Load 1)

The dead weight Q_1 is the weight of the shell over the centre-to-centre distance between two stiffeners, together with the estimated weight of one stiffening ring. This weight is allocated to one stiffener and is:

$Q_1 = 2\pi R \times t \times \gamma_m \times L + W$ (kN)

where γ_m is the weight of vessel material per m^3 (kN/m^3)

A.4.2.2 Weight of Liquid Fill (Load 2)

The weight of the maximum volume of liquid Q_2 to be allocated to one stiffener is:

$Q_2 = \pi R^2 \times \gamma_l \times L$ (kN)

where γ_l is the weight of contents per m^3 (kN/m^3)

The formula is correct for test conditions. However, in normal operating conditions there is always a gas pocket, giving a slight reduction of liquid load and thus of stress in the vessel wall. National regulations may allow the operator of an installation to guarantee a maximum filling level below 100% (e.g. 90%) and to have this taken into account in the design of the vessel, leading to a thinner wall than would otherwise have been the case.

A.4.2.3 Internal Design Pressure (Load 3)

With regard to the stiffener design, the internal pressure only affects the normal force N_3 in the stiffening ring, not the bending moment or the shear force. Part of the shell plates will act together with the ring to carry the loads to which the rings are subjected. This part, the working width w, is:

$w = 2 \times 0.78 \times \sqrt{(R \times t)}$ (m)

The internal pressure, acting on the working width, will cause a normal tensile load N_3 which is carried by the combination of stiffening ring and working width of the shell plate.

$N_3 = p_3 \times w \times R$ (kN)

where p_3 = the internal design pressure.

A.4.2.4 Negative Internal Design Pressure (Load 4)

Internal pressure may become negative in extreme conditions, e.g. very high outward flow rates, or rupture of a bottom outlet pipe resulting in gas freely bleeding into the open air. The buoyancy effect of the negative internal pressure adds to the external soil pressure exerted by the mound.

The negative internal pressure only affects the normal force N_4 in the stiffener, not the bending moment or the shear force. For the reasons described in A.4.2.3, the negative internal pressure p_4 will cause a compressive normal load N_4 in the stiffening ring and the plates of the working width.

$N_4 = p_4 \times w \times R$ (kN)

where p_4 = the negative internal design pressure.

p_4 should be taken equal to 0.5 bar, unless agreed otherwise with the Purchaser.

A.4.2.5 Pressure due to Mound (Load 5)

A.4.2.5.1 Pressure of Mound on Cylinder

The weight of the mound assumed to be resting on top of the cylinder is:

$Q_5 = (2RH - \pi R^2/2 + H^2/3) \times \gamma_s \times L$ (kN)

per ring, see Figure A.1, where:

γ_s = the weight of soil per m^3 (kN/m^3)

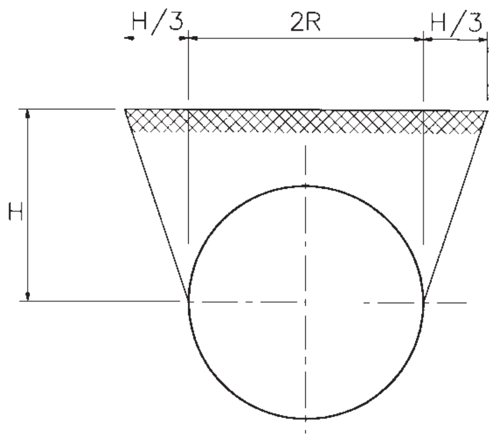

Figure A.1

It is further assumed that this weight results in a radial pressure q on the cylinder, as shown in figure A.2 ($\psi_0 = 90°$)

At angle ψ: $q_\psi = q_0 \cos \psi$

q_0 is maximum pressure at $\psi = 0$,

$q_0 = Q_5 / \pi RL$ (kN/m^2)

$$q = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} q_\psi \, d\psi = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} q_0 \cos\psi \, d\psi =$$

$$\frac{Q_5}{\pi RL} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos\psi \, d\psi = \frac{2Q_5}{\pi RL} \quad (kN/m^2)$$

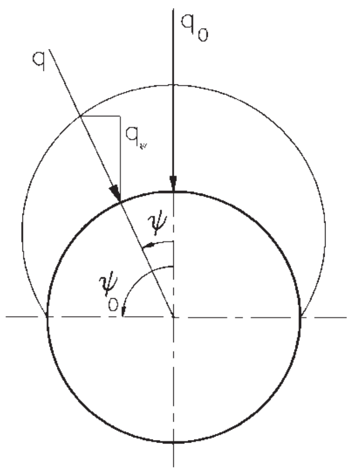

Figure A.2

A.4.2.5.2 Pressure by Mound on Domed Ends

The mound will also exert pressure on the domed ends of the vessel. This soil pressure p_s will increase linearly with the depth.

$p_s = C \times \gamma_s \times h$ (kN/m^2),

where

C	=	soil pressure coefficient	(–)
γ_s	=	weight of soil per m^3	(kN/m^3)
h	=	depth below top of mound	(m)