

Above ground flat bottomed storage tanks

A guide to inspection, maintenance and repair

4th EDITION

Publication No. 159

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.....

THE ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION

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ENGINEERING EQUIPMENT AND MATERIALS USERS ASSOCIATION

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Preface

EEMUA 159 was first published in 1994, with a slightly revised second Edition in 1997. In 2003 a complete revision was produced but subsequent to the publication of the third Edition, new Codes, techniques and maintenance philosophies became available. The publication has proved an EEMUA 'best-seller', and is used as the principal basis of the EEMUA CompeTank™ training scheme.

It was in that use that the desirability of improving the sequential layout of the subject matter became apparent. Accordingly, EEMUA's Storage Tanks Technical Committee decided to undertake a complete revision of the Publication. This Fourth Edition is the result.

In addition to improving the logical sequence of the subject matter, this Edition contains appendices offering additional guidance on how to perform assessment calculations on tank components, illustrated by means of sample calculations, as well as on repair methods. It also includes various new Sections such as that on risk and reliability-based maintenance (herein termed Probabilistic Preventive Maintenance—PPM), a subject that is given comprehensive coverage.

The reader's attention is also drawn to six companion EEMUA Publications:

- 147** *Recommendations for the design and construction of refrigerated Liquefied Gas Storage Tanks*
- 154** *Guidance to Owners on Demolition of Vertical Cylindrical Steel Storage Tanks and Storage Spheres*
- 180** *Frangible Roof Joints for Fixed Roof Storage Tanks: Guide for designers and users*
- 183** *Guide for the Prevention of Bottom Leakage from Vertical, Cylindrical, Steel Storage Tanks*
- 213** *Emission reduction from oil storage tanks and loading operations*
- 217** *Safe and effective operation of storage tanks for oil movements*

Note on terminology

The term 'stored product' is used in the text to describe the contents of a storage tank. 'Product' therefore includes unrefined or unprocessed feedstocks.

Both SI and former British units are used in the text. 'Bar' and sub-multiples thereof when used without further qualification indicate gauge pressures (i.e. above atmospheric), except, of course, where used as the unit for atmospheric pressure.

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1 Introduction and scope

1.1 Introduction

This Publication is intended primarily to assist in the establishment of essential inspection and maintenance requirements for aboveground vertical cylindrical, steel storage tanks, in order to minimise in-service problems and extend useful life. However, for such requirements to be properly interpreted and understood, comprehensive guidance is given on many key design features, on common problems experienced during operation and on repair methods.

The Publication primarily addresses storage tanks built in accordance with relevant British Standards but where appropriate it also refers to and makes use of commonly accepted international Standards and Codes, such as those of the American Petroleum Institute (API). These differ little in the in-service conditions that they cover and the resulting inspection requirements. Accordingly, this publication is intended as a general inspection, maintenance and repair guide applicable to aboveground vertical cylindrical steel storage tanks built to standards such as those listed in Section 1.3.

The detailed topics covered are the more significant known issues to require attention, selected by the authors based on many years' experience in storage tank operation. However, it should be noted that some tanks in particular or unusual locations or operating situations may require additional or special attention. In such cases it is most important that any special requirements are defined and agreed between the relevant design and inspection authorities.

The recommendations contained herein are written particularly for the guidance of inspection and maintenance engineers. Recent developments in maintenance philosophy and practices have led to the formulation of new maintenance programmes, and this revision of EEMUA 159 includes a large section on such programmes. Some sections should also be of interest to operational personnel who need to be made aware of the parameters and conditions that may make equipment unsafe or accelerate rates of deterioration.

In addition to general inspection and maintenance guidelines, several sections on repair methods have also been included in this revision. Despite this, it is important that defects and damage found during inspection and maintenance together with full inspection details be brought to the attention of a specialist with particular knowledge of the original design of the item in question, and/or of the relevant section herein. This will allow the appropriate type and method of repair to be specified.

1.2 Scope

This guide sets out the key features required for planning and executing inspection, maintenance and repair works on aboveground fully supported vertical steel storage tanks.

The descriptions of key tank components that require inspection and/or maintenance, of degradation mechanisms, and of common inspection techniques, are followed by sections describing the Probabilistic (risk- and reliability-based) Preventive Maintenance (PPM) concept and, for each tank component, a detailed description of inspection and repair methods.

Guidance is given on sources of additional information that will assist both continued operation and inspection.

This document mainly addresses atmospheric storage tanks for oil and chemical products (referred to elsewhere in the text as conventional storage tanks). Tanks for refrigerated storage of liquefied gases are covered in EEMUA 147⁽¹⁾.

1.3 Codes and history

Conventional storage tanks are generally built in accordance with the following codes (see References for full titles):

- British Standard BS 2654⁽²⁾;
- American Standards API 620⁽³⁾ and API 650⁽⁴⁾;
- German Code DIN 4119-1⁽⁵⁾ and DIN 4119-2⁽⁶⁾;
- French Construction Code 'CODRES'⁽⁷⁾;
- Dutch Code G0801⁽⁸⁾; and
- European Norm EN 14015⁽⁹⁾.

The original design may have influence on the inspection requirements. It is therefore necessary to check the year of construction of the tank and the requirements of the code to which the tank was designed and constructed at that time.

Tanks built before 1945 may be of a riveted construction. Tanks built up to about 1965 to BS 2654 have tank shells designed with a joint efficiency factor¹ 0.85, and the weld quality would only have been inspected visually during construction. These tanks were generally made from mild steel with an ultimate tensile strength not exceeding 420 N/mm². After 1965, medium and large sized storage tanks were often made from high tensile steels with an ultimate tensile strength over 420 N/mm². Usually top courses of lower thickness were still made from mild steel.

After 1968 it also became normal practice to have the shells designed with a joint efficiency factor of 1.00, with weld quality inspected by spot radiography during construction.

The above-mentioned points have some influence on certain aspects of inspection and maintenance requirements. They should be considered before an inspection plan is developed.

1.4 Abbreviations

Some of the abbreviations that follow are specific to this document.

ACFM	Alternation current field measurment
AISI	American Iron & Steel Institute
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BS	British Standard

¹ The joint efficiency factor is the ratio of the strength of the joint divided by the strength of the parent plate

CEN	Comité Européen de Normalisation (European Committee for Standardization)
CODRES	Code Français de Construction des Réservoirs Cylindriques Verticaux en Acier UCSIP et SNCT (French Construction Code for Vertical Cylindrical Steel Storage Tanks)
CP	cathodic protection
CUI	corrosion under(neath) insulation
DPT	Dye Penetrant Testing
EN	European Norm (CEN standard)
ETBF	estimated time between failures (see Section 2.2 for definition)
FMEA	Failure Mode and Effect Analysis
FS	floor scan (ultrasonic thickness measurement technique)
GRE	Glass fibre Reinforced Epoxy resin
GRP	glass reinforced plastic
H	High (risk or rating)
HAZ	heat affected zone
HAZOP	hazard and operability study
HDPE	high density polyethylene
IFC	Internal Floating Cover
L	low (risk or rating)
LNG	liquefied natural gas
LODMAT	lowest one-day mean ambient temperature
LORUS	LOng Range Ultrasonic System (NDT technique)
M	medium (risk or rating)
MIC	Microbial induced corrosion
MFL	Magnetic Flux Leakage (NDT technique)
MPI	Magnetic Particle Inspection
MTBF	mean time between failures (see 2.2 for definition)
N	negligible (risk or rating)
NACE	National Association of Corrosion Engineers
NDT	non-destructive testing
NRV	non-return valve
ONL	On Line Examination.
OFL	Off Line Examination
PA	Phased array
PPM	probabilistic preventive maintenance
RAM	risk assessment matrix (see Section 2.2 for definition)
RBI	risk based inspection
RCM	reliability centred maintenance
RLG	refrigerated liquefied gas
RLT	remaining life time
SHE	safety, health and environment(al)
SNCT	Syndicat National de la Chaudronnerie et de la Tuyauterie Industrielle (National Association of the Boilermaking and Piping Industries)
SRB	sulphate reducing bacteria
TIA	tank integrity assessor
UCSIP	Union des Chambres Syndicales de l'Industrie du Pétrole (now UFIP: Union Française des Industries de Pétrolières—French Petroleum Industry Association)
ULSD	Ultra Low Sulphur Diesel
US	ultrasonic/ultrasound
UT	Ultrasonic testing
UT WT	Ultrasonic testing wall thickness survey

UV

ultraviolet

2 Tanks and their components: Terminology and materials of construction

2.1 Tank components

Anchor-ring	Ring of bolted connections between tank shell and ring beam, to fix tank on foundation; usually installed for fixed roof tanks operating at high internal pressure, or which are subject to seismic loads, or on high tanks subject to wind loads.
Annular plate	Tank bottom peripheral plate supporting the shell and to which the shell is welded.
Articulated drain	Floating roof internal drainpipe. Hard pipe with articulated swivel joints.
Anti-rotation device	Guide pole(s) fixed to the shell through pontoon of floating roof to prevent rotation.
Automatic bleeder vent	Floating roof vent that opens/closes automatically when the roof is landed and after initial floating.
Base	Either the tank bottom or the foundation pad or slab.
Beams	Fixed roof support members.
Bottom	Floor of tank.
Bumpers	Bars fitted to periphery of floating roof to maintain concentricity of roof in shell.
Bund/bund wall	Wall enclosing an area around the tank to provide tertiary containment.
Bunded area	Area surrounding the tank bounded by the bund wall.
Coating	A layer painted on or otherwise applied to a surface for the purpose of corrosion protection or minimise emissions or to maintain product quality (internally).
Column supports	Internal supports for fixed roof.
Cone up/down bottom	Pre-formed shape of tank floor.
Curb angle	Reinforcement angle welded at top of shell.
Deck	Floating roof central area.
Dipping device	Device for measuring product level in tank.
Dome roof	Type of self-supporting fixed roof.
Drain	Device to remove water collecting at the tank bottom, and product remains when emptying the tank. Also used for draining accumulated water on floating roofs.
Double deck floating roof	Floating roof structure with a top and bottom deck and bulkheads forming compartments.
Earthing lug	Earth connection fitted to provide protection against static discharge.
Emergency drain	Floating roof drain with upstand pipe in case of primary drain

	failure or overload, or flanged nozzle when roof is in its landed position.
Fabric seal	Part of mechanical shoe seal.
Fixed roof	Roof supported on tank shell or shell and columns.
Floating roof	Roof floating on the product.
Floating suction	Suction pipe that floats near the surface of the product.
Foam-filled seal	Type of floating roof rim seal.
Gauging platform	Platform on top of open top tank for access to tank gauging instruments.
Guide pole	Pole fixed to top and bottom of tank to guide floating roof.
Geodesic roof	Fixed roof or cover of geodesic construction.
Hanger arm	Weighted arm on pantograph mechanical seal.
High level alarm	Alarm indicating a high product level.
Hose drain	Type of flexible floating roof drain pipe.
Intermediate wind stiffener	Additional wind stiffener to prevent buckling of tank shell. Also referred to as 'secondary wind girder'.
Internal floating cover	Floating roof fitted inside a fixed roof tank.
Jacking lugs	Lugs provided on external shell to allow re-levelling.
Ladder	Usually refers to the floating roof rolling ladder.
Lining	Installed for internal corrosion protection on floor or shell.
Liquid-filled seal	Type of floating roof rim seal.
Manhole/manway	Opening in shell, roof or pontoon for personnel access.
Mechanical shoe seal	Type of floating roof rim seal.
Nozzle	Opening for connection in tank.
Pantograph seal	Type of mechanical shoe seal.
Pontoon	Tank roof flotation device, normally annular.
Primary seal	Main sealing device between floating roof and tank shell.
Primary wind girder	Main stiffener near top of open top tank. Also used for access to gauging platform and rolling ladder.
PV valve	Pressure-vacuum relief valve.
Rafter	Fixed roof supporting member.
Rim seal	Floating roof peripheral seal.
Rim space	Gap between floating roof and tank shell filled by rim seal.
Rim vent	Vent for rim space between product and sealing member.
Ring beam	Annular foundation ring.
Roof drain	Device to remove (accumulating) water from floating roof deck.

Roof leg	Floating roof support leg.
Sampling device	Device to permit product sampling.
Sand foundation	Type of foundation pad
Secondary seal	Additional peripheral seal between floating roof and tank shell.
Secondary wind girder	Additional wind stiffener to prevent buckling of tank shell. Also referred to as 'intermediate wind stiffener'.
Side entry mixer	Mixer mounted on the shell of the tank.
Shell	Cylindrical wall of tank.
Shunt	Metal electrical connection between floating roof and tank shell.
Stairway	Usually refers to stairs on the outside of the tank to the roof.
Stilling well	Pipe in which dipping device (see above) travels up and down.
Sump	Well in tank bottom or floating roof deck for drainage.
Trusses	Structural support members in floating roof.
Tank pad	Foundation below tank.
Tank pad shoulder	Annular ring of material protecting and reinforcing the perimeter of the foundation pad
Tank rim	Tank bottom annular area.

2.2 Glossary of terms

Alteration	Any work on a tank involving cutting, burning, welding or heating operations that changes the physical dimensions and/or configuration of a tank.
Asset	The tank and other permanent tank-related items required by the user to store the product.
Availability	The ability of an item to be in a condition to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided.
Banding	Circumferential deformation associated with horizontal weld distortion.
Bulging	Tank bottom, shell or roof deformation.
Buckling	Shell or roof deformation associated with excessive compressive stress.
Circumferential settlement	Differential settlement of the foundation under the tank shell relative to horizontal or tilted plane.
Component	Refer to Section 2.1 for tank components.
Condition based maintenance	Proactive maintenance carried out according to the need indicated by condition monitoring. Also known as predictive maintenance.
Condition monitoring	The continuous or periodic measurement and interpretation of data to indicate the condition of an item to determine the need for maintenance.

Consequence of failure	The consequence of damage or potential damage of a failure to the safety of an asset, its economics and its environment.
Corrosion allowance	The thickness of material which can safely be allowed to corrode having regard for the operating environment and applied stresses.
Credible event	A failure mode that is considered probable within the life of the asset.
Criticality	A measure of risk, related to the mode of failure of a tank item, based on the following assumptions: i) no maintenance ii) independent inspection iii) unrecognised failure of the protective system.
Criticality rating	Classification of criticality by means of an alphanumeric indicator.
Degradation mechanism	The physical, chemical or other process that ultimately leads to a failure. Also called 'failure mechanism'.
Design life	That period during which an item or component is intended to remain fit for service under the specified design and operating process conditions.
Depression	Foundation settlement deformation in a tank floor.
Differential settlement	Localised or non-uniform settlement of tank foundation.
Dominant failure mode	Failure mode most likely to be responsible for a functional failure, either predicted or actual.
Edge settlement	Settlement of the tank shell and bottom annular plate.
Estimated time between failures without maintenance (ETBF)	The estimated time between failure if no maintenance is performed (i.e. without human observation and intervention).
Failure causes	The factors relating to design, construction/manufacture or use which have led to failure.
Failure characteristics	General properties (e.g. failure pattern and behaviour) of a failure mode or modes.
Failure mechanism	(See 'degradation mechanism'.)
Failure mode	A qualitative description of how an item can fail (e.g. leaking pinhole in shell, blocked filter, seized bearings etc.)
Failure rate	(See mean time between failures.)
Hazard	A situation that could occur during the lifetime of an asset, that has the potential for human injury, damage to the asset, damage to the environment or causing economic losses.
Inspection	The process of measuring, examining, testing or otherwise comparing an entity with the applicable requirements for design and operation

Integrity	Technical integrity of a system exists when under specified operating conditions there is no foreseeable risk of its failure endangering people, the environment or asset value.
Maintenance	The combination of all technical and associated administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state in which it can perform its required function.
Mean time between failures (MTBF)	Average time between failures, usually assuming a zero or negligible repair time. $MTBF = 1/\text{failure rate}$. For items with no repair, 'mean time to failure' (MTTF) is sometimes used.
Mitigation	Either makes the consequence of a failure mode less severe or reduces the probability of the occurrence.
Non-intrusive inspection	Inspection which can be carried out externally, usually without the need to take the tank or tank item to be inspected out of service.
Peaking	Vertical shell weld deformation associated with weld shrinkage.
Planned maintenance	The maintenance organised and carried out with forethought, control and the use of records to a predetermined plan.
Preventive or proactive maintenance	The planned maintenance carried out at predetermined intervals or corresponding to prescribed criteria (conditions) and intended to reduce the probability of failure or the performance degradation of an item.
Probability of failure	A measure of the likelihood that a failure occurs within a given time interval.
Quantitative risk assessment	Structured approach to identifying potentially hazardous events, estimating their probability and the consequences for people, the environment and resources arising from these hazardous events.
Reactive maintenance	The maintenance carried out after a failure has occurred and intended to restore an item to state in which it can perform its required function. Also known as 'corrective', 'breakdown' or 'failure-based' maintenance.
Reliability	The probability that a tank item (or component) can perform a required function under given conditions for a given time interval.
Remanent life	The period since the last inspection, for which it is judged that an item or component will remain safe to operate within the agreed operating window.
Rippling	Deformation of a floating roof deck or tank floor.
Risk	A combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.
Risk analysis (API 581⁽¹⁰⁾)	Combining appropriate measures of consequence and likelihood of occurrence to obtain risk or expected value; the act of determining or calculating risk.
Risk assessment (API 581)	The prioritisation of risk values determined in the risk analysis; exploring whether or not these are acceptable to the operator.

Risk classification	A rating of the relative risk from a hazard. A risk matrix may be used to determine this rating.
Risk management (API 581)	Developing and implementing a plan to manage and mitigate risks. Also incorporates results of the plan and a search for improvements to the risk analysis process.
Risk assessment matrix	The matrix portraying risks as a combination of probability and consequences, used as basis for qualitative risk determination. Considerations for the assessment of consequences are shown on the other axis. Plotting the intersection of the two considerations provides an estimate of the risk.
Susceptibility to failure	A rating which reflects the actual (exposure to) degradation in comparison with the degradation assumed in design.
System	A collection of items organised to accomplish one or several specific functions.
Tank item	One of the parts (e.g. bottom, plates, roof drain) that make up a storage tank. A tank item may be subdivided into other items/components.

2.3 Types of storage tanks

2.3.1 Standard atmospheric storage tanks

Vertical cylindrical steel storage tanks can be divided into two main groups: those having fixed roofs and those with floating roofs.

a) **Fixed Roofs**

Fixed roof atmospheric tanks are sub-divided into 3 types:

- Non-pressure;
- Low pressure;
- High pressure.

Fixed roof tanks, designed according to BS 2654, are considered as atmospheric tanks and can be non-pressure (free vented), low pressure tanks (to approx. 20mbar internal pressure) or high pressure tanks (to approx. 56mbar internal pressure) - see Figure 1 (values in brackets are in mbar).

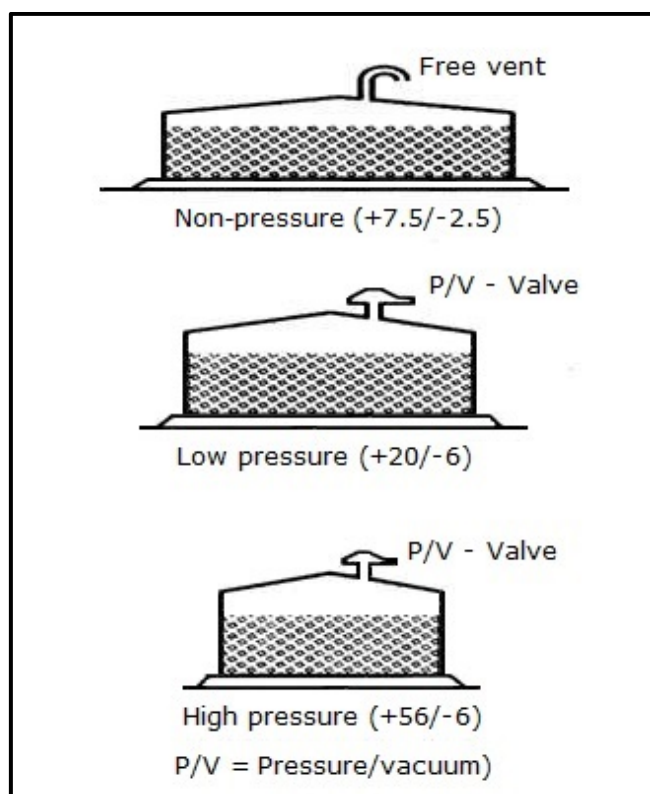


Figure 1 Types of fixed roof tanks

Note that EN 14015 introduced new pressure and vacuum design pressures as follows:

- Non-pressure +10/-2.5mbar;
- Low pressure +25/-6mbar;
- High pressure +60mbar/-6mbar.

A typical fixed roof tank is shown in Figure 2. This figure shows a conical shaped roof which is typical for larger diameter fixed roof tanks. The roof has a roof support structure, which may be constructed from beams, trusses or rafters.

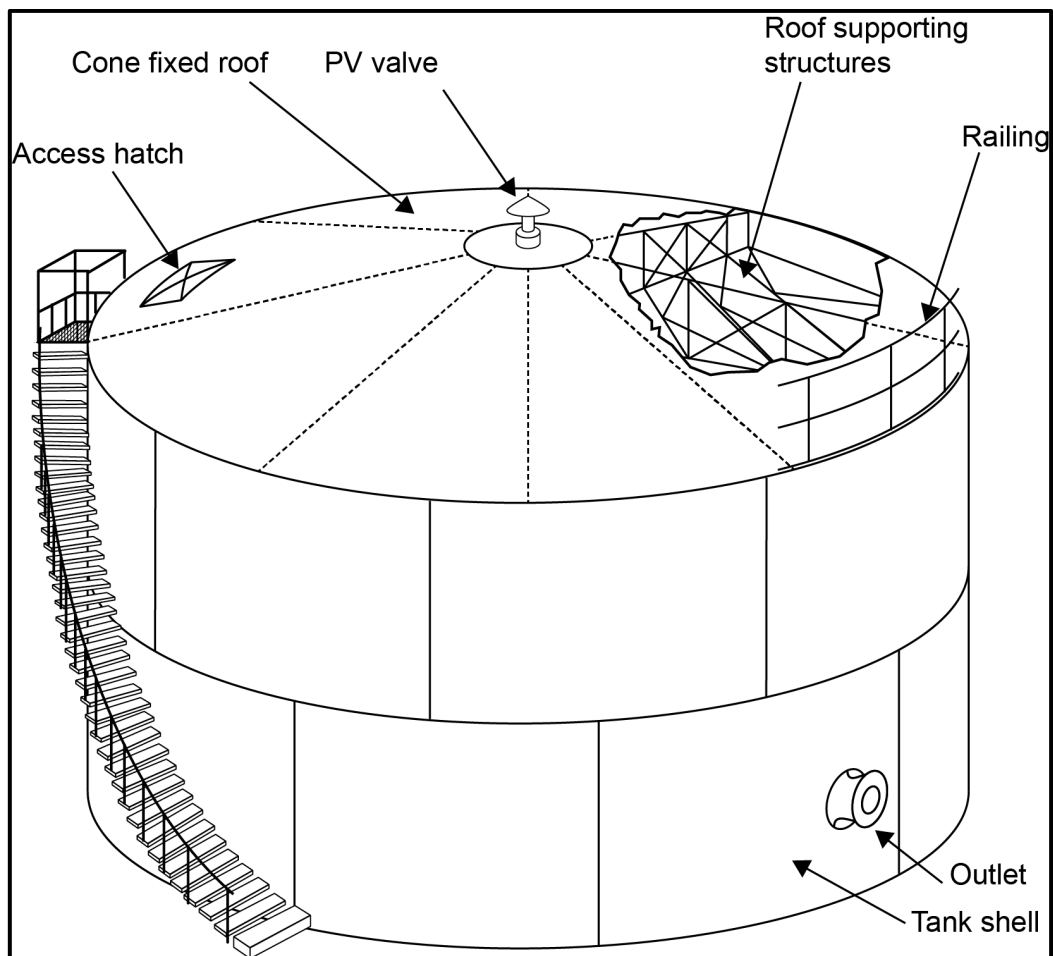


Figure 2 Typical fixed roof tank

Self-supporting roofs can be conical or dome shaped but are generally only used for smaller diameter tanks.

Roof structures of fixed roof tanks vary in design in relation to the diameter of the tank. Table 1 lists the different fixed roof structures employed relative to tank diameter.

A geodesic roof is another type of self supporting roof which is increasingly being used. A typical geodesic roof is shown in Figure 3.

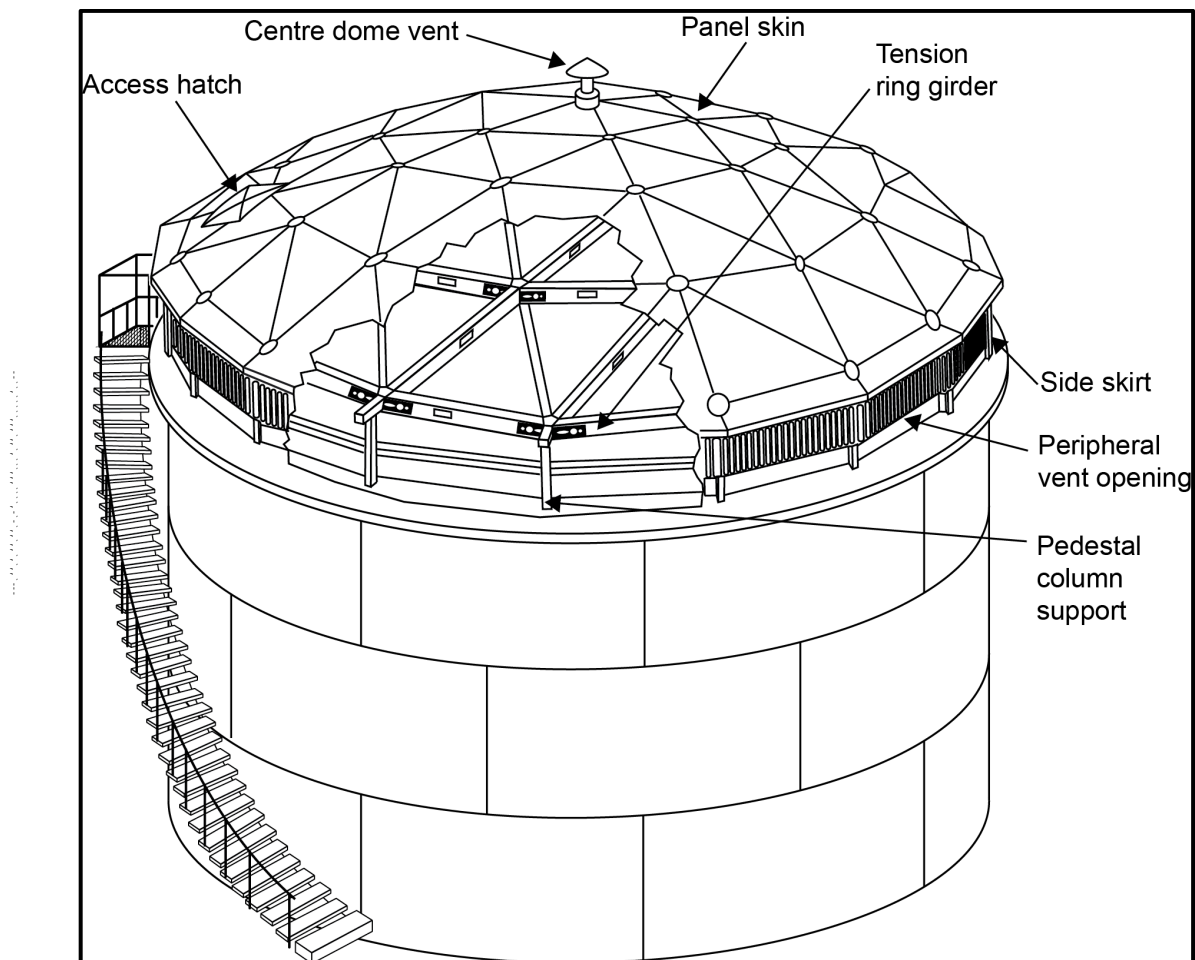


Figure 3 Typical open top tank with geodesic dome roof

Note: Cut-away section shows triangulated space frame for dome cover

Table 1 Recommended type of fixed roof for tanks of different sizes

Note. Areas shaded green in the body of the table indicate the best choice of roof type for the particular tank diameter.

* R = radius of curvature of dome; D = tank diameter

Total steel weight of various fixed roof structures [kg]														
Type	Membrane cone		Membrane dome R = D*		Membrane dome R = 1.5 x D*		Cone (beam rafters)		Cone (ring girder)		Dome R = 1.5 x D*		Cone (lattice trusses)	
Diameter [m]	Weight	Weight /m ²	Weight	Weight /m ²	Weight	Weight /m ²	Weight	Weight /m ²	Weight	Weight /m ²	Weight	Weight /m ²	Weight	Weight /m ²
5	871	44	911	46	878	45	1042	53						
7.5	2957	67	1986	45	1913	43	2334	53						
10	7087	90	3474	44	3978	51	4540	58						
12.5	15015	122	5441	44	8212	67	7469	61						
15			9255	52	14615	83	11806	67			14182	80		
17.5			14556	61	23715	99	16382	68						
20			24234	77	35988	115	23153	74			24462	78		
22.5							31130	78						
25							41608	85	41401	84	38205	78		
27.5							50434	85	54829	92	46829	79		
30							59385	84			56829	80	48315	68
35											75812	79	67315	70
40											101929	81	91185	73
45											139969	88	120815	76
50											170383	87	153158	78

b) **Floating Roofs**

There are three main types of floating roof:

i) *Pontoon type (single deck) floating roofs* (Figure 4)

For these roofs, the buoyancy is supplied by an annular pontoon with typically up to 30% of the total roof area. For design criteria, see original design Codes and Chapter 11 of this Publication.

ii) *Double-deck floating roofs* (Figure 5).

For these roofs the entire roof area is provided with a double deck, making the roof more rigid than the pontoon roof. Double-deck roofs can be fitted with emergency drains which discharge any accumulation into the stored product.

Double-deck roofs are generally fitted to large diameter tanks (e.g. over 50m diameter). They are structurally stronger and prevent wind problems which occur in the centre decks of large pontoon roofs.

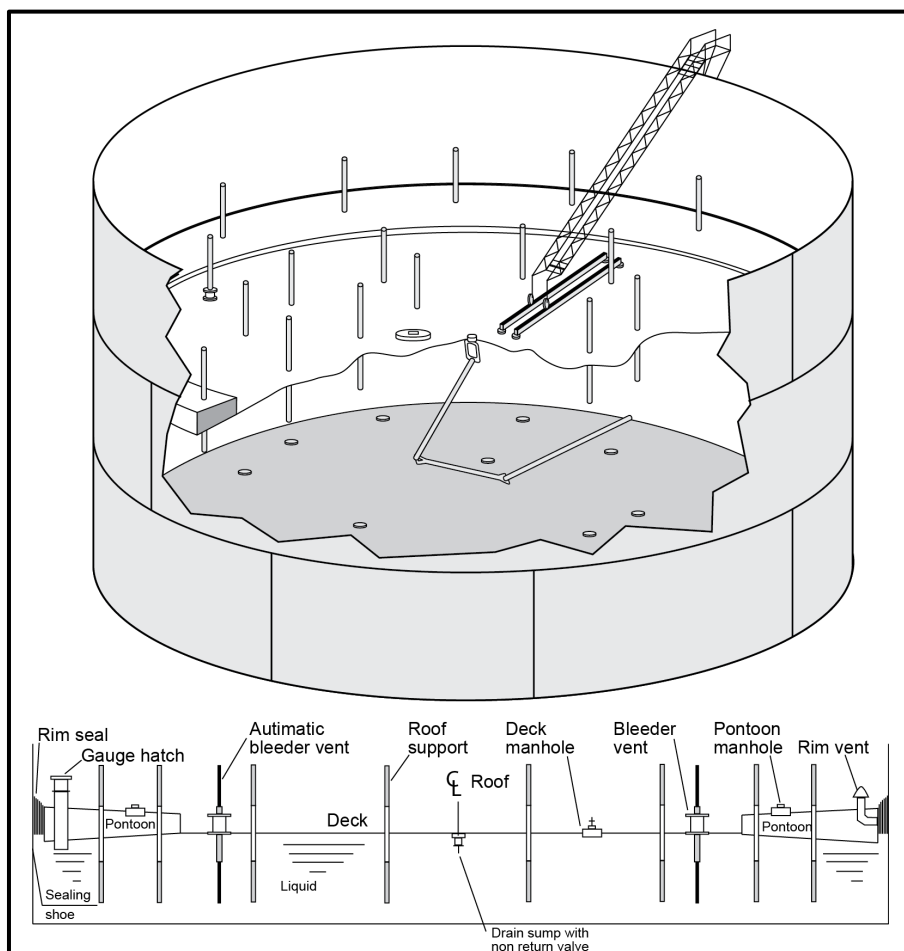


Figure 4 Typical floating roof tank with pontoon floating roof

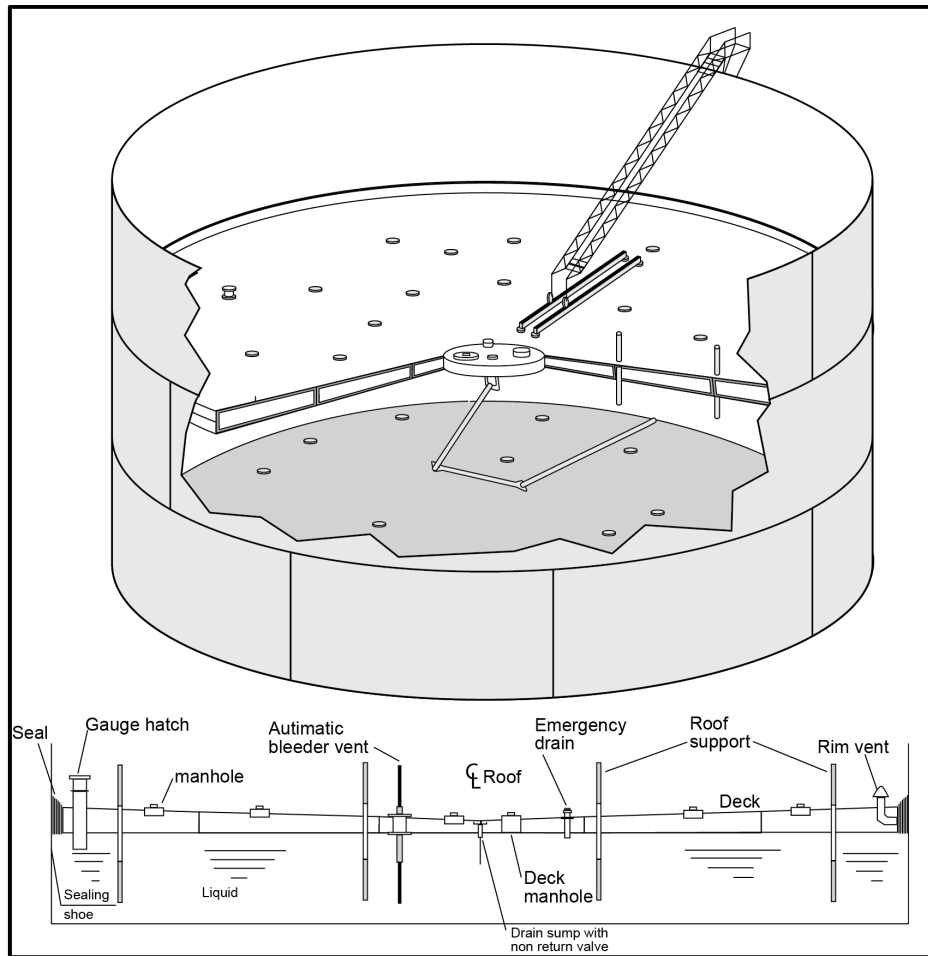


Figure 5 Typical floating roof tank with double deck floating roof

iii) *Special buoy type and radially reinforced roofs*

The buoy type roof is a pontoon roof with a relatively small annular pontoon, but has in addition a number of small diameter circular buoys spread over the centre deck to provide additional buoyancy.

Radially reinforced roofs have a pontoon ring and a buoy in the middle of the centre deck. These roofs are built with a certain sheer to force rainwater to the drains at the centre of the deck, thus preventing water accumulation. Product vapours are forced to the edge of the deck where they are released via rim vents. Radial stiffeners are installed to maintain the sheer when the roof floats. These roofs are vulnerable to collapse when landing on the support legs.

Roofs of this type, mainly used for large diameter tanks, are hardly built nowadays, because double deck roofs perform much better in tanks of that size.

2.4 Materials

2.4.1 Ambient conventional storage tanks

The majority of existing tanks were designed and built in accordance with the Codes and Standards listed in Chapter 1 and the materials specified within those Codes.

Since the late 1960s, the potential for brittle fracture of ambient storage tanks has been recognised and the standards now require consideration of the low temperature properties of the materials.

Since 2005, in the European Union, carbon/carbon manganese steels and stainless steels are selected from those codes specified in EN 14015.

The majority of ambient tanks are built from S235, S275 and S355.

3 Degradation mechanisms and failure modes

A summary of the most common degradation (or failure) mechanisms to which tank components may be subjected and examples of consequential failure modes are given in this Chapter. Further examples of failure modes, effects and consequences thereof, and possible causes are given in Appendix E.2. Degradation mechanisms may occur over a period of time or can be the result of sudden events.

3.1 General corrosion

General corrosion in combination with pitting corrosion can occur both internally and externally.

- Internal corrosion can result from:
 - the presence of aggressive substances or contaminants in the stored product (sometimes in combination with other conditions). An example is vapour space corrosion, degrading the top part of the inner tank shell and the underside of the tank roof due to, for instance, the presence of sulphur components in an air-vapour mixture under relatively warm and humid conditions;
 - the ingress and accumulation of water in the tank caused by breathing of the tank due to temperature differences and condensation of water vapour, presence of water in the stored medium, or leakage of rainwater through the floating roof seal; and/or
 - Poor welding of annular and bottom plates.
- External corrosion (bottom) can result from:
 - sub-standard quality of the sand-bitumen top layer of the foundation pad (contaminants in the foundation pad, including clay, stones, cinders, or other sharply pointed materials, can set up an oxygen concentration cell where they touch the tank bottom. The relatively small areas of contact between the bottom and the contaminants become anodic, and the large remaining area of the tank becomes cathodic. Accelerated attack of the contact area results in pitting corrosion);
 - the ingress of rainwater by permeation and capillary action due to unevenness in the top of the foundation pad;
 - corrosion at a water trap formed by mounding of the tank foundation and/or edge settlement;
 - edge lamination of the annular plates particularly in areas where water and debris collect around the base of the tank;
 - poor welding of annular and bottom plates; and/or
 - inadequate removal of mill scale from bottom plates.
- External corrosion (shell and roof) can result from:
 - pooling of water:
 - by poor design and installation of primary and secondary wind girders;
 - in the case of a roof with external rafters;
 - at gusset plates around nozzles;
 - at toe bars of handrails; and/or

- around undulating membrane of the floating roof (inadequate drainage).
- Corrosion under insulation factors:
 - due to water entrapment; meaning degradation is enhanced by higher temperature (of stored product);
 - improper installation of cladding; or
 - high chloride content insulation.
- General corrosion mechanisms and corrosion enhancing factors:
 - Tanks for storing heated liquids are predominantly designed with cone-up bottom configurations. Accelerated corrosion of bottom annular plates is more likely when heated tanks are built with cone-down bottoms; and/or
 - Bimetallic corrosion, resulting from the coupling of dissimilar metals in the presence of moisture, is a problem frequently overlooked, particularly in storage tank earthing systems.

3.2 Tank settlement and consequential problems

Issues that can arise in relation to tank settlement include:

- Differential settlement and edge settlement of tank pad shoulder due to erosion;
- General settlement of tank pad leading to instability and ultimately slip failure;
- Liner underneath tank damaged due to (differential) settlements; and/or
- Jamming of floating roof structure around guide pole (this may also occur in fixed roof tanks equipped with internal floating covers).

3.3 Structural failure and/or failure of tank components/appendages

Issues that can arise due structural failure and/or failure of tank components/apendages include:

- Buckling of internal floaters due to inadequate support, vacuum, or seal jamming;
- Loss of buoyancy of floaters and/or floating roofs due to liquid in pontoon or on roof;
- Roof drains leaking or being blocked;
- Derailing of rolling ladder on top of a floating roof tank;
- Buckling of the supporting legs of a floating roof tank due to inadequate support, or vacuum conditions;
- P/V valve or non-return valve blocked or not adequately sized;
- Jamming of roof seals due to (progressively increasing) out-of-roundness of the tank shell;
- Roof seals giving a gap as the result of out-of-roundness and/or tilting of the roof;
- Failure of instruments, such as level indicator, pressure indicator, temperature indicator, and level alarm, due to corrosion, or jamming, or floater cable/instrument distortion etc.; and/or
- Wear and tear scratching seal shoe plates/tank shell.

3.4 Combination of degradation mechanisms and other influences

Issues that can arise due to a combination of degradation mechanisms and other influences include:

- Internal and external corrosion in combination with excessive settlement are often the main causes of bottom leakage;
- The interface between the tank structure and the foundation as well as the design and construction of the foundation itself are important factors. Short cuts, cost cutting exercises and inadequate, budget-driven repairs (the consequences of which may be underestimated) are often the culprits identified in tank bottom/foundation failure reports; and/or
- A corrosion phenomenon often not recognised is bacterial corrosion (or microbial corrosion). This particular form of corrosion should be looked for when bacteria may be present in the liquid stored, usually in free water. Growth of bacteria can occur in localised spots within a tank even when there is no free oxygen available, but occurrence of this type of corrosion is limited due to specific circumstances under which bacteria can grow (availability of nutrients, pH value, temperature etc.).

3.5 Microbial Induced Corrosion (MIC)

The main concerns about MIC:

- are not readily understood by operating personnel, as being critical for the steel components of storage tanks;
- have rates of corrosion much higher than normal corrosion mechanisms
- can result in serious damage within standard inspection intervals, hence prevention by inspection not usually an option; and
- results in high repair costs (repeated costs if not recognised as the corrosion mechanism).

MIC is normally caused by Sulphate Reducing Bacteria (SRB), which can be delivered within fuel stock dependent upon quality and generally occurs in areas of stagnated flow, e.g. tank sumps, floors, nozzles etc. Where stagnation (or dead legs) are operational (i.e. stagnation occurs for varying amounts of time dependent upon process conditions/controls) corrosion rates can accelerate due to the increase in a number of factors such as nutrient replenishment, temperature increases or the effects to other corrosion mechanisms such as oxygenated corrosion.

SRBs proliferate within environments where oxygen free water and suitable feedstocks or nutrients are available for the development of the bacteria.

Once developed deposits or tubicles form thereby creating an aggressive environment where corrosion rates can significantly escalate for the norm.

MIC can be detected using a number of inspection methodologies both operationally and during major overhauls/inspections. Some methods of detection are:

- Sampling and trending of produced water for the presence of microbes and sulphides;
- Ultrasonic Testing (UT); and

- Radiography (for accessible areas such as nozzles).

Operational management of MIC can be achieved by the application of a number of methodologies, which can vary dependent upon process requirements and applicability. Methods such as:

- Application of biocides (dependant upon product implications);
- Removal of dead legs; and
- Review of the operation of drain lines/dead legs.

can be considered to manage such corrosion.

Prevention of MIC to be accomplished by prevention of contamination of stored products with potentially MIC containing products such as rainwater, slops, drainage and known MIC containing sources such as some crude types.

4 Corrosion of tanks

4.1 General

Corrosion is the prime cause of deterioration of steel storage tanks and accessories. Locating and evaluating the extent of corrosion is therefore a major reason for inspection.

4.2 Corrosion rates

Both the nature of the stored product, and the vapour in the space above the product in fixed roof tanks, are determining factors for corrosion rate. The grade/quality of the tank material in respect of its resistance to the aggressiveness of the stored product is another. The corrosiveness of various products is presented in Table 2 (overleaf), where typical corrosion rates are identified for various products in cases where only the particular product is stored.

However, change of service (i.e. change to a different stored product) may result in different corrosion rates, which will change the lifetime of the tank.

The remaining (expected) life, after a certain period of service, is of relevance when deciding whether or not to take a tank back into service. Careful recording of corrosion over a defined period of time is required for predicting remaining life. This is also termed 'trending' (see also Appendix D.4).

The typical corrosion rates tabulated are based on data for carbon steel tanks (only) collected from various tank owners. Chemical products with a pH less than 5 are predominantly stored in tanks made from stainless steel; corrosion rates for those products are not therefore listed.

4.3 Bottom plates

4.3.1 Failure modes under consideration

Experience from the past (2005 Kallo incident⁽¹¹⁾) indicates that besides the corrosion hole in the bottom plate, some other corrosion mechanisms should be considered when assessing a tank bottom.

First and most probable scenario is the corrosion hole in the bottom of the plate. The consequences that need to be considered are:

- Leak into tank bund;
- Possible pollution of ground water below tank;
- Pollution of soil underneath tank;
- Extensive soil settlements/loss of support – see Section 6.1.2. These different settlement degradation mechanisms, are a major failure mode for bottom plates and for the bottom/shell connection.

The second failure mode is a rupture of the tank bottom due to excessive leaking causing structural instability of the foundation. The consequences that need to be considered are:

- Filling of tank bund, major soil/groundwater pollution;
- Possible wash over, pollution outside tank bund area;
- Loss off the tank;
- Disruption of the neighbourhood: Odour complaints (air pollution).

Table 2 Expected internal corrosion rates (typical (mm/year)) for tanks

Stored Product	Tank						
	Bottom	Shell		Roof			
	Plates ¹	Liquid Exposed Area	Vapour Space Area ²	Fixed roof		Floating roof	
				Plates	Supporting Structure	Plates	Pontoon/Rim Area
Crude							
High Sulphur Content	0.4–0.8	0.2–0.4	0.4–0.6	(0.4–0.6)	(0.4–0.6)	0.4–0.6	0.5 – 0.7
Low Sulphur Content	0.3–0.5	0.1–0.3	0.2–0.4	(0.2–0.4)	(0.2–0.4)	0.2–0.4	0.3–0.5
Intermediate Feed							
Distillates	0.15–0.35	0.15–0.35	0.65–0.85	0.65–0.85	0.65–0.85	(0.15–0.35)	(0.65–0.85)
Fuel oil							
Gas oil	0.1–0.3	0.05–0.25	0.1–0.3	0.1–0.3	0.1–0.3	–	–
Kerosene (Jet A1)	0.1–0.3	0.05–0.25	0.1–0.3	0.1–0.3	0.1–0.3	–	–
Mogas							
Gasoline	0.05–0.25	0.05–0.15	0.05–0.25	0.05–0.25	0.05–0.25	0.05–0.15	0.05–0.25
Naphtha	0.15–0.35	0.05–0.25	0.15–0.35	0.15–0.35	0.15–0.35	0.05–0.25	0.15–0.35
Slops and aggressive Products							
	0.6–0.8	0.4–0.6	0.6–0.8	0.6–0.8	0.6–0.8	0.4–0.6	0.6–0.8
Chemicals							
<i>Acids with pH < 5³</i>							
<i>Neutral liquids 5 < pH < 8</i>							
Acetone, Acrylate,	0.1–0.3	0.05 – 0.25	0.1–0.3	0.1–0.3	0.1–0.3		
Alcohol, Methanol,	0.05–0.25	0.05 – 0.15	0.05–0.25	0.05–0.25	0.05–0.25	0.05–0.15	0.05–0.25
Styrene, Toluene etc.	0.1–0.3	0.05–0.25	0.1–0.3	0.1–0.3	0.1–0.3		
Caustic products pH > 8							
	0.6–0.8	0.4–0.6	0.6–0.8	0.6–0.8	0.6–0.8	0.4–0.6	0.6–0.8

Notes:

Values in brackets indicate product not usually stored in this type of tank.

¹ No bottom coating or internal lining applied.

² Vapour space corrosion can be as high as 1mm/year [subject to product type (sulphur content) and climate].

³ Predominantly stored in tanks made from stainless steel (AISI 304 or equivalent).

4.3.2 Bottom plates (underside/external)

General underside corrosion should be slight where there is a well prepared and maintained foundation, typically 0.125mm/year for carbon steel. However, problems of severe attack are common, though not always for the same reasons.

The first failure scenario should be a leak due to external pitting corrosion. This may grow faster than the general corrosion rate. This means that a local leak might be experienced earlier than otherwise anticipated.

The second failure scenario that should be considered is a tank annular ring rupture close to the shell. This is caused by a band of corrosion at the periphery of the tank leading to a large thinned area. The consequences of a rupture are described above.

The major causes of underside corrosion are discussed below (See also EEMUA 183⁽¹²⁾):

- Poor drainage around the tank;
- Mill scale, which when present on the underside of the tank bottom causes preferential attack;
- Water collecting around the tank and migrating under the bottom;
- Significant tank settlement that lowers the tank below a level for adequate drainage. This may lead to corrosion of the annular plate around the tank perimeter. Corrosion may be severe adjacent to the shell, but it is generally restricted to about one metre from the outside of the tank bottom/annular plates;
- High ground water table or underground springs;
- Coral and beach sand with high chlorides used for the foundation, leading to rapid pitting;
- Acidic coal-based cinders or slag being included in the foundation;
- Sharp or large stones being included in the foundation. This may give rise to deep pitting by oxygen concentration cell corrosion;
- Poor underside, external, coating application (seldom applied initially, only after jacking);
- Poor quality of bitsand, e.g. road mix rather than bitumen rich;
- Where cathodic protection has been installed after commissioning the tank, the presence of impervious plastic membranes or asphalt pads makes it difficult if not impossible to ensure that sufficient protective current reaches all areas of the bottom (Note: Cathodic protection, when operated outside of its design limits, may also increase corrosion rates (especially on tanks fabricated from stainless steel plates));
- In tanks storing heated products such as asphalt, there are large differences in tank-to-soil potential across the bottom. This can cause deep random pitting. Potentials become more anodic from the centre of the tank outwards;
- Hot tanks increase water permeation under bottoms, and corrosion rates increase with increasing temperature;
- Stray DC currents may cause extremely high local corrosion. This occurs when an external source of direct current, such as a nearby electric railway, causes current to flow through the ground to the tank bottom;
- Other isolated cases have included rapid galvanic corrosion resulting from improper installation of a new bottom on top of an old bottom; and

- Failure of protective cuffs placed around the protruding external rim of the bottom annular plate. These cuffs can be a felt or lead flashing. The outer edge is embedded in the tank foundation and the tank shell with bitumen. Embrittlement of the seal material, as well as separation of the seal from the tank due to movement, allows rainwater to run underneath the tank. Due to the difficulty of inspection behind these cuffs and their lack of integrity, there is a strong incentive to remove them. Some modern cuff designs are made from ultraviolet-resistant rubber, and might perform better than the ones made from felt or lead. However, the difficulty of inspection of the underlying bottom-shell connection and the annular plate still remains.

4.3.3 Bottom plates (topside/internal)

Topside corrosion of bottom plates occurs at low spots where water collects. With settlement, a low spot adjacent to the shell is quite common, and this is one of the areas of the floor most prone to corrosion.

However, because the floor is normally constructed using lap joints and fillet welds, water can collect virtually anywhere across the bottom.

Rates of attack can be quite high. In crude service, 6mm (¼ inch) thick bottoms have been penetrated due to internal corrosion in less than 6 years under abnormal conditions. Many locations apply coating layers on crude tank bottoms. This is now being proven as a sound judgement. Increasing the floor plate thickness may also be considered. However, provision of a uniform corrosion allowance for the floor (particularly in crude service) is both uneconomical and technically unsound. This is because tanks corrode preferentially in selective areas.

This localised corrosion can lead to an extended area of thin bottom plate material, which can lead to a mechanical failure and rupture of tank bottom plate. This scenario has been described in publications as "gutter" type of corrosion (See Kallo incident).

The probability of the gutter corrosion is dependent on the size of the storage tank, the local compressibility and a relative elastic underground. The gutter is not always detectable with cross banded ultrasonic measurements. Adapted floor scanning techniques should be considered if there is a risk for accelerated internal corrosion. The consequences of this incident are described above.

Water draw-off sumps are usually constructed of thicker steel than the rest of the bottom, and are painted and sometimes cathodically protected by sacrificial anodes to achieve a reasonable life.

Anchor chains from flexible hose drains rubbing on the floor, articulated drain attachments, roof legs, and dipping and sampling devices have also caused accelerated failure.

Pitting is another type of internal corrosion on bottom plates, although preferential attack on welds also occurs. The internal corrosion of the bottom plates is usually caused by acid salts, hydrogen sulphide, water etc. Excessive pitting corrosion may be caused by localised oxygen concentrations under wax deposits or debris, or by the presence of hydrogen sulphide which reduces local

pH. Hydrogen sulphide may be formed due to the action of sulphate reducing bacteria (SRB), which can lead to accelerated corrosion of the plates and in the HAZ of welds.

4.4 Shell plates (internal and external)

Shell side corrosion occurs in lighter products such as solvents, naphtha and gasoline tanks. These products are less conductive. Both water and caustic carry-over is often present in these tanks, and will increase corrosion rates substantially.

With heavier darker petroleum products, crude, fuel oils, bitumen, shell corrosion in the liquid phase is not as severe, as oxygen solubility is low. Corrosion in the vapour space depends on the climate and the effectiveness of a protective coating which can be provided by the product itself. The tank emptying and filling schedule can also contribute.

For crude service, the lower 500mm can be prone to corrosion.

Corrosion may occur on the shell above and below the liquid level in gasoline and other light product storage tanks. Below the liquid level there may be general metal wastage and pitting corrosion. Accelerated attack may occur where the shell oxide scale is not protective or is less adherent. Protective scale may be removed by cracking and spalling due to successive cycles of wet and dry conditions, changes in temperature etc. With floating roof tanks the scraping action of roof shoes may further accelerate removal of protective scales and cause vertical grooving of the shell. This can be a serious problem that significantly reduces the effective thickness of the shell. Scale from a corroded shell can build up in the foam dams of floating roof tanks, thus reducing their efficiency. This can also apply to the roof drainage system.

Preferential corrosion at welds is quite common. A galvanic cell is set up where the weld metal or (sometimes visible when storing non-corrosive products – conductivity < 50 pS/m) the weld metal in the Heat Affected Zone (HAZ) is anodic to the rest of the shell plate. The corrosion rate may be double at welds. Visual inspection is the only reliable method for its detection. Preferential corrosion of vertical welds is more important than that of circumferential (horizontal) welds from the standpoint of shell strength.

Corrosion may take the form of a uniform loss (a general, even wastage of a surface area) or leave a pitted appearance (irregular wastage).

Uniform corrosion may be difficult to detect visually, and thickness readings may be necessary to determine its extent. Pitted surfaces may be thinner than they appear visually and, when there is a question of residual thickness, measurements may also be necessary.

Shell corrosion is generally not a problem in floating roof tanks used for storing crude oil because a protective layer is deposited, although some pitting and general corrosion has been found on the shell plates in the area within 300mm to 450mm above the bottom plate. This is due to the water content of the stored liquid, or rainwater getting past the seals to mix with the contents of the tank. In tropical climates particularly, storage tanks containing leaded gasoline are known to have suffered internal corrosion in the middle section.

Shell external corrosion may occur just above the line where soil settlement has raised the ground level to create a water trap, covering the lower portion of the shell. An acidic atmosphere can break down the protective paint coating resulting in general corrosion.

External fittings such as wind girders, if not provided with proper drainage, can suffer corrosion where welded to the shell.

4.5 Roof plates

4.5.1 Fixed roofs including roof support structure

General corrosion and/or pitting corrosion can occur on the underside of cone roofs, support structures etc. in the vapour space. This is most severe when aggressive products have been stored.

Water condenses on metal surfaces in the vapour space, and if the design allows this water to be trapped it can cause severe corrosion. Hence, the reverse shingle method of construction is generally employed for cone roof plates.

The condensed water film becomes saturated with air from the tank's breathing, and with H_2S , if present. Corrosivity is generally low in the absence of both air and H_2S in the vapour space, e.g. with gas-blanketed operation.

When severe vapour space corrosion occurs, as in humid environments, roof plates can be holed as in Figure 6, in as little as two years.



Figure 6 Example of vapour space corrosion

A dark colour paint on the outside increases metal temperatures, and corrosion rate increases with temperature. Industry has seen that corrosion rates will double for each 10–15 °C temperature rise.

The total sulphur content of the product stored is not necessarily a guide to corrosivity in the vapour space. This is governed by the free H_2S that evolves.

Corrosion on the outside of the roof can be caused by vapours emitted from any (open) vents on the roof.

Structural members suffer in particular at the bottom edges of vertical members, at the vertical ends of members (end grain corrosion), and at bolt holes. The examination of roof structures, where corrosion is known to occur, should always be carried out with extreme caution. On no account should personnel be allowed access to roofs without first establishing that it is safe to do so. The results of any inspection should always be discussed with the design authority for guidance on any necessary actions.

4.5.2 Floating roofs including supporting legs

Floating Roofs are generally constructed from steel plates of 5 or 6mm thick. Poor drainage may result in pools of rainwater on the centre deck. In combination with sand or dirt blown onto the roof by wind, this may damage the protective paint layer and cause corrosion. The corrosion may in turn increase the possibility of fatigue cracking of lap welds (see 11.1.3).

Serious corrosion may cause leaks in the centre deck of pontoon roofs and, as the oil level is higher than the centre deck, will result in a flooded roof. To avoid flooding and progressive corrosion, regular inspection and maintenance should be conducted.

Corrosion may also be present around roof supporting legs and sleeves both internally and externally

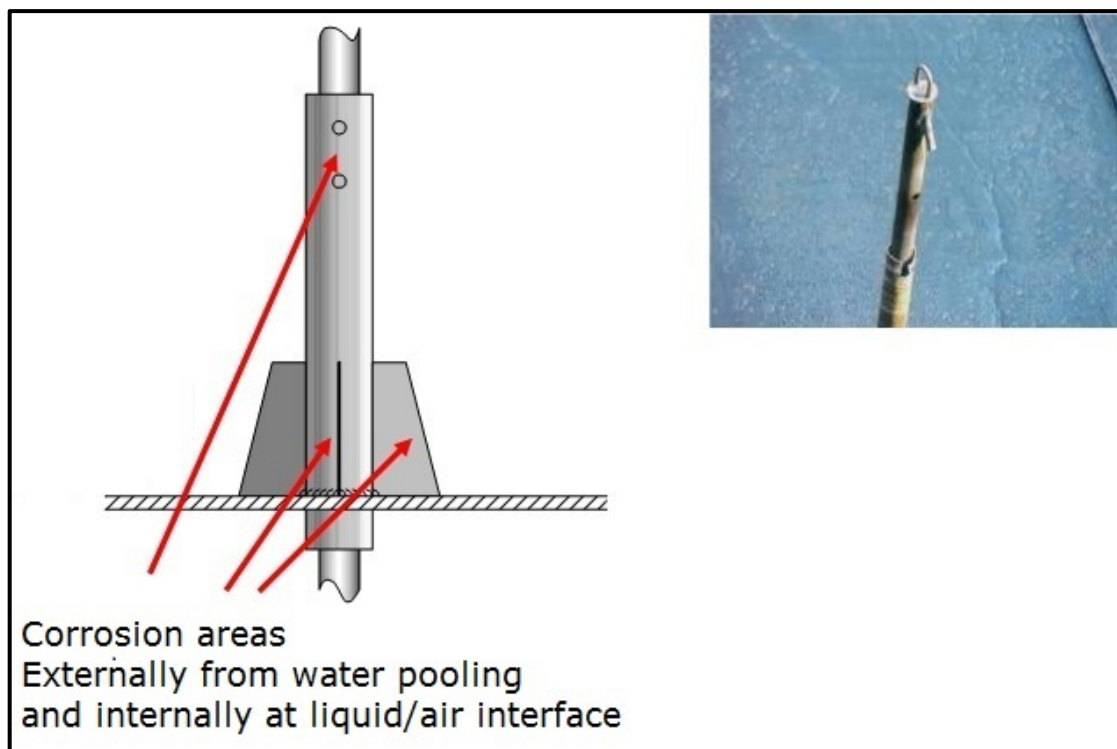


Figure 7 Corrosion areas for roof supporting legs

Corrosion can also occur at the periphery of the centre deck where it is welded to the annular pontoon and at any low point on the roof.

4.6 Corrosion Under Insulation (CUI)

For insulated tanks, Corrosion Under Insulation (CUI) is a particular problem at the lower section of the shell, at stiffening rings, on the roof and where there are penetrations through the insulation weatherproofing. The rate of corrosion is dependent upon water or water vapour penetration and its retention in the insulation. Metal/ambient temperature, corrosion inhibitors within the insulating material, and paint coatings under insulation all influence the rate of attack (see also Section 4.1).

Good design, material selection, attention to detail and good standards of workmanship are fundamental in minimising CUI issues. The use of cellular glass closed cells are recommended for susceptible areas that include the bottom section of the shell, at secondary wind girders, on insulation support rings, or locations where water could pool. This is due to the low moisture retention qualities of the 'closed cell'. Appropriate adhesives and sealants/mastics should be selected as the end of their functional life, which may allow water ingress between insulation and shell, is difficult to detect.

Some operators prefer to leave the bottom section of the shell un-insulated. There is some loss of heat, but a critical part of the tank is readily accessible for inspection, and CUI degradation is removed in this location. However the un-insulated part may be affected by thermal stresses during periods of low ambient temperature. Insulation requirement in this location should therefore be periodically reviewed.

Heating coil penetrations in this (bottom shell) area should be equipped with annular pipes to separate insulation from contact with the nozzles. This will prevent accelerated corrosion at these spots.



Figure 8 An example of corrosion under insulation

Penetrations through insulation weatherproofing should be minimised. All penetrations should be well sealed. Regular inspection and maintenance is

necessary to retain the weather proofing watertight qualities and prevent water ingress (See Table 21, Appendix B2 for inspection guidance).

Associated piping should also be considered for inspection as part of the tank CUI evaluation, with special attention afforded to PV/EV nozzles that are traced & insulated due to process considerations..

Heavy weatherproofing material (cladding) that reflects solar radiation is beneficial since this reduces thermal stresses and degradation in the coatings.

The provision of proper walkways to prevent personnel from walking on insulation is essential. Any insulation damage should be rectified as soon as practicably possible.

It must be noted that insulation removal will be required as part of the ONL (online examination) or OFL (offline examination) inspection event, to enable UT WT (ultrasonic testing wall thickness survey) monitoring as identified on Table 21 of this Guide. The tank surfaces can be evaluated at this time for evidence of water ingress, i.e. corrosion particulate of water salts staining. Any wall loss to be evaluated, actioned accordingly, and locations recorded for monitoring & scheduling purposes. Insulation re-instatement is to be fully sealed and weather proofed and scheduled for regular inspections or maintenance to maintain integrity.

Consideration should be afforded to design out the CUI degradation by installing (for example) removable insulation jackets in specific areas, sumps and associated piping, associated piping and valves, traced/heated Pressure Vent Valve (PV) / Emergency Vent (EV) nozzles.

4.7 Corrosion of stubs and appendages

The following corrosion phenomena can occur:

- pitting corrosion underneath the inner surface of the stubs;
- corrosion of the tank shell near the lower parts of nozzles; and/or
- attachments welded to the tank shell and covered by insulation are areas susceptible to CUI.

5 General inspection techniques and interpretation of inspection data

5.1 References

Reference should also be made to the inspection routines and techniques described in EEMUA 183 and/or API RP 575⁽¹³⁾.

5.1.1 Inspection and maintenance

For more than a century, e.g as shown in Figure 9, storage tanks have been in use within the petrochemical industry. At some locations in the world, tanks aged one hundred years or more still fulfil their intended purpose: to store products.



Figure 9 Example of tank built in 1900 and still operational

But this is only possible through proper and sufficient maintenance to minimise the effects of degradation mechanisms such as corrosion and settlement. If parts of the tank are degraded beyond a defined limit, extensive repairs are required to keep the tank or a specific tank component fit-for-purpose.

Inspection/maintenance periods

In order to maximise its functionality and structural integrity, a tank must be inspected and maintained at predetermined intervals to check the progress of unwanted degradation mechanisms. When degradation of a specific tank component nears its rejection limit, proper repairs need to be carried out.

However, to prevent unwanted shut-down, routine maintenance and inspection should also be carried out during the in-service period of a storage tank. Figure 10 shows the four main activities that are constantly repeated during a tank's entire lifetime.

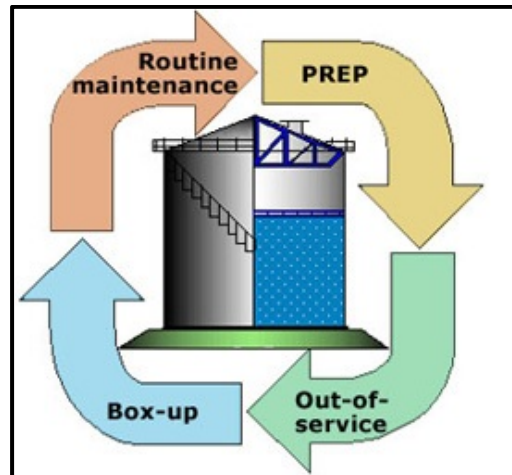


Figure 10 The four activities of tank maintenance

When a tank is due to be taken out of service for internal inspection and maintenance, the first activity, preparation, deals with arranging adequate contracts with NDT (Non-destructive Testing) inspection companies and contractors as well as purchasing long-lead delivery items. A well organised preparation activity may shorten the out-of-service period.

The second activity is the actual out-of-service period where various other tasks have to be performed. After this out-of-service period the tank should be boxed-up again and connected to the plant utilities, control room and pipeline systems. The fourth activity is the in-service period, where normal preventative maintenance and routine inspections are carried out.

During the fourth activity of the operational life of a storage tank routine inspection and maintenance tasks are to be carried out in order to prevent premature failure of tank components or the tank itself. The provided table in Appendix B1 shows proposals for intervals of required routine inspections to storage tanks and their components.

During the in-service periods of tanks so called routine operator inspections should be performed, preferably every 3 months, independent of the product that is stored in the tanks. Appendix B2 provides a checklist of items that should be addressed during these three-monthly inspections. Table 20 also specifies maximum interval for in-service inspections. The extend of these inspections are covered in Appendix B2 "In-service inspections". Appendix B2 also provides general inspection lists for required non-destructive testing on tank components that should be performed during the in-service periods of a tank.

When going into detail of the many tasks that are to be addressed during the out-of service period of storage tanks (the seconds activity) – see also the final column in Table 20 for advised intervals of out-of-service inspections – it is advised to follows the 7 steps that are to be taken into account during this second activity.

The 7 steps of the out-of-service period

It is most important to recognise the following seven steps for the out-of-service maintenance period:

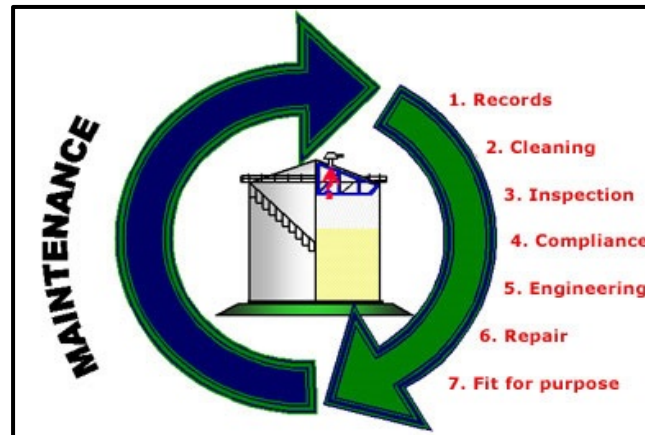


Figure 11 The 7 steps in the out-of-service period

Step 1: Records

Proper maintenance is dependent on certain criteria being met, and this is the first step in EEMUA's maintenance loop. The tank's original data must be available. As built files, inspection, modification, product change records must be well maintained and accessible to maintenance and inspection personnel. Of course, following the out-of-service period, a description of all repairs, inspection reports and NDT reports must be added to these files so they are properly updated. This step actually represents the loop's final step.

Step 2: Cleaning

The second step is the cleaning – and gas freeing – activity.

Step 3: Inspection

When the tank has been cleaned and declared gas-free, internal and external inspections must be performed to assess the actual status of all tank components. These activities are addressed in Appendix B2 where a general inspection checklist and required detailed NDT-inspection lists are incorporated.

Step 4: Compliance

The fourth step is the most important step in tank maintenance. A compliance check on each tank component has to be performed to assess whether the component is still fit-for-purpose or whether it should be replaced.

This publication addresses, per main tank component, the method to assess the rejection limit. The rejection limit is the most important degradation parameter as it determines whether a component, such as tank bottom plates (annular ring plates and normal bottom plates), tank shell plates, tank roof plates, and floating roof plates, nozzle bodies etc. should be replaced. The methods provided should be used in the calculation of a main tank component's remaining lifetime. When

the remaining lifetime is calculated prior to the next planned out-of-service period, evaluations should be performed to replace such items in the current out-of-service window.

Step 5: Engineering

When it is evaluated that tank components need to be repaired or even replaced, engineering tasks are needed to assess where, how and when these repairs will be performed.

Step 6: Repair

The next step involves the actual repairs at the site. As in this stage new plates or tank components are being welded to the original tank structure, it is necessary to use and apply only suitable materials, as detailed in the original design and building standards and codes applicable for subject tanks. It is also necessary to perform adequate non-destructive inspection to assembly welds and to welds that are introduced in the tank whilst inserting new plates, structures or components. Also, reference should be made here to using the originally required non-destructive testing by ultrasonic or radiography inspections to those welds specified in the design codes and standards. Where such standards are not known nor available, the use of the latest revisions of design and construction codes, such as EN 14015 or API 650, should be considered.

Step 7: Fit for purpose

When all repairs have been executed, the tank must be declared fit-for-purpose by a responsible staff member of the tank owner before the tank is allowed back in service.

Here the loop must be closed by adding all available documents, produced during the out-of-service period of a tank into the tank files (records).

By following the sections of this Publication all of the above activities and steps are being addressed and proper information about what, when, how, where and with what tools/techniques inspection and maintenance tasks should be performed, are documented and described.

5.1.2 Assessing the tank norm or standard

As highlighted in Section 5.1.1, above, records should be (made) available of a tank in order to make a sound investigation to the actual technical status of such tank (the Fit-for-Purpose analysis). One of the premier items that should be assessed is to what norm or standard subject tank was designed or constructed: the so called "as built norm".

As built norm:

This is the norm used for the construction of the tank (or tank component) in question. If this norm is not known, the as built norm is the standard that was in effect at the date of the installation of the tank (component). If the date of the installation of the tank (component) is unknown then the current applicable standard shall be considered to be the as built norm.

Where EN 14015 (European Union), BS 2654 (United Kingdom and Northern Ireland), DIN 4119 (Germany), Codres (France) etc. were valid in the past: Make use of the latest revision of EN 14015. Where API 12C⁽¹⁴⁾ or API 650 were valid in the past: Make use latest revision of API 650.

Available norm versions of BS2654:

This norm was withdrawn by the British Standard Institute upon publication of EN 14015:

- BS 2654, "Vertical mild steel welded storage tanks with butt-welded shells for the petroleum industry";
Part 1, Design and fabrication: 1956
Part 2, Erection: 1961
- BS 2654, "Vertical mild steel welded storage tanks with butt-welded shells for the petroleum industry";
Part 1, Design and fabrication: 1965
Amendment No. 1: November 1966
Amendment No. 2: May 1967
Amendment No. 3: April 1968
Amendment No. 4: January 1970
Part 3, Higher design stresses: 1967
- BS 2654: "Specification for vertical steel welded storage tanks with butt-welded shells for the petroleum industry": 1973;
Amendment No. 1: August 1975
- BS 2654, "Specification for manufacture of vertical steel welded non-refrigerated storage tanks with butt-welded shells for the petroleum industry": 1989;
Amendment No.1: 1997

The available norms for API 12C and API 650 are listed in Table 3.

Table 3 Available norm versions of API 12C and API 650

API Standard 12C All welded oil storage tanks		API Standard 650 Welded tanks for oil storage	
Edition	Date	Edition	Date
First	July 1936	First	December 1961
Second	October 1937	Supplement	1963
Supplement 1	April 1938	Second	April 1964
Supplement 2	September 1938	Third	July 1966
Supplement 3	April 1939	Supplement 1	December 1967
Third	April 1940	Fourth	June 1970
Fourth	March 1941	Supplement 1	April 1971
Fifth	May 1942	Fifth	July 1973
Sixth	August 1944	Supplement 1	October 1973
Seventh	August 1946	Supplement 2	April 1974
Supplement 1	September 1947	Supplement 3	March 1975
Eighth	September 1948	Sixth	April 1977
Supplement 1	December 1949	Revision 1	May 1978
Ninth	October 1950	Revision 2	December 1978
Tenth	September 1951	Revision 3	October 1979
Eleventh	September 1952	Seventh	November 1980
Supplement 1	September 1953	Revision 1	February 1984
Twelve	October 1954	Eighth	November 1988
Thirteenth	September 1955	Ninth	July 1993
Supplement 1	October 1956	Addendum 1	December 1994
Fourteenth	October 1957	Addendum 2	December 1995
Fifteenth	1958	Addendum 3	December 1996
		Addendum 4	December 1997
		Tenth	November 1998
		Addendum 1	March 2000
		Addendum 2	November 2001
		Addendum 3	August 2003
		Addendum 4	December 2005
		Eleventh	June 2007
		Addendum 1	November 2008
		Addendum 2	November 2009
		Addendum 3	August 2001 includes Errata 1 October 2001
		Twelfth	January 2013 includes Errata 1 July 2013

Note: Ordering information for past editions of API 12C and API 650 is available from INC Inc.

Fit-for-purpose analysis of storage tanks:

- Welding and repairs shall be executed in accordance with the materials used and the weld processes used during the original design and construction of the storage tank under consideration. When such Norms or Standards are not available nor known, use the latest editions of the EN 14015 and/or API 650, whichever is most appropriate;
- A FFP analysis should be assessed by using results of previous performed inspections. This Publication details in particular the requirements for routine in-service and out-of-service inspections as detailed in Appendices B2 to B4;
- In case a time based regime is used for the in-service and out-of service inspections, it is advised to use the table, provided in Appendix B.1 for determining the most appropriate intervals between these inspections. When inspection intervals are determined based on a risk assessment

approach the out-of-service inspection intervals may be set by that risk based inspection process. Note that, according to the theory provided in Chapter 17 of this Publication, this impacts upon the time intervals of the in-service inspections, provided in Table 20;

- Items that should be evaluated and addressed during a total Fit-for-Purpose analyses are detailed in Table 4.

5.2 Inspection

5.2.1 General

Storage tanks require inspection at regular intervals to ensure that signs of deterioration are detected at an early stage. Effective inspection identifies the need for remedial action to be taken before the deterioration progresses to the point where leakage or other failure occurs. Remedial action before leakage avoids environmental contamination and product loss, or even catastrophic failure, and reduces the chance of unnecessarily expensive repairs.

Typically, a storage tank is designed and operated such that it can remain in service for many years without being opened for internal inspection and maintenance. However, it is necessary that there is a scheme in place to review the inspection and operational history of the tank to assess whether there is a need for external inspection of the tank structure, surrounds and ancillaries, on a routine basis, at more frequent intervals.

Personnel concerned with tank operations often believe that leakage will occur before a failure, thus drawing attention to thinned areas of shell. However this sequence cannot be relied upon. There are many instances where catastrophic failure of an in-service tank has occurred without there being any prior leakage through the shell. The inspection process should therefore be capable of identifying the rare signs of potential total failure as well as the more likely corrosion that leads to leakage. The availability of a well maintained set of tank records (see Appendix A.1) is essential for the effectiveness of this process.

Table 4 Fitness for purpose analysis sheet

Item	Allowable		Max. measured		Conclusion
Planar tilt (mm)					
<i>Differential settlement:</i>					
between highest and lowest point (mm)					
between two adjacent points (mm)					
Edge settlement (deg)					
Radial bottom settlement (mm)					
Roof	t_{as-built}	t_{measured(ave)}	t_{measured(min)}	t_{allowable(ave)}	Conclusion
Plates (mm)					n.v.t.
Supporting structure					
Minimum calculated plate thickness under internal pressure (mm)					n.v.t.
Minimum calculated plate thickness under external pressure (mm)					OK
Top curb angle			A_{available}	A_{allowable(min)}	Conclusion
Section modulus (mm ²)					
Used profile for top curb angle	Min. profile required		Min. profile present		Conclusion
Dimensions top curb angle					
Shell	t_{as-built}	t_{measured(ave)}	t_{measured(min)}	t_{allowable(ave)}	Conclusion
course 1					
course 2					
course 3					
course 4					
course 5					
course 6					
course 7					
course 8					
course 9					
course 10					
Shell stability under wind and vacuum					
Shell stability under axial loads					
Bottom	t_{as-built}	t_{measured(ave)}	t_{measured(min)}	t_{allowable(ave)}	Conclusion
Membrane plates (mm)					
Annular plates (mm)					
Sump (mm)					
Shell to bottom weld		Z_{as-built}	Z_{measured(min)}	Z_{allowable(min)}	Conclusion
Leg length of weld (mm)					
		a_{as-built}	a_{measured(min)}	a_{allowable(min)}	Conclusion
Throat size of weld (mm)					
External edge of annular section	Allowable		Min. measured		Conclusion
Projection bottom wall connection	9.5mm (L) and 2.5mm (t)				
Frangibility in conformity with BS2654					
Frangibility in conformity to EN14015 App K					

Emergency relief capacity if frangibility is not available	Present	Calculated	Proposal	
Product name (Nm ³ /hr)				
Required capacity of normal operational relief vents	Present	Calculated	Proposal	
Pressure, for product name (Nm ³ /hr)				
Vacuum, for product name (Nm ³ /hr)				

Other tank components		
Anchorage bolts		
Shell nozzles		
Roof nozzles		
Internal piping		
External piping		

The total inspection scheme for a tank will typically depend on three main elements:

- Observations made by the operating personnel as they carry out their routine duties;
- Scheduled in-service inspection examinations made by the inspection engineer on an approximately annual frequency or at intervals as suggested in Table 20 of Appendix B.1;
- The out-of-service inspection when the tank is gas freed and cleaned for internal inspection and maintenance. This is carried out at much greater intervals, established either in accordance with the suggested periods outlined in Table 20, or as justified by a risk-based approach as explained in Chapter 17 of this Publication.

5.2.2 Operator observations

Operations personnel make frequent visits to the tanks under their control. They should be alert to any signs of deterioration or change to the tank or its surrounds, especially of leakage or indications of over- or under-pressure and of malfunction of ancillary equipment such as drains or roof ladders. Mal-operation, change of product or severe weather conditions can affect the ladder stability as shown in Figure 12. There should be a system in place for the operator to record these observations and to convey them to the inspection engineer for further evaluation.

Frequent, relatively brief observations will usually detect a rapid change of condition but are prone to miss slow changes. Furthermore, there may be unawareness that a condition which might be normal for other tanks might not be acceptable for the particular tank under its operational conditions. The effects of slowly changing conditions are more likely to be observed during a dedicated, detailed inspection examination.



Figure 12 Effects of mal-operation, product change or severe weather on ladder stability

5.2.3 Routine and detailed visual inspections

Appendix B2 (for in-service and out of service inspections) provide detailed inspection checklists for this activity.

Detailed visual inspection

1. Either ASME V⁽¹⁵⁾ or EN 13018⁽¹⁶⁾ should be applied for detail requirements in methods and procedures, and additional requirements specified herein.
2. These procedures contain methods and requirements for visual examination applicable. The visual examination involved in interpretation of the various non-destructive examination methods is not intended to be included in this article, since such visual examination is included with the procedures describing the particular non-destructive examination methods.
3. Visual examination is generally used to determine such things as the surface conditions of a part, alignment of mating surfaces, shape or evidence of leaking.
4. Direct visual testing may usually be made for local visual testing when access is sufficient to place the eye within 600mm of the surface to be tested and at an angle not less than 30° to the surface to be tested. Mirrors may be used to improve the angle vision, and aids such as magnifying lens may be used to assist examinations.
5. Direct visual testing may also be made at greater distances than 600mm specifically for general visual testing. A viewing distance appropriate to the test shall be used.
6. In some cases, remote visual examination may have to be substitute for direct examination. Remote visual examination may use visual aids such as mirrors, telescopes, borescopes, fibre optics, cameras or other suitable instruments (Remote visual testing).
7. All visual aids shall have a resolution capability at least equivalent to that obtainable by direct visual observation.

5.2.4 In-service inspection

External visual examination or in-service inspection of every tank and its surroundings should be made at regular intervals. Whatever the chosen frequency, which will depend on local conditions, it is important that inspection is carried out thoroughly and in accordance with the guidelines in this document. Frequent but cursory inspections serve little purpose, and can lead to a false sense of security.

A routine in-service inspection of a tank consists basically of a review of the tank's operational and inspection history followed by a walk round the tank bund and then the tank pad before climbing the tank stairs to view the roof. Inspections should usually be organised and led by the site inspection engineer, but there is benefit in personnel from the site maintenance and operations groups also being involved.

A combined approach to in-service inspection:

- means that there is less likelihood of any significant deterioration being overlooked;
- makes more people aware of the factors that can cause premature deterioration of the tank;
- encourages maintenance and operational practices that extend the service life of equipment.

During an in-service inspection, the tank and ancillaries are examined to detect any signs of deterioration or change since the previous inspection. Such inspections identify potential problems before they have a chance to become serious, and the consequential maintenance work carried out early will eliminate the need for more extensive work at a later date. Problems affecting safety items, such as blocked vents or drains, defective stairways, breached bund walls, etc. can also be detected. Any leakage from the tank shell or bottom should be noted and its significance evaluated. Changes in paint condition should also be noted and recorded.

The inspection should include an examination of the bund wall and all equipment within the bunded area of the tank under review. As well as the main structure of the tank, all connecting pipework, pumps, valves etc. should be examined. Means of access to the tank should be shown to be safe. The tank roof needs to be viewed, including roof seals, drains, pressure-vacuum devices, roof ladders, etc. The condition of shell and roof coatings should be assessed.

Because on many sites there are a large number of tanks to be inspected, the task is routine and can become tedious. To reduce the problems that may result from this, it is advisable that the in-service inspections follow a checklist thus giving greater assurance that all relevant features will be examined. A suggested checklist with explanations is included in Appendix B.1.

Dependent upon the visual condition of the tank and its inspection history, the routine inspection may be extended to include ultrasonic thickness measurements of the tank shell and acoustic emission examination of the tank floor. Both of these techniques can be applied to an in-service tank if suitable precautions are taken.

Measurement of ancillary pipework may also be carried out, and checks made on cathodic protection systems. There should be written confirmation that all instruments associated with the tank have been checked and are functioning as required.

Inspection techniques are also available for in-service inspection of annular plates, e.g. acoustic emission, long range ultrasonic measurement and eddy current technique. These techniques, however, do not measure actual thicknesses of bottom plates, but may be used to prioritise tanks. Refer to EEMUA 183 Chapter 5.

5.2.5 Out-of-service inspection

An out-of-service inspection is the prime means of confirming that a tank is fit for return to service for a projected period of time. It allows the condition of the tank and ancillaries to be assessed, measuring how they have performed under

service conditions since the previous major out-of-service inspection, and the work necessary to bring the tank back to good condition to be identified. It also allows prediction of the length of time the tank can remain in service before another major shutdown is required.

A major shutdown, when the tank is isolated, gas freed, and cleaned for inspection and maintenance, is a significant package of work for a site to carry out, and needs to be carefully scheduled to avoid undue interruption to operations, and unnecessary expenditure. Suggested intervals between out-of-service inspections of tanks in different services are given in Appendix B, Table 20.

The interval between inspections for any particular tank should take into account:

- relevant mandatory regulations;
- company and industry experience of the type of tank;
- the operating conditions of the tank; and
- the inspection and operating history of the tank.

When opened, gas freed, and cleaned, the tank can be entered and the shell, roof, floor, internal drains etc. inspected.

Viewing the interior shell and roof means that there is a much better opportunity to detect local deterioration than during an external examination. Great attention should be paid to detecting small patches or areas of deep corrosion or corrosion pitting of the shell, especially if it is in the form of vertical grooves that could subsequently extend to become a single groove.

The only time that the floor can be physically examined is when the tank is empty and clean. A visual examination should be supplemented by full floor scanning using a Magnetic Flux Leakage (MFL) or an eddy current followed up with manual ultrasonic testing device, both of which will give information concerning the underside of the floor. The once common practice of cutting floor plates, in order to assess the condition of the underside of the floor, is not carried out by many companies. It is considered that the newer inspection tools have rendered the technique obsolete, and that it presents a now unnecessary hazard.

A visual examination together with a MFL floor scan can confirm the validity of any diagnosis that has been made by an acoustic emission examination.

The observations made and the conclusions reached during an out-of-service inspection should be accurately recorded in a history file peculiar to the tank. This record will provide much of the information needed to determine the service time that defines the next major inspection.

The main elements of the out-of-service inspection are listed in Appendix B.2.

5.2.6 Safety considerations during inspection

There should be in place a set of written safety procedures that govern all activities that occur during all inspections. As well as being conversant with the safety precautions and rules common to any operational site, the inspection engineer needs to be particularly aware of the following points:

- Walking on tank roofs, either floating or cone, whilst the tank is in service is a hazardous undertaking, except where designs allow sampling and dipping from roof levels. The condition and thickness of the roof plates should be confirmed before anyone is permitted to walk on a tank roof. If there is any doubt about the condition of the roof, and if access to the roof is essential, then duckboards or other methods of spreading the load should be used;
- If access to an external floating roof is permitted by the company safety code, then the tank roof should be in the highest practicable position, preferably within 1.5m of the top of the shell. There should be no movement whilst people are on the roof;
- Any roof compartment should be considered as an enclosed space, gas tested accordingly, and only entered with suitable precautions;
- Access to an internal floating roof whilst the tank is in-service should only be considered under extreme circumstances, and will require breathing apparatus and lifelines, and dedicated rescue procedures. The delicate construction of the internal floating roof should be recognised at all times, and care taken not to penetrate the roof membrane;
- It should be realised that when a tank is opened for maintenance, gas can be released from sludge, scale and damaged floors for many days. If there are openings in the tank shell then gases can escape from the tank, and there may be a flammable mixture in the bunded area. This situation should be especially considered at the start of each day's work. The tank should be gas tested frequently whilst work is in progress. The frequency will depend on the condition of the tank, and should continue until the tank is clean and the condition of the floor is known.

5.3 Ultrasonic thickness measurements

5.3.1 General

Ultrasonic measurement is the most practical method of measuring the thickness of the shell of a tank and providing the data on which to base the calculations that show that the shell is fit for purpose. However, it must be appreciated that external ultrasonic measurement, as it is usually carried out, will not detect areas of isolated thinning and is not a substitute for the occasional internal inspection and measurement of the tank.

Instruments used for ultrasonic inspection should be of an acceptable standard⁽¹⁷⁾. The operators of the instruments should be certified as being of an approved standard. It is important that there is an approved procedure in place that describes how the inspection will be carried out and specifies the instruments, instrument settings, probes, couplants, access etc. that will be used.

Note: Ultrasonic measurement instruments are being improved continuously. Digital read out instruments give acceptable and accurate results if the surface is smooth and clean and the reverse surface not badly pitted. These conditions are often present on tanks in clean product service. If conditions are not good for measurement or if the plate is badly pitted then instruments that give a screen display are more accurate and should be used.

5.3.2 Phased Array Ultrasonic Testing (PA UT)

PA UT is an advanced method of ultrasonic testing that has applications in industrial non-destructive testing to find flaws in manufactured materials such as welds⁽¹⁸⁾.

Single-element UT probes, emit a beam in a fixed direction (fixed angle). In order to test or interrogate a large volume of material, a conventional probe must be physically scanned (moved or turned) to sweep the beam through the area of interest. In contrast, the beam from a phased array probe can be moved electronically, without moving the probe, and can be swept through a wide volume of material at high speed as seen in Figure 13.

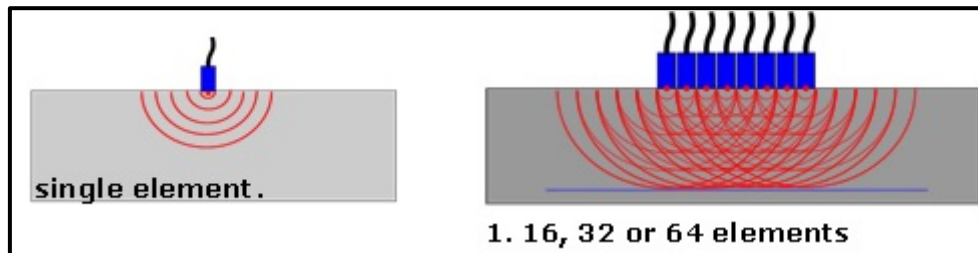


Figure 13 Comparison of a phased array probe with conventional UT

The PA probe consists of many small ultrasonic transducers each of which can be pulsed independently. By varying the timing, for instance by pulsing the elements one by one in sequence along a row, a pattern of constructive interference is set up that results in a beam at a set angle. In other words, the beam can be steered electronically. The beam is swept like a search-light through the plate or weld volume and the data from multiple beams are put together to make a visual image showing a slice through the object as in Figure 14.

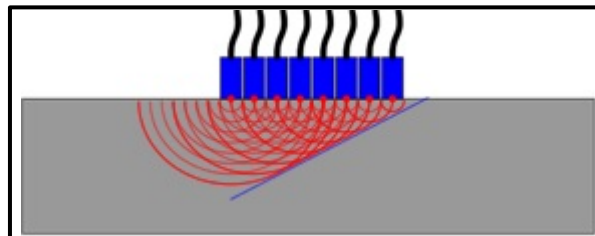


Figure 14 Detection of flaws using phased array UT

Due to the possibility to control parameters such as beam angle and focal distance, this method is very efficient regarding the defect detection and speed of testing.

Where radiography (X-ray) is particularly suitable for detection and identification of volumetric defects such as cavities, solid inclusions, and incomplete penetration where a gap exists, phased array flaw detection, being a semi- or fully automated ultrasonic inspection technique with increased reliability regarding planar defects, is highly suitable for the detection and sizing of more critical planar defects such as cracks, lack of fusion and tight incomplete penetration in ferritic steel. Use of phased array technique is the most appropriate alternative. As opposed to radiography ($T \geq 6 \text{ mm}$) because of advantages such as:

- Increased Possibility of Detection (PoD) for planar defects⁽¹⁹⁾;
- No use of ionizing radiation allows for day time shift works;
- No time lost for exposure, film development and evaluation; and
- No use of hazardous chemicals (X-ray films and development/rinsing liquids).

Apart from detecting weld flaws, phased array can also be used for plate thickness measurements in conjunction with corrosion testing. Phased array can be used for the following tank inspection & NDT purposes:

- Flaw detection and sizing of butt welded tank shell and tank floor (annular ring) welds (100% NDT in case of shell insert plates – in combination with Magnetic Particle Inspection (MPI) test for surface breaking defects);
- Thickness measurements (roof, shell, floor & nozzles);
- Corrosion inspection (supplementing MFL) soil side tank floor indications, enabling dead zone inspection in addition to MFL tank floor scanning); and
- In-service flaw detection in tank bottom-to-shell connection (indications of low cycle fatigue cracking, corner weld decay) provided double bottom-to-shell fillet weld have thorough weld penetration.

Characteristics of PA UT:

- Multiple probe elements produce a steerable, tightly focused, high-resolution beam;
- Produces an image that shows a slice through the object (C or T-scan, 3D imaging);
- International standards/code compliance (e.g. ISO 13588) limits use of PA to minimum plate thickness of 6 mm. Also, ISO 13588 is not applicable for coarse-grained metals and austenitic welds;
- Compared to conventional, single-element ultrasonic testing, PA instruments and probes are more complex and expensive;
- For validation & verification purposes calibration or reference blocks need to be manufactured;
- PA requires use of couplant (water or oil based between probe and testing surface, and has more limitations to surface roughness); and
- PA technicians require more experience and training than conventional UT technicians, therefore availability of staff & equipment may be an issue with local non-specialised NDT service providers.

5.3.3 Alternating Current Field Measurement (ACFM)

ACFM is an electromagnetic inspection technique that relies on the principle that an alternating current flowing in a component will be disturbed by the presence of a discontinuity (crack). The AC Field Measurement probe induces an electric current locally into the structure and measures the associated electromagnetic fields close to the surface. The presence of a defect disturbs the associated fields and the information is then converted to a graphical display on the computer for the system operator to analyze.

The "tips" of the defect are easily identified to provide information on defect location and length.

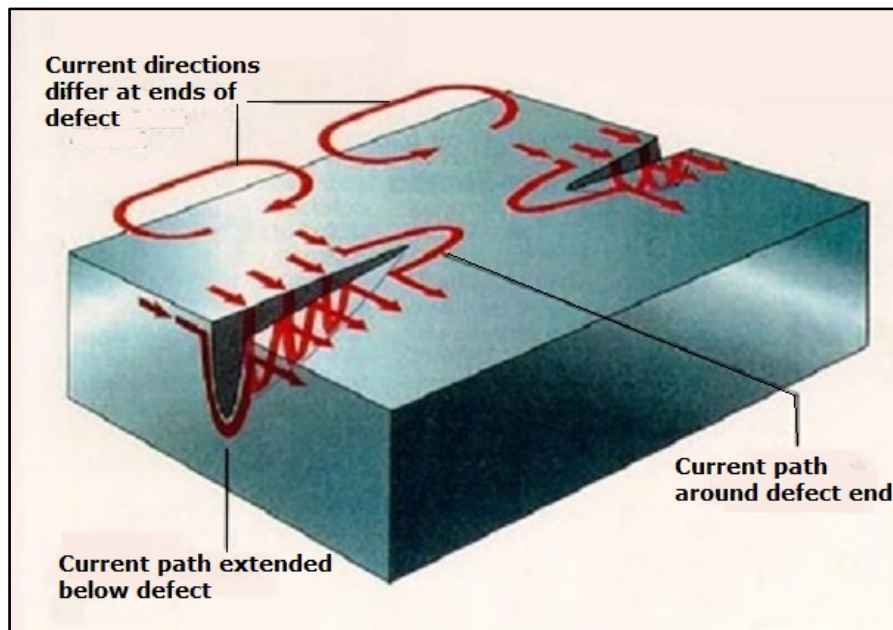


Figure 15 Detection of defects using ACFM

The significance of a defect in terms of structural integrity generally depends on the depth of the defect. Using mathematical modeling, the system also provides the actual through wall depth of the defect, thus allowing an immediate evaluation of the significance of individual indications.

This is a major advantage in comparison to other techniques utilized for the detection of surface breaking indications (like magnetic particle or dye penetrant testing) that are only capable of detection or at best, providing length information. ACFM systems have been used for a range of applications where rugged inspection systems are needed. The speed of scanning provides a rapid cost effective means of inspecting welded connections with reduced cleaning requirements compared to conventional techniques. The probes have been developed to minimize signals from features that are not cracks, i.e. corrosion, undercut, HAZ and material property changes, thus overcoming the problems often associated with other electromagnetic systems false calls.

As opposed to MPI and Dye Penetrant Testing (DPT), ACFM technique comes with reduced cleaning requirements, with no need to clean to bare metal. Also the

technique is capable of inspecting through thin metallic coatings or through non-conducting coatings up to 6mm thick, dependent on probe type used.

The ACFM technique can be used as a general alternative for magnetic particle or dye penetrant testing of welds (testing for surface breaking defects) with the advantage that coating does not need to be removed and no testing liquids or contrast paint are required. Furthermore full data storage for back-up, off-line view and audit purposes (cross check examination data) and imaging capabilities enable future reference.

Typical examples of ACFM applications on storage tanks are:

- Weld inspection tank floor lap welds (fillet welds);
- Weld inspection bottom-to-shell connection (internal);
- In-service inspection of bottom-to-shell connection (external);
- In-service inspection of shell nozzle welds; and/or
- In-service inspection of frangible roof joint.

Characteristics of ACFM include:

- Scanning speed is about 50mm per second;
- The examination surface should be free of loose scale, rust, or flaking paint to allow for a smooth probe travel. (coating layers well bonded to steel surface is no problem);
- The examination area shall be in un-magnetized state. Remnant magnetization from previous magnetic inspection methods (MPI or MFL) can produce false signals;
- Areas with grinding spots or local HAZ's, which produce changes in material properties can result in strong signals and may be confused with a defect signal and should be reported by the NDT operator;
- Scans should always be made along both weld toes with the probe travelling perpendicular to the weld. If the weld cap exceeds 15mm in width, the weld cap should also be covered;
- ACFM technicians require more experience and training than conventional eddy current technicians, therefore availability of staff & equipment may be an issue with local non-specialized NDT service providers.

5.3.4 Tank shell measurement

5.3.4.1 General

It is never acceptable to base tank corrosion rates and the integrity of a tank shell upon measurements taken from the external spiral stair case or ladder. Such random measurements of thicknesses can be very misleading and may lead to incomplete indications of the actual corrosion rate.

Various measurement techniques exist that use remotely operated crawlers to carry the measurement instrument up the side of the tank. These do not require any scaffolding, unless additional wind girders obstruct an upward movement of the crawler. If the surface condition is good and sufficient readings are taken, they give satisfactory results. All vehicles should be suitably tethered at all times while being deployed.

The use of rope access is common practice for shell thickness detection.

5.3.4.2 Areas to be examined

As indicated in Table 20 (see Appendix B.1) thickness measurement shall be taken on the tank shell of each different shell course. Generally the tank shell is measured from the outside and this method is acceptable to assess general metal loss in various areas of the shell. This provides useful information on the condition of the tank shell.

However, it is important to know that EEMUA considers the use of thickness measuring techniques for establishing two different modes of integrity. A shell plate has adequate structural integrity when the minimum thickness found is still adequate to take up all required normative loads. When such plates show pit corrosion (or pitting) even extending to small holes, the structural integrity of the steel plates may still be sufficient. However, the operational integrity is potentially compromised (loss of containment). For this reason EEMUA requires different inspections to be carried out for determining the fitness-for-purpose of a tank's shell when attacked by corrosion.

The extent of measurement required is suggested in the following procedure: EEMUA recommends the use of vertical scan lines, starting from a dedicated point (plant North or true North), along which thickness measurements are to be performed.

The number of vertical scan lines is to be established from the following Table 5:

Table 5 Number of vertical scan lines

Tank diameter D [m]	No of initial vertical scan lines
$D < 20$	4
$20 \leq D < 36$	8
$D > 36$	at intervals around the tank circumference not exceeding 15m from each other

At minimum vertical interval of 100mm thickness measurements are to be taken and the minimum thickness shall be recorded.

Tanks containing non-conductive products of which the conductivity is less than 50 pS/m (pico-Siemens/metre) may develop horizontal corrosion groove areas in horizontal shell welds near the HAZ of these welds (particularly when storing some Naphtha types or Ultra Low Sulphur Diesel (ULSD) and/or product not dosed with static dissipation additives when required to raise the conductivity above the mentioned level). In this case it is required to ultrasonically scan each shell course 150mm above and below the horizontal welds across the full width of 1m (0.5m west and 0.5m left of a scan line).

In case such automatic crawler machines may not be available in remote countries, EEMUA uses a statistical approach for determining thicknesses of tank shells when these tanks are in use. Also, here the scan lines shall be used but as a minimum – instead of taking measurement at intervals of each 100mm, it may be sufficient to take at least three measurements per scan line on each different

shell course. The number of locations to make these measurements should as a minimum be as per Appendix B.

If the tank shell surface is too rough to permit ultrasonic scanning, then the average depth of pitting should be determined using a pit-depth gauge. The tanks shell should then be carefully ground to no more than half pit-depth over an area of at least 50mm x 50mm. The shell thickness should then be measured by ultrasonic scanning at all ground locations.

Using the procedures described above and in Appendix B4 the measurements of shell plate thicknesses obtained need to be suitably adjusted for any additional metal loss due to pit corrosion and/or grooving to obtain an effective minimum plate thickness when such pits are not widely scattered.

5.3.5 Tank bottom measurement

Quantitative thickness measurements of shell bottom plates can only be performed when tanks are taken out of service. Table 20 indicates the maximum advised periods between tank outages for making these measurements.

Also, for this tank component different measurements are to be performed depending on the need to assess structural integrity (i.e. is the plate under consideration strong enough to taking up normative loads) or operational integrity (i.e. could the plate suffer from almost through thickness pits) of the tank bottom.

- Operational integrity

Operational integrity is best ensured whilst using the so called bottom scan techniques (Magnetic flux leaking technique and/or eddy current based techniques). EEMUA requires all bottom plates to be scanned by these techniques. 100% area coverage is, in most cases not achievable as overlaps of interconnecting welds between the bottom plates cannot be measured by these techniques. For further information reference is made to section 5 of EEMUA 183.

- Structural integrity

Structural integrity is best ensured in critical areas and along scan lines if plate thicknesses are measured by means of the ultrasonic technique. EEMUA requires the scan lines used for the shell measurement be connected to each other and to make thickness measurements on these scan lines at the following points:

- 1st measurement as close as possible near the welds between the tank shell and tank bottom;
- 2nd measurement 300mm away from the tank shell;
- 3rd measurement 750mm away from the tank shell; and
- Further measurements at intervals not exceeding 3m distance from each other.

In addition to these measurements the areas near the bottom/to shell connection should be checked by ultrasonic measurements at least at three locations per annular plate (see Figure 16 below). Measure also the thickness of the external section of the annular plates outside the tank shell.

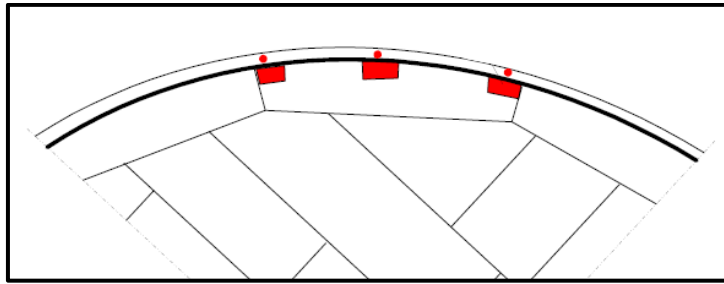


Figure 16 Locations for bottom to shell connection UT measurements

When external bottom corrosion is detected 100% scanning of a circumferential grid line just inside the shell-to-bottom fillet weld should be performed for that annular plate. If more corrosion is found, the area of scanning should be extended.

Include in the number of ultrasonic measurements the thickness measurements of components of (drain) sumps by the following example – Figure 17.

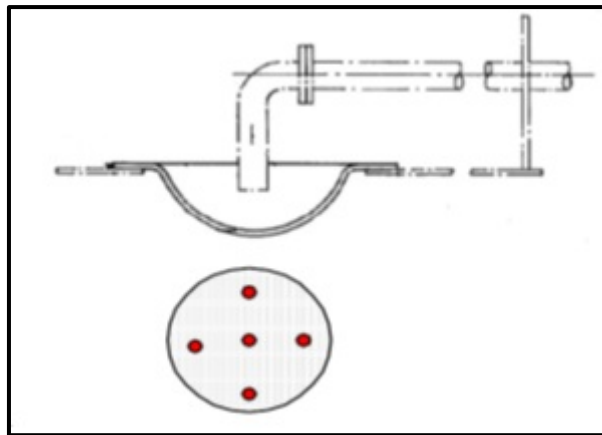


Figure 17 Ultrasonic measurements for drain sumps

5.3.6 Tank roof measurement

5.3.6.1 Fixed roofs

For this tank component different measurements are to be performed depending on the need to assess structural integrity (is the plate under consideration strong enough to taking up normative loads), operational integrity (could the plate suffer from almost through thickness pits), or does it even have perforations that allow the vapours to escape to atmosphere. Due to the requirement for personnel to check the functions of installed instruments on the roof (level, pressure, temperature indicators and/or a proper function of the pressure/vacuum relief vents etc.), or for any other required access to the roof, an additional integrity requirement to be checked is the safety integrity.

a) Operational integrity

Operational integrity is best ensured by using suitable NDT techniques.

b) Structural integrity

Structural integrity is best ensured in critical areas and along scan lines, when plate thicknesses are measured by means of the ultrasonic technique. EEMUA requires the scan lines used for the shell measurement to be connected to each other and to make thickness measurements of these scan lines at the following points:

- 1st measurement at a distance of 200mm away for the tank shell;
- 2nd measurement at 2/3 of the roof radius;
- 3rd measurement at 1/3 of roof radius;
- 4th measurement in the centre of the roof.

c) Personal safety

For safety reasons it may be required to perform thickness measurements on all areas where personnel will be working with heavy equipment. When crevice corrosion is anticipated between the roof plates and the roof supporting structure it may also be required to scan all areas of the roof plates where these supports are situated.

5.3.6.2 Floating roofs

EEUMA requires the plates of floating roofs to be examined in a similar way as fixed roofs on tanks as in Figure 18.

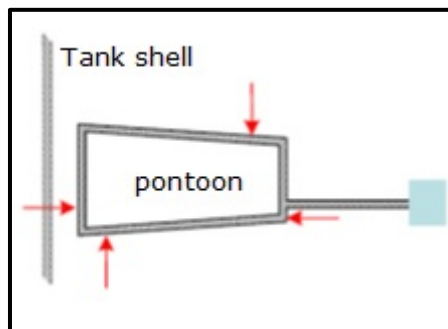


Figure 18 Areas to be scanned on the pontoon

For locations and techniques to be used, the articles above are described per integrity type.

However, additional locations may be required to be measured as the function of these roof components so dictate. This is based on the criticality of such components, where corrosion may be expected near the liquid level in the rim area or in the sleeves of the landing legs – see Figure 19.

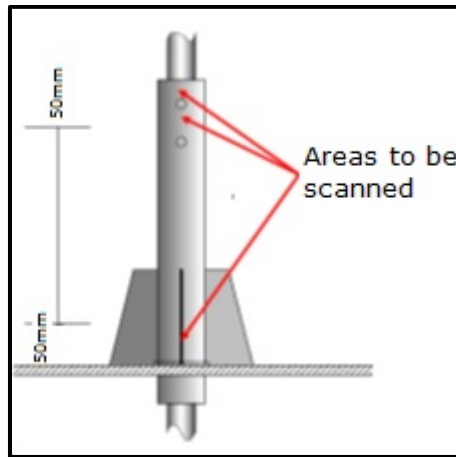


Figure 19 Areas to be scanned on landing legs

5.3.7 Measurement of nozzles and manhole neck plates

Ultrasonic thickness measurements of nozzles and manhole neck plates should be taken as close as possible to the reinforcing or shell plates at 12, 3, 6 and 9 o'clock positions as follows.

Tank Shell Nozzle Inspection

1. Carry out ultrasonic thickness measurements on tank nozzles up to the first flange. A minimum of 4 readings at 12:00, 03:00, 06:00 and 09:00 o'clock position around the nozzles shall be recorded as close as possible to the HAZ of the shell or reinforcement pad.
2. UT measurements will also include the reinforcement pad of the tank nozzles and manways.
3. Result of the thickness reading should be compared with the nominal wall thickness specified in the tank code applicable to the corresponding manhole/nozzle size.
4. Type (A-E) and dimensions of reinforcement to be measured as illustrated in Figure 20.
5. If excessive soil settlement has occurred, all pipe connections to the tank must be visually inspected for possible distortion.

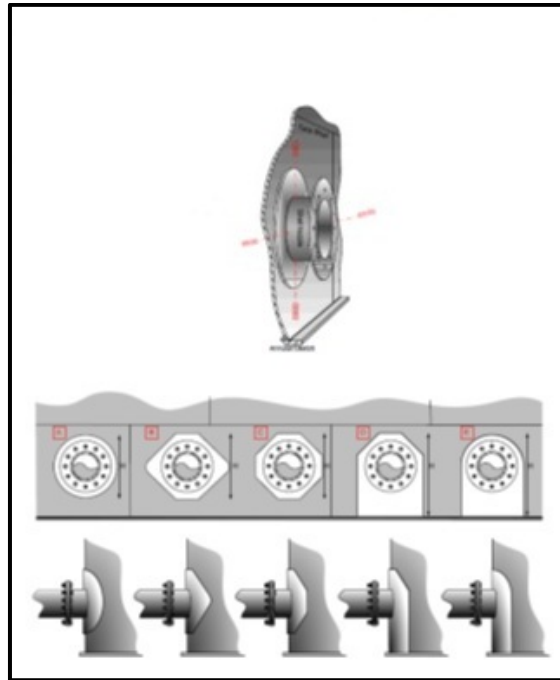


Figure 20 Dimensions of reinforcement to be measured

Tank roof nozzle inspection

1. Carry out ultrasonic thickness measurement on the roof nozzles up to the first flange. A minimum of 4 readings at 12:00, 03:00, 06:00 and 09:00 o'clock position around the nozzles (as close as possible to the roof plate) shall be recorded as close as possible to the HAZ of the roof plates (see Figure 21). Where 12:00 is pointed towards plant North.
2. UT measurements will also include the reinforcement pad of the tank nozzles and manways.
3. Result of thickness reading should be compared with the nominal wall thickness specified in the tank code applicable to the corresponding manhole/nozzle size.

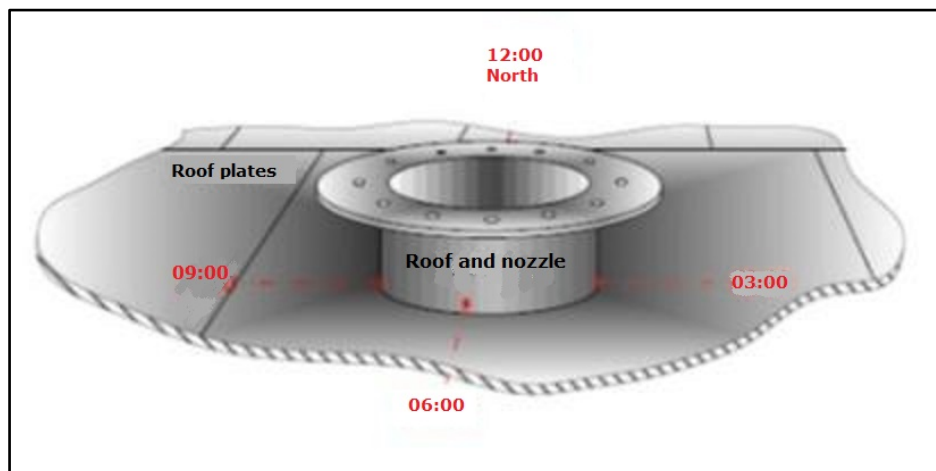


Figure 21 Positions for UT thickness measurements on roof nozzles

5.4 Evaluation of localised shell inspection data

Having recorded the plate thicknesses for all points gauged, the inspector should derive a representative minimum thickness for each shell course. Corrosion rates and remaining life can be calculated where constant operating conditions can be assumed.

Care should be taken regarding the effect of past and planned changes in operating conditions on the tank life. It is good practice to consider the whole of the shell course and not individual plates for corrosion rates, remaining life calculations, and repair requirements. The basis of this procedure is that it is impractical to inspect more than a small but significant area of a shell, therefore it has to be assumed that uninspected areas of a course will be in a similar condition or possibly slightly worse.

Locally corroded areas may be evaluated by averaging thickness in accordance with the following procedure (see Figure 22):

- (a) For each area, the inspector determines the minimum thickness $t_{\min \text{ measured}}$ at any point in the corroded area, excluding widely scattered pits.
- (b) The critical length, L , is then calculated from the formula:

$$L = 0.034\sqrt{(D \cdot t_{\min \text{ measured}})}$$

Where:

L = the maximum vertical length in metres, over which hoop stresses are assumed to 'average out' around local discontinuities.

Note: the actual vertical length of the corroded area may exceed L .

D = tank diameter in metres.

$T_{\min \text{ measured}}$ = the least thickness, in mm, in an area of corrosion, exclusive of pits. The value of $t_{\min \text{ measured}}$ is not to be less than 60% of $t_{\min}$ calculated in accordance with Section 8.3.

- (c) When $t_{\min \text{ measured}} < 60\%$ of $t_{\min}$ calculated as specified in Section 8.3 the method as described below cannot be followed and the structural integrity of the tank shell depends on that minimum measured thickness ($t_{\min \text{ measured}}$). The same would be valid in the very case where the outcome of the formula (b) gives a result of ' L ' > 1.0m. The use of an averaged thickness may not be considered and the minimum thickness ($t_{\min \text{ measured}}$) found, should be evaluated against the $t_{\min}$ calculated as specified in Section 8.3.
- (d) Only when the outcome of the formula (b) gives a result of ' L ' ≤ 1.0m, it may be assumed that the hoop stresses will, in fact, be 'averaged out' around the local discontinuities. The inspector then decides, by visual or other means, which vertical plane(s) in the area is likely to be the most affected by corrosion. Profile measurements are then taken along each (minimum number of 5) additional vertical grid line for a distance ' L '. In

the plane(s), the lowest average thickness, $t_{\min \text{ average}}$ is determined, using at least 100mm spaced measurements over length 'L'. The value of $t_{\min \text{ average}}$ should not be less than $t_{\min \text{ measured}}$.

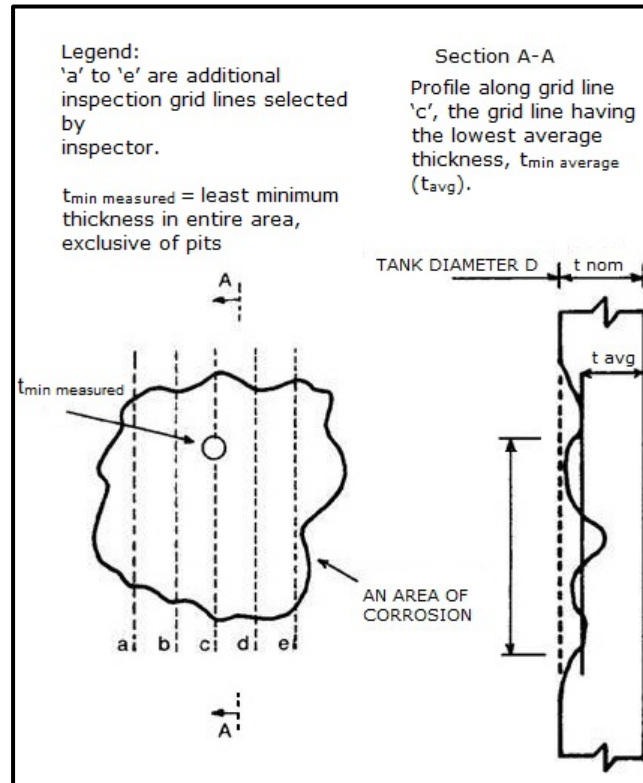


Figure 22 A typical area of corrosion

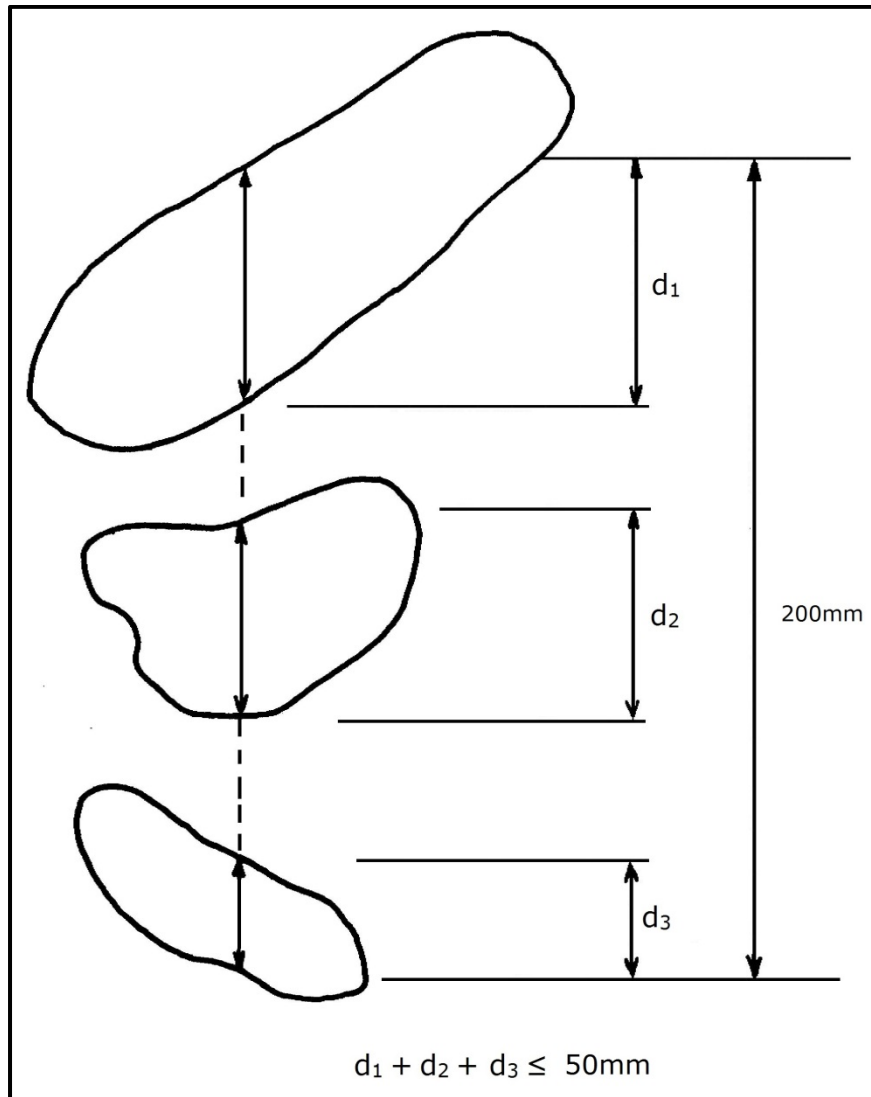


Figure 23 An example of a pitted area

Pitting does not normally represent a significant threat to the overall structural integrity of a shell unless present in a severe form with pits in close proximity to one another.

Widely scattered pits may be ignored provided that:

- i) no pit depth results in the remaining shell thickness being less than 50% of the minimum acceptable tank shell thickness exclusive of the corrosion allowance (i.e. 50% of t_{min} calculated in accordance with Section 8.3); and
- ii) the sum of their dimensions along any vertical line does not exceed 50mm in a 200mm length (see Figure 23).

Note: the above procedure to evaluate widely scattered pits in plate configurations is valid for bottoms, shells and roofs (fixed or floating) of all types of storage tanks.

6. Tank foundations

6.1 General

6.1.1 Introduction

Storage tanks are relatively unique structures, having very flexible envelopes such that the tank shell and bottom will generally follow the settlements of the subsoil. The dead weight of the tank structure is relatively small compared with the live load of the contents. Because of the flexibility of the tank structure, foundation settlements can be tolerated provided they stay within acceptable limits. Hence foundations are not generally piled, and cheaper, flexible foundations have been developed that are often sited on poor soils.

Because of the wide variety of surface, subsurface and climatic conditions at tank locations, it is not possible to prescribe a single type of foundation design. However it is common practice to build tanks on the following foundation types:

- Type A - 'traditional' (granular soil/sand) pad;
- Type B - sand pad with annular ring of coarse granular material;
- Type C - concrete ring wall;
- Type D - concrete raft under the entire tank;
- Type E - piled concrete raft.

For further information about these foundation types see EEMUA 183 Sections 2.1 – 2.5.

6.1.2 Failure modes of tank foundations

At locations where weak, compressible layers are present in the subsoil (e.g. clay, peat and silt), excessive soil settlements may occur due to the weight of the tank and its liquid content. Soil settlements may be even or uneven, depending on the possible variation in thickness of the soil layers and their location.

At locations where serious soil settlements are expected, subsoil improvements may be undertaken, such as pre-loading and soil replacement. Level measurements at the bottom-to-shell connection should be taken during the construction period of the tank, and made at prescribed intervals during the life of the tank. These latter measurements should be compared with those taken during construction to know whether they are reaching critical values.

Failure modes of foundations include:

- even soil settlements;
- uneven soil settlements;
- edge settlements;
- planar tilt; and
- follow-up failure mode from leakage through tank bottom.

Each of these failure modes are described in the sub-sections that follow.

6.2 Soil settlement

6.2.1 Settlement under loads

If a soil mass is compressed, its volume will be decreased in three different ways:

- elastic compression of the soil particles, such that when the load is removed the compressed volume recovers its original value;
- elastic compression of the pore water and air trapped between the soil particles that recover volume when the load is removed; and
- non-elastic escape of water and air to the surface.

In most soils the magnitude of the last effect, known as foundation consolidation, far outweighs the first two effects of compression, especially below ground water level where the pore spaces are assumed to be completely filled with water.

6.2.2 Consolidated settlement

Consolidated settlement of a tank foundation occurs very slowly over many years. Since it is permanent and non-elastic, the soil does not spring back when the tank is emptied and the live load of the content removed.

When excessive consolidated settlement is predicted for a new tank, foundation improvement is usually undertaken to limit the extent of settlement where this is practical. Special precautions have to be taken when new foundations are planned, that overlap existing consolidated foundations, or where there are rock outcrops under part of the foundation.

6.3 Effects of soil settlement

6.3.1 Even (uniform) settlement

Even (uniform) soil settlement is generally not dangerous because it occurs gradually and increases uniformly. In these cases it does not cause stress to the imposed tank structure when staying within acceptable limits. When it becomes excessive however, remedial action may be required. The extent of settlement should therefore be monitored and checked to avoid problems occurring during operation of the tank.

The following areas require special attention due to tank settlement:

- **Pipe connections:** Excessive even settlement may cause problems for the pipe connections at the tank shell. Pipe supports close to the shell may no longer be at the correct elevation. Alternatively, the pipe supports may settle faster than the tank on its foundation. Ultimately, such a difference in level may seriously overstress the pipe connection. Two solutions are possible:
 - the tank may be jacked up and the tank with its foundation re-levelled to its original position, bringing the connecting piping and its supports back into the original position;
 - the pipe supports may be adjusted to compensate for the higher or lower level of the tank nozzle.

- **Pipe connections with bellows:** Large storage tanks may have pipe connections provided with double bellows. These are provided to compensate for the outward movement of the shell under liquid loading and for any differences in level due to soil settlement. In this way, high loads on the shell are avoided.

During service, bellows should be checked at regular intervals to ensure that any deflections do not exceed their design limits.

The external surface of the convolutions (ribs) should be examined for signs of mechanical damage. Exceeding the ultimate tolerances of the bellows may cause their collapse resulting in serious product leakage.

6.3.2 Tank shell settlement into the foundation

A problem frequently experienced is that the edge of the tank bottom penetrates the tank foundation. This creates a trough in the tank pad shoulder around the tank shell. Rainwater running from the tank shell will collect in this trough and cause serious corrosion (see Figure 24).

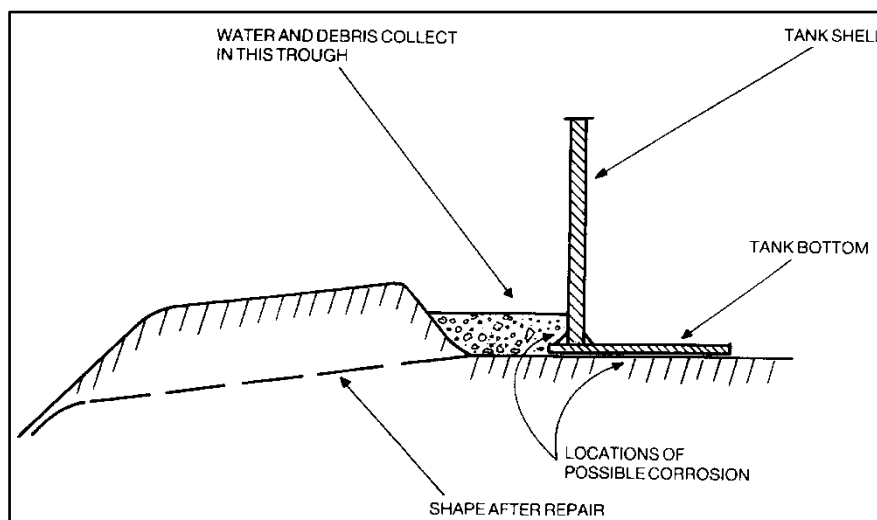


Figure 24 Tank shell settlement into the tank foundation

It is also possible for rainwater to penetrate under the bottom annular plates and initiate corrosion on the underside of the bottom plates.

6.3.3 Difference in soil settlement between centre and periphery of the tank

The even settlement at the centre of the bottom will often be up to 50% more than at the periphery under the shell. This is due to the vertical stress distribution in the foundation induced by the tank liquid load (see Figures 25 and 26).

This stress distribution is about 30% higher in the middle of the tank than at the edge.

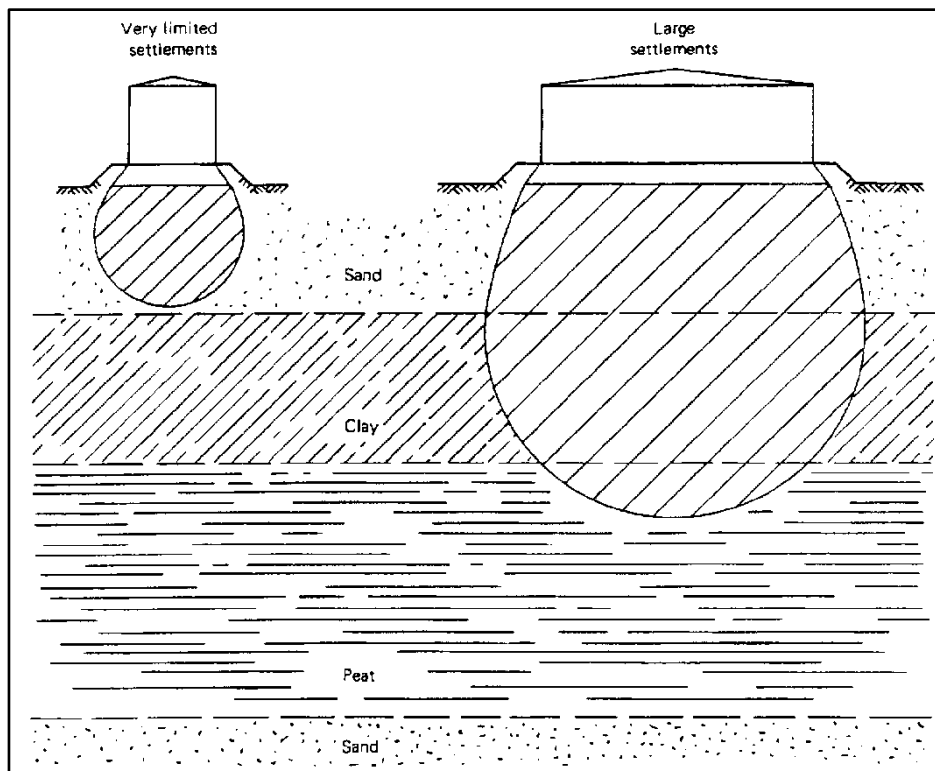


Figure 25 Typical effect of tank loads on soil settlements

The acceptance limits for this type of settlement are dependent on the size of the tank, and are related to some extent to the initial degree of cone-up or cone-down specified in the design of the tank bottom.

One purpose of cone-shaped bottoms is to control drainage. When large centre-to-edge settlements are predicted for a foundation for a large diameter tank, it is common practice to specify cone-up bottoms to minimise the stress in the bottom plate and the shell-to-bottom connection, by pre-setting of the deflection upwards. An upward cone of maximum slope of 1 in 120 is usually specified, with a maximum centre height of 300mm.

At some locations the increased cone-down settlement in the centre may be so serious that the bottom plates will be brought into contact with the ground water. This will cause corrosion at the underside of the bottom plates. This problem, which may be found during inspection, can be rectified by jacking up the tank and reshaping the foundation to its original level.

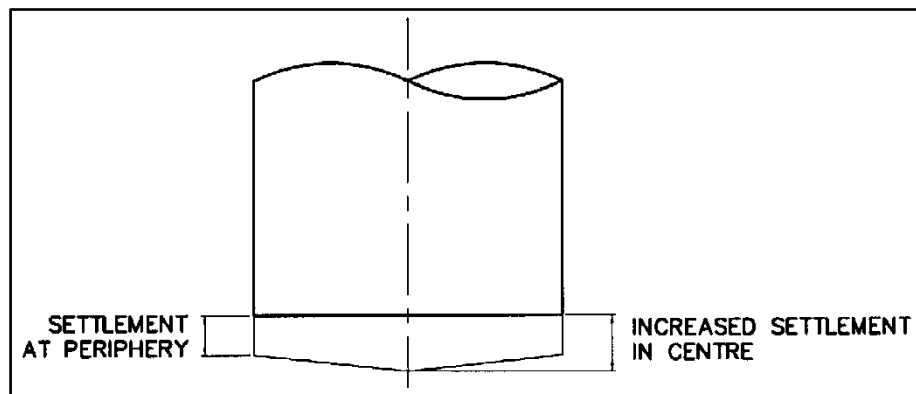


Figure 26 Difference in settlement between centre and periphery

As settlement occurs and the bottom approaches the flat condition, excess plate length across the diameter can give rise to long ripples in the centre plates. The excess material is accommodated by the formation of the ripples. These form predominantly parallel to the line of lap welds in the long direction of the bottom plates.

The ripple will act as a stiffening beam of the 'membrane type' bottom. This may cause local cracking in the lap welds resulting in leakage. (See Figures 27 and 28)

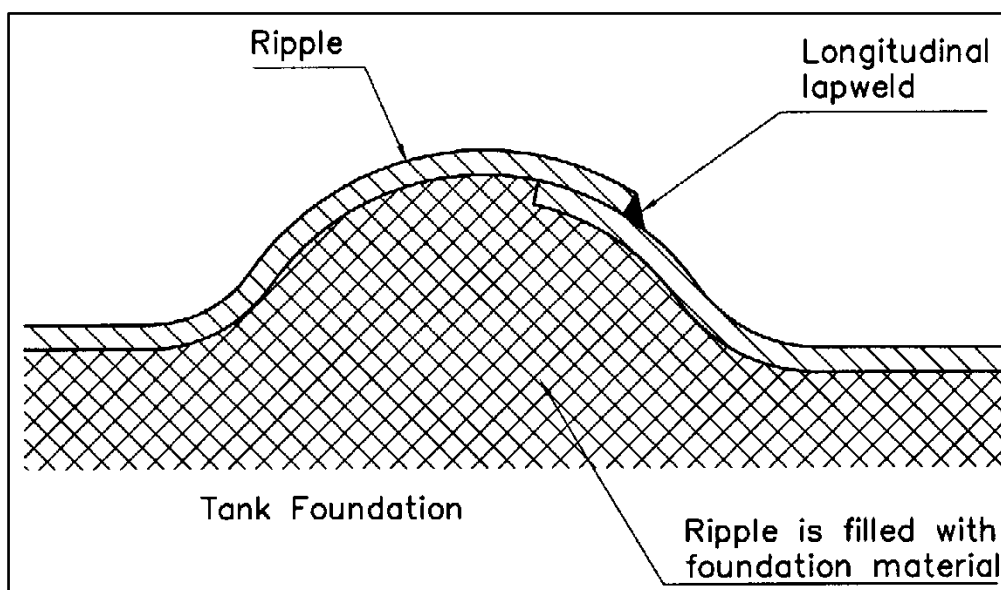


Figure 27 A ripple in a tank bottom

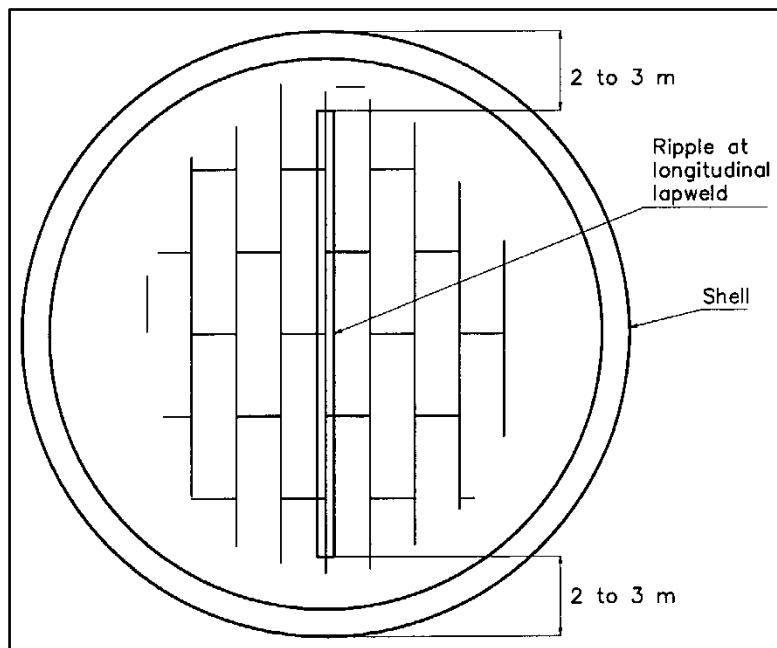


Figure 28 Typical location of a ripple in a tank bottom

6.3.4 Uneven settlement

Uneven soil settlements or localised differential settlements of a tank bottom at the periphery are of greater concern than depressions in the bottom at a distance from the shell. In the event of localised depressions away from the shell, the liquid loading causes the relatively flexible flat bottom plates to follow the uneven pattern of the soil settlement. However, near the shell its stiffness will cause the bottom plates to try to form a bridge over the area where local settlement occurs. The bottom plates at that location may therefore not be properly supported by the foundation, but may be suspended from the shell. This is an unfavourable condition for the shell-to-bottom connection and ultimately a rupture at the inner fillet weld may occur (See Figure 29).

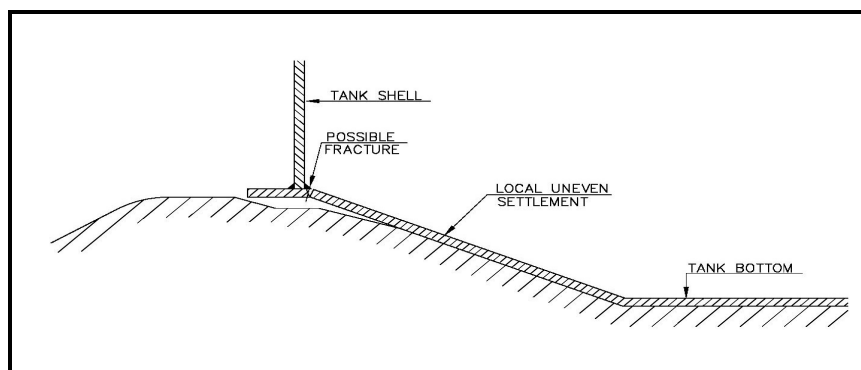


Figure 29 Local uneven settlement under the tank shell

Local uneven settlement under a tank shell should always be treated seriously. Uneven soil settlement should be rectified by local filling of the foundation at the low spots by means of partial jacking, or in serious cases by complete jacking-up and re-levelling of the tank foundation.

6.3.5 Edge settlement

Edge settlement occurs when the tank shell settles sharply around the periphery, resulting in deformation of the bottom plate near the shell-to-bottom junction (see Figure 30).

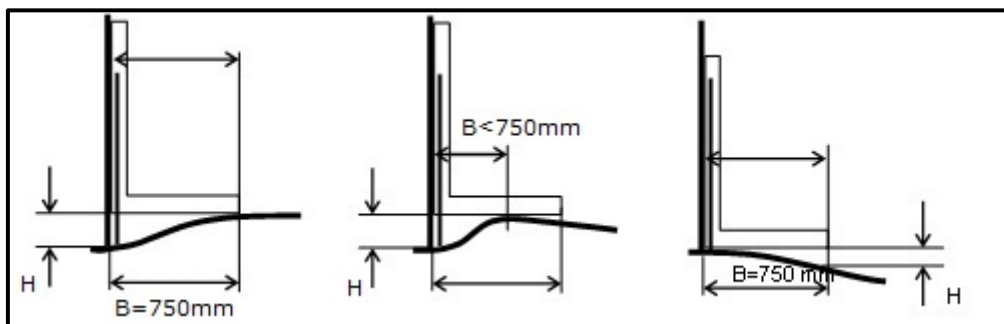


Figure 30 Edge settlement

Causes of edge settlement are:

- Shell penetrating into the foundation

This may occur, for example, due to insufficient compaction of the tank pad under the tank shell (see Figure 31). A ring of crushed stones under the shell instead of sand will considerably reduce this possibility.

Rainwater collecting in the depression around the shell will decrease the quality of the foundation under the shell and increase the possibility of edge settlement.

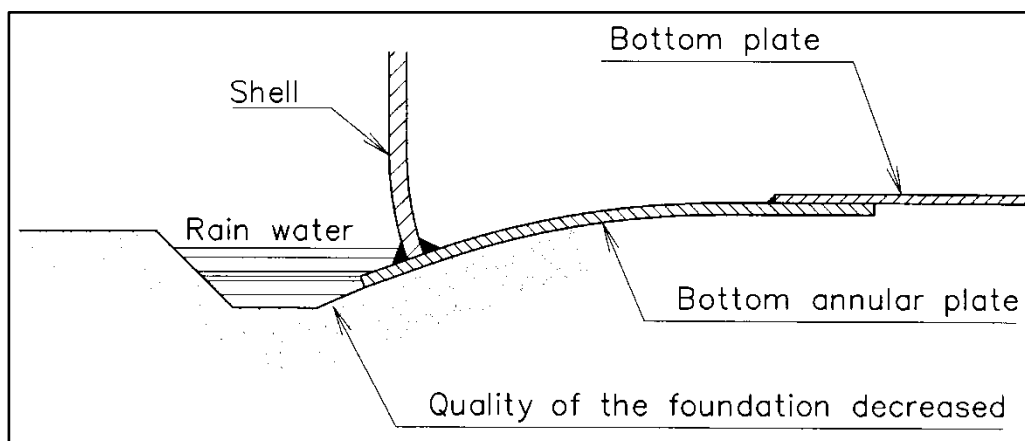


Figure 31 Edge settlement due to penetration of the shell into the foundation

- Tank pad shoulder with insufficient width or poor construction quality

When the shoulder of a tank pad is not wide enough, and particularly when the tank pad is placed high above grade level, the shoulder may slip away when the tank is fully loaded. This will result in serious edge settlement (see Figure 32).

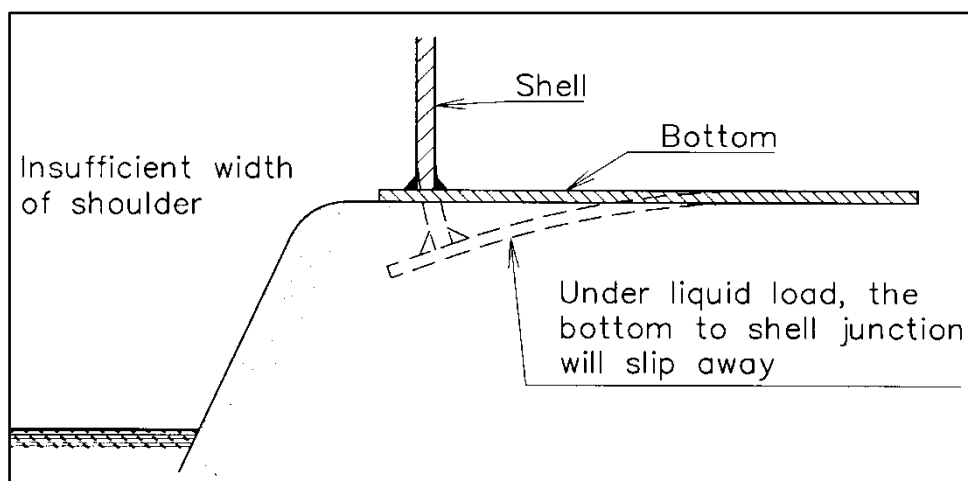


Figure 32 Insufficient width of tank pad shoulder

- Tank pad shoulder damage or erosion by rain and wind

The shoulders of tank pads should be well maintained to prevent damage or erosion by rain or wind, particularly rain flowing down from the tank which can penetrate into the foundation materials of the tank pad. When the waterproof top cover of the shoulder is damaged, serious settlement may occur (see Figure 33).

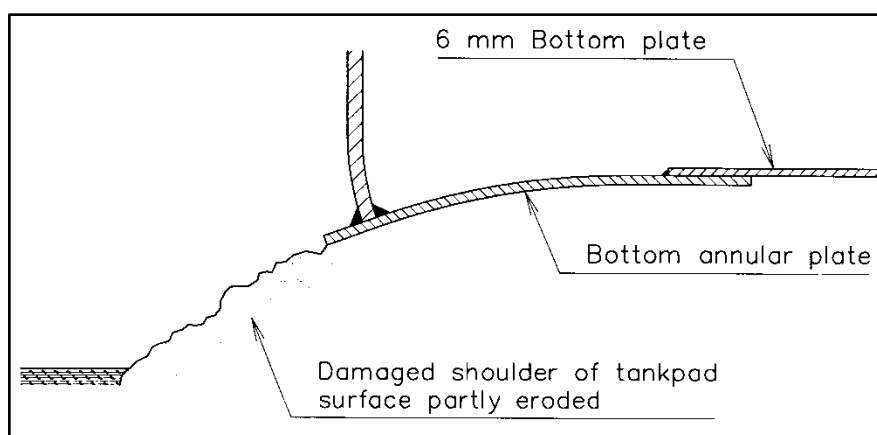


Figure 33 Edge settlement due to a damaged or eroded tank pad shoulder

6.3.6 Planar tilt

Planar tilt of a tank is the situation where the tank leans over to one side without local, uneven settlements (see Figure 34). It will only slightly increase the stresses in the tank shell. The problems associated with tilting are therefore almost the same as for even soil settlements.

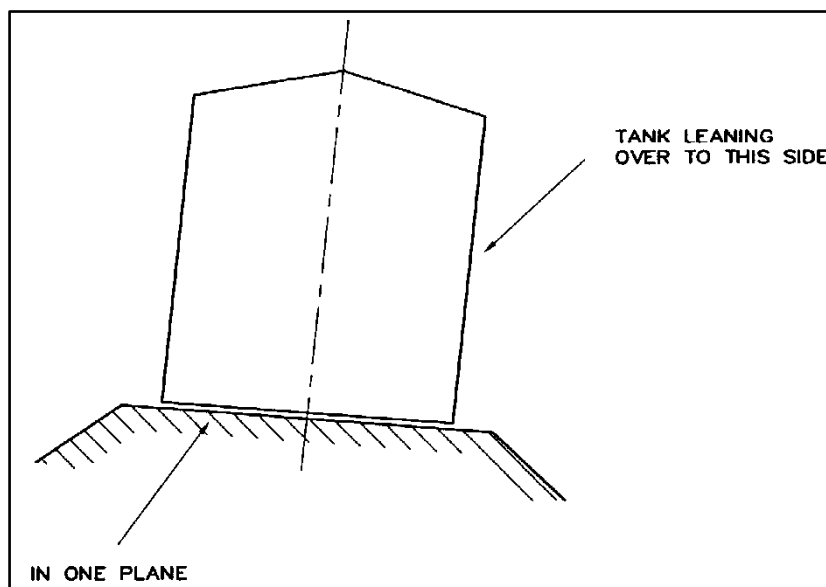


Figure 34 Tilting of a tank

6.3.7 Differential shell settlement around circumference

Differential shell settlement around the circumference of a tank generally occurs when the shell is not founded properly by a well-constructed crushed rock ring within the annular area of the foundation, or when the soil is not uniform. The consequences of differential shell settlement are generally not too serious for a fixed roof tank, but can cause significant out-of-roundness, which might be not acceptable for internal floating covers within these tanks or for external floating roof tanks.

The out-of-roundness can cause floating roof-cover seal gaps and possible roof-deck malfunction, such as holding up, jamming, excessive emissions of product vapours through the seal gap, and sometimes even roof sinking.

An in-service settlement survey should be carried out preferably with the tank full, or nearly full, taking elevation readings at each survey point around the circumference. Survey points should be clearly marked along the bottom edge, otherwise permanent settlement measuring lugs may be welded to the bottom edge. The minimum number of survey points should be diameter D in metres divided by 3.05 (or $D/10$ where D is in feet), but should not be fewer than 8. Spacing between the survey points should not exceed a circumferential distance of 10 m.

For floating roof tanks it is recommended that verticality readings be taken at the same survey points used for level readings (compare 5.3.2).

A graphical representation of differential shell settlement is shown in Figure 37. The figure shows the plane of rigid tilt represented by the optimum (i.e. best fit) cosine curve, with the actual differential settlement plotted at, in this instance, 24 points around the circumference. The difference between the optimum cosine curve and the actual settlement are evaluated against acceptable limits. These settlements may be correlated with the degree of out-of-roundness arising for internal or external floating roofs/decks.

6.3.8 Evaluation and measurements for shell out of roundness

Tank shell flexibility involves both inward and outward radial deformation which may be induced by:

- Local differential settlements along the circumference;
- Tilting of the tank; or
- Localised overstressing of connecting piping.

The first two of these are a result of foundations movement which need regular monitoring as in Table 20 when the tank is in service.

If displacement leads to excessive levels, gaps between the roof and shell will occur.

Measurement of the annular rim space is often completed and then plotted in plan view. Additional data is sometimes taken in order to obtain better plots. However, it is important to understand that users often assume that the floating roof is perfectly circular and has not drifted.

Previous measurements to determine out of roundness have included the use of a plumb line from the top of the shell and measuring the deviation vertically from equal points around the tank.

A self-adjusting laser can be used in the detection of out of roundness. A survey can be taken to the outside of the tank shell.

6.3.8.1 Seal design

For tanks experiencing excessive out of roundness, modern seal design may be installed to accommodate larger radial displacement. This may be a temporary or even a permanent solution. Re-levelling the shell using pre-determined evaluations by computer tools has also been successful. One or both actions may provide the best solution

6.4 Leakage

If external inspection reveals leakage from the tank bottom, it is an indication that product is penetrating into the foundation and possibly also into the subsoil. This may create a serious condition for the safety of the tank and at the same time cause soil pollution. When small leakages are observed, a temporary solution may be to operate the tank with a water bottom, provided that the specific weight of the product in the tank is less than that of water. When a significant leakage is found, the tank should be taken out of service and emptied as soon as practicable to enable a thorough internal inspection.

Leakage close to the periphery of the tank shell should be considered as a very serious problem requiring urgent attention. It should therefore be remedied immediately as the leak may cause a local washout of the tank foundation under the shell.

A washout will cause loss of support for the bottom plates and may result in a rupture at the inner fillet weld of the bottom-to-shell connection or the bottom lap

welds. This would cause a sudden complete discharge of the tank contents into the tank bund area. As it is impossible to predict the probability of a washout occurring, corrective action should always be taken as soon as possible.

The possibility of a rupture increases when the tank is filled to a high level.

6.5 Maximum tolerances and limits for settlement and out-of-verticality of tank shell

As atmospheric storage tanks are relatively flexible, they will generally follow the settlements of the subsoil and the foundation. Because of the flexibility of the structure, settlements are acceptable as long as they remain within certain limits. Excessive settlement may induce stresses in the tank floor and shell that can eventually lead to rupture, jamming of a floating roof or otherwise affect the integrity of the storage tank. The following paragraphs describe the different settlement criteria that are to be assessed and evaluated.

6.5.1 Planar tilt/out-of-verticality

The out-of-verticality, also known as the planar tilt, is limited to a certain maximum. Figure 35 gives the result of the allowable planar tilt, based on the h/d ratio of a storage tank.

Where:

h = tank shell height

d = tank diameter

The maximum planar tilt can now be assessed by multiplying the found allowable percentage of out-of-verticality (from Figure 35) by the tank shell height.

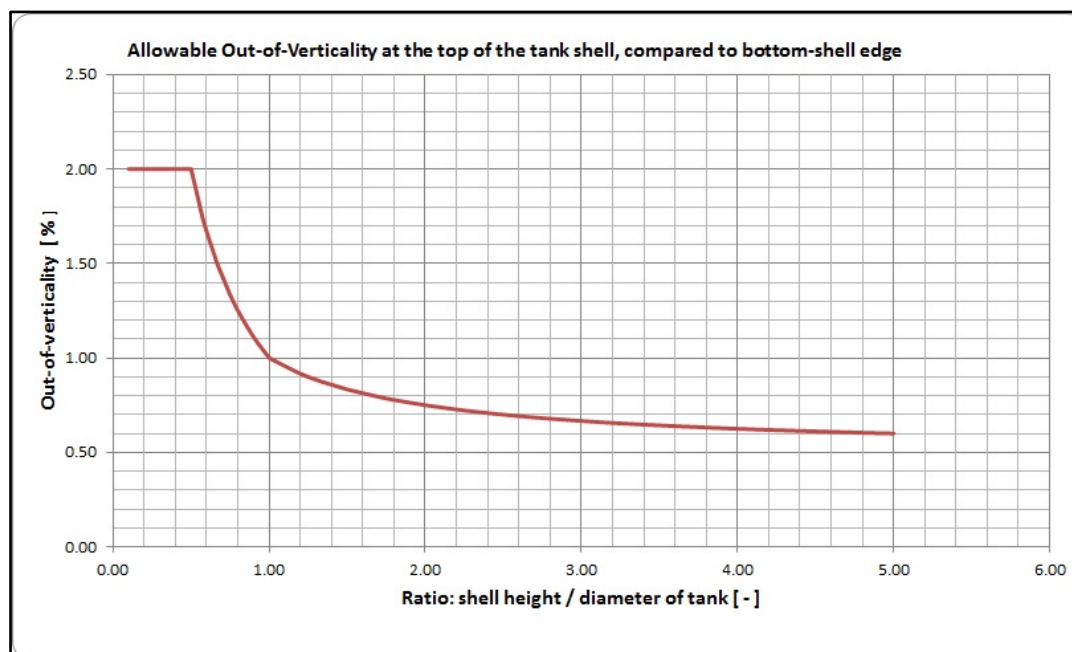


Figure 35 Planar tilt

Example 1:

$h = 18.5 \text{ m}$

$d = 25 \text{ m}$

ratio $h/d = 0.74$

From figure 35 the allowable out-of-verticality is assessed to be: 1.40%

Maximum allowable out-of verticality at the top of the tank shell compared to the bottom to shell edge: $H * 1.4\% = 0.259 \text{ m (259 mm)}$

Example 2:

$h = 16.5 \text{ m}$

$d = 9.05 \text{ m}$

ratio $h/d = 1.823$

From figure 35 the allowable out-of-verticality is assessed to be: 0.78%

Maximum allowable out-of verticality at the top of the tank shell compared to the bottom to shell edge: $h * 0.78\% = 0.129 \text{ m (129 mm)}$

However, the established allowable out-of-verticality of the tank shell, derived by this method, does not take into account the material strength of the shell, the product specific gravity, nor the maximum operational liquid/product level in the tank. It is, therefore, advised to use the above method only as a first general (rule of thumb) assessment and to perform a more in-depth and sophisticated investigation when results of out-of-verticality measurements are nearing the rejection limits, specified by the above method.

Palmer⁽²⁰⁾ developed a method that deals with planar tilt and the compressive and shear stresses induced in the shell as a component of the loads due to tilt. The method presupposes that the compressive stress is a function of; tank height and diameter, product density, roof and shell loadings, product maximum working level, shell thickness and material strength.

The method assumes that the tank floor is fully supported throughout, such that only planar tilt can be experienced by the tank/base, i.e. a concrete pad base, and that the method does not apply to non-planar tilt

The aim of the method is to calculate the total axial (compressive) stress and the total shear stress which can then be compared with the maximum allowable values.

The remainder of Section 6.5.1 describes first the equations needed to calculate the maximum allowable values. Next, the method for working out the actual values is presented. Finally, a worked example is outlined to help clarify Palmer's method.

Maximum allowable values

The maximum allowable compressive stress is a function of Youngs Modulus, shell thickness and tank radius namely,

$$S_a = \frac{C * t}{R} \quad \text{where } C = 12411 * \frac{E}{210000}$$

Where:

- S_a = allowable axial compressive stress in shell plates in **N/mm²**
- t = thickness of the lowest shell course in **mm**
- R = radius of tank in **mm**
- C = constant
- E = Youngs Modulus in **N/mm²**

When considering tanks using normal carbon steel at temperatures below 100 °C or stainless steel at temperatures below 50 °C, Youngs Modulus can be taken to equal 210000 N/mm², which simplifies the formula for S_a to,

$$S_a = \frac{12411 * t}{R}$$

The maximum allowable shear stress can be calculated by the following formula,

$$S_v = 0.487 * E * \left(\frac{R}{H}\right)^{0.5} * \left(\frac{t}{R}\right)^{1.25}$$

Where:

- S_v = allowable shear stress at the base of the tank in **N/mm²**
- E = Young's modulus in **N/mm²**
- R = radius of tank in **mm**
- H = height of tank shell in **mm**
- t = thickness of lowest shell course in **mm**

Calculating actual values

When considering planar tilt, the calculated total compressive stress (s_a) must take into account both the static and tilt induced components, whereas the total shear stress (s_v) can be considered as negligible other than in cases of extreme tilt, and therefore the formula only addresses the tilt induced component.

As stated s_a is the summation of the static (Sⁿ) and tilt induced (S^t) axial stresses which can be determined by the following formula,

$$S^n = \frac{W_{total}}{\pi * D * t}$$

$$S^t = \frac{M_{total}}{\pi * D * t * 2}$$

Where:

- W_{total} = total load (not including tank contents) in **N**
- D = diameter of the tank in **mm**
- t = thickness of the lowest shell course in **mm**
- M_{total} = total moment (includes the effect of the contents) in **Nm**

Note: the exact make up of W_{total} and M_{total} will depend on the specific tank in question, but as shown in the following example, W_{total} usually accounts for the load of the shell, the roof and the anticipated snow load. Furthermore, M_{total} takes into account the tank moment, the snow moment and the contents moment.

The shear stress (s_v) due to tilt is calculated by the formula,

$$s_v = \frac{2 * Q}{\pi * D * t}$$

Where:

Q = the shear force in **N**

D = diameter of the tank in **mm**

t = thickness of the lowest shell course in **mm**

and the shear force (Q) can be calculated by,

$$Q = (W_{total} + W_{contents}) * \sin(\theta)$$

given that,

$$W_{contents} = \frac{g\pi D^2 H \rho_p}{4 \times 10^9}$$

Where:

W_{total} = total load (i.e. shell load + roof load+ snow load) in **N**

$W_{contents}$ = load of the contents in **N**

θ = tilt angle in **Degrees**

g = **9.81 m/s²**

D = diameter of the tank in **mm**

H = height of tank shell in **mm**

ρ_p = product density in **kg/m³**

Note: the value of $\tan(\theta)$ can be closely approximated by using the same angle in Radians, which for the purposes of the following example is notated as ϕ .

Worked example calculation

The following worked example relies on a number of assumptions and parameters about the tank being assessed.

Tank Diameter (m)	D	20
Tank Height (m)	H	30
Youngs Modulus N/mm ²	E	210000
Steel Density kg/m ³	ρ_s	8000
Tilt Angle of 1 in 200 (Degrees)	θ	0.285
Tilt Angle (radians)	ϕ	0.004974
Gravity (m/s ²)	g	9.81
Product density kg/M3	ρ_p	1000

Assuming each different course is of a height 2.5 m, the tank is a, so called, "non pressure" tank (i.e. maximum vapour pressure is 7.5 mbar), the minimum specified yield strength of the shell plates $Y = 235 \text{ N/mm}^2$, the joint efficiency factor $E = 1.0$ (tank was constructed after 1968) and a product level of 100% of

the shell height, BS 2654 allows us to calculate the shell weight as per the table below:

liquid level each shell course	[m]	Shell Course	calculated shell course thickness [mm]	as built thickness [mm]	weight of each course [kg]	weight of each course [kN]
hu1	27.5	t1	17.05	17.1	21488.54	210.80
hu2	25	t2	15.49	15.5	19477.92	191.08
hu3	22.5	t3	13.93	14	17592.96	172.59
hu4	20	t4	12.36	12.4	15582.34	152.86
hu5	17.5	t5	10.80	10.8	13571.71	133.14
hu6	15	t6	9.24	9.3	11686.75	114.65
hu7	12.5	t7	7.68	7.7	9676.13	94.92
hu8	10	t8	6.11	6.2	7791.17	76.43
hu9	7.5	t9	4.55	6.0	7539.84	73.97
hu10	5	t10	2.99	6.0	7539.84	73.97
hu11	2.5	t11	1.42	6.0	7539.84	73.97
					total weight [kN]	1368.4

Note the as built thickness of the lowest shell course is 17.1 mm. In reality a tank of this size would need some form of internal structure (wind girders) which would add to the total weight. As a "non pressure" tank, a maximum vacuum value of 2.5 mbar should be taken into account, and according to Section 7.3.2.6 of BS 2654, a value of 2.5 mbar should be added to the pre-set value of the vacuum. The maximum calculated vacuum of 5 mbar should then be used to assess the required number and weight of the wind girders. The normal 3 second wind gust velocity of 45m/s is assumed to be valid. The required number and profile of the wind girders as well as their weight is assessed below:

Shell Course	He
t1	0.182
t2	0.233
t3	0.301
t4	0.407
t5	0.575
t6	0.836
t7	1.340
t8	2.303
t9	2.500
t10	2.500
t11	2.500
HE	13.677
K	9.39
HP	9.260
n	1
Profile	100*65*8
weight of profile [kg]	663.5
weight of profile [kN]	6.5

Total axial (compressive) stress (s_a)

In order to calculate S^n and S^t (and therefore s_a) the values of W_{total} and M_{total} must first be found.

From the given information, the shell weight is the addition of the weight of each course and the weight of the profile:

$$W_{shell} = \Sigma \text{Weight of each course} + \text{weight of profile} = 1374.9 \text{ kN}$$

The roof weight can be estimated from Table 1 so for a 20m diameter tank with a cone roof with beam rafters as supporting structure:-

$$W_{roof} = 23153 \text{ Kg} * 9.81 = 227.13 \text{ kN}$$

According to BS 2654 the load that is to be taken into account working on the horizontal projected area of the roof is a superimposed load of 1.2 kN/m^2 . This superimposed load combines (snow load + internal vacuum) or (live load + internal vacuum), whichever is the greatest.

For the given tank dimensions, the snow load to be taken into account would, therefore, be:

$$W_{snow} = \pi \frac{D^2}{4 \times 10^6} (1.2 \times 10^3) = 377 \text{ kN}$$

Where:

D = the diameter of the tank in **mm**

We can therefore now work out both the total load and as a result the axial stress due to normal static loading:

$$W_{total} = W_{shell} + W_{roof} + W_{snow} = 1979.02 \text{ kN}$$

$$S^n = \frac{W_{total}}{\pi * D * t} = 1.84 \text{ N/mm}^2$$

When calculating the total moment, the impact of the tank's contents must be taken into account. Given the previously stated assumption of a contents level equal to 100% of the shell height, we calculate the weight of contents as,

$$W_{contents} = \frac{9.81 \pi D^2 H \rho_p}{4 \times 10^9} = 92457.071 \text{ kN}$$

The moment can simply be calculated for the $W_{contents}$ as well as for W_{total} by multiplying by the height of the tank (in **meters**) and the tan of the angle of tilt (or approximated by the tilt angle in radians),

$$\text{Contents moment } M_c = W_{contents} H \phi = 13796444.13 \text{ Nm}$$

$$\text{Tank Moment } M_t = W_{total} H \phi = 295309.36 \text{ Nm}$$

$$\text{Total Moment } M_{total} = M_c + M_t = 14091.753 \text{ kNm}$$

The axial stress due to tank tilt can therefore be calculated as

$$S^t = \frac{M_{\text{total}}}{(\pi * D * t * 2)} = 6.56 \text{ N/mm}^2$$

Finally that gives us,

$$s_a = S^n + S^t = 1.84 + 6.56 = 8.4 \text{ N/mm}^2$$

Total shear stress (s_v)

The total shear stress only takes into the account the shear force (Q) under tilt conditions as the static component is considered as negligible.

$$Q = (W_{\text{total}} + W_{\text{contents}}) * \phi = 469725.1 \text{ N}$$

from which we can calculate the total shear stress (s_v)

$$S_v = \frac{2 * 469725}{\pi * D * t} = 0.87 \text{ N/mm}^2$$

Comparison with maximum allowable values

For the given tank details, the maximum allowable axial stress is worked out as

$$S_a = \frac{12411 * (17.1)}{10000} = 21.22 \text{ N/mm}^2$$

which compared to the calculated value s_a of 8.4, indicates a,

$$\text{Unity check} = 21.22 / 8.4 = 2.5$$

Similarly, for the given tank details the maximum allowable shear stress is worked out as

$$S_v = 0.487 * E * \left(\frac{10000}{30000}\right)^{0.5} * \left(\frac{17.1}{10000}\right)^{1.25} = 20.53 \text{ N/mm}^2$$

which compared to the calculated value s_v of 0.87, indicates a,

$$\text{Unity check} = 20.53 / 0.87 = 23.6$$

6.5.2 Edge Settlement

The vertical height of the edge settlement (H) is limited to 125mm, providing the maximum distance measured away from the tank shell internally shall not exceed 750mm – see Figure 30 reproduced below as Figure 36.

Max. edge settlement: $H = 125 \text{ mm}$

Where:

H Vertical height of the edge settlement (mm)

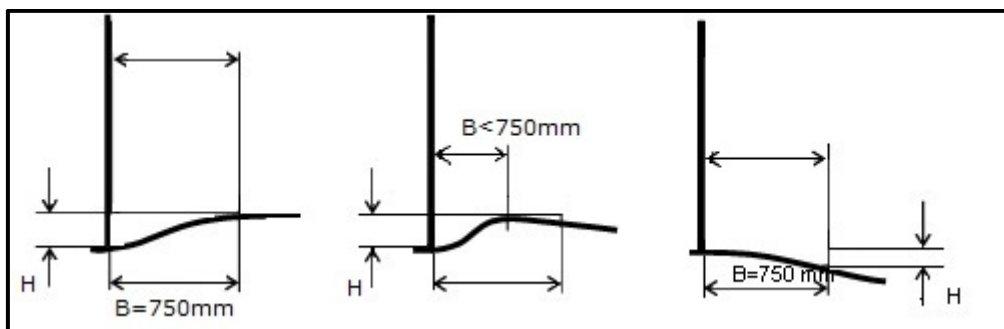


Figure 36 Edge settlement

The ratio between H and B should not exceed 1/6.

$$\text{Max. edge settlement ratio: } \frac{H}{B} = \frac{125}{750} \text{ or } 0.1667$$

Where:

H Vertical height of the edge settlement (mm)

B inward distance of settled area with a maximum of 750mm (mm)

6.5.3 Differential settlement

Since a storage tank is not completely rigid, the settlement of the circumference will never be in one plane, but will normally show some kind of sinusoidal curve.

In the case where the summit of the mound of the edge settlement (see the middle sketch in Figure 36) lies at a shorter distance inwards of the tank shell than 750mm (dimension B), this shorter dimension should be used to assess the maximum allowed difference in height between the summit of the edge settlement and the inner corner weld of the bottom-to-shell connection, i.e. when the summit lies at a distance of 550mm inwards of the shell, the maximum allowed difference in height is then:

$$B = \frac{550}{750} * 125 = 91.7 \text{ mm}$$

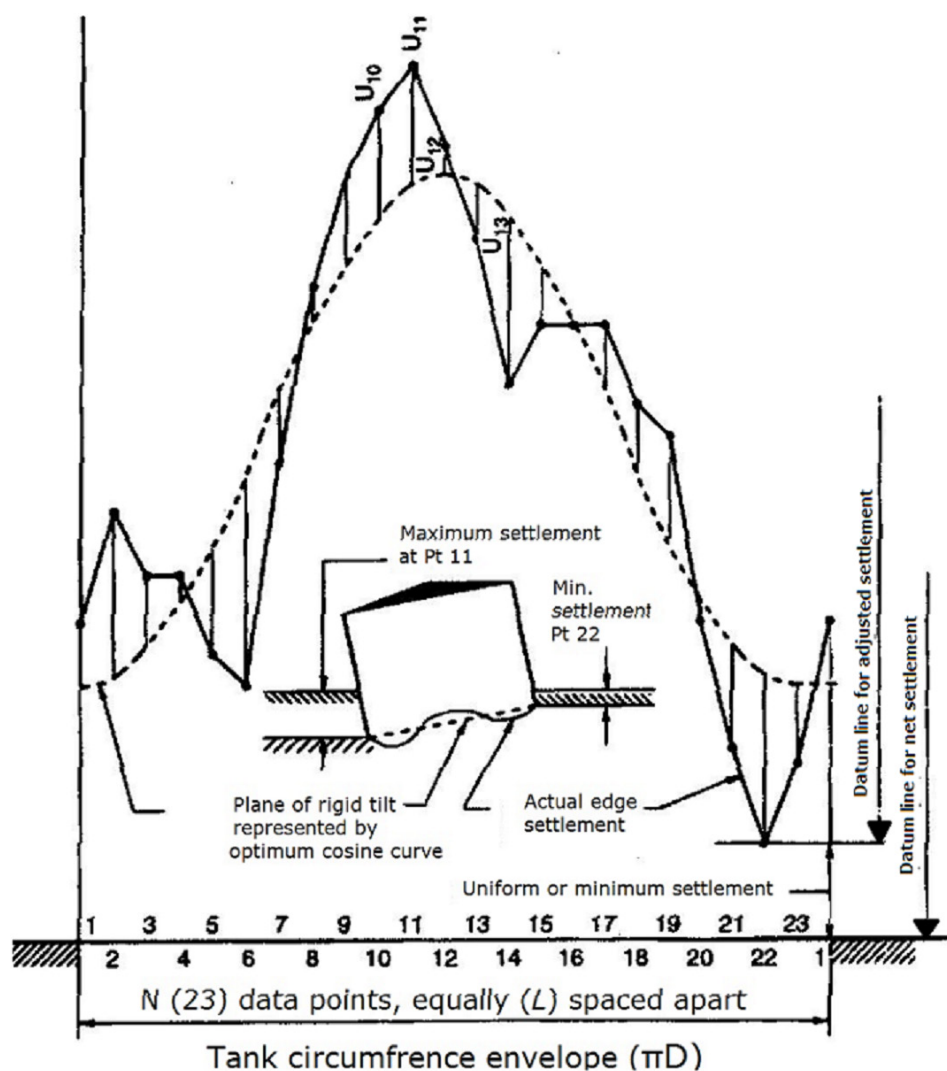


Figure 37 Differential settlement

The maximum vertical height difference because of differential settlement between any two adjacent points at 10m intervals around the circumference of the tank shell, shall not exceed 100mm or 1% of the arc length.

When determining the maximum differential settlement between any two points around the circumference of the tank shell (the highest and the lowest points) a distinction is made between fixed roof tanks and floating roof tanks.

a) Fixed roof tanks and floating roof tanks with -X/+3X rim seal (see Appendix D3)

In the maximum differential settlement calculations for tanks with a fixed roof without an internal floating cover, tanks with a fixed roof equipped with an internal floating cover with a rim seal satisfying the criteria of Appendix D.3 and floating roof tanks equipped with a rim seal satisfying the criteria of Appendix D.3 (the -X/+3X working range criterion) need to be calculated as follows.

The maximum differential settlement between any two points around the circumference of the tank shell is as shown in Figure 38.

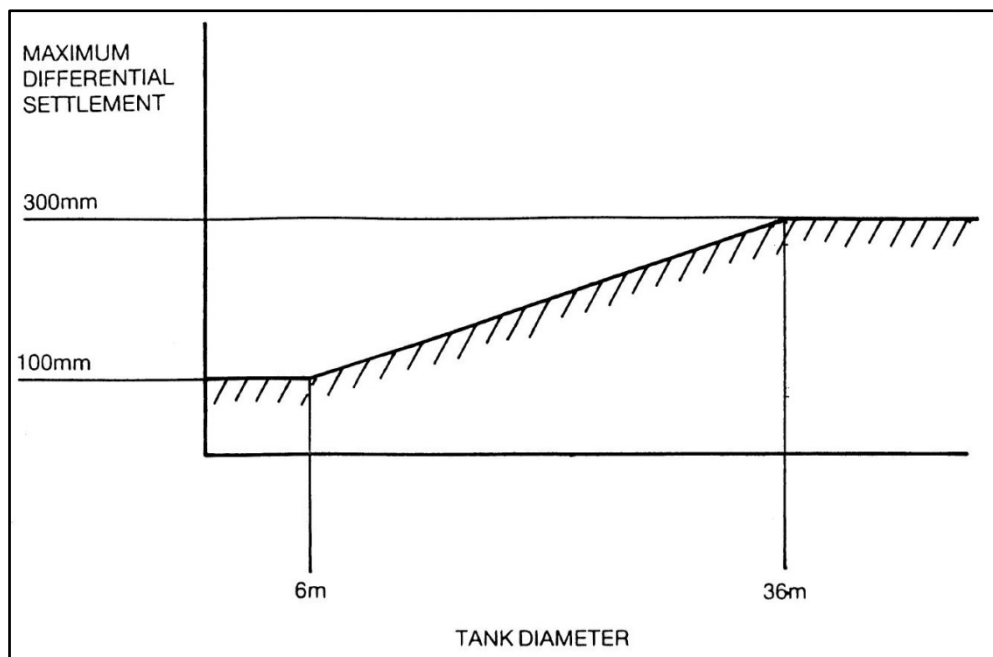


Figure 38 Differential settlement fixed roof tank

For tanks with diameters ≤ 6 m: 100mm

For tanks with diameters ≥ 36 m: 300mm

For tanks with intermediate diameters between 6 and 36 m: The maximum allowed difference in height should not exceed the value derived from the formula:

In formula:

$$\text{Max. differential settlement: } S_{\max} = \frac{(D - 6)}{(36 - 6)} \cdot (300 - 100) + 100$$

Where:

S Maximum differential settlement (mm)

D Tank diameter [m]

b) Floating roof tanks with -X/+X rim seal

The differential settlement calculation for tanks with a floating roof with a -X/+X seal and fixed roof tanks with an internal floating cover and a diameter of more than 40 metres will need to be calculated as follows:

The maximum differential settlement between any two points around the circumference of the tank shell is calculated using the formula below.

$$\text{Max. differential settlement: } S = \frac{11000 \cdot Y \cdot L^2}{2 \cdot (E \cdot H)}$$

Where:

S Maximum differential settlement (mm)

Y Minimum specified Yield strength of the bottom (annular) plate [N/mm²] with a maximum of 240N/mm²

- L Arc length between two adjacent measurement points [m]
 E Young's modulus [N/mm²]
 H Tank shell height [m]

6.5.4 Sagging/centre-to-edge bottom settlement

As indicated in Figure 39 it is quite common for a tank to settle into a dished shape due to settlement. This will result in stretching of the bottom plates and will induce biaxial tensile stresses in the bottom plates. These stresses are generally not very high, unless the sagging becomes excessive. The fillet welds forming the lap joint will normally be the limiting factor. Furthermore, excessive sagging causes the bottom-to-shell connection to be pulled inwards. This phenomenon can cause buckling of the tank shell.

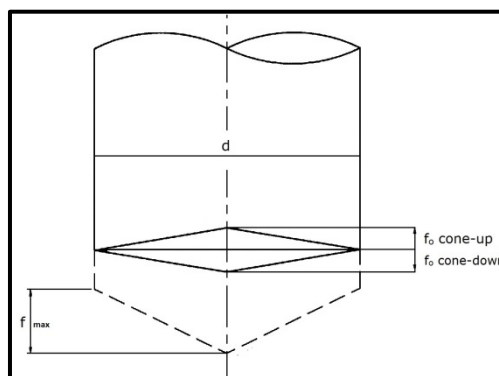


Figure 39 Sagging

The maximum allowed difference in height between the centre of the tank bottom and the elevation of the floor plates near the tank shell should not exceed the value f_{max} derived from the formula:

$$f_{max} = \frac{d}{100} * \sqrt{\left(\frac{f_o * 100}{D}\right)^2 + 3280 * \frac{Y}{E}}$$

Where:

- d diameter of dish in floor (this could be less than the diameter of the tank where the identified dished section in the floor exists (mm))
 D Tank diameter (mm)
 f_o the original as-built difference in height of the floor between the tank centre and the floor near the tank shell, with a maximum of 300mm
 Y minimum specified Yield strength of the floor plate material with a maximum of 240 N/mm²
 E Young's modulus of the floor plate material at operating temperature (N/mm²)

6.5.5 Bottom ripples

When a tank is built with a cone-up bottom, and centre-to-edge bottom settlement causes the bottom to approach the flat condition, excess plate length across the diameter gives rise to the creation of long ripples in the centre plates (see Section 6.3.3).

These ripples are acceptable provided the aspect ratio of height to width of the ripple is not greater than 75:500 (mm:mm), i.e. 0.15 (see Figure 40) and they do not form a severe crease (ridge) over any of their length.

In the event of ripples being unacceptable, they need to be cut out and the floor replated in the area of the ripples.

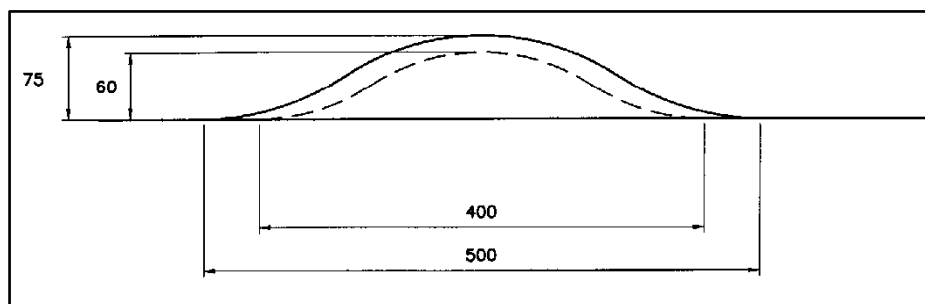


Figure 40 Maximum ripple aspect ratio

Example: The allowable height of a 400mm wide ripple is $0.15 \times 400 = 60\text{mm}$.

6.6 Re-levelling of tank foundations

When settlements have reached their maximum limits, re-levelling of the foundations and the tank will be necessary. In some areas sub-soils are weak and re-levelling may be necessary on a periodic basis.

Re-levelling is frequently done by raising the tank with hydraulic jacks placed around its periphery at equal distances of approximately 6 metres.

The tank is jacked up to a level of 2 to 2.5 metres above the foundation to provide sufficient space under the tank for the repair of the tank foundations (see Figure 41).

Jacking has been successfully carried out on tanks up to 120 000 m³ capacity with diameters up to 80 metres. The jacking of such large tanks requires a contractor with specialised experience.

Methods for tank jacking are described in Appendix C.1.

A water test should be carried out to check the quality of the repaired foundation and to ensure that the tank is free from leaks. The water test may also reduce stress peaks which may have been caused by the jacking and re-levelling (see Chapter 15).



Figure 41 A 36 metre diameter tank jacked up 2.5 metres above the foundation

6.7 Tank lifting operations

The purpose of lifting tanks is to allow remedial works to be carried out either to the foundation of the tank, the storage tank itself or in some cases relocation. The work may include either partial or complete reconstruction of the foundation and/or to install a membrane for secondary containment. Other reasons might be to replace the floor plates and/or annular plates or to raise the tank to insert a new or partial course of shell plates. Tank lifting is also carried out during the construction phase of tanks to restrict the need to work at heights by working at ground level and jacking up completed courses.

Tank lifting is therefore an essential part of maintaining integrity of storage tanks and their associated foundations and a means by which under floor membranes can be installed to meet local Regulatory requirements for secondary containment.

Tank lifting operations (see Appendix C1) need to be performed safely and without damage to the tank. Appropriate management systems should be in place for effective planning and execution. The following areas need to be considered.

6.7.1 Preliminaries

The areas listed below indicate the preliminary considerations when performing tank lifting operations:

- The tank operator and Tank lifting contractor must agree the method statement and risk assessment prior to any works commencing on site;
- Ground conditions are critical to the lifting operation and should be surveyed to ensure the ground can accommodate the lifting jack loadings;
- Calculations need to be performed for the lifting operation and need to accommodate both vertical static loadings and wind loadings and allow for elements of redundancy in terms of the number of jacks and spacing between jacking points. Consideration should also be given to the effect of suction between ground and tank bottom;
- Depending on the risk assessment and the method of jacking secondary supporting structures (for safety) independent to the lifting jacks should be considered once the tank has been lifted;
- The level of redundancy in the number of jacks and the available loading of each jack coupled with ability to lock the jacks mechanically. This greatly reduces the need to provide secondary supports which may inhibit the ease of constructing civil bases and installing membranes. The lifting attachments and associated fixings welded to the tank shell should be designed appropriately to accommodate jack loading. NDE should be performed to identify adequate thickness and laminations in the shell material;
- NDE on the lifting bracket welds should be performed to identify surface breaking defects.

6.7.2 Tank lifting

- Tanks are successfully lifted with the floor in place, and with the floor removed. If the floor needs to be removed, as a minimum, the annular plates should remain intact to retain the shell stability and the tank roundness. However, where this is not practicable, then adequate steel bracing should be welded around the lower shell to maintain shape before the old floor is removed. This brace must remain in position until the shell is welded onto the floor;
- When lifting a larger tank with the floor intact, the weight of the floor and imposed loads can cause shell distortion and tank floor deflection. For this reason it is common practise to minimise this bending loading by bracing the floor plates to the roof structure to alleviate any floor sagging. This measure must be subject to roof structure calculations;
- The stress and strain imposed on floor welds due to tank lifting operations. It should be recognised that floor plates not only exert a static loading but also a bending force on the lower shell, the floor plates themselves and associated welds. This problem is greatly reduced for small tanks but still exists;

6.7.3 Wind loading

- Wind loading calculations using data from EN 14015 take into account different levels of exposure and gust loadings and these should be included as part of the jack loading calculations;
- When it is anticipated that wind conditions are likely to approach or exceed those assumed levels in the above calculations, consideration should be given

to lowering the tank to ground level for the duration of the event or attaching suitable guy ropes;

- Consideration should also be given to lowering the tank, if practicable, during long periods of inactivity. However, due to the time constraints and working patterns, it may not be practical to lower the tank on every occasion;
- For tanks exposed to potentially high winds approaching those levels used in the lifting calculations and the anticipation of such events, it is normal practice to lower the tank to ground level for this period.

6.7.4 Safety measures against wind damage

The following list indicates suitable safety measures to prevent wind damage:

- Never leave an uncompleted shell course at the end of the day;
- Guy off the tank during windy weather and when leaving over-night. Tirfors are effective, being connected to the shell by cleats or clamps and into the ground, anchor bars or concrete blocks. See Figure 42;
- Tank erection staging can form a temporary wind girder (overlap and tie boards);
- Temporary steel angle wind girders stitch welded to the tank resisting buckling.

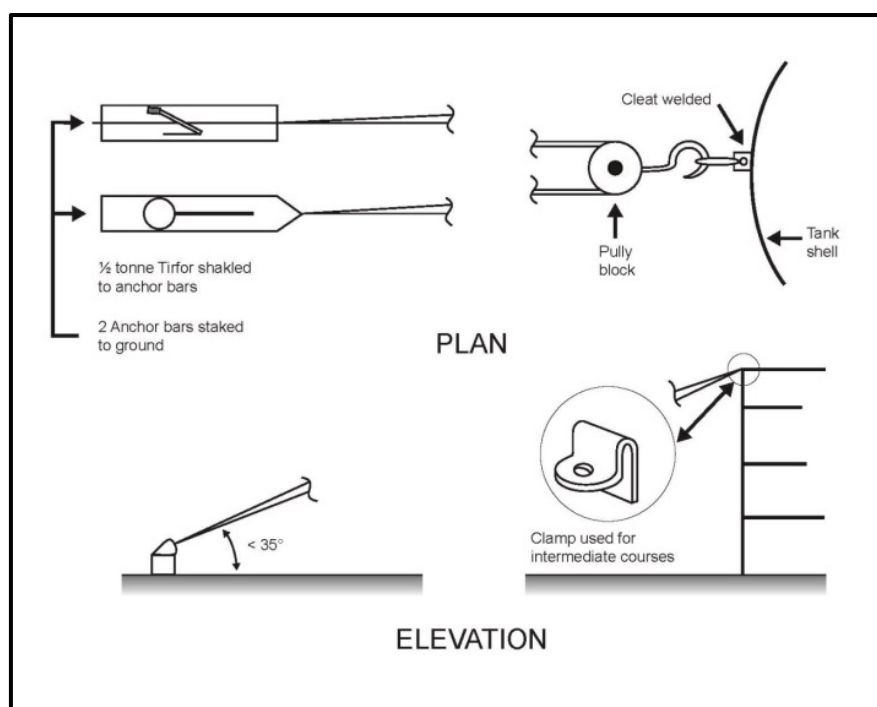


Figure 42 Example of tirfors and cleat to prevent wind damage

6.8 Repair/modification methods - some typical examples

Repair methods for tank foundations are described in Appendix C.2.

7 Tank bottoms (with or without annular plates)

7.1 General

The design of tank bottoms should be performed, and the materials to be used in their construction selected, in accordance with recognised national standards such as BS 2654, API 650 or DIN 4119-1. These standards show typical arrangements of bottoms, which may be with or without annular plates, the latter case being typical of small tanks only.

Note: For further information about these types of bottoms, refer to EEMUA 183.

7.2 Introduction

The metal bottom of a tank can generate a disproportionate inspection and maintenance effort compared with its initial cost. This reflects the difficulty in detecting deterioration of the floor, especially on the underside, and the fact that a perforated floor can give rise to an insidious loss of product and damage to the environment. Whilst it is unusual for a failed floor to lead directly to catastrophic failure of a storage tank, it is not impossible for it to do so. A more common failure mechanism is leakage through the floor damaging the tank foundations, which could lead to instability and eventual catastrophic failure.

There are now means of detecting leakage whilst the tank is in operation, and the consequences of a leak can be ameliorated by secondary containment systems that reduce environmental damage. Nevertheless the integrity of the original tank bottom remains the prime means of preventing product loss and associated damage to the environment, and thus it needs to be maintained in a sound condition. (This is discussed at greater length in EEMUA 183).

Recent developments in the methods available to inspect tank floors make remaining life predictions easier. These methods include the various 'floor scanners', advanced ultrasonic techniques and acoustic emission surveys. New methods and improvements to existing ones are continually being developed and made available for use.

Any inspection, and the preparation needed before it can be performed, is expensive. The possible various results of an inspection and consequential maintenance actions should be considered before any inspection is carried out; this can help avoid unnecessary work.

The degree of inspection and repair that it is economically sensible to perform before the whole floor is replaced will be influenced by many factors. These obviously include material and contracting costs, but a major factor will be the time and cost of cleaning the tank and preparing it for work. This latter cost will vary greatly depending on whether the tank is holding clean, light product or is handling crude or heavy oil or a dirty liquid.

Despite improved inspection tools, forecasting the remaining life of a tank bottom is problematic; accurate inspection and service records will make the task easier and the prediction more reliable. This is a reason for the inspection or refinery engineer being a party to decisions to alter tank service or to run different crudes or feedstocks.

Some large tanks experience cracking in the HAZ of the interconnecting welds in bottom plates, and the bottom-shell connection. When inspection of bottom plates is scheduled, the opportunity may be taken to carry out weld inspection in such areas by means of the vacuum box technique.

A Flowchart for assessing the fitness for purpose of tank bottoms and annular plates is shown in Figure 43.

7.3 Determination of floor thickness and condition

Floors may be corroded both underside and topside (see Sections 4.3.1 and 4.3.2).

Topside corrosion can be evaluated, after cleaning, by visual examination and mechanical or ultrasonic gauging (see Chapter 5). The extent of cleaning and inspection varies depending upon the tank's history. Ultrasonic thickness gauging from the topside also determines if there has been underside corrosion at that location.

Often in the past only a small percentage of the floor was gauged to determine thickness. With such a sampling technique, it should be noted, significant corrosion can go undetected.

However, existing techniques to more rapidly determine topside and underside corrosion are now available. They employ permanent magnets or electromagnets, thickness being determined by monitoring changes in magnetic flux. Permanent records of the inspection can be preserved, and suspect areas of the floor marked up for further evaluation by ultrasonic inspection and/or repair.

Use of these techniques makes it practical to inspect much larger percentages of the floor area. The technique cannot however be used to inspect areas in lap welds or areas immediately adjacent to the shell.

The following techniques should be utilised for a sound condition based assessment of tank bottoms:

- a) Check operational integrity:
Perform a 100% floor scan by the MFL of eddy current technique and assess the loss of thickness by corrosion attack. Report these losses in a scale of 20%, 40%, 60% and 80% loss of material. All areas found should be subject to further investigation by visual inspection (in order to assess whether the attack is top side of underside of the bottom plates) and by ultrasonic inspections to determine the actual material loss.

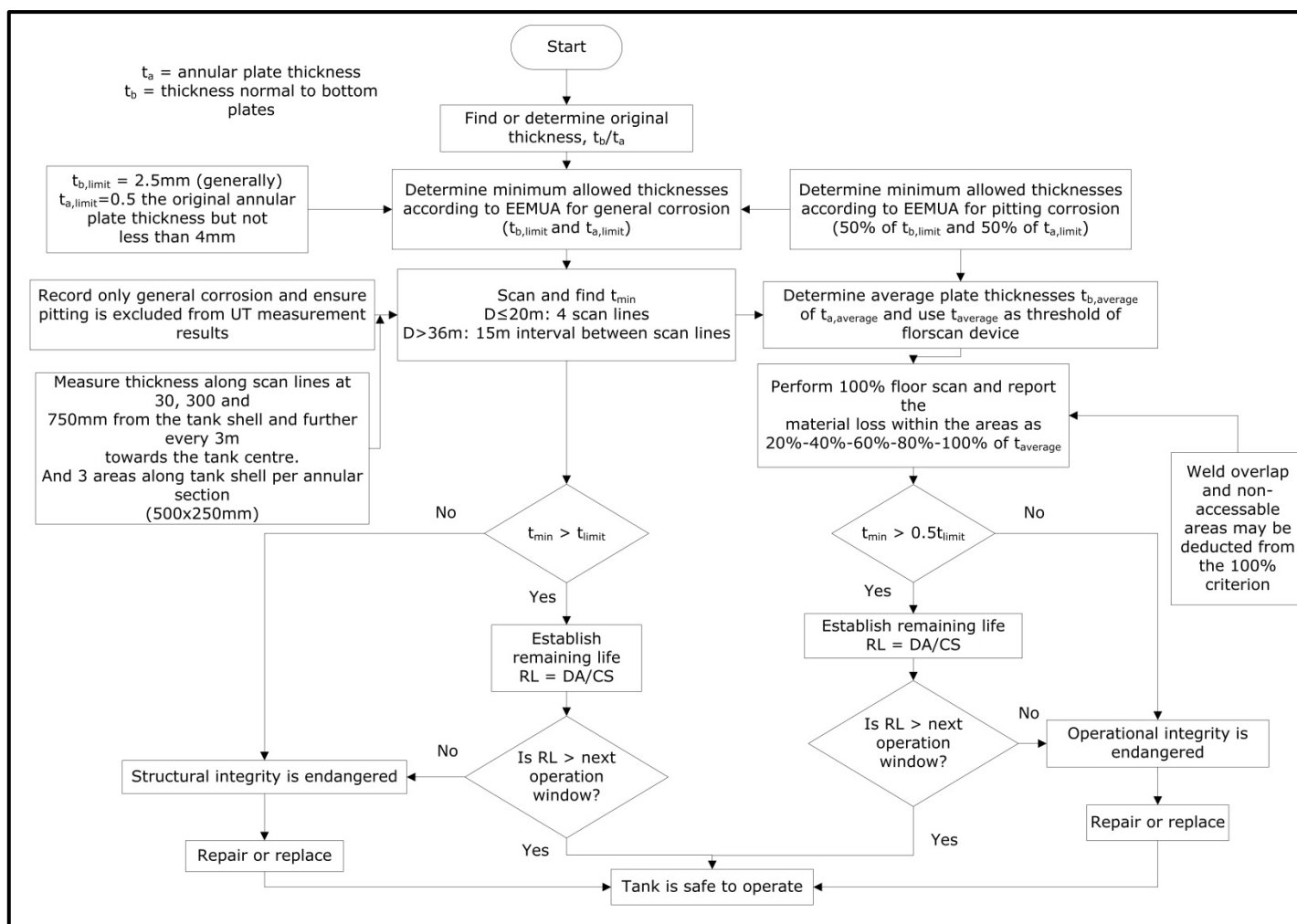


Figure 43 Flowchart for assessing fitness for purpose of tank bottoms and annular plates

b) Check structural integrity

Perform Ultrasonic inspection at the following measurement points in order to assess the minimum thickness of bottom plates and annular plates:

- Extend the vertical grid line system applied to the tank shell, horizontally over the tank bottom plates and measure the plate thicknesses at the following points:
 - As close as possible near the inside corner weld of the bottom-to-shell connection, but not further away than 25mm inwards of the shell;
 - 300mm inwards of the shell;
 - 750mm inwards of the shell;
 - And further every 3m. towards the centre of the tank.
- Include in the ultrasonic inspections 3 areas (of 500 * 250mm each) each of annular plate as close as possible near the inside corner weld of the bottom-to-shell connection. One area near the left interconnecting weld between the plate under consideration, at half length of that plate and, finally, near the right interconnecting weld between the plate under consideration. In case corrosion is found extent the inspection to 100% of the circumferential length of the annular section as close as possible near the inside corner weld of the bottom-to-shell connection.

If internal inspection indicates that underside corrosion has reached serious levels, remedial action, such as plate replacement, should be taken.

In cases where construction or size or other features allows access to the underside of the tank bottom for inspection, an in-service external inspection can be undertaken in lieu of internal inspection of the floor. In some cases for small tanks, jacking may be employed when the tank is out of service to undertake an under-floor inspection. This method is unlikely to be employed for large tanks unless the tank is to be jacked up for other reasons.

The extent of any tank bottom inspection should be such that all necessary data is obtained to evaluate its condition, and enable a determination to be made as to corrosion rates and the minimum thickness remaining after any remedial work has been carried out.

Appendix E provides a method for evaluating remaining life of the bottom plates together with the probability class of a failure mode occurrence. This probabilistic method can be applied even when minimal data is available, since it introduces confidence factors that recognise the quality of the data.

7.4 Rejection limits

7.4.1 Floor area

Rejection limits for the thickness of the tank bottom can only be prescribed in relation to the probability of leakage due to corrosion. Away from the critical annular area, the bottom is not subjected to stress unless there is significant differential foundation settlement. With a good foundation, the floor acts only as a sealing membrane, and consequently is assessed only on the probability of leakage when prescribing permitted remaining thickness or rejection limits. In the event of serious settlement, an experienced engineer (Tank Integrity Assessor) should be consulted.

For bottoms subject to general corrosion or localised corrosion in fairly large areas, the minimum allowable bottom plate thickness is 2.5mm for tanks situated on standard A, B or C type foundations (see Section 6.1.1 and EEMUA 183, Sections 2.1 through 2.4), with or without a leak detection management system (an impermeable foil in the foundation underneath the total tank bottom). This rejection criterion has been assessed by applying the maximum allowed radial settlement degradation mode, when stresses will pass through the minimum throat size of interconnecting bottom plate welds and the minimum plate thicknesses. However, for tanks situated on D or E type foundations (see Section 6.1.1 and EEMUA 183, Section 2.5), where the possibility of settlements are considered to be minimal, the minimum allowable bottom plate thickness may be reduced to 1.5mm, providing a risk assessment has been performed where exposure of personnel and the environment to the tank content shows acceptable levels.

Note: The 1.5mm minimum allowable thickness is an extrapolated theoretical minimum, calculated from the predicted corrosion rate and used to determine the next inspection date. The predicted corrosion rate should be based on actual measurements made during inspections.

The method of assessment provided in Appendix E uses the above limits for evaluation of the remaining life of the bottom, and calculation of the interval before the next required inspection. The Appendix E method does not depend on a detailed knowledge of pitting corrosion rates. The effect of pitting is taken into account by multiplying the general corrosion rate by an 'acceleration factor', although if the user has good data this may be used instead. It should be noted that if there is significant pitting corrosion with negligible general corrosion, this factor could underestimate the effect of pitting. A more deterministic approach may be required in this case. The user has to apply his own judgement when assigning levels of confidence to his own specific data.

Because the limits discussed above for bottom plate thickness relate to the probability of tank bottom leakage, which leakage is assumed to be detectable before it results in serious deterioration of the foundation, the user of this document should make his own assessment based on the quality and quantity of data and information at his disposal. It is recommended that care be taken not to confuse different criteria, especially the difference between a deterministic method as outlined in API 653⁽²¹⁾ and the probabilistic method given in Appendix E of this document.

7.4.2 Annular area

The following applies whether or not separate annular plates are provided.

When the bottom plates extend under the shell as sketch plates, the rejection criteria should apply to the critical area of the floor extending from the shell inwards for a distance of 500mm.

From the standpoint of leakage, an assessment of the tank bottom needs to include the annular area. However, because the annular area of the floor can be subjected to significant stresses, the general strength of the annular area also needs to be assessed.

The minimum thickness for bottom annular plates subject to general corrosion should be evaluated against the code / standard used for the original design. Appendix A.2 recommends the minimum allowable thicknesses of the plates, both where they lie inside the tank and where they project beyond the tank shell, for tanks designed to BS 2654 and to API 650. In general the minimum allowed thickness of annular plates and in the 500mm area inwards of the shell when such annular sections are not provided in tanks is 50% of the original thickness with a minimum of 4mm.

The indicated minimum thicknesses exclude any chosen corrosion allowance used in the original design. An incremental thickness may be added to this minimum as a future corrosion allowance. Appendix A.2 also specifies the minimum allowable, corroded length of projection of the bottom plate beyond the outside toe of the shell-to-bottom weld, as well as the minimum allowable, corroded thickness of the projection.

If the annular plate is subject to top or bottom-side pitting corrosion, this should be assessed using the method given in Section 5.4 for determining whether widely scattered pits can be ignored or not

7.4.3 Annular projection

The minimal acceptable length (L) between the leg length of the external fillet of the weld of the floor-to-shell connection and the outer rim of the annular/bottom plates is 9.5mm.

The minimal acceptable corroded thickness (t) of the annular projection is 2.5mm as shown in Figure 44.

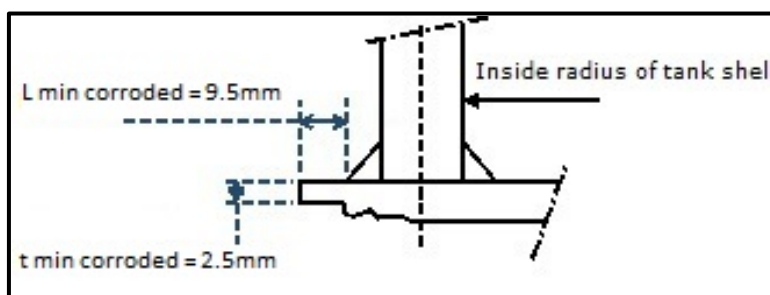


Figure 44 Rejection limits annular projections

The minimal acceptable corroded throat thickness of the internal fillet weld of the bottom-to-shell connection 50% of the original fillet throat thickness, with a minimum of 3mm.

$$a_{\text{min corroded}} = 50\% \cdot a_{\text{nom}}$$

Where:

$a_{\text{min corroded}}$	Minimal acceptable corroded throat thickness of fillet weld (mm)
a_{nom}	Nominal as-built thickness of fillet weld, excluding an initial applied corrosion allowance (mm)

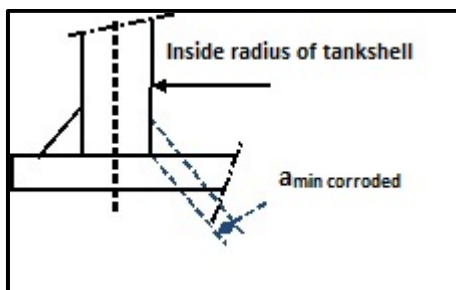


Figure 45 Rejection limits throat thickness fillet weld

In case no measurement data are available the throat thickness can be derived from measurements taken at the annular plates. For tanks design in accordance with BS 2654, the leg length of the fillet weld of the floor-to-shell connection equals the thickness of the annular plate with a maximum of 12.5mm. This results in a maximum throat thickness of the weld of 8.8mm. When corrosion is measured on the annular plate, an identical value of $0.707 \times$ the remaining thickness of the annular plate, will then be found for the remaining throat thickness of the weld.

Example 1:

Original thickness of annular plate: 10mm; gives an original throat thickness of floor-to-shell connection of 7mm.

Measured thickness of the annular ring at a certain time is 8mm, which identifies a corrosion of 2mm during the time the tank was used.

From the throat thickness an equivalent value of $0.707 \times 2\text{mm} = 1.4\text{mm}$ is corroded, resulting in a new corroded throat thickness of $7 - 1.4 = 5.6\text{mm}$. This is still 2.6mm away from the rejection limit.

For tanks designed in accordance with the EN 14015 this is slightly different as in this standard the throat thickness of the weld equals the thickness of the annular plate with a maximum of 9.5mm. When corrosion measurements are taken from the annular plates the throat thickness of the fillet weld of the floor-to-shell connection can be assessed as follows. When corrosion is measured on the annular plate, an identical value can be found for the remaining throat thickness of the weld.

Example 2:

Original thickness of annular plate: 10mm; gives an original throat thickness of floor-to-shell connection of 9.5mm.

Measured thickness of the annular ring at a certain time is 8mm, which identifies a corrosion of 2mm during the time the tank was used.

It can be assumed that from the throat thickness an equivalent value of 2mm is corroded, resulting in a new corroded throat thickness of $9.5 - 2 = 7.5\text{mm}$. This is still 4.5mm away from the rejection limit.

7.4.3.1 Groove corrosion to the annular plate

Above ground steel storage tanks are subjected to fluctuating pressures from tank filling/emptying operations and thermal expansion. These pressures can introduce high stress ranges in the fillet weld between the tank shell and bottom annular ring plating, (this varies in thickness based on the tank diameter), which often results in low cycle fatigue damage and weld cracking.

There have been a number of studies completed on low-cycle fatigue in recent years resulting in differing opinions on the subject. This has been based on 1300 cycles and above. However, tank failure in the critical area, caused by groove corrosion, has occurred in several locations globally in recent years.

Groove corrosion is sometimes also referred to as "gutter corrosion". The failures have occurred in the area immediately below the shell to annular, (or shell to floor), fillet weld. Product side corrosion can also occur. This corrosion to the top-side could be accelerated by edge settlement or simply, a cone-up floor. However, this would be clearly evident upon an out of service inspection of the tank.

Such corrosion differs with the tank foundation type. For example, a concrete ring-wall for a concrete raft would create more stress. A flexible foundation, e.g. crushed stone or sand is more flexible. Heated tanks would also see more rotation at the shell to floor weld.

7.4.3.2 Inspection

Groove corrosion occurs in an area which is difficult to detect. As with general annular or tank bottom underside corrosion the normal causes may be attributed. These include local ground or soil conditions, settlement and the appearance of plant life in the immediate area.

There have been a number of NDT methods which have attempted to detect general corrosion under the shell. Many are limited and require a clean surface, with the chime or outer annular to be of a minimum width. Some systems can detect pitting and not knife edge corrosion.

Pulsed eddy current has been successful for some users. This requires excavation and gives a quantitative measurement. The tank assessor can visually select a number of locations for excavation. Occasionally, further calculations may be necessary to ascertain shell loading. Follow-up inspection and corrosion rates can be determined based on minimum thickness found. Practically, even this system would not be able to detect 100% of the tank diameter due to the amount of excavation required.

7.4.3.3 A case study

In 2010 intervention by a regulatory authority was completed when they detected liquid bubbling close to a 54m diameter tank. The bottom protrusion from under the shell was visually in poor condition. In this case the tank was fitted with a sketch plate design rather than annular plate.

The result can be seen in Figure 46. The intervention prevented a potentially significant environmental incident, as both top and underside grooving corrosion was found to the underside of the HAZ upon removal from service.

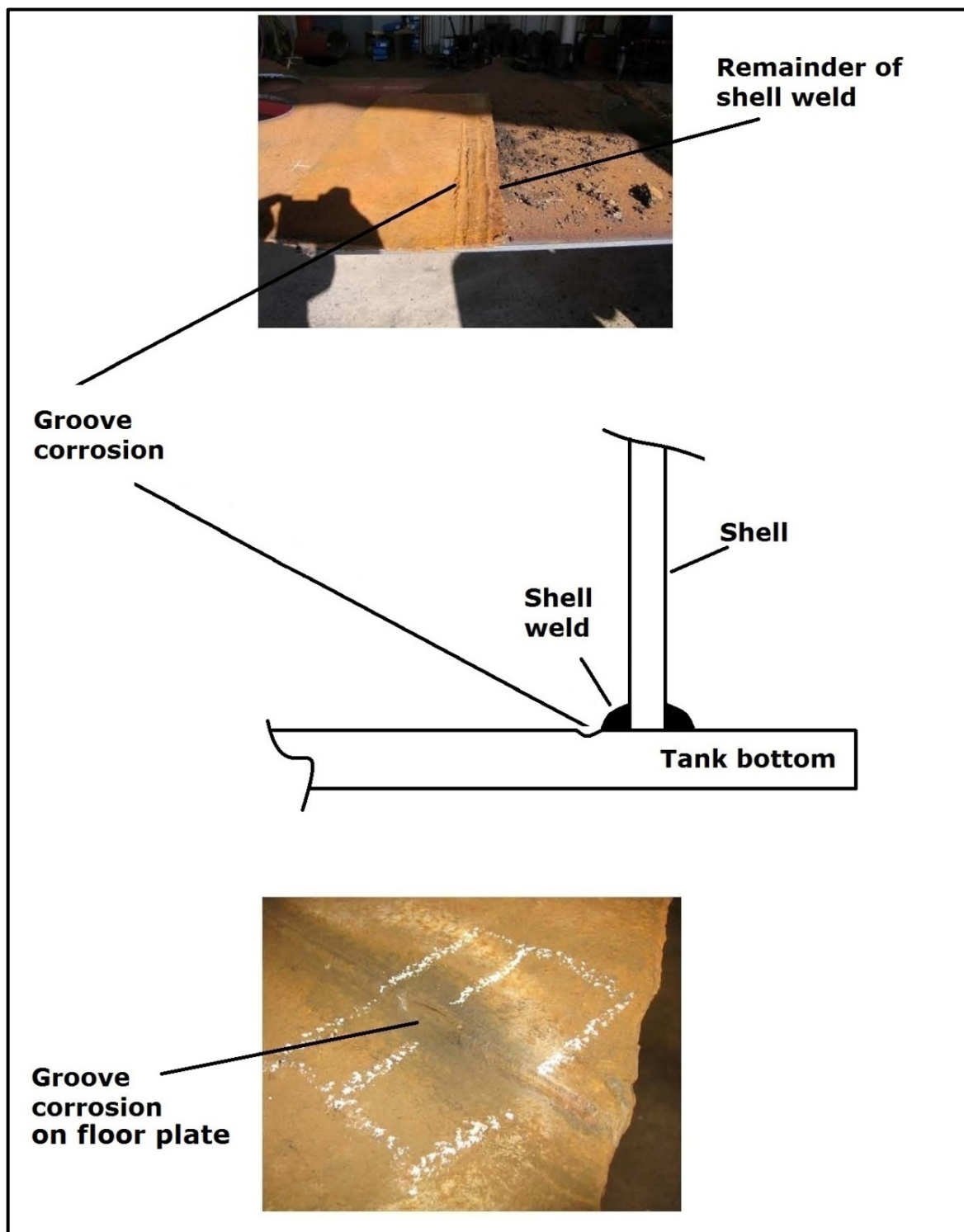


Figure 46 An example of groove corrosion

7.5 Bulges and depressions in tank bottom plates

Bottom plates are generally rectangular plates 6mm thick, lap welded by a fillet weld on the topside only.

Due to distortion caused by welding of the bottom plates, bulges and depressions will always be present in the bottom after construction. When the tank is filled with liquid the bulges tend to disappear as the bottom plates are pressed flat on the foundation.

The centre of the tank bottom will always settle approximately 50% more than the periphery. When the composition and thickness of the soil layers under the tank vary, unequal soil settlements will occur resulting in bulges and depressions in the tank bottom.

When the deformations are formed gradually, without sharp edges, over a large area, the tank bottom will follow the pattern of the settled foundation so that the bottom plates will be adequately supported. Consequently, these bulges and deformations present no risk for a failure of the bottom welds (See Figure 47).

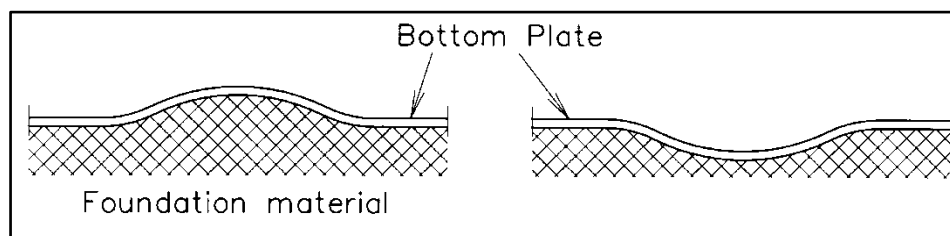


Figure 47 Bulges/depressions without sharp edges supported by the tank foundation

However when bulges are formed and not filled with foundation material (voids) there is a risk of rippling when the tank is filled and the liquid contained presses the bottom plate downwards. Figure 48 gives guidance on the dimensions when such a bulge requires attention for possible repair. Repair by cutting-out and patching or by cutting and flattening is recommended if the depth-to-width ratio of the void exceeds 1:15.

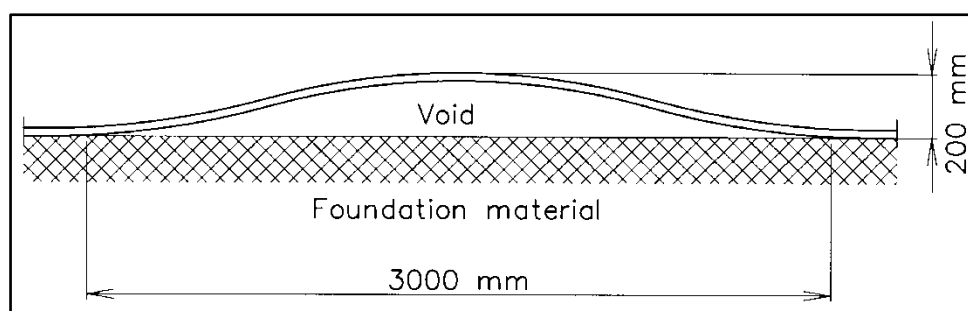


Figure 48 Bulges not filled with foundation material

Sometimes it is proposed that these voids are filled with a liquid concrete to give support to the bottom plates at that location. This is however unwise. The slurry will not fill the voids but flow to those locations where the bottom can move

upward easily, so that ultimately the tank bottom will rest on a number of concrete points instead of being supported evenly over its entire surface.

7.6 Cathodic protection

Cathodic protection is sometimes used to protect the underside of the bottoms of steel storage tanks and associated buried pipework. Sometimes sacrificial anodes are installed in crude tanks used for water separation. For a full description of the available techniques and their suitability refer to Section 6.6 of EEMUA 183 and to API RP 651.

7.7 Repair/modification methods - some typical examples

Appendix C.3 presents a method for replacement of annular plates. When annular plates only are replaced, the sequential jacking method can be applied, see Appendix C.1.

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8 Tank shells

8.1 General

The primary function of the tank shell is containment of the liquid inventory against the pressure loading produced by the internal hydrostatic head. As this applied head reduces with increasing height, so does the required shell plate thickness. Tank design codes place a practical limit on minimum and maximum plate thickness to be used in tank shell constructions.

Tanks designed to an appropriate standard and a full knowledge of the required operating duty and applied loadings are unlikely to suffer accelerated general overall shell corrosion above the specified corrosion rate included in the design parameters. For tanks which contain aggressive products or are located in extreme environments, additional precautions may have been taken to mitigate the deterioration of the shell with time (e.g. internal or external coatings). Loss of part of the internal or external coating, for example, would lead to excessive local corrosion and a reduction in the useful life of the tank shell. Guidance is given in this Chapter on the calculation of the minimum allowable in-service shell thickness, and on appropriate repair procedures.

In addition to internal pressure, storage tank shells are subjected to loads that must be transmitted through the structure without gross deformation of the tank plates or their appurtenances. Examples of these loads include the tank roof weight, wind-induced forces, vacuum load, connected pipe loads and dead weight of mixers. The ability of the tank shell to adequately transfer these loads depends on the condition of the various components, and in some cases the quality of the welded connection to the shell. As an example, inlet and outlet nozzles are fitted with reinforcing pads that must be routinely examined for corrosion and weld faults if leakage and failure are to be avoided.

It should be noted that tank shells have a limited ability to carry loads that result in compressive stresses (e.g. seismic and wind loads). Excessive stresses of this nature may result in unstable buckling type failures. The ability of a tank shell to withstand the compressive stresses generated by external pressure is considerably enhanced by fitting external stiffeners. Obviously any significant deterioration in the condition of the stiffeners would have a detrimental effect on the tank shell's ability to withstand vacuum induced external pressure.

In general, the ability of a tank shell to continue performing its required duty depends on the quality of the maintenance, inspection and repair of the tank components (e.g. nozzles, manholes, stiffeners etc.) and plates. The remainder of this Chapter provides detailed guidance on the assessment of plate thicknesses, component failure mechanisms and typical examples of shell repairs and modifications.

A flow chart for assessing fitness for purpose of tank shell is given in Figure 49.

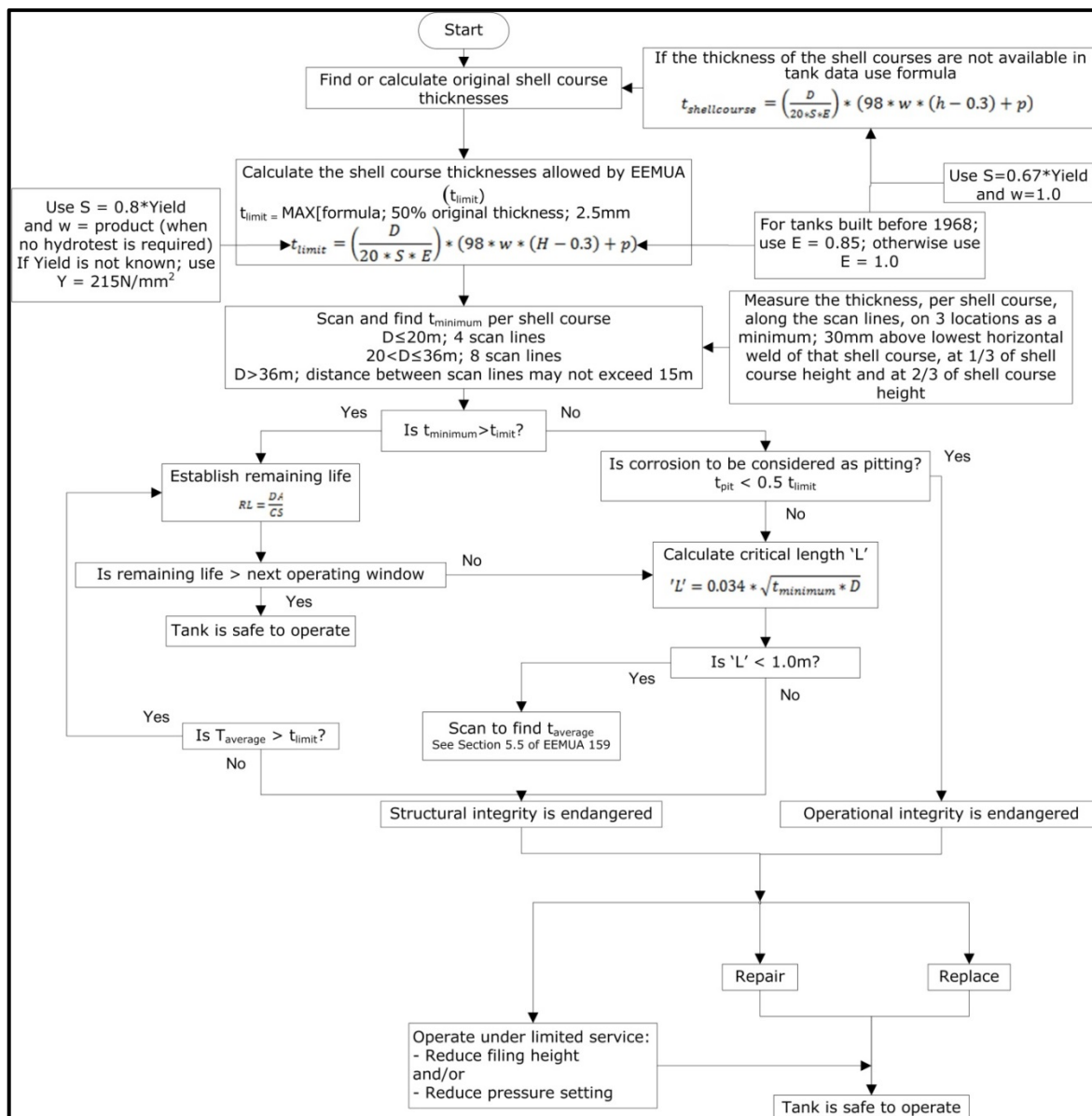


Figure 49 Flowchart for assessing fitness for purpose tank of shells

8.2 Determination of effective shell plate thickness and condition

The outside of the tank shell generally suffers little corrosion if paint coatings have been well maintained. Paint breakdown generally indicates problems. However, when tank shells are externally insulated this might not be noticed and severe corrosion may occur under the insulation.

Visual examination of the paint coating readily alerts the inspector to where metal loss can be expected.

Accelerated corrosion of the shell plates inside the tank may occur in fixed roof tanks above the liquid level (vapour space corrosion). Tank access is required for inspection of these areas which will require cleaning to allow a thorough examination.

Shells of floating roof tanks are vulnerable to accelerated inside corrosion caused by scratching of the roof seal along the tank shell, in particular when the seal is damaged. Internal tank shell corrosion on floating roof tanks may also be induced by wind or rain since in most cases the inside of tank shells is not coated.

Ultrasonic thickness measurement (see 5.3) may be necessary for determination of 'effective' shell thickness (t_1 or t_2 ; see 5.5).

8.3 Rejection limits for shell plates

The minimal acceptable shell plate thickness for general and localized general corrosion of the shell plates is determined by the maximum of the following: minimal acceptable thickness for liquid load, the minimal acceptable thickness for wind and vacuum load, the minimal acceptable thickness for roof load, 50% of the nominal thickness excluding corrosion allowance or 2.5mm. This is given in the formula:

$$t_{\min \text{ acc. shell gen}} = \left[\begin{array}{l} t_{\min \text{ acc. shell liq.}} ; t_{\min \text{ acc. shell wind/vac.}} ; \\ t_{\min \text{ acc. shell roofld.}} ; 50\% \cdot t_{\text{nom shell}} ; 2.5\text{mm} \end{array} \right] \text{ (whichever is larger)}$$

Where:

$t_{\min \text{ acc. shell gen.}}$	Minimal acceptable thickness of shell courses for general corrosion or localized general corrosion (mm)
$t_{\min \text{ acc. shell liq.}}$	Minimal acceptable thickness of shell courses for liquid load and vapour pressure load (mm) (see section 8.3.1)
$t_{\min \text{ acc. shell wind/vac.}}$	Minimal acceptable thickness of shell course for wind and vacuum load (mm) (see section 8.3.2)
$t_{\min \text{ acc. shell roofld.}}$	Minimal acceptable thickness of shell course for roof load and superimposed load (mm) (see section 8.3.3)
$t_{\text{nom shell}}$	Nominal as-built thickness of shell courses, <u>exclusive of corrosion allowance</u> (mm).

The following paragraphs provide an overview of the different formulas that are required to calculate the minimal acceptable shell plate thicknesses with respect to the different loads and load combinations that are acting on the tank shell. The tank shell will also need to be evaluated with respect to pitting corrosion.

When using a UT crawler the average measured/reported thickness may be used in the data-analysis for calculating the rejection limits of the tank shell with respect to wind and vacuum loads and roof loads as described in Sections 8.3.2 and 8.3.3.

8.3.1 Liquid Load and vapour pressure

The liquid load (stress on the shell exerted by the weight and pressure of the stored product) combined with the vapour pressure above the liquid level is in most cases crucial for the rejection limit of the tank shell. In this calculation the most important parameters are the 'filling height', material strength and the 'joint efficiency factor'.

The minimum acceptable plate thickness of a shell course can be calculated according to:

$$t_{\min \text{ acc. shell liq.}} = \frac{D}{20SE} (98w(H_u - 0.3) + p)$$

Where:

$t_{\min \text{ acc. shell liq.}}$	Minimal acceptable thickness of shell courses for liquid load and vapour pressure (mm)
D	Internal tank diameter (m)
S	Maximum allowable stress (N/mm^2). ($S = 0.8 \times$ minimum specified Yield Strength of the material in use or 172 N/mm^2 if material quality and grade is unknown)
E	Joint Efficiency factor (-)
w	Relative density of product when no hydro-static test is foreseen, otherwise use $w = 1.0$ (-)
Hu	Distance from the lower edge of the shell course under consideration to the maximum filling height (m)
p	Design vapour pressure of subject tank (see also Table 6)(mbar)

The joint efficiency factor 'E' is the ratio of the strength of the joint divided by the strength of the parent plate. Since 1968, it has been accepted to use $E = 1.0$ for double butt welded joints, $E = 0.35$ for single lap welded joints and $E = 0.50$ for double lap welded joints, as since that very year adequate weld inspection techniques and required coverage of inspections to welds were prescribed in the applicable design and construction codes (BS, API, DIN etc.).

For tanks that have been designed before and including 1968 the minimum joint efficiency factor for butt welded joints of $E = 0.85$ was used in the design.

For determining the minimum acceptable shell plate thickness according to EEMUA 159, the joint efficiency used for the original tank design shall be used. Use $E = 0.85$ for butt welded shells of tanks built before and including 1968.

A joint efficiency of $E = 1.0$ may be used when determining the minimum acceptable thickness according to EEMUA 159 in a corroded plate, away from the joint by at least the greater of 25mm or twice the plate thickness.

IMPORTANT: *The maximum allowable yield stress should also be corrected for the operating temperature and when stainless steel is used for the shell plates of the tank.*

When the design metal temperature of carbon and carbon manganese steel is above 100 and below 200 degrees Celsius, the maximum allowable design stress should be reduced by the factor 0.89. When the design metal temperature of carbon and carbon manganese steel is between 200 and 300 degrees Celsius, the maximum allowable design stress should be reduced by the factor 0.79 as per EN 1993-1-2⁽²²⁾.

Note: *The minimum specified Yield strength Y for any material is only valid for thicknesses $\leq 16\text{mm}$. When original – un-corroded – plate thicknesses are available in subject tanks under consideration which exceed the 16mm threshold, the value of the minimum specified yield strength should be reduced by 10 N/mm^2 .*

The design internal pressure as given on the construction drawing may be used. In cases where the design pressure is unknown Table 6 can be used as reference (all values in mbar).

Table 6 "Standard" design pressures and vacuum values in mbar

Code	Floating roof		Fixed roof					
			Non pressure		Low pressure		High pressure	
	Pressure	Vacuum ⁵	Pressure	Vacuum	Pressure	Vacuum	Pressure	Vacuum
BS 2654	0	5	7.5	2.5 ^{1, 2}	20	6 ¹	56	6 ¹
EN 14015	0	5	10	2.5 ⁶	25	6 ⁶	60	6 ⁶
Other or unknown	0	5	note 3	note 4	note 3	note 4	note 3	note 4

¹ 2.5mbar need to be added in formula for factor K calculations in accordance with Section 7.6.2.3 of BS 1654

² 4mbar for tanks with column supported roofs

³ Use pressure of pressure relief vent when full flow is created or when fully open

⁴ Use vacuum of vacuum relief vent when full flow is created or when fully open for factor K-calculations

⁵ Vacuum level indicated is only used for stability calculations

The above thickness determinations consider liquid loading only. When applicable, consideration should also be given to other loads or conditions as follows:

- Wind-induced loads;
- Seismic loads;
- Operation at elevated temperatures;
- Vacuum-induced external pressure;
- External loads caused by piping, tank-mounted equipment, holding down lugs etc.;
- Mechanical damage that may occur during operations around the tanks;
- For small tanks there is a possibility of wind-induced overturning if retirement thicknesses are based exclusively on minimum thickness for internal pressure. Therefore, the total weight of other anchoring systems should be evaluated for a fully corroded condition with low liquid level;
- Deformation due to anticipated excessive settlement.

It is not necessary to routinely hydrotest tanks as part of their periodic inspection.

However, a test is recommended when forms of deterioration, which are unusual or difficult to evaluate, are discovered during inspection. After major repairs and jacking or re-levelling, re-hydrotesting of the tank should also be done. Any modification or repairs carried out on a tank shell, should be designed, constructed and inspected in accordance with approved procedures. Full NDT inspection should be carried out particularly where a hydrotest is not practicable (See also Section 15.2).

8.3.2 Wind and vacuum loads

The formulae describing how to calculate wind and vacuum loads are clearly described in the EN 14015. However, other regional standards for wind speeds may apply.

Buckling of the shell can be induced by:

- 3 seconds wind gusts in combination with the design vacuum of the tank during pumping-out of product;
- the thermal effect of cooling down during the night;
- the thermal effect of cooling down during a rain shower on a sunny day.

This can be prevented by installing an additional wind girder. To determine whether the tank shell is acceptable for these conditions the following calculations shall be performed:

$$H_e = h \sqrt{\left(\frac{t_{\min}}{t}\right)^5}$$

$$H_E = \sum H_e$$

$$K = \frac{95000}{3.563 V_w^2 + 580 v_a}$$

$$H_p = K \sqrt{\left(\frac{t_{\min}}{D^3}\right)^5}$$

$$n = \left(\frac{H_E}{H_p} - 1\right), \text{ rounded up to the nearest integer value}$$

$$L = \frac{H_E}{n + 1}$$

Where:

D	Tank diameter (m)
$t_{\min}$	Averaged minimum thickness of thinnest shell course (which may well be a lower shell course than the top shell course) (mm)
t	Averaged minimum thickness of the shell course under consideration (mm)
h	original Height of the shell course under consideration (mm)
H_e	Transposed shell course height using $t_{\min}$ (m)
H_E	Transposed total tank shell height (m)
K	Load factor for combined wind and vacuum loads
H_p	Maximum unstiffened height of transposed shell under wind- and vacuum loads (m)
V_w	wind speed as per EN 14015 (m/s)
v_a	Design vacuum of tank (mbar)
L	Interspacing between existing or additional wind girders on H_E
n	number of existing or additional wind girders

The design vacuum as given on the construction drawing shall be used, in case the design pressure is unknown, Table 6 can be used as a reference.

Note that 2.5mbar needs to be added to the design vacuum value of fixed roof tanks when the tank is constructed according to the BS 2654, in accordance with paragraph 7.3.2.6 of that code. When the tank is constructed according to EN

14015 this additional 2.5mbar is already included in the design vacuum. In case the values are being used for the vacuum relief vent when full flow is created or when fully open, this additional 2.5mbar will also need to be added to the design vacuum value in the *K*-factor calculations.

IMPORTANT: ' H_p ' needs to be larger than ' H_E ' to maintain sufficient structural integrity in the tank shell. If this is not the case, additional strengthening is required.

See Appendix D.1.3 for further explanation and a sample calculation.

However, in case the distance between an existing and an additional wind girder on the actual tank shell $\leq 1.0\text{m}$ the advice would be to refrain from installing the additional wind girder on this shell section.

The comparison between ' H_p ' and ' H_E ' can only be made when known values of ' $t_{\min}$ ' (the averaged minimum thickness of the thinnest shell course) and t (the thickness of the other shell courses) are entered in to the equation. The values of ' $t_{\min}$ ' and t are calculated using ' t_{last} ' (the averaged minimum thickness during the last inspection) of the different shell courses and CR (the corrosion rate of the individual shell courses).

8.3.3 Roof loads

In the case of fixed roofs, the weight of the roof as well as the applicable live loads exert an axial pressure in the tank shell. If the total axial load is too high or the shell too thin, this may induce buckling of the tank shell. The calculation is a comparison of the actual axial compression exerted on some point in the shell and the maximum allowable axial compression.

$$F_a = C \frac{t}{R}$$

$$f_a = \sum W_{\text{sup}}, W_{\text{rpl}}, W_{\text{rc}}, W_{\text{rs}}, W_{\text{shr}}$$

Where:

- F_a Allowable axial compression (N/mm^2)
- f_a Calculated axial compression (N/mm^2)
- t Minimum average thickness of a shell course under consideration (mm)
- R Radius of the tank (mm)
- W_{sup} Superimposed load (N/m^2) (1200 N/m^2 for tanks designed in accordance with BS 2654 or API 650 but higher for tanks designed in accordance with EN 14015 dependent on the snow and live loads specified in the Euro codes EN 1991-1-3⁽²³⁾ and EN 1993-4-2⁽²⁴⁾)
- W_{rpl} Load of the roof plates (W_{rpl} and W_{rc} are combined in Table 1)
- W_{rc} Load of the roof support structure (W_{rpl} and W_{rc} are combined in Table 1)
- W_{rs} Load of the top angle
- W_{shr} Load of the Shell courses above and including the course under consideration
- C Factor. In SI-units this factor is 12411 for carbon and carbon manganese steels at operating temperatures below 100 degrees Celsius.

For stainless steel tanks and for tanks operated under elevated temperatures the value of the constant C should be re-assessed by using the formula:

$$C = 12411 * \frac{E}{210000}$$

Where:

E Young's modulus of stainless steel under appearing stress or under elevated temperatures exceeding 50 degrees Celsius

or

E Young's modulus of carbon and carbon-manganese steels under elevated temperatures exceeding 100 C

IMPORTANT: The superimposed load (W_{sup}) may vary for different regions. In BS 2654 the superimposed load was set at a value of 1200 N/m². For tanks built after 2005, the live and snow loads that should be used are to be found in the Euro codes EN 1993-4-2 and EN 1991-1-3.

8.3.4 Pit corrosion assessment

Independent from the rejection criteria for general or localised general corrosion of the tank shell with respect to the combined liquid and vapour pressure loads, the combined wind and vacuum loads, and the combined roof and superimposed loads, the tank shell will also need to be evaluated with respect to pit corrosion.

The minimal acceptable thickness of the shell courses with respect to pit corrosion is 50% of the rejection limit with respect to general corrosion of the shell courses, provided that the pits are widely scattered and that the sum of the pit diameters over a straight line of 200mm does not exceed the value of 50mm. In formula:

$$t_{\min \text{ acc. shell pit.}} = 50\% \cdot t_{\min \text{ acc. shell gen.}}$$

Where:

$t_{\min \text{ acc. shell pit.}}$ Minimal acceptable thickness of shell courses under pit corrosion (mm)

$t_{\min \text{ acc. shell gen.}}$ Minimal acceptable thickness of shell courses under general corrosion or localized general corrosion (mm)

See also Section 5.4.

8.4 Minimum thickness calculations for riveted tank shells.

The minimum acceptable thickness for riveted tank shells shall be calculated using the equation in Section 8.3, except that the following allowable stress criteria and joint efficiencies should be used:

$$S = 144.83 \text{ N/mm}^2$$

E = 1.0 for shell plates, 150mm or more away from rivets.

See Table 7 for joint efficiencies for locations within 150mm of rivets.

Table 7 Joint efficiencies

Type of joint	Number of rivet rows	Joint efficiency E
Lap	1	0.45
Lap	2	0.60
Lap	3	0.70
Lap	4	0.75
Butt ^a	2 ^b	0.75
Butt	3 ^b	0.85
Butt	4 ^b	0.90
Butt	5 ^b	0.91
Butt	6 ^b	0.92

Notes:

^aAll butt joints listed have butt straps both inside and outside

^bNumber of row on each side of joint centre line

The rivet joint efficiencies given in Table 7 are conservative minimums for riveted tanks construction details and are included to simplify evaluations. However, in some cases it may be advantages to calculate the actual rivet joint efficiency using computational methods, applicable to lap and butt weld types rivet joints. When this alternative of calculated joint efficiencies is used, the following maximum allowable stresses shall apply:

- For the maximum tensile stress in the net section of the plate, use the lesser value of 0.8 times minimum specified yield strength of the shell plate (or $0.8 * 215 \text{ N/mm}^2 = 172 \text{ N/mm}^2$, if not known);
- For the maximum shear in the net section of rivet, use 110 N/mm^2 ;
- For the maximum bearing stress of plates and rivets, use 220 N/mm^2 for rivets in single shear and 141.38 N/mm^2 for rivets in double shear.

For tank with riveted joints, consideration should be given to whether, and to what extent, corrosion affects such joints. If calculations show that excess thickness exists, this excess may be taken as corrosion allowance.

8.5 Top wind girder and intermediate wind stiffeners

8.5.1 Shell top wind girders

Horizontal surfaces are potential sites for accelerated corrosion. Drain holes should be present at the lowest points. Since the section modulus is mainly a function of the ring geometry, some local corrosion of the shell is of secondary importance. For medium and large floating roof tanks, the shell top wind girder functions as a walkway. Weak spots from corrosion should therefore be repaired for reasons of personnel safety.

Important areas of inspection are the attachment welds. Because of access difficulties, except in the vicinity of the access stairway, inspection needs to be done largely by general observation of a breakdown in the paint system, possibly followed by a local inspection.

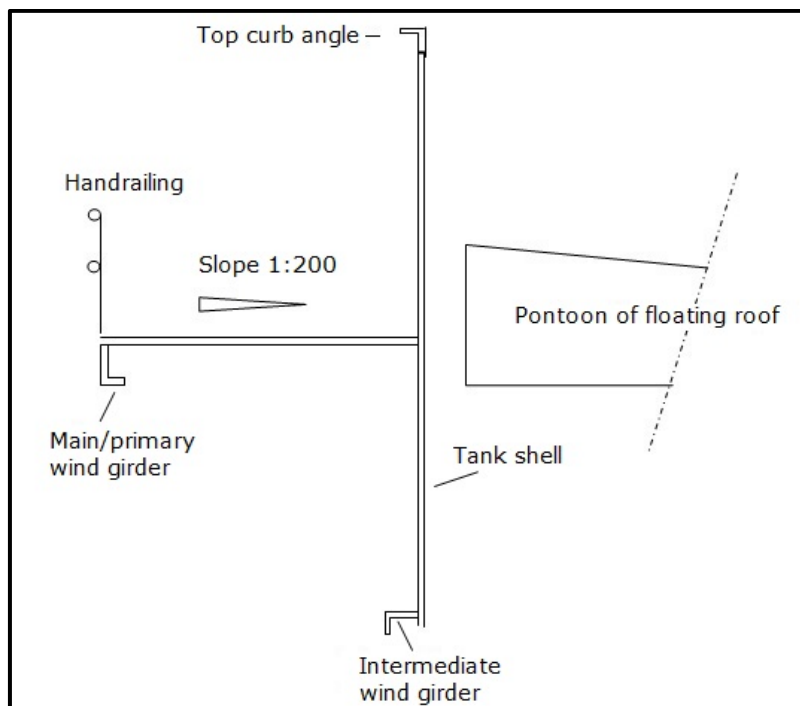


Figure 50 Main wind girder on a floating roof tank

8.5.2 Intermediate wind stiffeners

Intermediate wind girders are designed to stiffen the tank shell when exposed to wind loads or internal vacuum loads. Also here, drain holes (mouse holes) should be provided to prevent accumulation of rainwater, which in turn could induce excessive corrosion (See Figure 52.).

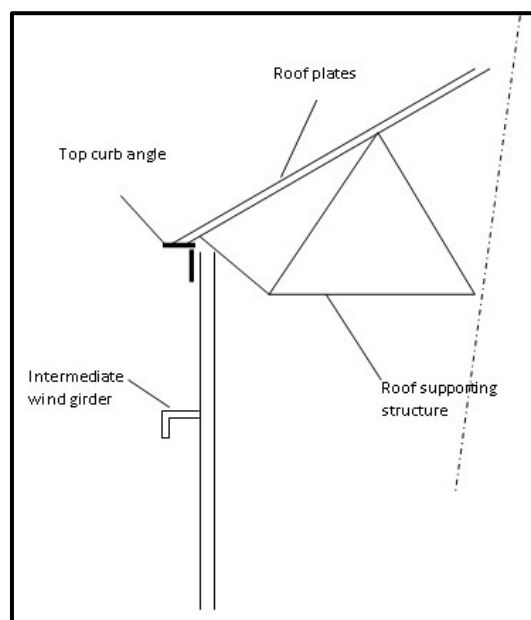


Figure 51 Intermediate wind girder on fixed roof tank

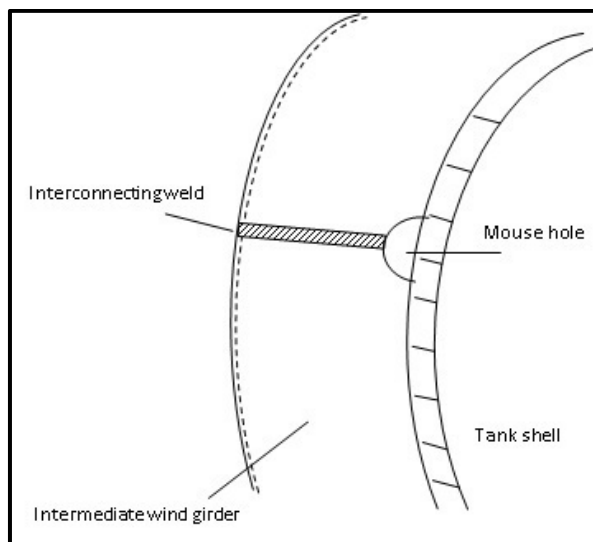


Figure 52 Intermediate wind girder with drain mouse hole

Where tanks are insulated, the wind stiffeners should be covered by the insulation (see Figure 53). The state of the insulation should be examined regularly for signs of deterioration. Note that large tank shells flex considerably during filling operations. This generally reduces the integrity of any system of insulation unless specially designed to cope with movement. The butt welds between adjacent sections of the wind stiffeners require special attention. Although full penetration welds are required by the design codes, this is not always achieved.

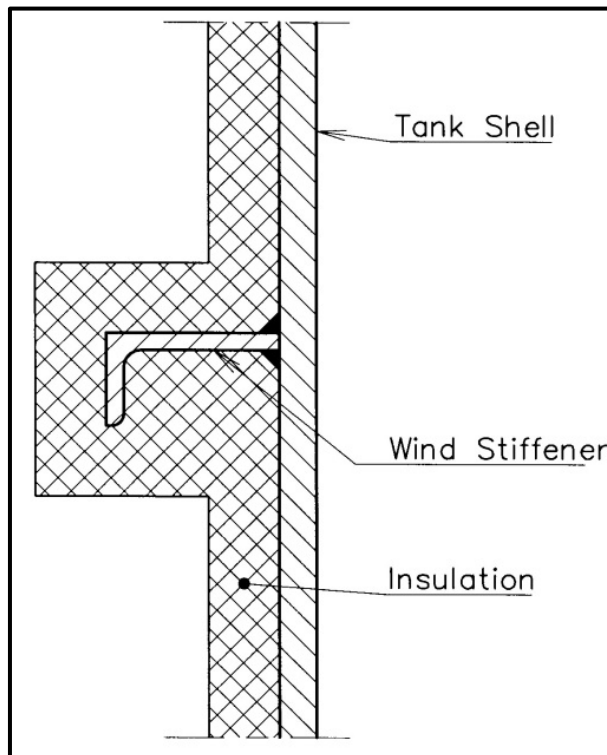


Figure 53 Intermediate insulated wind girder

8.6 Buckling problems of tank shells and top wind girders

8.6.1 Buckling problems of tank shells

8.6.1.1 Buckling due to wind gusts

Buckling due to wind gusts is one of the most common forms of shell buckling. It takes the form of a single or small number of waves in one section (the windward side) of the shell (See Figure 54). The cause of this type of buckling may be due to one or more of the following:

- abnormally high wind speeds (e.g. cyclones, hurricanes);
- reduction in shell thickness by corrosion;
- soil settlements;
- local flat spots of the tank shell induced by incorrect construction methods or by excessive repair work;
- loss of section in stiffening rings due to corrosion; and/or
- reduced integrity due to cracked welds of the stiffening rings.

A combination of two or more of the above will increase the possibility of shell buckling. This mode of failure is concentrated in the thin upper courses of the tank shell. It generally occurs when the product level is low and no liquid pressure is acting on the top part of the shell. Local isolated buckling caused by wind load may be corrected by pulling out the dent or, for fixed roof tanks, by filling to a higher level. Buckling caused by soil settlements may be corrected by jacking up the tank and re-levelling the foundation.

The incorporation of an additional intermediate wind stiffener can overcome the problem of buckling due to corrosion extending over a large area of the tank shell. Guidance for designing against wind-induced buckling can be found in the appropriate tank design standards, e.g. BS 2654 (see Appendix D.1 for sample calculations; also D.4). This form of buckling generally exists in large diameter floating roof tanks and in tanks with out-of-roundness problems, e.g. flat spots.

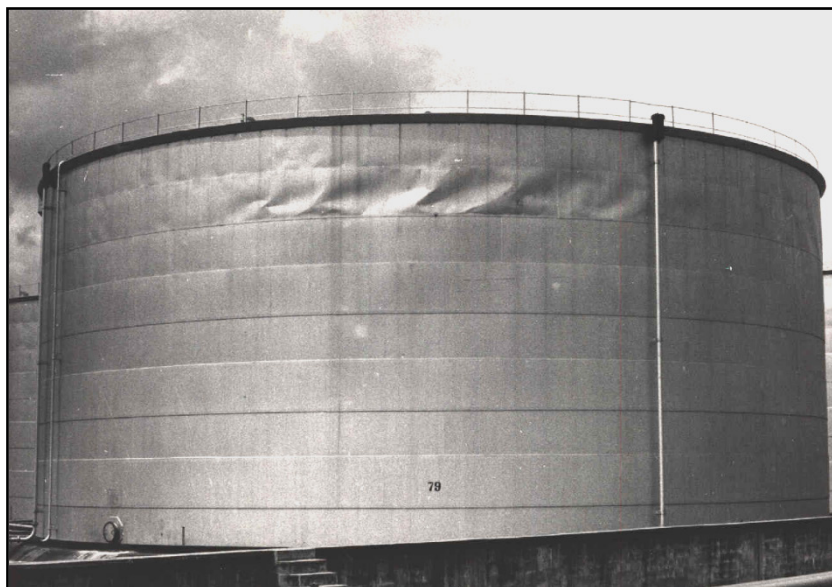


Figure 54 Fixed roof tank with buckled top courses due to wind gusts

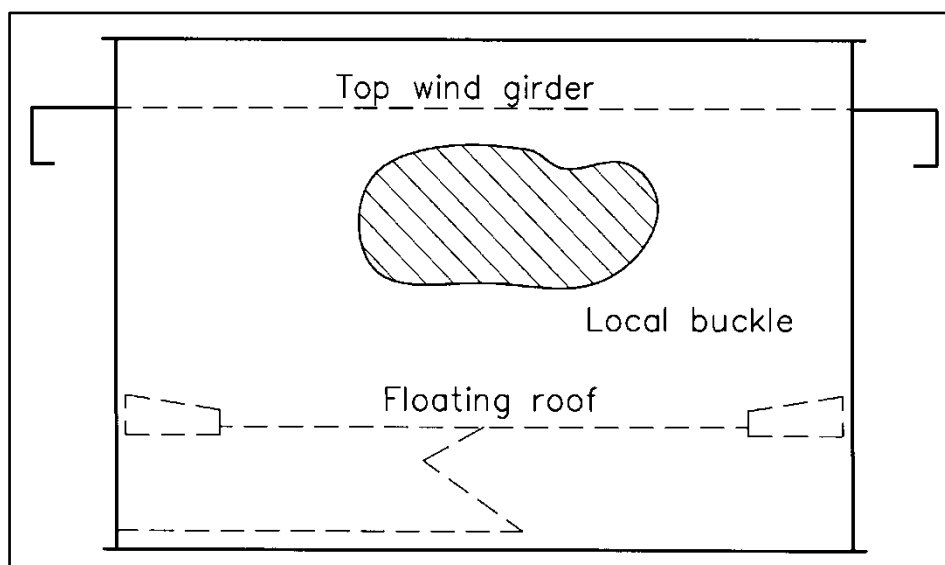


Figure 55 Wind induced buckling below wind girder

8.6.1.2 Buckling due to partial vacuum inside the tank

Buckling of shells in fixed roof tanks may be caused by failure of the vacuum relief valve(s) on the roof. The partial vacuum caused inside the tank will result in a uniform coaxial compressive load on the tank shell from the downward pressure on the roof combined with radial inward pressure acting all around the tank shell above the liquid level.

Buckling results in a uniform distribution of waves around the shell with one or more tiers of waves stacked vertically. When the extent of the deformation is relatively light, the buckles may be elastic, and removal of the load sometimes results in a tank recovering its original shape. However, if the buckles are so acute as to result in plastic deformation, recovery will not occur. In that case a repair will be necessary. Installation of an additional intermediate wind girder will adequately repair the buckled area.

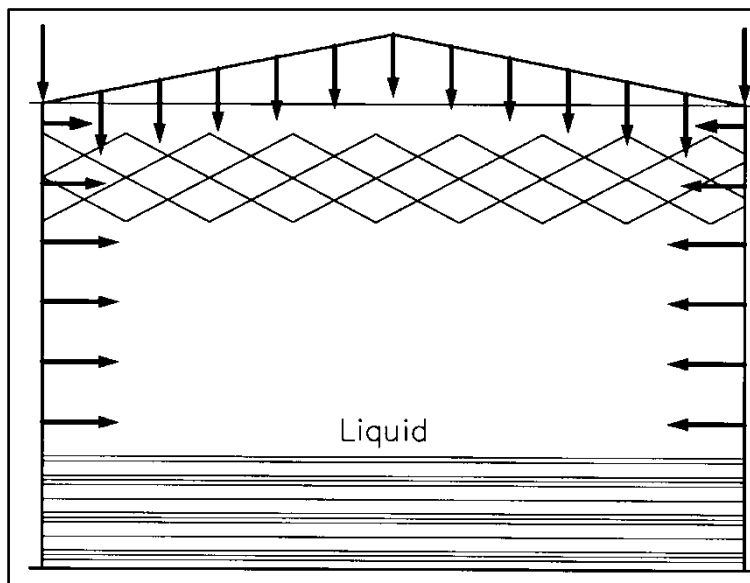


Figure 56 Buckling due to downward load on roof and external pressure on shell

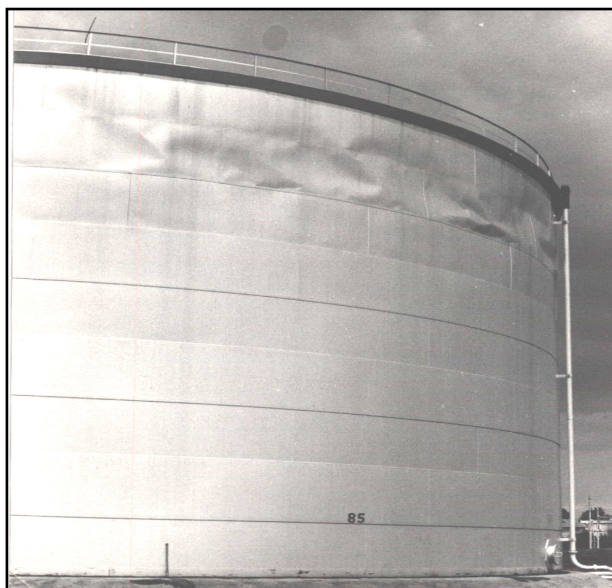


Figure 57 Fixed roof tank with internally corroded top course buckled due to vacuum

8.6.1.3 Buckling at the bottom-to-shell connection

This type of buckling is frequently referred to as 'elephant's-foot' buckling (see Figure 58). The deformation arises as a result of non-uniformly distributed axial loading, such as that experienced when the tank is subjected to horizontal acceleration during an earthquake. The sloshing motion of the liquid produces an overturning moment on the tank which results in compressive stress. This form of buckling may also be seen on fixed roof tanks that have experienced failure of the roof due to excessive overpressure or an explosion in the vapour space. A

roof failure will commence at the weakest point, generally the roof-to-shell connection, which gives rise to a non-uniform compressive load on the shell.



Figure 58 Elephant's foot buckling induced by an earthquake

8.6.2 Shell top wind girders

Floating roof tanks are provided with shell top wind girders to withstand all external loads acting on the top part of the tank shell and to transfer this load via the tank shell to the foundation. These external loads are the combined wind load and the vacuum caused by wind induced suction of air and vapour from the tank. In most cases a wind speed of 160 km/h (100 miles per hour) is assumed in the design calculation of the wind girder. During hurricanes or cyclones, extreme wind speeds, sometimes up to 260 km/h (160 mph), may be experienced (see Figure 51).

In countries where hurricanes can occur, it is recommended that tanks be kept at least 50% filled during the hurricane season. The tank shell is then supported by the product load and should be strong enough to resist the extreme external loads.

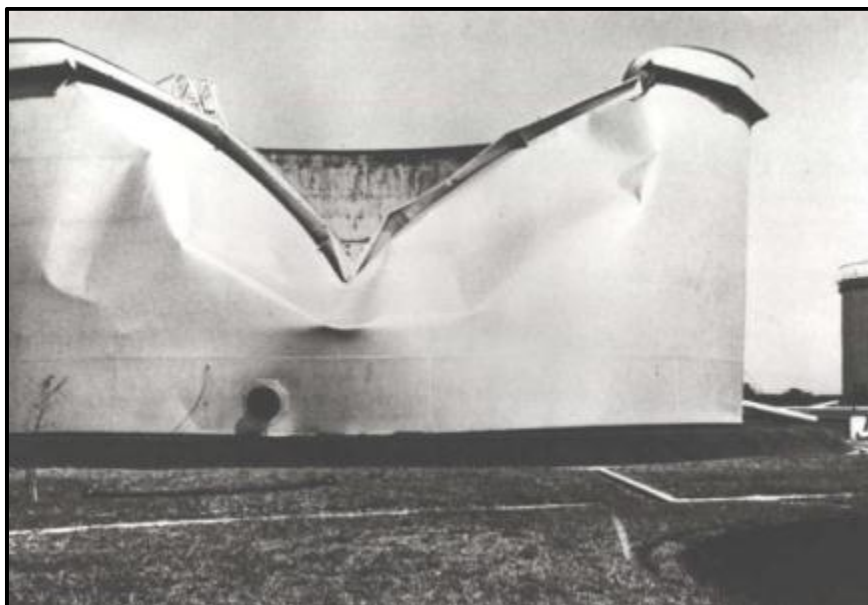


Figure 59 Empty floating roof tank collapsed during a cyclone
Wind speed - 260 km/h (160mph)

8.7 Manholes, nozzles and connecting piping

8.7.1 Shell manholes and nozzles

Shell manholes and nozzles blanked off with cover plates should be regularly inspected. For very large storage tanks the manholes and nozzles installed in the lowest one metre of the tank shell will follow the outward bulging of the tank shell when the tank is filled. This bulging of the tank shell may increase the possibility of leakage and rotation of the nozzle flange (see Figure 52).

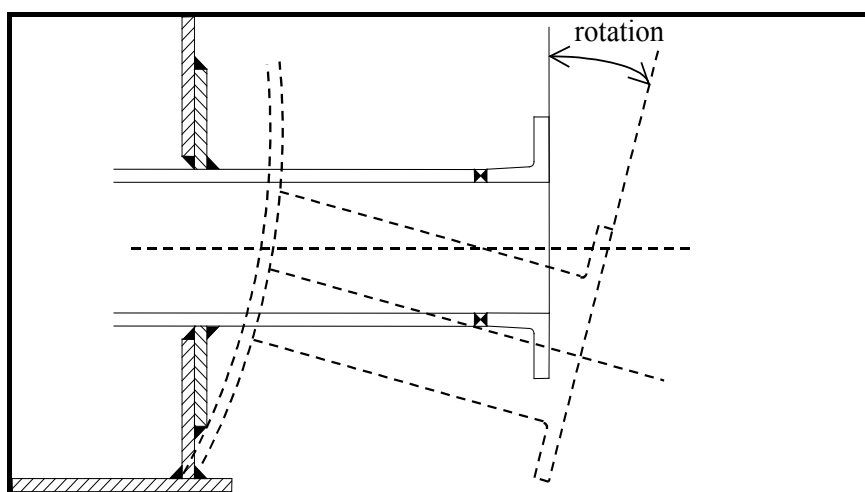


Figure 60 Rotation of nozzle flange induced by outward bulging of shell

When new manholes or nozzles are installed in an existing tank it is good practice to re-hydrotest the tank to full filling height. This will ensure tank integrity, minimise peak stresses induced by the welding process, and improve resistance to brittle fracture. (See also Section 8.3.)

8.7.2 Connecting piping

The connecting piping should be regularly inspected for leakage at the flanged connections to the tank nozzles.

Differential settlement between tank and connected piping may cause additional bending moments and loads not allowed for in the original design. It may become necessary to readjust the pipe supports near the tank shell. In extreme cases it may be necessary to jack up and re-level the tank foundation, or realign the piping.

Where excessive settlements are likely to occur, expansion joints or bellows may be introduced to minimise the transfer of forces from tank connections to the shell (see Figure 53).

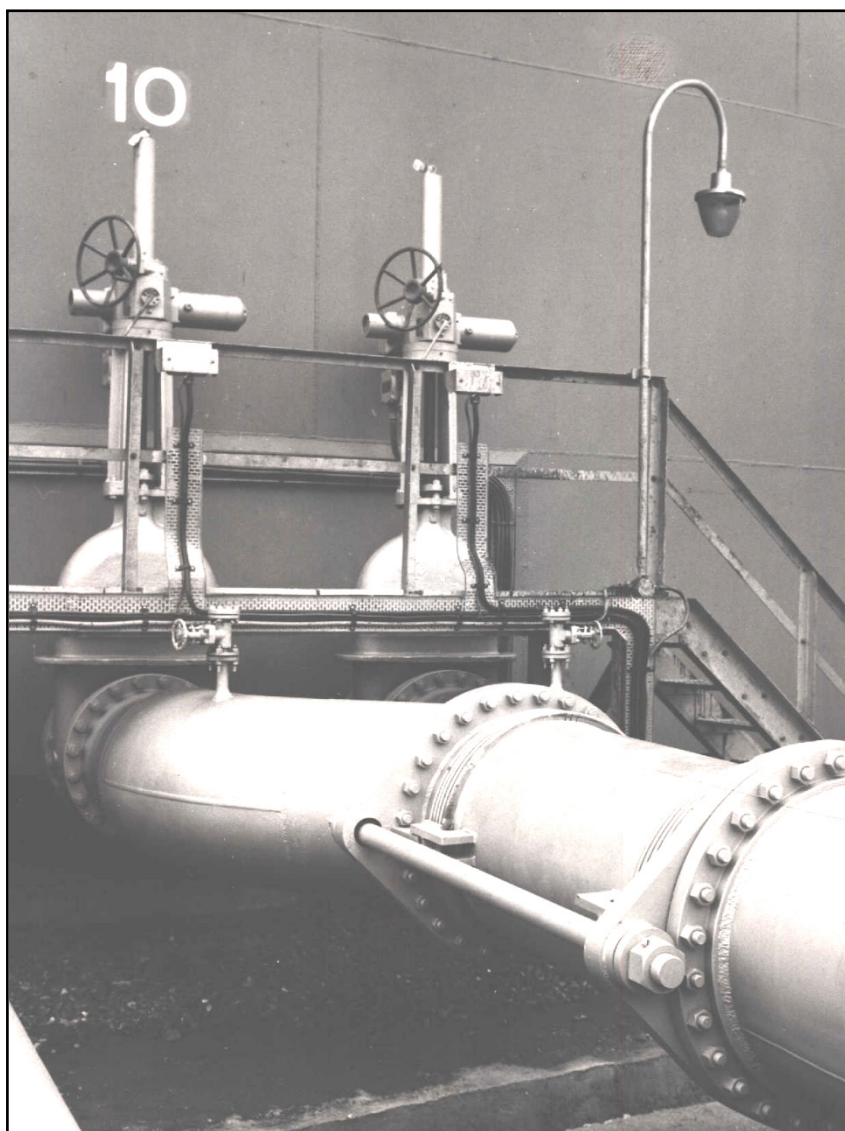


Figure 61 Expansion bellows in pipe connection to tank nozzle

8.7.3 Rejection limits shell nozzles

When the integrity of the tank is being assessed, an assessment of the nozzles is equally important. Thinning of the nozzle can result in failure of the nozzle and subsequently the tank. This can be by leakage caused by the internal pressure acting on the wall of the nozzle or by leakage caused by excessive bending of the nozzle due to settlement of the tank.

8.7.3.1 Stresses induced by even and un-even circumferential settlement

Excessive settlement of the tank induces moments in the nozzle that may have an effect on the integrity of the nozzles. Appendix P of API 650 provides a method for calculating acceptable criteria for the (shell) nozzles connection. Another suitable method is to perform a FEM Analysis on the nozzle structure which includes the connecting piping from its furthest existing fixed support away from the tank and including the rotation of the tank shell under the static head of the maximum product level in the tank. When assessing the maximum allowable stress the following formula applies:

$$\sigma_{\text{actual}} \leq \sigma_{\text{max. allowable}}$$

Where:

σ_{actual} Actual stress in the shell local to the nozzle connection or the reinforcement plate (N/mm²)

$\sigma_{\text{max. allowable}}$ Maximum allowable stress in the shell (N/mm²)

The above mentioned assessment is required when the option "moments present, effect on integrity" is selected in the confidence assessment of the tank shell.

8.7.3.2 General corrosion nozzles

When it can be assumed that a tank operates within its settlement limits as described in Chapter 6 of this document, so that the actual stresses in the nozzle are not affected or increased by additional loads from settlements, the rejection criteria with respect to general corrosion of both the shell and roof nozzles is the larger of 50% of the nominal thickness or 2.5mm.

$$t_{\text{min acc.}} = 50\% \cdot t_{\text{nom}}, 2.5\text{mm (whichever is larger)}$$

Where:

$t_{\text{min acc.}}$ Minimal acceptable nozzle thickness (mm)

t_{nom} Nominal nozzle thickness (mm)

If settlement conditions are reaching their prescribed limits, the design of the nozzle is insufficient or thickness is less than 50% of nominal thickness, an FEM analysis is required to determine the rejection limit.

8.7.3.3 General corrosion internal piping

For internal piping the same conservative factor of 50% is adopted for rejection. When thickness is less than 50% of nominal thickness the following is required to determine the rejection limit.

For internal piping subject to at least 0.5 bar internal pressure the following applies: Rejection limits for internal piping subject to internal pressures exceeding 0.5 bar the rejection limits shall be established in accordance with PD 5500.

8.7.3.4 General corrosion circular bolted blind off plates

For minimum thickness calculations of reinforcing plates the following applies:
If the outer diameter D_0 of the reinforcing plate is in the following boundaries:

$$1.5 * d \leq D_0 \leq d$$

then the minimum allowable thickness is two-thirds of the original design thickness.

If the outer diameter is not to these limits, then the minimum allowable thickness is calculated from:

$$t_{c \min} = \left(\frac{2 * d}{D_0} \right) * 0.6667 * t_c \text{ original}$$

Where:

D_0 outer diameter of the reinforcing plate (mm)

d outer diameter nozzle (mm)

8.8 Clean-out doors and openings

8.8.1 Clean-out doors

Clean-out doors fitted flush to a tank bottom are generally installed only in oil tanks where sediment may settle on the bottom of the tank, e.g. sand in crude oil tanks near oil fields. Where such clean-out doors, with openings of approximately 1.2m x 1.2m, are installed, the bolted door cover should be inspected for leaks. This is particularly important for large diameter tanks, where the lowest shell course will bulge due to normal liquid loading. A clean-out door has a very thick bottom annular plate, which is relatively stiff. This prevents it following the bottom settlement as readily as the adjacent bottom plates. Regular inspection should include checks that clean-out doors are properly supported by the tank foundation. Unacceptable gaps and uneven settlements should be repaired if necessary by re-levelling of the foundation.

8.8.2 Clean-out openings

When clean-out doors are not installed, a clean-out opening can be cut in the lowest shell course for access during maintenance. If removed carefully, the door plate can be reinstalled. It is recommended that when removing the door plate, an upstand of 100mm of shell plate is left in place to avoid disturbing the bottom-to-shell connection. All corners of the cut-out should be generously radiused.

During cleaning operations, the upstand should be protected from damage, e.g. by placing some material to form a slope on both sides of the opening (see Figure 62).

After cleaning, the plate should be reinstalled using a full penetration weld and be 100% radiographed or 100% volumetric UT scanned. A special welding procedure and weld sequence is required to minimise distortion and welding induced stresses. Finally, before re-commissioning the tank should be full height hydrotested.

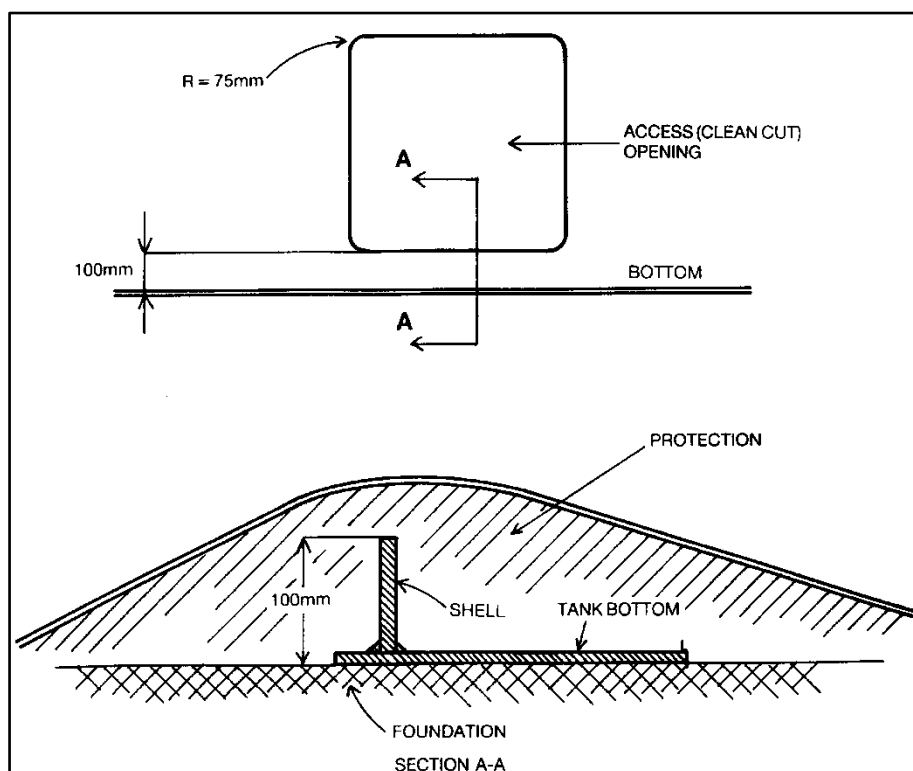


Figure 62 Uprand of a clean out opening protected from damage

8.9 Earthing

Above ground metal storage tank shells are provided with earthing systems to prevent build-up of potential differences between steel tank components and the product, caused by liquid transport/movement, lightning or electromagnetic radiation. Earthing systems should be designed by specialist companies, and should take into account additional measures such as cathodic protection systems. Although similar in nature, it is recommended that lightning protection systems be separate from tank earthing systems. When designing earthing systems, special attention needs to be given to all tank accessories (e.g. level gauges, high level shut down systems etc.).

Depending on the size of the tank, several earthing points may be provided at equally spaced locations round the shell base. Typically, each earth point consists of a lug or boss welded to the shell. An earth conductor is bolted to the lug or boss and leads to one or more earth electrodes. These electrodes are electrically conducting rods driven into the ground or buried plates that ensure intimate contact with, and electrical connection to, earth. Some installations include an earth grid located below grade that connects individual electrodes.

Inspection of a tank shell earthing system includes a visual inspection and an electrical integrity test. A routine visual inspection is limited to the above grade components. Suitably qualified personnel should carry out the electrical test.

In conducting a visual inspection, the inspector should pay particular attention to the following items:

- loose and/or missing components;
- mechanical damage;
- damaged or inadequate protective coating;
- corrosion;
- possible insulators (e.g. gaskets, metal face corrosion (rust)); and
- tank accessories (or changes in tank accessories).

Electrical integrity tests should measure the resistance value of the earthing system and should test its electrical continuity. These tests should be requested at the time of an inspection.

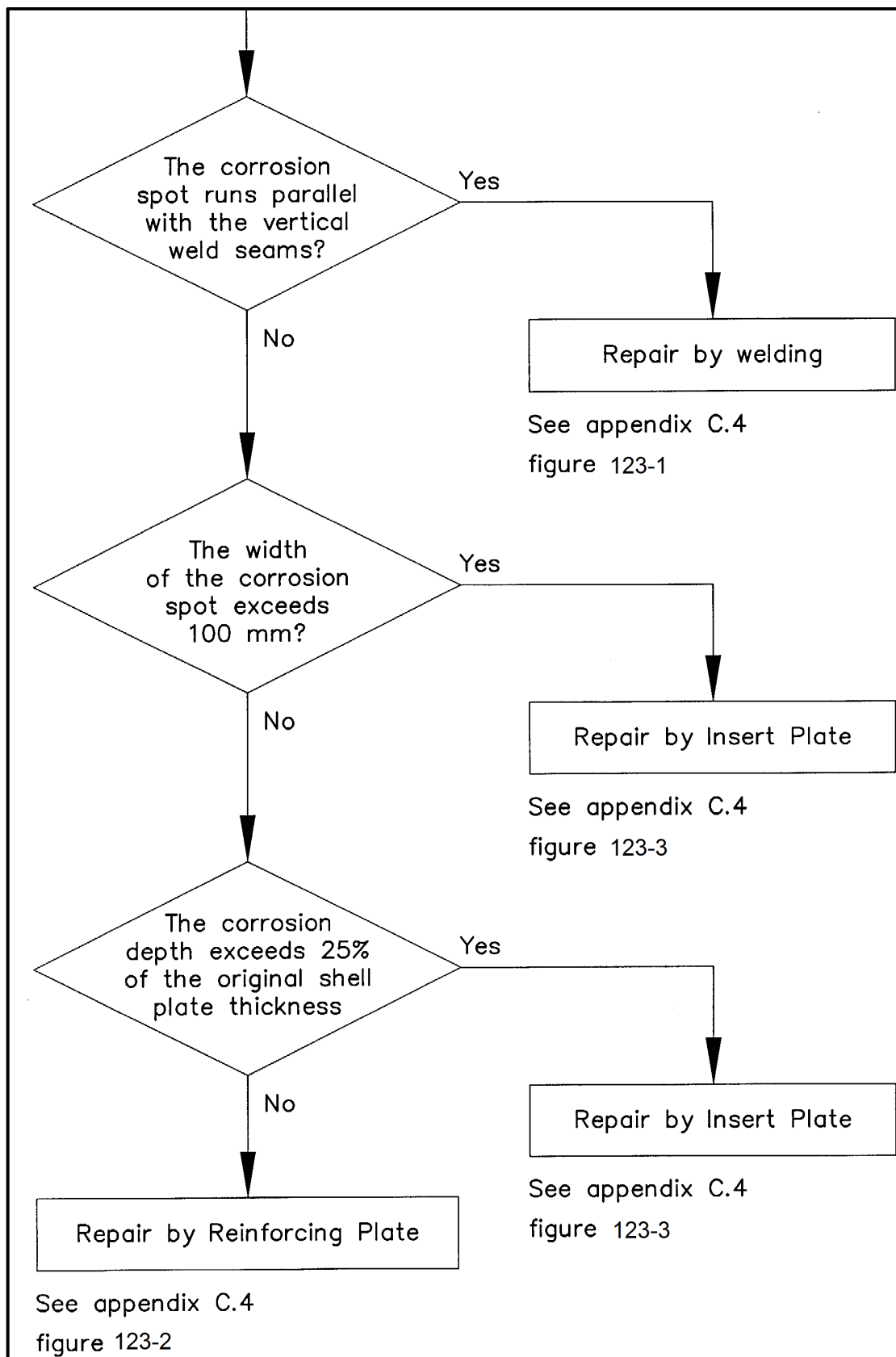
It should be noted that where a cathodic protection system is employed to reduce tank corrosion, a more complex earthing system is required.

Earthing of a storage tank floating roof is described in Section 11.8.

8.10 Repair/modification methods - some typical examples

Each spot exhibiting excessive corrosion should be evaluated for a proper repair. The repair method should be based on international standards. The flow scheme shown in Figure 65 will assist in establishing a proper repair procedure for each corroded spot. Typical repair solutions are presented in Appendix C.4.

Buckled areas in tanks should always be repaired using insert plates. Because indentations are generally larger than corroded spots, the shell will always need to be supported by extra beams when a dented shell is repaired.

**Figure 63 Corrosion repair flow chart**

9 Tank roofs - general

9.1 Introduction

Tank roofs are designed in accordance with recognised national or international standards such as EN 14015 and API 650. They are designed to withstand the specified (design) loads, and are made from materials as specified in the standards.

Various construction solutions are possible to cope with specific site conditions, but in general the following types are used:

Fixed roofs (see also 2.3.1a)):

- cone or dome membrane roofs (roofs without supporting structures);
- cone or dome roofs with supporting structures; or
- column supported roofs.

Floating roofs (see also 2.3.1 b)):

- single-deck pontoon roofs;
- double-deck pontoon roofs; or
- special buoy type and radially reinforced roofs.

9.2 Determination of roof plate thickness and condition

The topside of fixed and floating roofs generally suffers little corrosion if paint coatings have been well maintained. Paint breakdown generally indicates problems.

Visual examination of the paint coating readily alerts the inspector to where metal loss can be expected. Since underside corrosion on cone and floating roofs is generally quite uniform, sampling thickness by ultrasonic scans for mechanical measurement is satisfactory (see also Section 5.3.4).

Accelerated underside corrosion of cone roofs may occur at crevices between roof plates and support structure and at the roof-to-shell weld joint. With floating roofs, accelerated underside corrosion may occur on the sides of pontoons above the liquid level, also where rim seals are attached. Inspection of these areas is also required to discover if corrosion has occurred. Access is required by the inspector, and areas will require cleaning to allow a thorough examination.

9.3 Rejection limits fixed roofs

The minimal acceptable thicknesses of the different roofs and roof components are described in the following paragraphs.

9.3.1 Supported fixed roof

a) Structural integrity

Tanks satisfying the following requirement: distance between support structure at periphery close to the tank shell < 1.7m for cone roof tanks or < 3.25m for dome roof tanks.

The rejection limit with respect to general corrosion of the roof plates of a fixed roof is 75% of the nominal plate thickness. In formula:

$$t_{\min \text{ acc fxt. roof gen.}} = 75\% t_{\text{nom}}$$

Where:

$t_{\min \text{ acc. fxt roof gen.}}$ Minimum acceptable plate thickness of the fixed roof (mm)
 t_{nom} Nominal plate thickness (mm)

Tanks NOT fulfilling the following requirement: distance between support structure at periphery close to the tank shell < 1.7m for cone roof tanks or < 3.25m for dome roof tanks.

The rejection limit with respect to general corrosion of the roof plates of a fixed roof is 80% of the nominal plate thickness. In formula:

$$t_{\min \text{ acc. Fxt. roof gen.}} = 80\% t_{\text{nom}}$$

Where:

$t_{\min \text{ acc. fxt roof gen.}}$ Minimum acceptable plate thickness of the fixed roof (mm)
 t_{nom} Nominal plate thickness (mm)

or

The rejection limit with respect to general corrosion of the roof plates can be calculated considering the following normalised loads:

- dead-weight of the roof plates;
- Superimposed load.

The superimposed load is the larger of:

- The combined load by Snow load (see EN 1991-1-3) and design vacuum;
- The combined load by Live load (see EN 1993-4-2) and design vacuum;
- 1.2 kN.

or

The rejection limit with respect to general corrosion of the roof plates can be established by means of a Finite Element Analysis.

Only when the following additional requirements are satisfied:

- An effective snow accumulation prevention program should be in place;
- Access of personnel over 3 persons is denied and providing that they do not gather together in a small area of the roof.

or

- A vacuum should be prevented during the time access of personnel on to the roof is required (no liquid movements out of a tanks during the actual work time of personnel on the roof). A rejection limit under general corrosion attack may be used of 2.25mm.

$$t_{mn,acc. \text{ fxt roof gen.}} = 2.25\text{mm}$$

Where:

$t_{min \text{ acc. fxt roof gen.}}$ Minimum acceptable plate thickness of the fixed roof (mm)

b) Operational integrity

The rejection limit with respect to operational integrity is such that no perforations are allowed.

c) Safety integrity

The rejection limit with respect to safety is 2mm in a 500 x 500mm area.

$$t_{min \text{ acc. Fxt. roof sfty.}} = 2\text{mm}$$

Where:

$t_{min \text{ acc. fxt. roof sfty.}}$ Minimal acceptable plate thickness of a fixed roof (mm)

d) Internal pressure

The rejection limit shall be calculated using the following formula:

For spherical (dome) roofs:

$$e_p = \frac{pR_1}{20SJ}$$

For conical roofs:

$$e_p = \frac{pR_1}{10SJ}$$

Where:

- e_p Minimal roof plate thickness (mm)
- p Internal pressure less dead weight of roof plates (mbar)
- S Maximum allowable stress (N/mm²) ($S = 0.8 \times$ minimum specified yield strength or 172 N/mm² when no material data is available)
- J Joint efficiency factor [-]
- R_1 Radius of the curvature of the roof (m) (for conical roofs; $R_1 = R/\sin\theta$)

where:

- R Radius of tank (m)
- θ Slope of roof (°)

e) Roof supporting structure

In case the roof plates are corroded from the inside > 12.5% of the nominal as-built thickness; the structural integrity of the roof support structure is assumed to

be 25% corroded and will, in such occasion, need to be evaluated by means of a FEM analysis.

9.3.2 Self-supporting fixed roof

a) External pressure (buckling)

For self-supporting fixed roofs (roofs without roof support structure), the rejection limit for external pressure/buckling can be calculated using the following formula:

$$e_p = 40R_1 \sqrt{\frac{10P_e}{E}}$$

Where:

- e_p Minimal roof plate thickness (mm)
- P_e External loads plus self-weight of the plates plus design internal negative pressure where applicable (kN/m²)
- E Young's modulus (N/mm²) for the material in use and under the actual operating temperature of subject tank. For carbon/carbon-manganese steel the temperature where the factor E is to be adjusted is above 100°C. For stainless steel this temperature is 50 °C
- R_1 Radius of the curvature of the roof (m) (for conical roofs; $R_1 = R/\sin\theta$, where
- R Radius of tank (m)
- θ Slope of roof (°).

Note: For dome roofs the Radius (curvature) of the roof should not be beyond following boundaries:

$$0.8 * D_{\text{tank shell}} < R_{\text{roof}} < 1.5 * D_{\text{tank shell}}$$

f) Structural integrity

The rejection limit for structural integrity can be calculated using the following formula:

$$t_{\text{min acc. fxt roof gen}} = 80\% t_{\text{nom}}$$

Where:

- $t_{\text{min acc. fxt roof gen.}}$ Minimum acceptable plate thickness of the fixed roof (mm)
- t_{nom} Nominal plate thickness (mm)

Alternatively, the rejection limit can determined with help of an FEM analysis.

10 Fixed roofs (cone roofs and dome roofs)

10.1 General

Tank roofs are an integral part of the containment structure. It is therefore important to detect any deterioration at an early stage. The roof is also in many ways the weakest part of the tank, (for riveted tanks the roof can be as thin as 3mm).

Because the roof is usually the most exposed part of the tank, condensation/evaporation can occur on the inside resulting in accelerated corrosion. As roof plates are normally lap welded on the outside, deposits can also form in the internal crevice, which can cause roof cracking (see Figure 56).

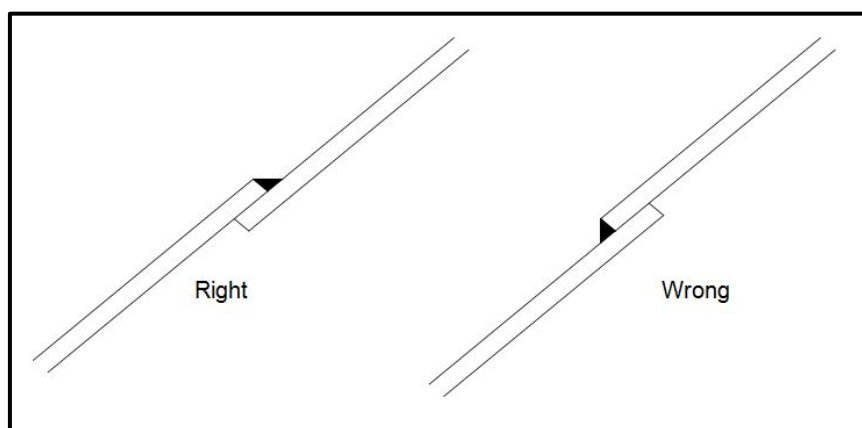


Figure 64 Detail of normal roof plate weld

The roof-to-shell weld, see Figure 68, is generally a single fillet weld between the edge of the roof plates and the top curb angle of the shell. This will create a crevice in which corrosion may also occur as shown in Figure 65.



Figure 65 Example of crevice corrosion

The roof plates form part of the shell-to-roof compression ring. The weld seam between roof plates and top curb angle is often made purposely weak to create a frangible roof joint (see EEMUA 180⁽²⁵⁾).

For larger diameter tanks, the roofs are generally supported by roof trusses, usually located inside the tank. Special designs for aggressive vapour-space corrosion are available where the roof supporting structure is situated on top of the roof plates.

The areas requiring a greater level of inspection are therefore mainly on the inside, and only limited information will be available from a general internal inspection unless adequate scaffolding is provided during inspections. However, external inspection of the roof can often give the first indication that the tank has been over-pressured, e.g. buckling of roof plates or tearing of the roof-to-shell weld.

Since the roof plates are thin, general as well as local corrosion can very quickly lead to penetration or partial collapse of the roof.

10.2 Roof manholes and nozzles

Vertical nozzle pipes of 'blanked off' branches (dead legs) accumulate condensation in a similar manner to roof structural members. This results in local thinning usually just above the outside attachment welds. The presence of the weld aggravates corrosion.

10.3 Roof vents (ventilation of tanks) and emergency relief vents

10.3.1 The functioning of roof vents

Fixed roof tanks have a vapour space above the stored liquid. This will cause two types of evaporation loss during operation: 'breathing loss' and 'filling loss'.

Breathing loss is caused by the difference in temperature between day and night (see Figure 66).

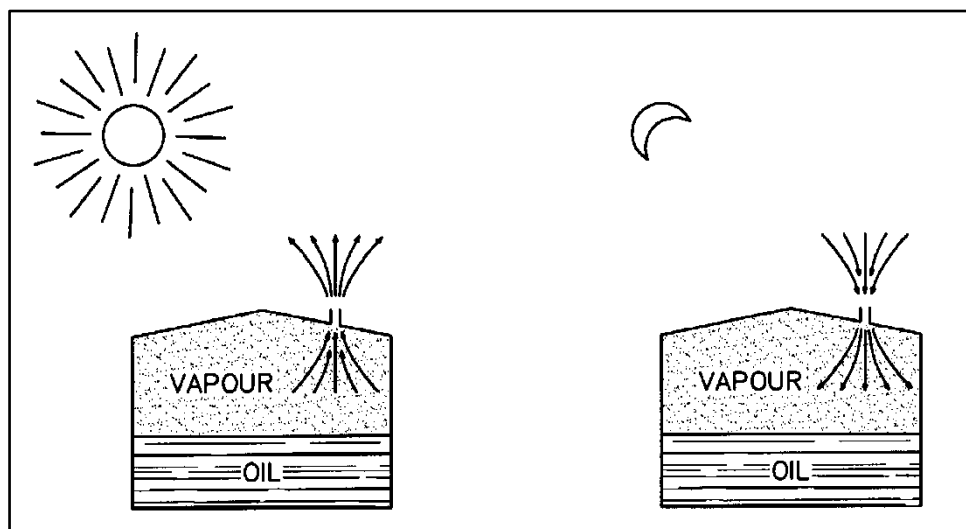


Figure 66 Breathing loss of fixed roof tanks

When a fixed roof tank is being filled, the vapour present above the rising liquid will be forced out of the tank into the atmosphere. This type of loss is called the 'filling loss' (see Figure 67).

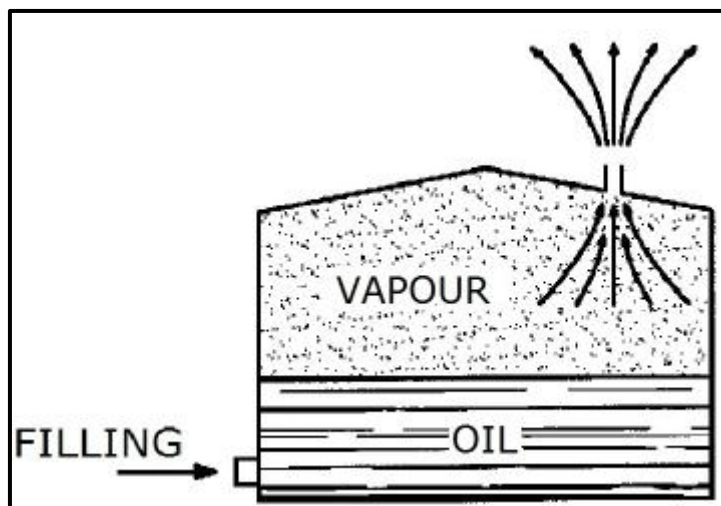


Figure 67 Filling loss of a fixed roof tank

Roof plates are not attached to the supporting structure but to the top curb angle of the tank shell only. The attachment is a small fillet seal, which helps to create a weak roof-to-shell connection (a possible frangible roof joint)—see Figure 68.

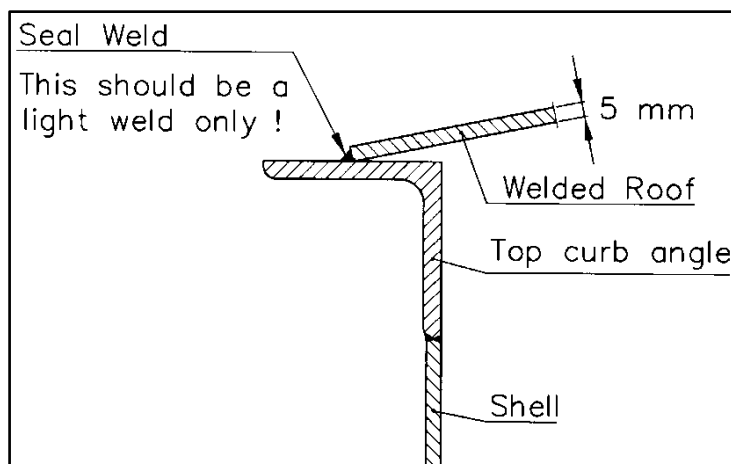


Figure 68 Weak roof-to-shell connection (frangible roof joint)

The purpose of the frangible joint is to allow relief of an abnormally high overpressure or internal explosion by means of failure of the weak roof-to-shell connection, and not via a ruptured tank shell or bottom-to-shell connection. When such an accident occurs only the roof is ruptured, and the product is safely contained inside the tank.

For small tanks, e.g. less than 12.5 metres in diameter, especially those designed with dome and membrane roofs, the effective functioning of a frangible roof joint may be less certain.

More information about frangible roof joints can be obtained in EEMUA 180.

10.3.2 Venting requirements for fixed roof tanks

Venting requirements and capacities of open or pressure/vacuum relief vents should be calculated using ISO EN 28300, whilst taken into account the remarks made in the 2nd edition of EN 14015 with respect to allowing the tank never to be exposed to internal pressures in excess of the design pressure. Venting capacities of existing tanks may have been assessed by using the theories of API 2000⁽²⁶⁾, Appendix F of BS 2654 or Appendix L of EN 14015, prior to the publication of the 2nd edition of EN 14015. In these cases the requirement for emergency vent calculations were based on an allowable (over)pressure of 110% of the design pressure, but this is not allowed (anymore) since the publication of Eurocodes 1 and 3 (EN 1991, respectively, EN 1993). The new theories expressed in these Eurocodes require alteration to the philosophy with respect to establishing the set pressure of these vents (the set pressure is the pressure at which operational and emergency relief vents – in case the frangibility requirements of the roof-to-shell joint can't be met – do open).

The following theory helps the operators and maintenance staff of storage tank to assess the opening pressure (= set pressure) of operational and emergency relief vents:

Example A:

Assume the storage tank has the following characteristics:

- The roof-to-shell joint is considered to meet the frangibility requirements of either Appendix F of BS 2654 or Appendix K of EN 14015;
- The tank is classified as a high pressure tank as specified in BS 2654 (i.e. maximum design pressure is +56 mbar and maximum design vacuum is -6 mbar); and
- The chosen vent has a pressure difference between (i) opening pressure and (ii) pressure when fully open of 15%.

The determined set pressure at the pressure relief side of the vent is:

- $56 \text{ mbar} -/- 15\% \text{ of } 56 (8.4 \text{ mbar}) = 47.6 \text{ mbar}.$

The determined set pressure at the vacuum side of the vent is:

- $6 \text{ mbar} -/- 15\% \text{ of } 6 (0.9 \text{ mbar}) = 5.1 \text{ mbar}.$

Example B:

Assume the tank has the following characteristics:

- The roof-to-shell joint is NOT considered to meet the frangibility requirements of either Appendix F of BS 2654 or Appendix K of EN 14015. This necessitates the tank being equipped with an emergency relief vent;
- The tank is classified as a low pressure tank as specified in EN 14015 (i.e. maximum design pressure is +25 mbar and maximum design vacuum is -6 mbar);

- The chosen vents (both the emergency relief vent as well as the operational pressure relief vent) have a pressure difference between (i) opening pressure and (ii) pressure when fully open of 10%;
- The nozzle to which the emergency vent is mounted has an inside diameter of 600 mm (24") whereas the pallet of the emergency relief vent has a diameter of 625 mm (25"), including the size of the gasket;
- A difference of 12.5% is assumed to be taken into account to allow the two different vents not to interfere with each other under operational conditions.

The determined set pressure at the emergency pressure relief side of the vent is:
 $25 \text{ mbar} \pm 10\% \text{ of } 25 (2.5 \text{ mbar}) = 22.5 \text{ mbar}$

The emergency relief vents do not close at the same level of the set pressure as the pallet diameter is bigger than the nozzle diameter at which it is mounted by 25 mm (1"). This causes closing of the emergency relief vent at a lower pressure, compared to the set-pressure of:

$$((\pi) / 4 * 600^2 / (\pi) / 4 * 625^2) * 22.5 \text{ mbar} = 0.926 * 22.5 = 20.74 \text{ mbar}$$

The full open pressure of the operational relief vent should now be set at a level of:

$$20.74 \text{ mbar} \pm 12.5\% \text{ of } 20.74 \text{ mbar} (2.59 \text{ mbar}) = 18.14 \text{ mbar}$$

The determined set pressure at the pressure relief side of the operational pressure relief vent is:

$$18.14 \text{ mbar} \pm 10\% \text{ of } 18.14 (1.814 \text{ mbar}) = 16.33 \text{ mbar}$$

The determined set pressure at the vacuum side of the vent is:

- $6 \text{ mbar} \pm 10\% \text{ of } 6 (0.6 \text{ mbar}) = 5.4 \text{ mbar}.$

Examples of vent sizing calculations in accordance with API 2000 are given in Appendix D.2.

Figure 69 shows a fixed roof tank where the effect of the temperature drop has been ignored in sizing the venting capacity of the vacuum valves, resulting in an inadequate number of vacuum valves.

10.3.3 Inspection and maintenance of roof vents

Roof vents and pressure–vacuum valves should be inspected at regular intervals to ensure that they are functioning properly. In particular, the ventilation openings should be checked to confirm that they are not plugged by dirt or foreign matter, which would cause a reduction in ventilation capacity.

Regular maintenance during service should be carried out to ensure operability.

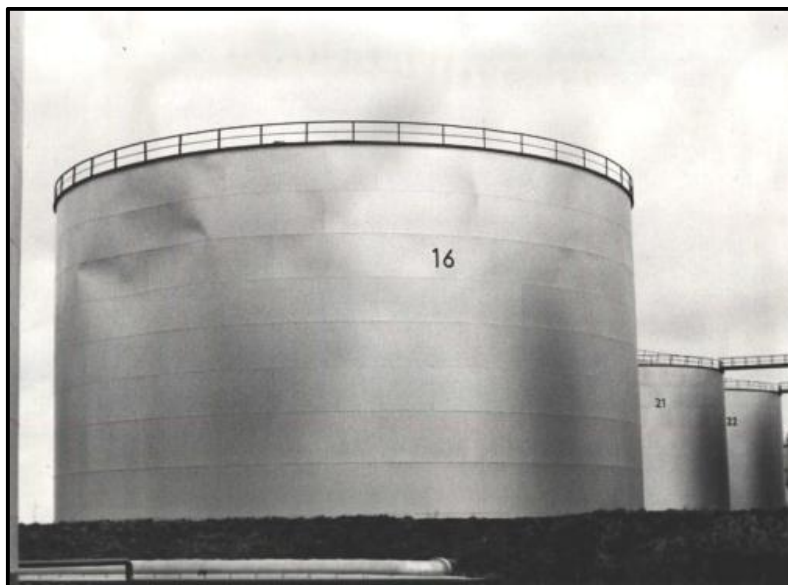


Figure 69 Fixed roof tank damaged due to inadequate venting

Emptying of tanks under gravity can result in high discharge rates. Where this is proposed, the venting capacity of the vacuum valves should be checked for adequacy. Otherwise buckling of the roof and/or shell may occur.

10.3.3.1 PVVs and 'valve' type emergency vents

These are normally automatic dead weight pressure relieving devices set at low pressures to prevent excessive pressure or vacuum. These will normally be scheduled for removal for full (off stream) testing and inspection at the same time as the tank item, which they are protecting, is released for its scheduled OFL examination.

They shall also be scheduled for interim (on stream) inspection in situ, to check for correct operation, seal/soft goods condition, overall condition (cages etc.), and ensuring they are free from blockage or fouling. Safety considerations should be discussed prior to the inspection due date, and detailed method statements & procedures produced prior to implementation of inspection.

The period between on-line inspections are to be determined from review of process conditions, the results from previous examinations, and specific site requirements. A maximum incremental on-line inspection interval should be identified, and the ONL interval penalised if anomalies are found during the on-site inspection.

A record of the valve design data, inspection results, and any repairs performed is to be maintained by the asset owner. This data should be made available to the competent & qualified overhaul & inspection technicians.

10.3.3.2 Bursting discs

Bursting discs (if fitted) are to be inspected by removal, and both sides of the membrane checked for signs of corrosion, or fouling. Following careful cleaning, the disc shall be examined for mechanical damage, cracking or fatigue.

A bursting disc shall be scheduled for replacement at inspection if:

- The manufacturer has specified a limited bolting torque to be used in the installation;
- Whether replacement is deemed more economic; and/or
- If there is a manufacturer's recommended life of the disc in the specific process environment.

10.3.3.3 Pivoted type emergency vents

These are normally pivoted or guided lids/flaps, which use a dead weight to provide a seal against a soft joint, and are designed to provide a safe release of a large volume of product. A maximum incremental on-line inspection interval should be identified, and the ONL interval penalised if anomalies are found during the on-site inspection.

The in-situ inspection of these items should consist of:

- Examination of the pivot/guide mechanism for corrosion or mechanical damage;
- Ensuring the lid is free to move, the hinge lubricated, and can provide full area venting;
- Ensuring that the item is not fouled;
- Checking the lid and seal for damage/distortion, and that the seal functions when closed; and
- Checking any weights used are securely fitted and have not been tampered with a record of the valve design data, inspection results, and any repairs performed is to be maintained by the asset owner.

This data should be made available to the competent and qualified overhaul & inspection technicians.

10.3.3.4 Vents, explosion doors, frangible joints etc.

These, and other similar items which are integral to the main equipment item, are not removable and are therefore inspected in situ as part of the main equipment item to which they relate. The main purpose of examination is to verify their condition, and make an assessment whether they would perform their intended protection function, if required to do so.

10.3.4 Possible ventilation problems

Ventilation problems are caused in fixed roof tanks by mal-operation or accident when the allowable overpressure or vacuum is considerably exceeded. Examples given below though not exhaustive have been experienced more than once. Operators and inspectors of tanks should be aware of these risks in order to reduce the possibility of such accidents.

i) Inadequate venting capacity due to modifications to the tank or its operation

The total venting capacity should be checked when:

- the pumping-in or pumping-out rates are changed;
- the function of the tank is changed (product change);
- the height of the tank is increased; and/or
- the tank is converted from a non-heated tank into a heated tank.

Such modifications may require additional venting capacity.

ii) Gravity discharge

Gravity discharge is sometimes proposed after a water test to remove the test water from the tank in the shortest time. In this situation it is possible to temporarily increase the venting capacity by opening roof manholes and dip hatches.

iii) Wire netting in the openings of vents or relief valves

Wire netting installed in the openings of open vents or relief valves to prevent birds nesting should have openings of at least 6mm, as specified by BS 2654. Fine mesh wire netting intended to act as a flame arrester (see Section 10.3.5) should never be installed, since the capacity of the vents or relief valves could be reduced by debris. Water on the mesh can freeze and cause further blockage (See Figure 70).



Figure 70 Collapsed fuel tank: vents clogged by frozen rain on the wire mesh

iv) Boil-over of a tank

Due to mal-operation, water may enter a tank storing a hot product in excess of 100°C. The water will vaporise and the resulting increase in pressure in the vapour space may rupture the weak roof-to-shell connection. The steam and oil will form emulsion which, due to the large increase in volume, may boil over the top of the shell. (See Figure 71)

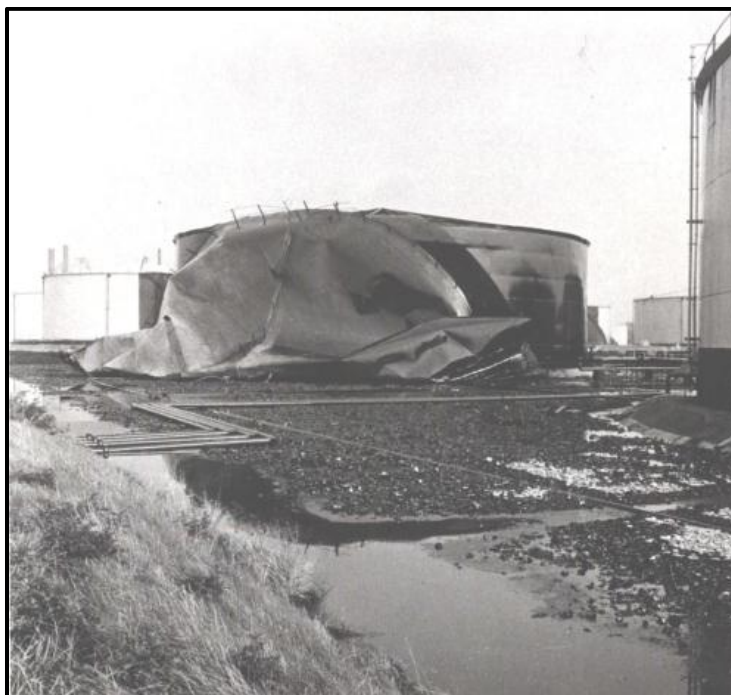


Figure 71 Roof plate blown off due to a boil over when water entered a hot oil tank

10.3.5 Flame arresters

Flame arresters are safety devices preventing the passage of a flame entering or leaving a pipeline or vessel in the case of an explosion, lightning strike or fire while permitting the flow of gases or vapours under normal operating conditions. They are installed in-line or as end-of-line devices such as detonation arresters or pressure-vacuum (P/V) tank breathing valves. In-line flame arresters installed in piping systems are to protect downstream equipment. End-of-line arresters are installed at the end of a pipeline or integrated into P/V tank breathing valves to prevent flames from entering the confined space.

Whereas the installation of flame arresters in vapour return and balancing lines carrying hazardous product vapours from or to a tank is mandatory in every country, the integration of flame arresters in P/V vents used as breathing devices on storage tanks preventing the described flame transmission is not allowed or mandatory in every country and needs to be carefully verified on a case by case basis (see also EEMUA 213⁽²⁷⁾).

Flame arrestors are divided into endurance burning arresters, withstanding a flame penetration for a longer period of time, and deflagration arresters which can only prevent a flame penetration for a single short term event such as a lightning strike or an explosion. Once the arrester has been hit by a flame it requires an immediate replacement.

Due to the very tiny mesh size attention must be paid to potential blockage of these devices. Causes for any kind of clogging can be related. They include:

- product vapour property and composition (e.g. danger of polymerisation);
- environmental atmosphere (e.g. dust); and/or
- weather condition (freezing mist during winter time).

End-of-line devices especially, being in direct contact with the external surrounding atmosphere, may be quickly affected by of these. Regular inspection and maintenance of flame arresters as stipulated in Section 10.3.3 need to be carried out. Required inspection intervals should be defined on a case by case basis taking storage condition and environmental impacts into account.

Differential pressure measuring devices over the upstream and downstream side of an in-line arrester may give a good indication about cleanness and condition of the mesh, but end-of-line devices especially require regular inspections and visual checks.

EN ISO 16852 ⁽²⁸⁾ stipulates the performance requirements, test methods and limits for the use of flame arresters. The required mesh size of an arrester depends on the product vapours and related explosion group. The MESG (Maximum Experimental Safe Gap) varies between <0.5mm and >0.9 mm. Flame arresters require an ATEX 94/9/EC ⁽²⁹⁾ approval certificate.

10.3.6 Pressure test of the fixed roof

After the tank shell has been tested by filling the tank with water, the roof joints should be tested by applying an internal air pressure of 5mbar for non-pressure tanks, and 3mbar above the design pressure for low pressure and high pressure tanks. Precautions should be taken to prevent overpressure.

Soap suds on the weld seams of the roof plates should be used for the detection of leaks. Attention is drawn to the need for careful monitoring of pressures during this testing.

The following recommendations are made to prevent accidents:

- Where pressure and vacuum valves are installed and have been blanked off prior to testing of the roof, it is essential to remove the blanks immediately upon completion of the test;
- Changes in weather conditions during the roof pressure test can cause sharp fluctuations in test pressure, e.g. a sudden drop in temperature can occur when cold rain falls on a hot roof during a thunderstorm. This can decrease the temperature in the vapour space and cause a vacuum. It is recommended that roof pressure tests are postponed when such weather changes are expected; and
- To avoid vacuum conditions due to changes in weather, roof vents should not be blanked off in advance of the pressure test.

10.3.7 Temporary closure of openings in open vents or pressure-vacuum valves during operation

The following are examples of where tanks have been damaged as a result of temporary closure of vents/valves.

- A roof was damaged when painters working on it placed a plastic bag over the roof vent to prevent the escape of noxious vapours. When product was discharged from the tank, the plastic bag blocked the opening of the roof vent;

- During a fire fighting exercise, water was sprayed on the fixed roof of a tank. The operators had laid a plastic sheet over the roof vent to prevent the entry of firewater. Again, the vent was blocked and damage resulted.

10.3.8 Protection against static electricity and lightning

Earthing connections, where provided, should be inspected at regular intervals, and checks made of the lug-to-shell weld to ensure that it is intact.

10.4 Column supported roofs

A column supported roof contains a number of vertical supported columns, which are arranged in a series of circumferential rings around a main single centre column. Maintenance on the roof supporting structure or columns is very costly and not easy compared to roof structures without columns.

The ringed columns are linked by girders, which also support the radial rafters on which the roof plating is laid. The roof normally has a shallow conical shape, typically 1 in 16.

Typical roof sections designs are given in Figure 72.

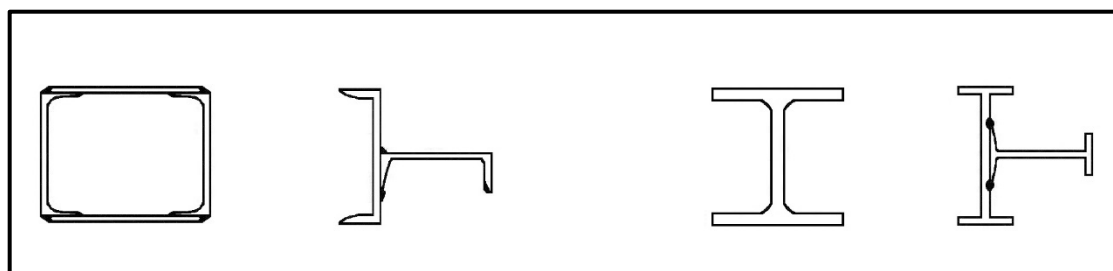


Figure 72 Typical sections in column supported roofs

This design is used all over the world and is particularly popular in the USA and Middle-East. Some users have column supported tanks which are 120 metres in diameter. It is important to understand the local ground conditions. Varying forms of settlement, whether it is bottom dishing, (sometimes referred to as centre to edge settlement), or differential settlement. Both can result in crease stresses in the roof members and their connections.

During operation, there is an amount of lateral loading to the columns based on product movement. It is recommended that the column bases are restrained in position on, (although not to), the tank floor. Such attachments should be prevented from movement by welded angle cleats to the floor at the edges of the column bases. A wear or compensating plate should be fully welded to the floor as failure has occurred due to product entrapment above the floor and below the wear plate when this has been only partially welded.

For tank roofs exceeding 15 metres in diameter cross bracing is provided in at least two bays of the roof structure.

10.4.1 Internal Inspection and repair

Tank floor replacement has been successfully completed by many users. Consideration should be given to methods of supporting the vertical columns when this activity is required.

Access should be provided for inspection to the roof underside, bracings, rafters, girders, tie-bars etc. Based on the location and product stored, vapour space corrosion can occur, requiring further integrity assessment.

Other areas to be considered while access is possible are where the girders connect the tops of the columns together, as they take various point loads from the radial rafters. In addition, where any supports or bracing attached to the upper shell should be examined for fatigue cracking.

Retention thicknesses to the tank roof and structures should be kept and compared by providing roof plans/ drawings showing the location of columns, orientations of girders and rafters.

Roof plate corrosion must be monitored during service as roof plates will have a higher corrosion rate than that of the various structures mentioned above.

10.4.2 Tank jacking or lifting

Specialist engineering is required when lifting a column supported tank. Consideration should be given to any loads placed upon roof support sections, ensuring spacing is maintained between rafters, girders and the upper shell.

Inspection should be made before any lifting is carried out, as vapour space corrosion in the roof may cause damage when the tank is lifted.

10.4.3 Column design

The selection of column design is interesting as most columns are usually quite tall. Therefore the minimum gyration through any axis of the column must be as large as possible. The obvious answer is to use a tubular section for the columns. Reluctance to use this design can be based on cost or internal corrosion, which in the present day is detectable and should be measured during out of service inspection.

If differential settlement between the columns or between the columns and the tank shell becomes excessive, the roof may buckle, thereby losing the support of the columns. Therefore, it is important the straightness of the columns is measured during each out of service inspection.

Some users adopt that column straightness should be within 6mm per every 3metres of length, with a maximum deviation of 25.4mm.

10.5 Membrane (self-supporting) roof

EN14015 states that membrane roofs shall be designed to withstand the internal design pressure and to resist buckling due to external loads. The code also states that roof plates and structural members should have a design thickness of 5.0mm

minimum, with plating being continuously double fillet welded with an overlap of 25.0mm minimum. Design thicknesses are detailed within EN 14015 Annex K.

This type of self-supporting roof can be of cone or dome construction, with a 1:5 fall on the cone style. The structural stability is supplemented by the installation of internal welded radial supporting members directly onto the roof undersides, the spacing of which should not exceed 2.0m. These can only be examined from tank entry, with the assist of scaffold. Any anomalies could impair roof integrity, and it is important that the design is understood to enable full inspection and condition assessment. Full visual, UT WT checks, and selective MPI examinations should be performed. Buckled or deformed members should be replaced.

These roof types normally have a frangible joint onto the curb, so it is important to confirm the joint configuration/design, to determine the inspection requirement and method for both internal and external examination. 100% visual inspection shall be performed on all roof components, with UT WT survey in accordance with section 5.3.4. Buckling or deformation of roof plates will give an indication of overall roof condition with possible stresses incurred to the frangible joint. If this condition prevails, it is recommended that access to the roof external be restricted until external inspections, roof gauging/appropriate NDT, and an internal condition assessment can be performed.

10.6 Internal Floating Covers (IFCs)

Between 1955 and 1960, IFCs were developed for the storage in fixed roof tanks of products sensitive to water contamination. IFCs have the additional advantage of preventing product exposure to air, thus greatly reducing evaporative loss. Like external floating roofs, IFCs float directly on the surface of the stored product; the tank itself is covered by a fixed roof.

Internal floating covers can be made of:

- (1) steel plates (steel pan type)
- (2) aluminium sheets fixed to aluminium tube floaters
- (3) aluminium 'sandwich structure' panels
- (4) lined/coated foam (e.g. polyurethane) panels
- (5) glass reinforced epoxy (GRE) panels
- (6) in-situ laminated GRE (sandwich structure).

The above IFCs can be further divided into **full contact** and **non-contact** covers. All the above types, except (2), are full contact covers.

IFCs are relatively easy to install in an existing tank with a fixed roof, since all the components required for the cover can be brought into the tank via the manholes. Construction is by welding (type (1)), bolting panels together (types (2), (3), (4) and (5)), or building a laminated cover inside the tank on a temporary support structure (type (6)).

With bolted panels, vapours may escape via the joints ('deck seams'), which is particularly the case with type (2), where most of the IFC surface is not in contact with the product.

Welded or in-situ laminated structures are seamless, and the only emission source is the seal rim space.

Selection of the type of cover is often decided by the client based on resistance to long-term exposure to the product as well as on cost, performance (durability), and maintenance aspects.

The steel pan type IFC requires a coating to prevent corrosion. Due to its simple design it may easily be subject to tilting, causing it to sink.

The aluminium and GRE types are far more resistant to most of the products and final selection is mostly justified on a cost-benefit calculation.

The external floating roof of an existing storage tank may be converted to an internal floating 'cover' by installing a fixed roof on top, such as a geodesic dome structure.

The emission reduction achieved by an IFC can be 95%, but this depends on the proper functioning of the cover and its seal (i.e. full contact and a liquid mounted gas tight rim seal: see Section 11.4.1).

The tank venting system will require some modifications when the design is based on API 650 or BS 2654, e.g. conversion to free venting. However some refineries and authorities recommend that P/V valves be retained, instead of installing open circulation vents, to further reduce the emission loss. The discussion point on whether the vapour space above the IFC is in the explosive range for a considerable time depends on the type of product and product movements ('turnovers' of the tank).

It should be noted that installing an internal floating cover will reduce the storage capacity of a tank by around 15–17%. This results from the required increase in dead stock at the bottom of the tank (the cover must be kept in a floating condition). A dead space is also required at the top of the tank to avoid contact between the IFC support legs and the roof trusses.

Some operational issues, recommendations, and common problems with IFCs are listed below:

- always keep the IFC afloat;
- install a high level alarm;
- do not use side entry mixers when the IFC is in a low position, i.e. less than 2.5m from the top of the circle described by the impeller
- ensure adequate earthing of the IFC;
- do not allow access onto the IFC when the tank is in use;
- frequent landing of the IFC will damage the roof supports;
- filling of the tank beyond the maximum level may cause contact with the roof support structure;
- side entry jet mixers should not be used when IFCs are installed, as the movement of the stored product will cause the IFC to drift to the opposite side of the tank creating an excessive rim gap at the mixer side; also cracking of the IFC structure may occur due to vibration induced by the product movement;
- excessive out-of-roundness of the tank shell will lead to emissions and/or jamming of the IFC;
- risk of product spillage onto the deck when taking product samples from the outer (fixed) roof.

10.7 Repair/modification methods

Fixed roofs are generally repaired using pad plates.

When repairing the weld of a frangible roof joint (see Figure 68), care should be taken to ensure that the joint is still frangible after the repair.

The seal weld can be modified if necessary (see Figure 73, below). Refer to EEMUA 180 for more information on the frangibility of roof joints.

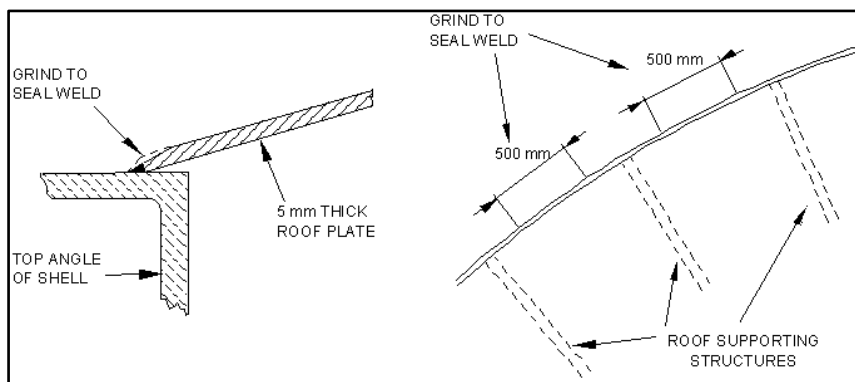


Figure 73 Modified roof-to-shell connection

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11 Floating roofs

11.1 Types

11.1.1 General

Floating roofs are generally installed when storing crude oil and/or light volatile products like gasoline, naphtha etc. The use of a floating roof structure will almost eliminate all evaporative losses, and reduce air pollution considerably since the roof floats on top the product, i.e. there is no vapour space as in a fixed roof tank. An annular space is required to allow free (up and down) travel of the floating roof structure within the tank. Rim seals are installed between the floating roof and the tank shell to guide the roof movement and at the same time cover the annular area to prevent ingress of rainwater and dirt. Vapour emission is only possible from the rim seal area, and this depends mainly on the type of rim seal selected.

Floating roof structures can be divided into three main groups:

- single-deck pontoon type;
- double-deck type;
- specially designed roofs such as the buoy type and radially reinforced roof structures.

11.1.2 Pontoon type floating roofs

For these roofs, buoyancy is provided by an annular pontoon of approximately 20 to 25% of the total roof area. Roofs are designed to enable the centre deck to carry approximately 250mm depth of rainfall over the total roof area, and with sufficient buoyancy for the roof to remain afloat when two adjacent pontoon compartments and the centre deck are punctured (See Figures 74 and 75).

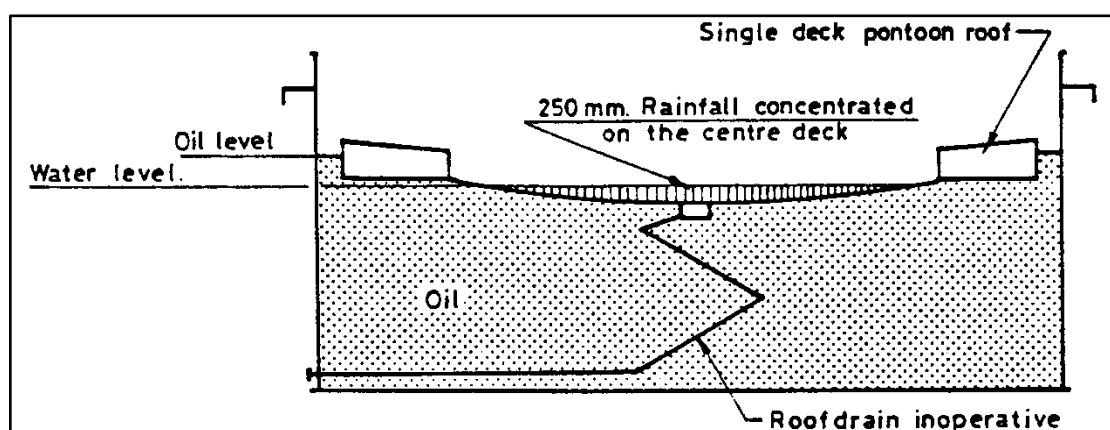


Figure 74 Rainwater load on the centre deck of a pontoon with drain inoperative

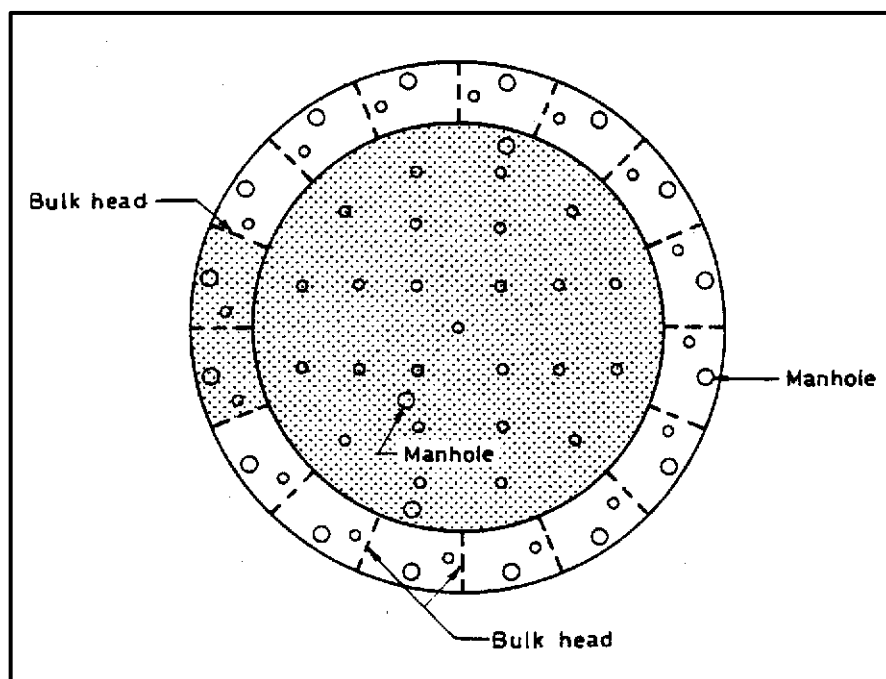


Figure 75 Design of a pontoon roof

(Capable of floating with centre deck and two bulkheads punctured)

Emergency roof drains cannot be installed as the level of the centre deck is below the level of the oil in the tank. Rainwater drains, such as syphon type (emergency) drains may still be found on older existing single-deck roofs but they should be flanged off or removed in view of operational problems and the high risk that such a drain could create, e.g. a centre deck leak.

11.1.3 Double-deck floating roofs

For these roofs, the entire roof area is designed/constructed with a double deck, making the roof more rigid than the pontoon roof. The double deck consists generally of an annular pontoon with concentric rings in the centre part of the roof: see Figure 76.

The design specification of double-deck roofs should require that the roof remain afloat with any two peripheral pontoon compartments and the centre pontoons punctured: see Figure 77.

Double-deck roofs are generally installed in large diameter tanks (over 50m dia.). They avoid the wind problems of pontoon roof centre decks. They are also used in small diameter tanks (e.g. up to 15m diameter), since for such diameters the centre deck of a pontoon roof would be too small.

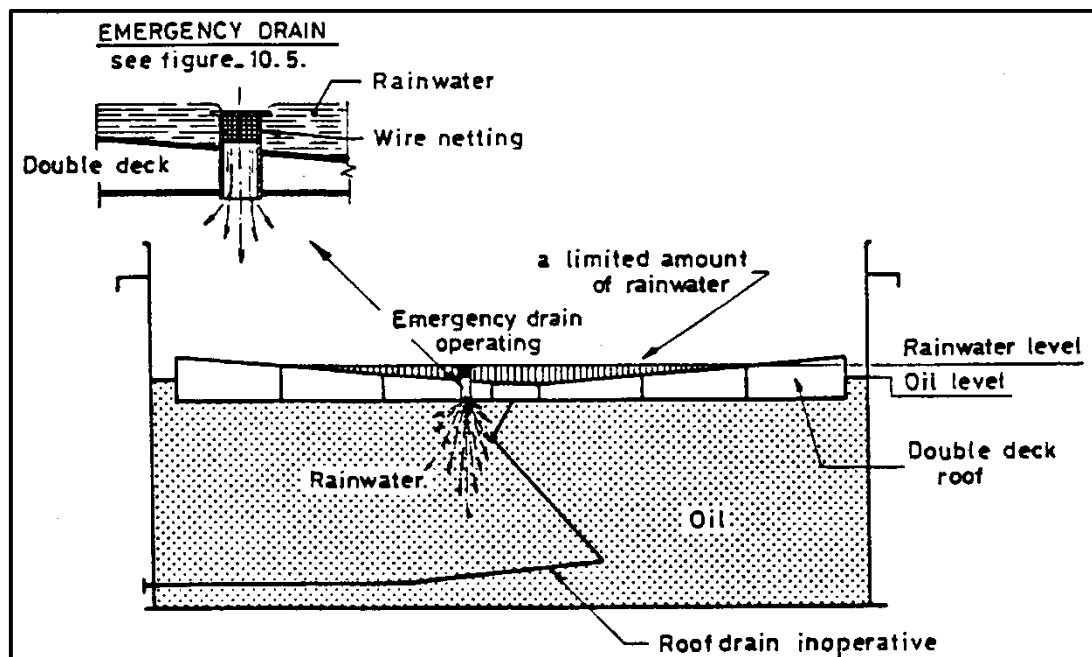


Figure 76 Rainwater load on the upper deck of a double-deck with drain inoperative

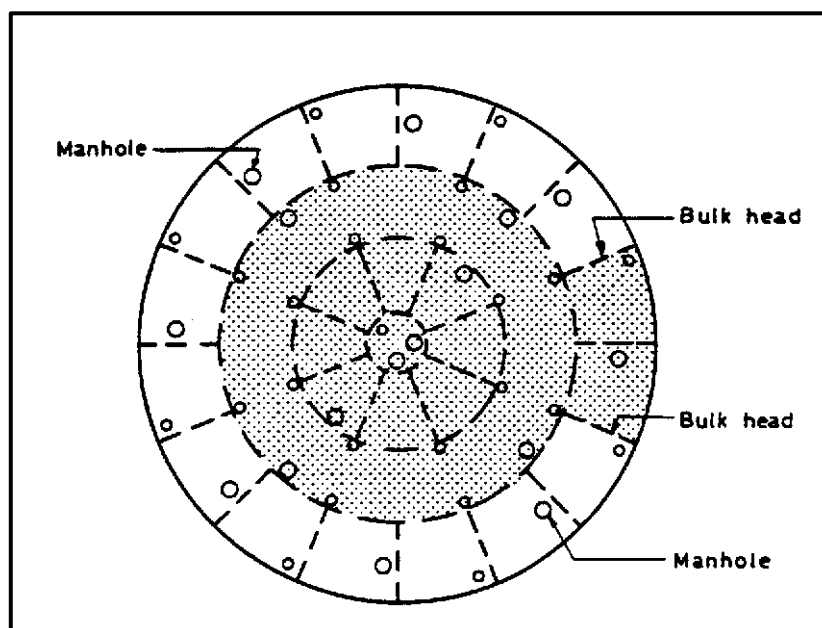


Figure 77 Design of a double deck roof
(capable of floating with centre pontoons and two peripheral bulkheads punctured)

Excess rainwater on the roof due to a non-functioning roof drain will be automatically discharged via the emergency drain into the tank product. The setting of the emergency drain overflow level should be checked against the draught of the deck in the product. The top level of the centre deck should always be above the level of the product in the tank.

11.1.4 Special roofs such as buoy type and radially reinforced roofs

The buoy type roof is a pontoon roof with a relatively small annular pontoon, but with a number of buoys spread over the centre deck to give additional buoyancy. It is mainly used for large diameter roofs.

The radially reinforced roof is a pontoon roof with heavy stiffening beams installed radially on the centre deck. It is a stiff roof designed for larger diameter tanks only (over 50m diameter) to prevent centre deck wind problems. Some owners' specifications restrict stiffening to circumferential concentric stiffening beams. Such stiffening does not affect the normal dishing profile of the deflected deck with a centre drain.

11.2 Rejection limits

Note that Section 11.2 is currently under review within EEMUA. The guidance and recommendations below are given based on the current available information and good practice. The reader should be aware that further discussion may result in changes.

11.2.1 General corrosion

The rejection limits as described in sub-sections a) and b) below are valid for tanks satisfying the so called "30% rule". The surface of the pontoons shall be equal to or higher than 30% of the total surface of the floating roof. In formula:

$$\frac{D^2 - d^2}{D^2} \geq 30\%$$

Where:

- d Inner rim diameter of the pontoons/centre deck diameter (m)
D Outer rim diameter of the pontoons (m)

For tanks that do not satisfy this requirement the rejection limits of the floating roof components should be calculated. However, when the following criteria are satisfied the rejection limits of sub-sections a) and b) may be used.

1. A three monthly visual inspection of the pontoons for leakages. In case leakage in one pontoon is detected the tanks should be taken out of service and the leakage will need to be repaired.

and

2. A effective drainage program including a program for monitoring the rainwater level. In case the rainwater level on the centre deck is larger than 100mm, the collected rainwater should be drained.

or

3. The installation/presence of (aluminium) dome roof covering the external floating roof.

a) *Centre deck*

The rejection criteria with respect to general corrosion of the centre deck of a floating roof is the larger of 50% of the nominal thickness or 2.5mm. In the formula:

$$t_{\min \text{ acc. fl. roof gen}} = 50\%t_{\text{nom}}, 2.5\text{mm (whichever is larger)}$$

Where:

$t_{\min \text{ acc. fl roof gen.}}$ Minimum acceptable plate thickness of the centre deck of a floating roof (mm)

t_{nom} Nominal plate thickness (mm)

b) *Floating roof pontoons*

b.1 Bottom plates

The minimal acceptable thickness of the bottom plates of the pontoons is 80% of the nominal thickness. In formula:

$$t_{\min \text{ acc. pont. bottom}} = 80\%t_{\text{nom}}$$

Where:

$t_{\min \text{ acc. pont. bottom}}$ Minimal acceptable thickness for of the bottom plates of the pontoons (mm)

t_{nom} Nominal plate thickness (mm)

b.2 Top plates

The minimal acceptable thickness of the top plates of the pontoons is 50% of the nominal thickness or 2.5mm. In formula:

$$t_{\min \text{ acc. pont. top}} = 50\% t_{\text{nom}}, 2.5\text{mm (whichever is larger)}$$

Where:

$t_{\min \text{ acc. pont. top}}$ Minimal acceptable thickness of the top plates of the pontoons (mm)

t_{nom} Nominal plate thickness (mm)

b.3 Rim plates

The minimal acceptable thickness of the inner and outer rim plates of the pontoons is 91% of the nominal thickness. In formula:

$$t_{\min \text{ acc. pont. rim}} = 91\%t_{\text{nom}}$$

Where:

$t_{\min \text{ acc. pont. rim}}$ Minimal acceptable thickness of the top plates of the pontoons (mm)

t_{nom} Nominal plate thickness (mm)

c) *Stiffness of a floating roof tank*

Alternatively the rejection limits for the thickness of the centre deck and the pontoons can be determined by a FEM Analysis.

11.2.2 Pit corrosion

The minimal acceptable thickness of the roof plates with respect to pit corrosion is 50% of the rejection limit with respect to general corrosion of the roof plates, provided that the pits are widely scattered and that the sum of the pit diameters over a straight line of 200mm does not exceed the value of 50mm. In formula:

$$t_{\text{min acc. fxt./fl. roof pit.}} = 50\% t_{\text{min acc. fxt./fl. roof gen.}}$$

Where:

$t_{\text{min acc. fxt./fl. roof pit.}}$	Minimal acceptable thickness of roof plates for pitting corrosion (mm)
$t_{\text{min acc. fxt./fl. roof gen.}}$	Minimal acceptable thickness of roof plates for general corrosion or localized general corrosion (mm)

11.3 Roof drains

11.3.1 General

There are three main types of primary roof drains:

- steel articulated pipe drains;
- flexible hose drains; and
- steel pipes with flexible hose type joints.

Two types of primary roof drains are shown in Figure 78 and the third in Figure 79. Their specific features, problems etc. are discussed in Sections 11.3.2, 11.3.3 and 11.3.4 below.

Roof drains should be fitted with an isolation valve at the discharge end, just outside of the tank shell. The valve is normally kept open to avoid rainwater accumulation on the roof but can be closed in the event of a leaking drain (inside the tank) to prevent serious loss of product. In such circumstances it is nevertheless important that the valve be reopened if water starts to accumulate on the roof (e.g. during a heavy downpour), with special precautions taken to handle the product–water mixture. This situation should not be allowed to exist for a long period on too many tanks at the same time. Repair of the roof drain should be carried out as soon as possible. In climates where stored product temperatures can drop below 0°C, the drain should be designed to allow complete drainage to prevent bursting of the pipe by frozen stagnant water in the drain.

As illustrated in Figure 74, the centre deck of a single-deck pontoon roof lies below the level of the stored product at the periphery. It is therefore necessary that the drain collecting sump at the centre deck be fitted with a non-return valve (NRV) to prevent back flow of product onto the roof in the case of a leaking drain when the isolation valve would be closed. This back flow could even cause the roof to sink if loads on the deck exceed the design parameters. Furthermore, in thunderstorms, product floating on the rainwater on the roof could be ignited by lightning.

It is also recommended that drainage sumps in double-deck roofs be fitted with NRVs, particularly in climates with heavy rainfall and frequent thunderstorms. Although no part of the top deck of this type of roof lies below the level of the

stored product - as is the case with single-deck floating roofs - a leaking drain (with a closed isolation valve and no sump NRV) would result in there being a level of product in the sump. Heavy rainfall could cause this to overflow onto the roof, with a fire risk as described above.

This may also be valid under a (rim) fire attack where foam and foam/water solution may be sprayed on the roof surface at such a great extent and volume that the water flow through the drain opening may rotate at such a speed, that product from within the leaking drain pipe may be pushed upwards and flow onto the roof level.. This risks causing the product level to be ignited by the fire; the action the foam spraying wished to prevent.

Occasionally, roof drains mal-function causing an accumulation of rainwater on the roof. This can cause the floating roof to sink, resulting in severe damage to the roof. The need for correct operation, maintenance and inspection cannot be over-emphasised.

The number, size and location of the roof drains are determined by the diameter of the roof, the location of the tank, and the type of roof. The normal sizes of roof drains are DN 80, 100 or 150 (3, 4 or 6 inch). In all cases, water is collected in sumps in the roof. It is most important that the sumps, their drain holes or strainers, if installed, are not allowed to become blocked by debris. Accidents have been caused by blockage by scale, leaves, rags, sample bottle bungs, birds, etc. In areas with heavy rainfall, it may be necessary to install more than one roof drain for large diameter roofs.

Water sometimes forms pools and fails to drain from the area where the rolling ladder is supported on the centre deck. Drainage may be arranged from that area via an additional drainpipe to the sump under the roof.

The efficiency of a primary roof drain is at its minimum when the floating roof has landed on its supporting legs, as the static head is very low.

Failures have occurred when roofs were landed during maintenance and the roof drains were inoperative, either intentionally or by accident, or when the drainage capacity of the roof drain was inadequate in the landed position.

It should be noted that an extra drain opening is required in the floating roof when it is to be landed for a prolonged period. Normally, a plugged additional drain is installed in the centre deck, and the plug removed after landing. Experience has shown, however, that it is often impossible to remove this drain plug after several years of service. In such cases, a temporary drain opening should be made in the centre deck to prevent the possibility of overload due to rainwater accumulation.

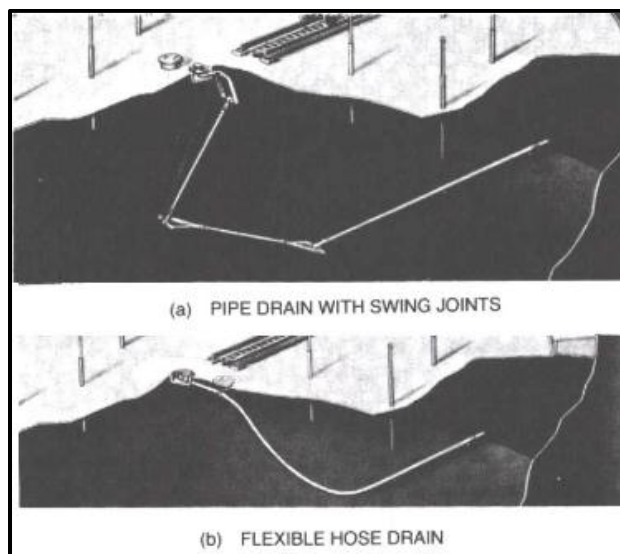


Figure 78 Two types of roof drains

11.3.2 Steel articulated primary roof drains

This is the most common type of primary roof drain. Straight lengths of steel pipe are connected together with packed swing joints, which allow movement of the drainpipe sections within fixed limits: see Figure 78(a).

Experience has shown that over long periods of service, the swing joints sometimes fail and allow stored product to leak into the drainpipe and to contaminate the drain water. When this occurs, tank operation has to be modified to prevent product leakage into the sewer system or the ground around the tank. Eventually, the tank has to be taken out of service and prepared for entry to enable the roof drain joints to be repacked or replaced, and tested.

The integrity of the roof drains is an important factor in deciding the inspection frequency of a tank. Careful testing of swing joints prior to service is essential to prevent premature leakage. It is important that the packing of the swing joint is suitable for the stored product. The following conditions may make the roof drain more prone to leakage:

- single off-centre joints, since they are subject to torsional forces;
- strong lateral movement of the liquid being stored, particularly when the roof is in a low position;
- tank inlet at right angles to the roof drain; and/or
- the action of side entry mixers, when operating with the roof in a low position.

Evidence from evaluated roof failures showed that in some cases a swivel joint (or swing joint) had deteriorated to such an extent by wear and tear that excessive friction occurred in the swivel itself. This led to extreme horizontal forces and stresses in the sump attachment of the drain system, causing fracture in the sump and consequent failure of the roof.

Note: This failure mode cannot be inspected nor observed during normal operations of the floating roof.

11.3.3 Flexible hose primary roof drains

To overcome leakage problems encountered with articulated pipe drains, reinforced flexible hose drains are sometimes specified (see Figure 78(b)).

The top and bottom sections of flexible hose drains need to be rigid (reinforced hose or rigid pipe) to prevent a possible airlock at the top or water-lock at the bottom which may prevent gravity flow.

Hoses should be manufactured from materials that withstand long-term exposure to the liquids to be stored. They are generally strengthened by helical steel reinforcement to prevent kinking and collapse, and to reduce the risk of mechanical damage. The hose is weighted to prevent flotation and formation of air locks, which may hinder drainage. The hose drain should not be used in a tank with water on the bottom that could freeze in winter, as part of the drain could be trapped in the ice. Also, rainwater freezing inside the hose would be a problem as the hose would lose its flexibility.

Hose drains are flexible and will therefore rest on the tank bottom in an arbitrary pattern. Hose movement can be restricted to certain areas of the bottom, and guards can be installed around the location of some roof supports to prevent mechanical damage. Fatigue failures of flexible hose drains have been known to occur at highly stressed locations, e.g. the connection to the shell nozzle and when tank operation causes frequent significant movement of the drain. Such a failure may occur very suddenly and will result in serious leakage, even causing release of the complete contents of the tank.

To prevent such a serious accident, it is sometimes recommended that the drain outlet valve is kept closed and only opened when rainwater begins to collect on the roof. This is not recommended in areas of high rainfall.

11.3.4 Special primary roof drains

Proprietary drain designs are sometimes proposed to overcome one or more of the problems stated in Sections 11.3.2 and 11.3.3 above. They should be less prone to leakage than the swing joints of the articulated pipe drains, and to fatigue failure of the flexible hose drains. Such designs should be checked very thoroughly to ensure that they do not introduce new problems.

A flexible hose joint in a typical, long proven design of pipe drain is shown in Figure 79.

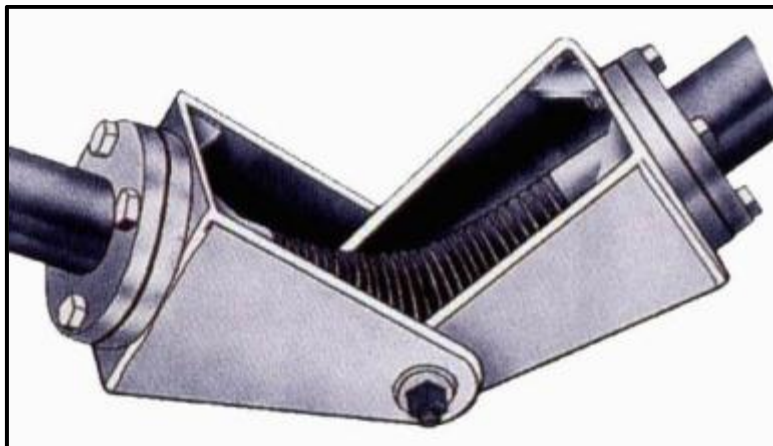


Figure 79 Well designed flexible hose joint

The main advantage of this type of flexible joint in the drain piping system is the philosophy that functions are well split between elements of the joint. The side flanges, including the so called "pivot" or "pin", are designed to take up loads during operation of the floating roof (level changes of the roof and side movements of the drain piping in the tank due to high in-pumping rates of product – sometimes predicted to be more than 4m side movements), whereas the liquid tightness of the joint is ensured by the hose.

11.3.5 Siphon drains

Siphon drains may have been installed in some of the older tanks as the main drainage option, or as emergency drains on single-deck floating roofs. They are, however no longer used because of operational problems encountered. They do not function when insufficiently primed with water, and may not function if the specific gravity of the product is different from that of the original design specification.

11.3.6 Emergency roof drains

When a primary roof drain is inoperative and rainwater begins to accumulate on the floating roof, an emergency drain allows discharge directly into the tank, settling at the bottom. This water should be drawn off to prevent contamination of discharged product and to reduce the risk of internal bottom corrosion.

Emergency drains should not be installed on single-deck pontoon roofs as the product level in the tank is always higher than the rainwater level on the centre deck. In this situation the product would discharge through the drain onto the roof rather than allow water to drain into the tank (see Figure 74).

Emergency drains are provided on the majority of double-deck roofs. The level of the product in the tank is always lower than the inlet of the emergency drain so the product stored cannot flow onto the roof (see Figure 76). The majority of emergency drains are simple open-ended pipes. They require little maintenance, and inspection is limited to a visual check to see that they are clear.

11.4 Roof seals

11.4.1 General

All floating roofs have an annular rim space between the tank shell and the floating roof to permit smooth travel of the roof within the tank. Rim seals are used to seal the annular space, primarily to reduce the emission and evaporative loss from the stored product and to maintain the product purity by reducing the amount of (rain) water that can enter the tank. The rim seal structure also helps to centre the roof in the tank.

Rim seals need to be designed to accommodate severe conditions, such as tank shell weld irregularities, small dents, and to a certain extent, out-of-roundness of the tank shell.

The seal system may consist of one or two separate seals. The first, called the primary seal, is mounted in the annular space, and is normally in contact with the product. The secondary seal is located above the primary seal to further reduce the evaporative loss and water ingress.

Three types of primary seals are normally used:

- the mechanical metal shoe plate type seal: see Figure 80;
- the liquid mounted seal (liquid-, gas- or foam-filled fabric seal): see Figure 81;
- the vapour-mounted seal (flexible wiper seal): see Figure 82. The first two seal types have been generally used for floating roofs for about 50 years. The vapour-mounted seal is a relatively new development introduced around 1985. Foam filled and vapour mounted seals are not suitable for use with riveted tanks.

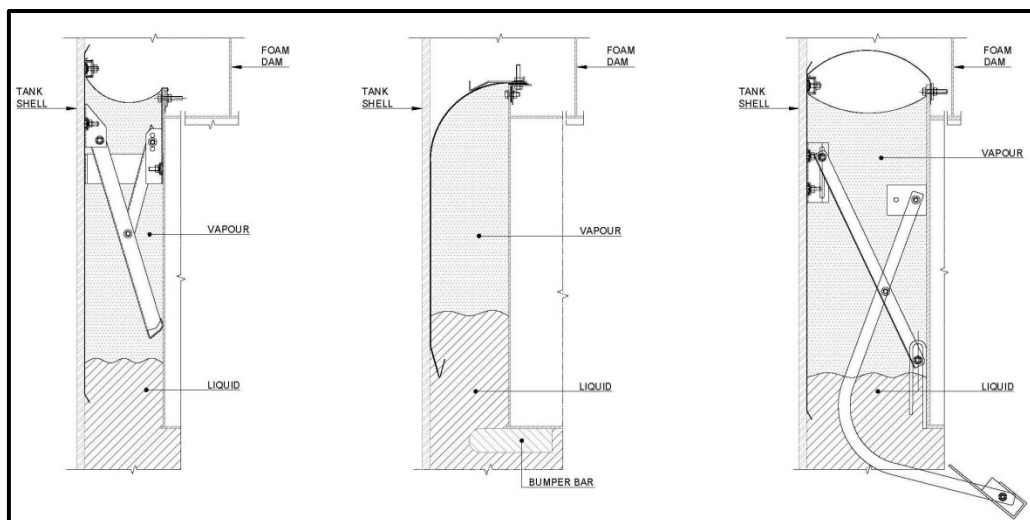


Figure 80 Various types of liquid mounted mechanical shoe seals

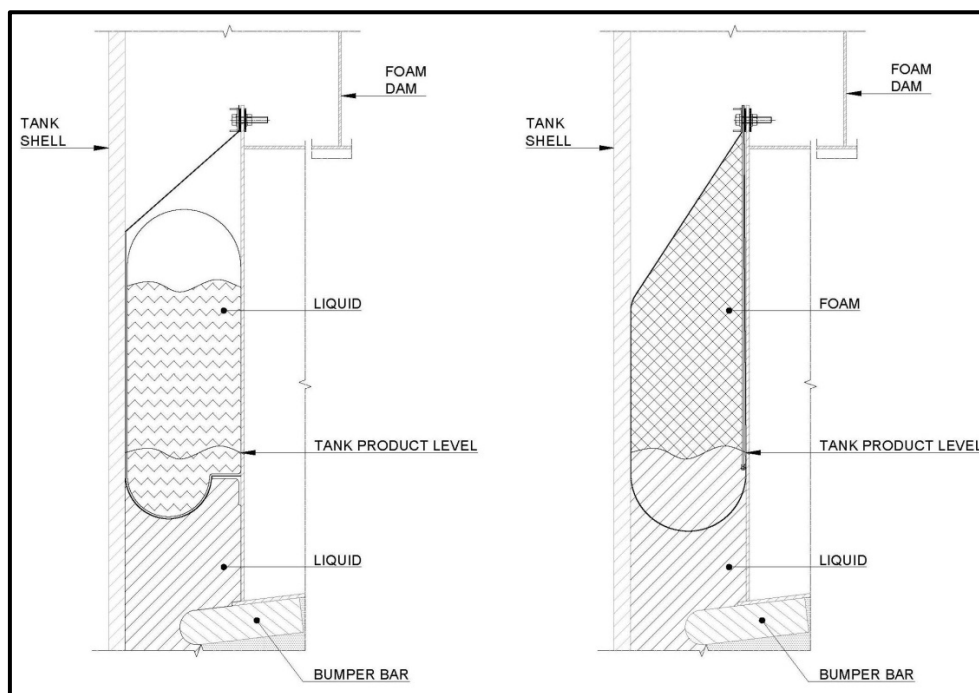


Figure 81 Typical liquid mounted primary foam and tube seal

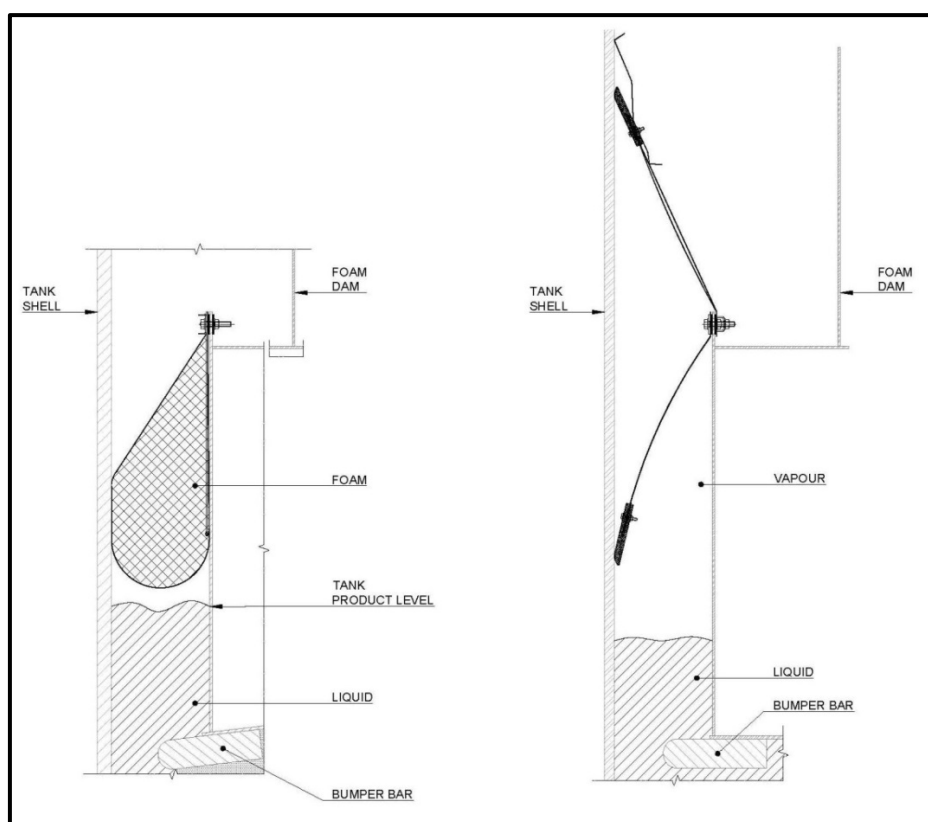


Figure 82 Typical vapour mounted seals

For secondary sealing, the shoe mounted or rim mounted type may be chosen (see Figure 83). The rim-mounted type, which covers the entire annular space, is the most effective and often required by local regulations.

Mechanical seals normally give good service for long periods when their maximum allowable outward and inward movements are not exceeded. They should be regularly inspected. The mechanical shoe type seal presses a thin galvanised or stainless steel sheet against the inside of the shell. It is important that these steel sheets are not allowed to deteriorate such that the lever arms wear vertical grooves in the shell.

Where corrosion is expected, stainless steel sheets are preferred. The hanger system should be cleaned and lubricated when necessary to ensure proper performance of the roof seal.

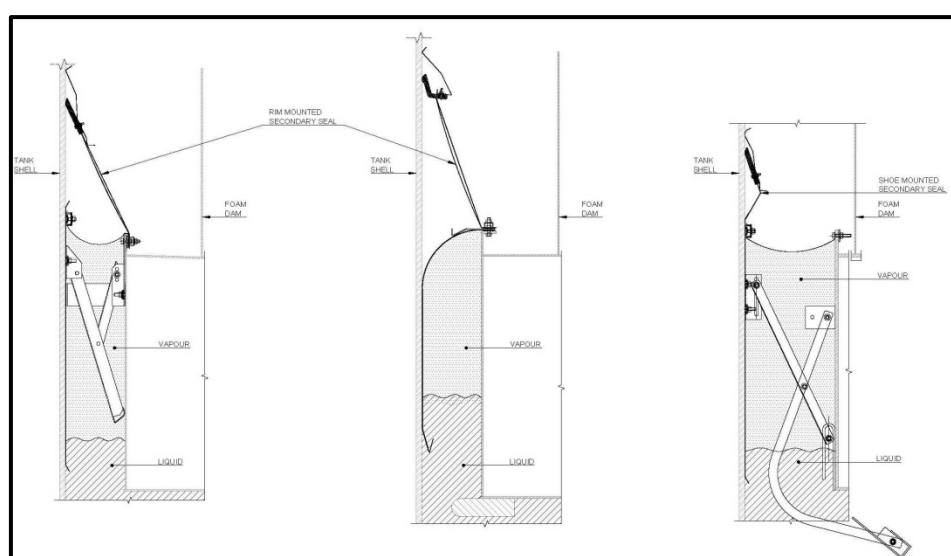


Figure 83 Mechanical shoe seal with shoe mounted and rim mounted secondary seal

Normally, a primary seal has a weather shield on top. This may be especially the case with older tanks. If such a shield is not provided, debris, e.g. scale, sand, leaves etc., starts to collect in the rim space. Such debris should be removed as it could ultimately damage the seal. It is important that the seal-shell gaps are checked regularly against specified criteria to ensure smooth movement of the seal. Typical examples of these criteria are given in Table 8. It should be noted that the tabulated criteria are for guidance, and are not to be considered as absolutes.

Liquid-mounted fabric seals are made with an elastomeric coated fabric envelope which rubs against the shell. They are susceptible to general wear and damage from shell roughness and projections. They are not recommended for riveted tanks. Liquid filled and gas filled envelopes immediately lose their seal function when punctured. Foam filled envelopes can absorb the product stored in the tank. This can cause safety problems when gas freeing the tank for maintenance. In such a case the foam filling should be removed to facilitate this.

Liquid-mounted seals are recommended for application in earthquake zones, as this seal type will protect the floating roof against clashing against the tank shell

better than the other two seal types, thus reducing damage to the shell and the roof.

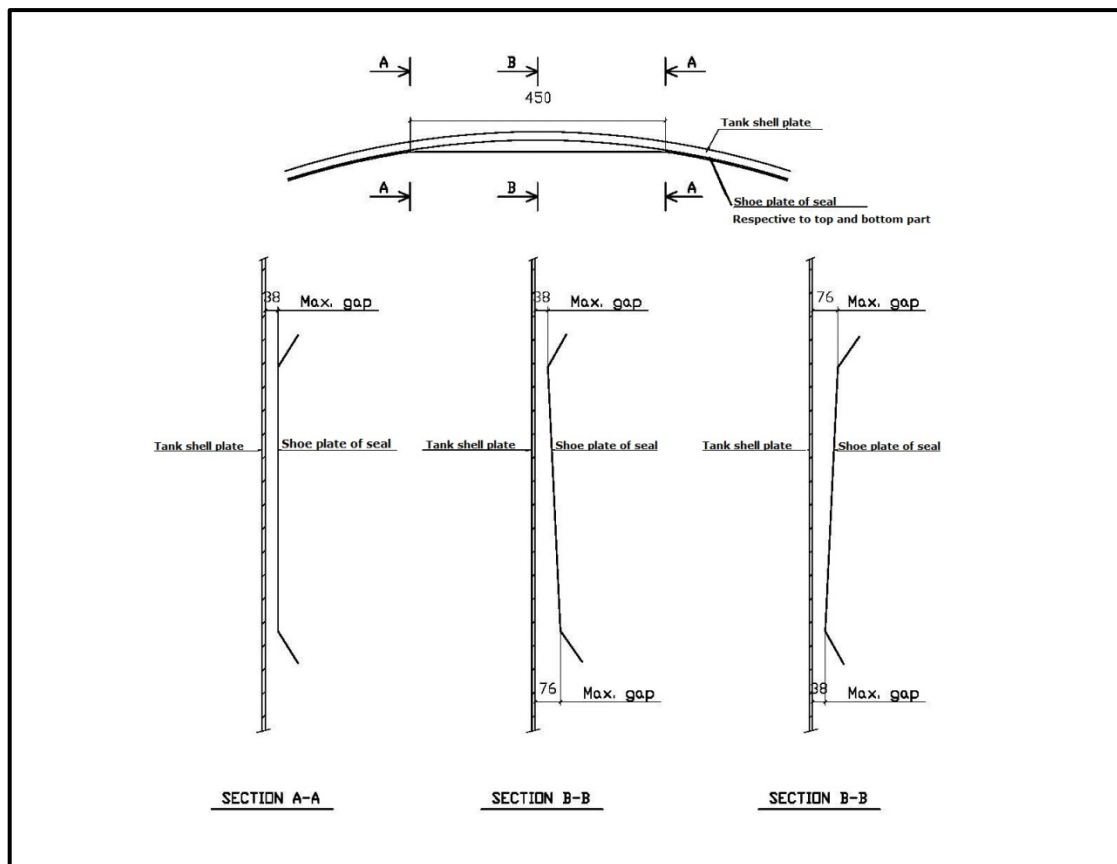


Figure 84 Liquid mounted mechanical shoe seal - allowable seal gaps

Table 8 Typical examples of allowable gap between seal and primary seals

Shell seams	Seal type	Maximum allowable gap area	Seal geometry
Butt-welded	Liquid-mounted mechanical shoe seal (see Figure 80)	HORIZONTAL No gap > 38mm (1½ in) - see also Figure 84. No continuous gap to exceed area equivalent to a 3mm (⅛ in) gap extending for 10% of tank circumferential length. Cumulative length of gaps > 3mm (⅛ in) but ≤ 6½mm (¼ in) not to exceed 40% of tank circumferential length. Cumulative length of gaps > 6½mm (¼ in) but ≤ 38mm (1½ in) not to exceed 10% of tank circumferential length. VERTICAL Where the seal shoe plate is tilted relative to the tank shell—see Figure 84 - a gap of up to double the allowable horizontal gap is permitted for a circumferential length not exceeding 450mm (18 in), provided the gap at the other end (top or bottom) of the shoe does not exceed the maximum allowable horizontal gap (38mm in the figure).	Seal should extend into liquid and at least 600mm (24in) above liquid surface.
	Liquid-mounted foam-filled seal (see Figure 81)	HORIZONTAL As for liquid-mounted mechanical shoe seal (above), except that Figure 84 does not apply, i.e. no gap to be > 38mm	
	Vapour-mounted seal (see Figure 82)	HORIZONTAL Cumulative length of gaps > 3mm (⅛in) not to exceed 5% of tank circumferential length.	
Riveted (see*)	Liquid-mounted mechanical shoe seal (see Figure 80)	HORIZONTAL - No gap > 64mm (2½in). - Cumulative length of gaps > 38mm (1½in) not to exceed 10% of tank circumferential length. VERTICAL - As for liquid-mounted mechanical shoe seal (above)	Seal should extend into liquid and at least 600mm (24in) above liquid surface.
Butt-welded and riveted	Average seal (see Figure 83)	HORIZONTAL - No gap > 6½mm (¼in). - Cumulative length of gaps > 3mm (⅛in) not to exceed 5% of tank circumferential length.	Seal arrangement should allow for: easy inspection of primary seal installation of fire detection tube (if applicable).
Butt-welded	Gas-tight seal (see Figure 83 and Appendix D.3)	HORIZONTAL - No gap > 1½mm (1/16in). - Cumulative length of gaps > ½mm (1/32 in) not to exceed 5% of tank circumferential length. - Gaps < 45½mm (1¾in) close to vertical welds can be ignored.	

*Foam-filled and vapour-mounted seals are not suitable for use in riveted tanks

Flexible wiper seals are a comparatively new development, and experience is therefore limited. Some types lose their flexibility during service when they have to frequently follow variations in shell contours. Their use is not therefore recommended for areas where uneven soil settlement is expected.

Liquid-filled, gas-filled or foam-filled fabric seals should be inspected for cracks and leaks. When local repair is not possible, complete replacement should be considered. They sometimes require renewal after 10 years' service.

Secondary seals should be such that easy removal is possible for regular inspection of the primary seal. When primary seals are replaced while the tank remains in service, no more than one quarter of the roof seal should be removed at any one time to minimise evaporation and potential hazard to personnel. Temporary spacers may be required to keep the roof centred during replacement work, and earthing continuity should be maintained across the gap between roof and shell.

11.4.2 Design

The primary and (rim-mounted) secondary seals should be designed to allow for the maximum inwards and outward movements of the floating roof structure in relation to the (new or existing) roundness of the tank shell. Future settlement of the tank foundation, which may influence the out-of-roundness, should be considered, when required, in the light of the service period of the tank.

The basic design requirement for a good performing rim seal is an inward movement of X in combination with an outward movement of 3 times X , i.e. $(-X/+3X)$. An explanation for this seal working range is presented in Appendix D.3, together with a sample calculation.

For an existing tank, the maximum and the minimum tank diameters need to be measured, and the rim space requirement calculated in relation to the diameter of the floating roof.

Note: Remarks on out-of-roundness in Section 11.10.3.

11.4.3 Rim seal materials

It is essential to select the correct material for the primary and secondary rim seals. Next to the requirement for chemical resistance, which is related to the stored product and the ultraviolet resistance of the seal material exposed to direct sunlight, it is important to check whether the material is flame retardant. This is applicable to the design of new seals as well as when replacing the old seal material.

The primary seals should always be hydrocarbon resistant since they are in direct contact with the product/product vapours, while the top coat of secondary seals needs to be ultraviolet resistant as well as flame retardant.

The tip structure of the secondary seals which slides along the tank shell should preferably be made of two kinds of material: the bottom section of a hydrocarbon resistant material, and the top section of a UV resistant material.

The vapour-air mixture in the space between the primary and secondary seals is assumed to be always above the higher explosive limit, and there is no requirement for the primary seal to be of a fire retardant material in such an arrangement.

The fire detection system (line/tube) should be placed just above the top of the secondary seal, and the foam/spray (fire fighting) system directed onto the same area. Foam injection between the two seals is unnecessary since there would be no fire in that area due to the very rich vapour-air mixture. Some of the most common seal materials are listed in Table 9 below.

11.4.4 Seal replacement

Rim seal replacement can be done while the tank is in service. Stringent safety procedures are necessary for in-service replacement of primary seal fabrics. Although the safety measures may differ between companies/countries, it is recommended that the seal be replaced, sequentially, in sections, with each section not exceeding $\frac{1}{4}$ of the tank circumference. Secondary seals can be added or replaced when the tank is in its high position.

Table 9 Material resistance against HCs/UV light, and fire retardation properties

Material/Reinforcement (See Notes and Abbreviations)	Resistance against		Flame retardant?
	Hydrocarbons	UV light	
Viton® (FPM)/nylon (PA)	Very good	Very good	Yes
Teflon® (PTFE)/glass	Very good	Very good	Yes
Neoprene (CR)/calcium silicate	Reasonable	Good	No
Polyurethane (EU)/nylon (PA) or polyester (TPE-E)	Good	Good	No ¹
PVC-nitrile (PVC-NBR)/nylon (PA) or polyester (TPE-E) or glass	Good	Reasonable	No ²
Nitrile (NBR)/Nylon (PA) or polyester (TPE-E)	Reasonable	Poor	No

Notes and Abbreviations

¹ Not water resistant

² Nitrile without PVC is poor under UV exposure; the addition of PVC will improve UV resistance, but PVC will nevertheless become brittle with time.

CR chloroprene rubber

EU urethane rubber based on polyesters (sometimes abbreviated AU)

FPM fluoro-rubbers (formerly designated FKM)

NBR butadiene acrylonitrile copolymer (nitrile rubber)

PA polyamide

PTFE polytetrafluoroethylene

PVC polyvinyl chloride

TPE-E thermoplastic polyetherester elastomer

11.5 Roof supporting legs

Floating roofs are provided with legs designed to support the roof when landed on the bottom, and when in operation, to keep the roof just above any tank appurtenances, e.g. inlet pipes, mixers, heating coils, outlet pipes. These legs are adjustable from the top of the roof to allow landing of the roof at a level higher than the operational (in service) level, e.g. 1.8m above the bottom, to allow access under the roof for inspection and maintenance.

Pads are continuous fillet welded to the tank bottom under the legs to distribute the loads and to prevent wear of the bottom plates. Due to differential soil settlement or uneven accumulation of sediment, it is unlikely that all roof-supporting legs will land simultaneously and take up equal loads. Frequent landing of the floating roof should therefore be avoided, as ultimately this may cause cracks and leaks. Moreover, frequent landing will also contribute to excessive emission losses, and hence air pollution, every time the tank is refilled, due to frequent opening of the bleeder vents (see Section 11.6, 'bleeder vent/vacuum breaker'). It should be noted that a single landing of the roof may cause about 50% of the normal annual emission loss when the tank roof is maintained in its floating position.

In cases where frequent landings are envisaged, it is recommended that roof plates are also fillet welded on the underside.

Due to the differences between the outer diameter of the leg and the inner diameter of the sleeve, the leg could take a sloped position as shown in Figure 85. Under this sloped position the stability and stress levels of legs should be checked whilst performing adequate structural calculations. A sample calculation method is enclosed in Appendix D.5 of this publication.

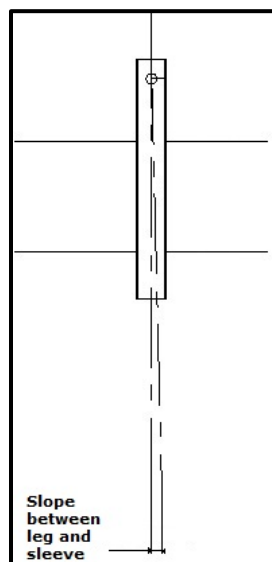


Figure 85 Slope of roof supporting legs

11.6 Floating roof venting

Floating roof tank venting fittings are as important to the operation/functioning of a floating roof tank as any other floating roof fitting, such as the floating roof

drain. The two vent types normally required for the roof structure are the **rim seal vent** and the **bleeder vent**; the latter is also known as a vacuum breaker.

The **rim seal vent** is only required for seals which have a vapour space under the primary rim seal. For example, vapour mounted seals and the mechanical shoe type. The liquid mounted typical soft/tube type seals do not require a rim vent.

Depending on tank diameter, the number of rim vents varies between one and five, spaced at equal intervals around the circumference. As a guide, the distance between the rim vents should be not more than 40 to 50 metres. The pressure setting of the vent (pallet or counterweight) is around 2.5mbar.

The main function of the rim vent(s) is to allow gas pockets (overpressure) to escape from under the rim seal to the atmosphere. The gas/vapour pockets are often found under the floating roof deck and normally find their way into the rim space. Overpressure inside the rim space may also impair the function and damage the material of the rim seal.

The **bleeder vent/vacuum breaker** is a very important venting device which functions in direct response to the rate of product movement when filling or emptying the tank.

When filling commences, with the floating roof standing on its supports, the vapour under the roof is forced via the bleeder vents out of the tank until the roof starts to float on the product. The bleeder vent will close automatically under its own weight as soon as the roof rises another 200–300mm. When landing the floating roof, the bleeder vent support leg will touch the tank bottom about 200–300mm before the main roof support legs and automatically open the vent(s). This will prevent a vacuum under the roof deck when the remainder of the product is pumped out of the tank. Figure 86 illustrates how the bleeder vent functions.

The number and size of the automatic bleeder vents required will depend on the design pumping rate, or on the gravity flow rate for tanks emptied by gravity.

It is important to have the bleeder vent pipe supports designed in a similar way to the roof support legs, i.e. to have both an operational and a maintenance setting. The change of roof support leg length will always require a similar change to the bleeder vent support setting, i.e. either both to be in their operational setting or both in their maintenance setting.

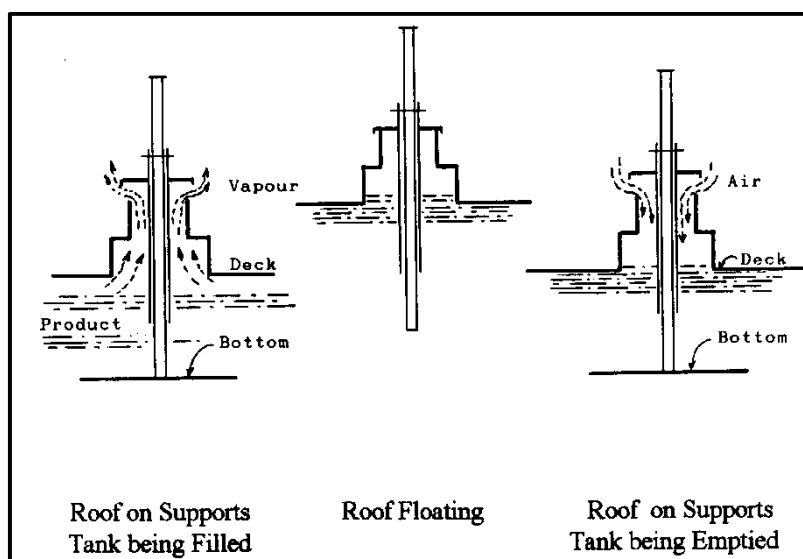


Figure 86 Operating principle of an automatic bleeder vent

11.7 Rolling ladders

Rolling ladders may be installed on floating roof tanks to provide access to the roof at all filling heights. The upper end of the ladder is attached to a platform at the top of the shell, and the lower travels along a track welded to the roof and extending radially from the edge towards the centre. The ladder changes its angle of inclination as the roof moves in order to accommodate the different heights it has to bridge. Such ladders were once universal on all floating roof tanks.

For safety reasons many companies now restrict access to floating roofs, and personnel are only allowed on a roof when it is at its highest position. In this case access to the roof can be gained via a short, vertical ladder. Emergency access to the roof in a low position can be achieved by use of a suitable flexible ladder. With such an operating philosophy, the rolling ladder becomes redundant and can be removed.

Note: The removal of the ladder has advantages, for even though used infrequently, it is the cause of much inspection and maintenance effort, since a malfunctioning ladder can seriously damage a roof and even sink it. The risk of this is high if the ladder becomes detached from its guide rails and jams. Figure 87 shows the consequence of failure, due to corrosion of the ladder support, caused in turn by poor drainage, where it connected to the deck. Part of the support pierced the deck: the liquid on the deck is gasoline. Fortunately the failure was noticed in time to prevent the roof from sinking; damage to the roof was minor. However there was severe damage to the gauge platform, and the ladder had to be completely replaced.

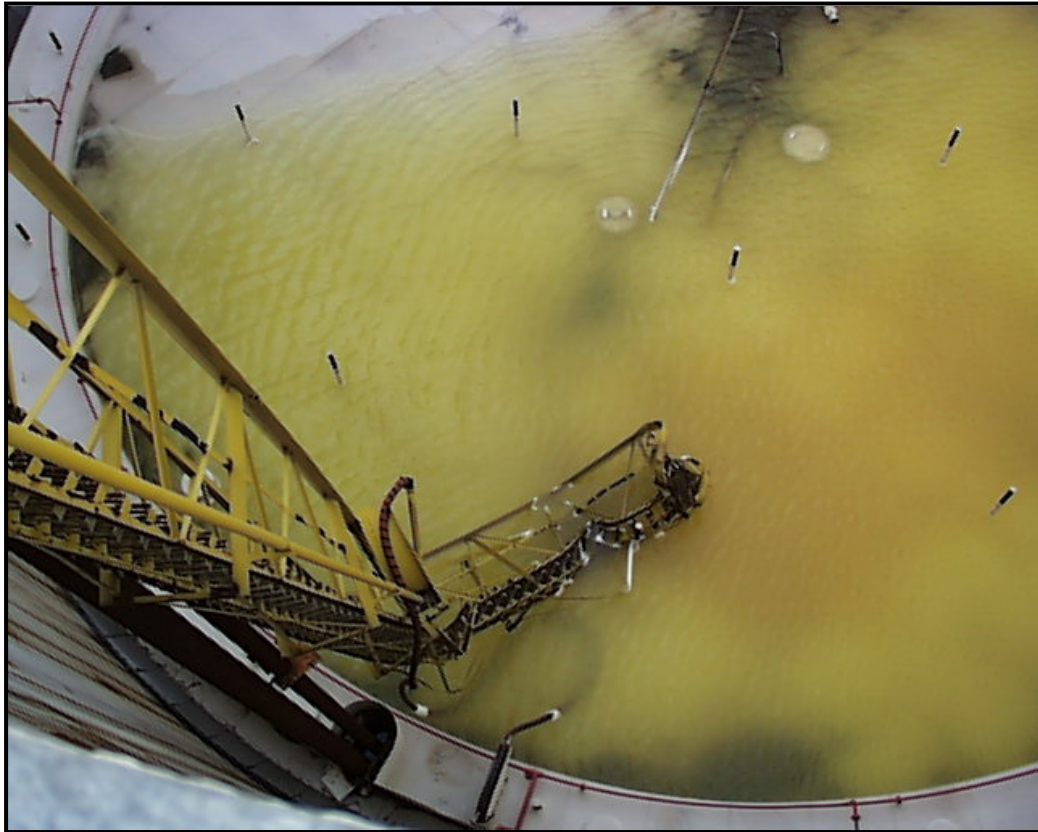


Figure 87 A failed floating roof ladder
(Liquid on the deck is gasoline)

If a rolling ladder is installed, then it should be carefully examined during the in-service inspection and given a complete overhaul at the out-of-service inspection. It should be realised that ladders can be blown from their tracks by high winds, and should therefore be inspected immediately after such weather conditions.

The following points should be noted during inspections:

- all parts of the ladder and track should be sound and undistorted (it should be noted that the ladder handrail is frequently a structural member);
- all welds should be sound;
- the track should be sound, straight, free from debris and un-corroded;
- welds connecting the track to the roof (preferably on doubler plates) should be sound;
- the area of roof around the ladder supports should be examined for corrosion;
- ladder treads should be un-corroded;
- all moving parts should be lubricated and free to operate as designed;
- earthing cables should be directed away from the ladder to prevent entanglement; and
- Paintwork on the ladder and track should be in good condition.

When the roof is landed in its maintenance position, the ladder is at its steepest and can twist out of position. The operation of the ladder should be observed as filling commences.

11.8 Earthing of floating roofs

In addition to the earthing bosses on the tank shell, electrical earthing facilities (spring stainless steel shunts) should be fitted for earthing of the floating roof across the rim space. These shunts should be spaced at intervals not exceeding 2.5 metres. Their sliding contact with the tank shell should preferably be in the open air above the secondary seal to allow easy inspection. However, when secondary seal design allows easy inspection, the shunts may be placed in the void space between the primary and secondary seals.

In addition to the above, the rolling access ladder should also be earthed by means of an electrical cable of adequate cross section.

11.9 Guidelines for the operation of floating roofs

Reference is made to EEMUA 217⁽³⁰⁾ for additional information on operating procedures of floating roofs.

11.9.1 Introduction

A floating roof is a moving structure, and requires attention to maintain maximum efficiency and to prevent accidents. Apart from the normal inspection of the storage tank, the guidelines given here should be made available to those actually responsible for the operation and maintenance of the floating roofs.

11.9.2 Before the roof is taken into service

After construction and water testing of the tank, the roof will be standing in its high (i.e. maintenance) position. Before the floating roof is taken into service the following actions are required:

Before filling:

- check that the valve of the roof drain at the tank shell is fully open;
- check that the roof drain and drain holes in the centre sump of the roof are not choked by dirt or any foreign matter; and
- close the drain plug in the centre of the roof (see also Section 11.3.1).

During filling:

- the first 2–3 metres of filling should be done at a reasonably low rate to prevent damage to roof drain or roof;
- check that side-entry mixers (if fitted) are not switched on before the roof is at least a few metres above the impellers of the mixers (the limit of 2.5m recommended in Section 10.5, last paragraph, 3rd bullet, may be applicable if the type of seal cannot withstand turbulence);
- adjust all roof support and automatic bleeder vents into their low (i.e. operational) position when the roof is floating; and
- observe the roof while floating it into service.

11.9.3 During the first month of operation

With the roof floating on product, check that no compartments are leaking. Owing to deeper immersion of the roof in oil than in water and the easier

penetration of oil through pinholes (compared with water during testing), small leaks not apparent during water testing may appear.

11.9.4 During operation

During operation of the roof ensure that:

- the roof is always kept floating;
- side-entry mixers are switched off when the roof is less than a few metres above the impellers; and
- filling and emptying rates are not increased above their original (design) values without the approval of the design authority.

By frequent inspection check that:

- the valve of the roof drain at the tank shell is fully open;
- no oil is leaking out of the roof drain;
- the roof drain and the drain holes in the centre sump of the roof are not choked by dirt or foreign matter;
- the centre deck is not leaking;
- the pontoon compartments are not leaking;
- the earthing shunts at the periphery are in good condition (not broken);
- the wheels of the rolling ladder are running smoothly over their tracks;
- the roof supports and automatic bleeder vents are all in their low (operational) position; and
- the seal is operating within its tolerances for inward and outward movement (the seal may pull away from the shell or press too tightly if the tank is out-of-round due to soil settlement).

11.9.5 Before landing the roof

Before a floating roof is landed on the supports, the following actions are required:

- check that the valve of the roof drain at the tank shell is fully open;
- check that the roof drain and drain holes in the centre sump of the roof are not choked by dirt or foreign matter;
- ensure that side-entry mixers are switched off when the roof is less than a few metres above the impellers of the mixers;
- check that the centre deck is not leaking;
- check that the roof compartments are not leaking;
- adjust the roof supports and the automatic bleeder vents to their high (maintenance) position;
- when required, also adjust the roof supports to suit differential bottom settlements; and
- observe the roof while it is landing.

11.9.6 Roof standing on its supports

While standing, the following actions are required:

- check that the valve of the roof drain at the tank shell is kept fully open (by locks if necessary);

- check that the roof drain and drain holes in the centre sump of the roof are not choked by dirt or foreign matter;
- instruct maintenance personnel and contractors on the importance of the first two items above;
- ensure that side-entry mixers are not switched on, e.g. for de-sludging purposes; and
- open the drain plugs or emergency drain in the centre of the roof (see also Section 11.3.1).

Additional recommendations and considerations:

- To facilitate adjustment of roof supports and automatic bleeder vents, the openings should be marked by colour bands, e.g. red for the maintenance position and green for the operational position;
- It should be understood that with respect to rainwater loading, the roof is in its most vulnerable position when standing on its supports. During periods of heavy rainfall (e.g. in tropical areas) special attention is therefore required;
- For special buoy type roofs, installation of an additional opening for drainage into the tank is recommended. This needs to be opened when the roof has landed on its supports. Instructions for the proper use of this opening should be fixed on top. The additional opening is to be considered as an equivalent to the drain plug provided in pontoon type roofs, and should be opened only when the roof is standing on its supports. It needs to be closed before the roof is floated.

11.9.7 Recommended filling rates for floating roof tanks

The filling rates for floating roof tanks are restricted to avoid damage to the tank internals, i.e. roof supports, rim seals and roof drains, especially during the initial filling, and to avoid the build-up of static electricity. The initial liquid velocity through the inlet nozzle piping is around 1 m/sec, and the maximum recommended velocity when the roof is floating on the product, and is about 1m above the highest tank shell protrusion (nozzle), is about 6–7 m/sec.

The recommended rate of rise of the floating roof is between 1.5 and 2.0 m/hour or about 30mm/minute.

The same considerations apply when emptying the tank: start pumping at the normal rate, slowing down towards the end when the roof is near its landed position, keeping the roof afloat.

11.9.8 Ballooning of single-deck floating roof

Gas pockets under single and double deck floating roofs, due to high vapour pressure, temperature influences (sun radiation) and/or process upsets (e.g. carryover of LPG) may result in ballooning of the centre deck as shown in Figure 88.

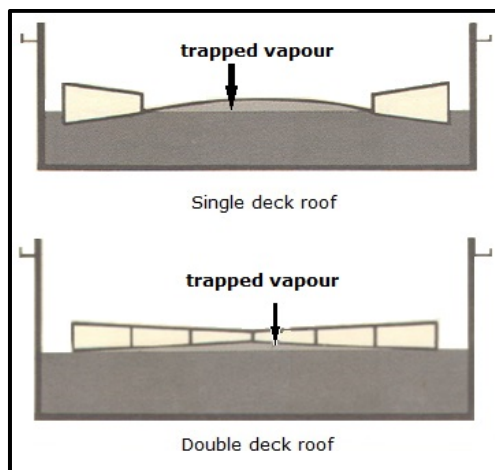


Figure 88 Trapped vapour under roofs

Some instances have been recorded where the vapour pressure underneath the floating roof exceeded the dead weight of the roof (approx. 8 mbar). This caused the developed gas pressure to lift the roof resulting in burping and extreme hydrocarbon vapour releases as shown in Figure 89.

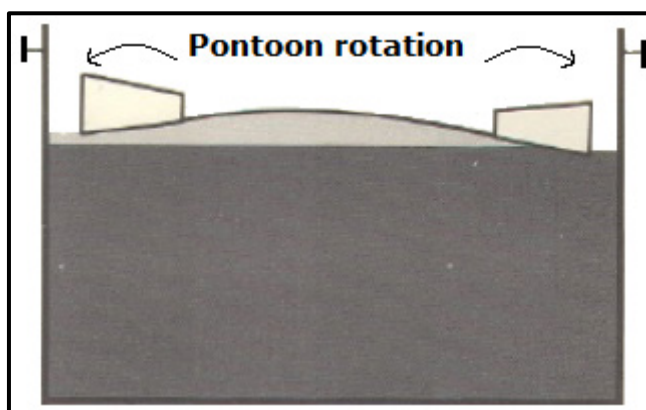


Figure 89 Burping of a single deck floating roof

Burping causes the roof to lift-off slightly from the liquid surface and vapours escape from underneath the roof, via the rim seal and/or the rim vents.

This situation will often influence the drainage of (rain) water from the roof and may result in stagnant water pools, corrosion and tilting of the total roof structure as in Figure 90.



Figure 90 Example of effects of burping

Operators sometimes try to avoid this ballooning and tilting by adding weights (e.g. precast concrete blocks) on the centre deck. This should, however, be avoided as the additional weight may, especially under storage of light density products, cause the roof to sink deep into the product with a higher risk that product level in the rim space may become too high and product may flow over the rim edge causing the roof to tilt and sink. This may also lead to limitation of the additional design load (water accumulation) that the roof can carry.

11.10 Possible problems

11.10.1 Leaking pontoon compartments

Poor welding or corrosion may cause leaks in pontoon compartments. The annular pontoon is divided into compartments by bulkheads, so that a leak in one compartment cannot be spread into adjacent compartments. All compartments should be regularly inspected for leaks through the openings provided.

11.10.2 Cracking in centre deck due to wind loading

In locations where frequent and prolonged strong winds occur, leakage in the centre decks of large diameter floating roofs has been experienced after relatively short periods of service, manifesting itself by the appearance of product on the centre deck.

The wind creates waves in the thin (5mm thick) centre-deck plates, which may lead to fatigue cracks. These are most likely to occur at lap welds, around roof supports, and at other welded attachments. Such cracks are generally experienced in large floating roofs, i.e. with diameters over 50 m. Rates of crack initiation and propagation depend on wind speed and gusting frequency. Cracks can occur after a few years, or depending on location, only become apparent after

many years of service. The problem is generally prevented by the installation of more rigid roofs, e.g. double-deck roofs. As a temporary repair, while the tanks are still in service, some operators have used plastic sealants to effect for a limited time. Such repairs require careful, continued inspection since the cracking may continue. Permanent repairs should be made when the tank is out of service.

11.10.3 Out-of-roundness tolerances

Out-of-roundness of a tank shell occurs due to the following:

- errors in dimensional tolerances during construction or repair;
- differential soil settlement under the tank shell;
- Tilting of the tank; and/or
- Localised overstressing of connecting piping.

Dimensional tolerances are specified in the design and construction codes, e.g. EN 14015. These tolerances include nominal radius, verticality, weld peaking and rim space. These are often difficult to achieve, particularly after major repair or modification work on the shell.

Differential soil settlement can cause ovality. This can result in rim gaps between floating roof seal and the shell exceeding the limits for satisfactory operation. These gaps will cause increased evaporative losses, and may cause some loss of earthing continuity of the floating roof. At other locations gaps may be reduced, resulting in jamming of the roof and damage to the roof seal. Recommendations for limits of settlement are specified in Section 6.5.3. When these limits are exceeded, the tank and its foundation should be re-levelled.

The paper by Marr et al.⁽³¹⁾ from which the formula in Section 6.5.3 is taken also proposes a limit for tank ovality based on the gap that could be accommodated by the roof seal. When seals are designed with working ranges $-X/+X$ (i.e. the inward working range equals the outward working range, which usually is $-125/+125\text{mm}$. over a rim gap of 200mm) the limit for settlement is based on following formula:

$$S \leq L^2 \frac{\text{Gap}}{(HD)}$$

where:

S = deflection in mm (out-of-plane distortion - see Section 6.5.3)

L = arc length between measurement points in m

H = tank height in m

D = diameter of tank in m.

However, when rim seals are designed in accordance with the requirements stipulated in Section 11.4.2 (working range $-X/+3X$) the seal has much more flexibility to accommodate tank shell ovality due to settlement. In this case the method and formula given in Section 6.5.3) will be sufficiently adequate for specifying the limit of settlement for a floating roof tank exceeding 40m in diameter.

The effectiveness of earthing straps (shunts), used to earth floating roofs to the tank shells to prevent sparking in the rim space, are also influenced by excessive ovality of the tank shell induced by settlements. When shunts are broken, or

when differential soil settlement causes long, wide rim gaps, earthing could become ineffective.

Regular inspection and maintenance is necessary to identify and rectify such problems.

11.11 Repair/modification methods

Any method of repair is acceptable that will restore a floating roof to a condition enabling it to perform as required.

The centre deck can be repaired by patch plates or by replacement of all deck plates. Pad plates are always placed on the outside of the roof. Pontoons can be repaired in the same way.

11.11.1 Overplating

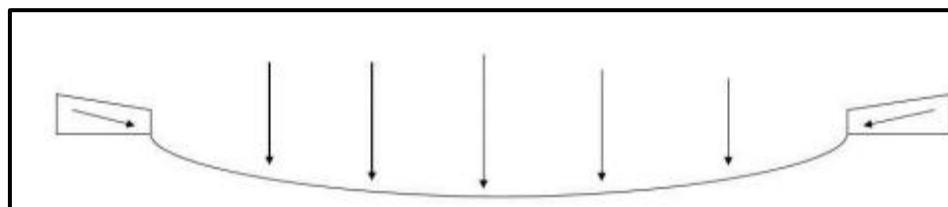


Figure 91 Potential effect of over plating floating roof centre deck

For single deck roofs compressive stress in pontoons is directly proportional to the deck weight. Weld shrinkage adds to the inward pull on the pontoons, increasing compressive stress as shown in Figure 91. It could also result in damage to the roof seals or even the roof sinking.

11.12 Snow loading

Based on local climate conditions, the density of snow can vary considerably. The loads should be taken from EN 1991-1-3.

An accurate estimation of the accumulation depth can be difficult, in particular when the snow drifts. In the case of single deck floating roof tanks, tilt has occurred leading to the sinking of the roof. Deflection can also lead to potential buckling.

An assessment should be made to the amount of fresh, wet or packed snow a floating roof can accommodate under floating conditions or standing on its legs.

11.12.1 Inspection history

This should be considered as any corrosion of the roof deck or supports will reduce the load carrying ability of the roof.

Landing of the roof should be discouraged in such cases, particularly if previous reports have revealed corrosion to the roof legs or roof leg supports. These are not designed to hold a snow load. Additional stress would be applied by the snow or ice and this could lead to significant roof damage including collapse upon

landing or fatigue cracking to the roof plate welds, causing a split and product entering the roof deck.

11.12.2 Removal of the snow

In the case of drifting, the immediate requirement may be to redistribute the snow.

This may simply involve personnel removing the snow by hand, (buckets, craneage with baskets etc.), or some users have used a vacuum truck, to which the need of adequate earthing should be considered.

For the safety of personnel, the tank should be filled to the maximum height. It is also recommended that the roof inspection records have revealed that there is adequate thickness and no significant areas of corrosion. A full risk assessment on personnel access should be taken as the probability of slips, trips and falls would obviously increase in such conditions.

In some cases the tank product stored in the tank may be above freezing, enabling the snow to melt during milder conditions. The tank roof can then be drained as necessary. Any snow accumulation to the pontoons would not be affected by product temperature. If conditions permit, this can be pushed onto the roof deck enabling it to melt at a later stage.

11.12.3 Operation of the tank

As previously mentioned, landing of the roof is not recommended. During periods of snowfall, a minimum fill height should be agreed. Many operators keep the roof at 300mm above its normal low level. This makes an allowance for immersion due to additional loading.

Roof drains and venting systems can be prone to freezing and should be suitably monitored.

11.13 Aluminium dome roofs

The typical aluminium geodesic dome roof structures, introduced in the mid-1970s as weather covers over water treatment facilities, are now also used for the storage tanks in the petrochemical industry (see Figure 92).

In addition to preventing snow accumulation on top of floating roofs, dome roofs are also advantageous in preventing rainwater accumulation, and hence the danger of overload, and tilting/capsizing and eventual sinking of the entire roof structure. This is especially important when the roof drain is not working or is normally kept closed.

The relatively high number of floating roof failures due to excessive rainwater accumulation justifies consideration of a dome structure on top of both new and existing floating roof tanks, especially in areas with high rainfall.



Figure 92 Typical geodesic aluminium dome on a fuel tank

Next to the advantage of keeping off rainwater is the elimination of the effect of wind on the top of the floating roof. Wind (drag factor) plays a major role in the emission loss from the rim seal and on maintenance costs of the seal which is subjected to the continuous radial movement of the roof structure. Other spinoffs are the lower maintenance cost due to the less frequent need to paint the floating roof, and the reduction in temperature on the top of the floating roof; particularly important when the stored product has a high vapour pressure.

Aluminium geodesic domes are available from various suppliers in Europe and the USA, in a range from about 6m up to 80m. The dome is usually constructed of prefabricated aluminium I-beams and panels. The beams are linked or bolted together to form triangular spaces, which are closed by pre-cut aluminium panels clamped on top of the beams. The geodesic framework is illustrated in Figure 3. Domes can be prefabricated within the tank and lifted in position, or assembled outside the tank and lifted in position by crane. However, the diameter/size of the dome is then limited by the available crane capacity.

The dome structure requires a tension ring to handle the outward radial thrust. This tension ring can either be integrated with the primary wind girder at the top of the tank shell or be an integral section of the dome structure itself. The latter (self-supporting dome) is the most cost effective solution, and does not require a lot of hot work on the tank shell.

Skylights are sometimes installed, covering 1 to 1½ % of the dome's surface area.

A retrofitted dome structure in combination with a new fibre glass internal floating roof deck is not only very low in maintenance cost (no corrosion) but will also increase the net storage capacity of an existing tank.

Special care should be taken where the reinforced tank shell top section has adequate horizontal support and domes are installed without a tension ring. Minor settlement of the tank could influence this support function, which might result in lateral movement of the dome section. This in turn could affect the joints between the dome panels and lead to leaks, and/or to situations where the stress in the members is increased thereby reducing the ability of the roof to accommodate the design live loads (e.g. wind, snow, maintenance crew etc.).

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12 Tank appendages

12.1 Shell and roof nozzles

When a fit-for-purpose assessment to a storage tank is being executed an investigation to the condition of the internal and external piping must not be forgotten. Chapter 5 specifies the minimum requirements for nozzle inspections by means of NDT.

It may be required to also perform an assessment on moments in the nozzles and the connecting piping induced by external loads (differential settlements between tank and pipe supports) and the rotation in the tank shell induced by the fluctuating product levels in the tanks. In general it is not the internal pressure that determines the rejection limit of the piping but the moments induced by the differential settlements.

Note that the shell reinforcements around a nozzle are only determined as a substitute for the hole in the tank shell and roof plates and the design codes used do not cater for any lateral forces nor moments induced in the connecting piping to be taken up into the shell and roof plate design.

In general differential settlements and lateral stresses in the connecting piping are compensated by expansion bellows or flexible joints in the piping systems. In such case where these compensation structures are installed the following rejection limits of the nozzle bodies could be considered under general corrosion:

$t_{\min \text{ nozzle body}}$ is either 50% of the original pipe thickness² or 2.5mm, whichever is greater.

In formula:

$$t_{\min \text{ nozzle body}} = \text{MAX [50\% of original pipe thickness ; 2.5mm]}$$

The determination of the 50% rejection limit can be performed whilst using the below tables, which are copied from EN 14015.

EN 14015 uses different specifications for shell and roof nozzles. For this reason, different tables are included: Table 10 shell nozzles and Table 11, roof nozzles

Table 10 Minimum design thickness of shell nozzles

Outside diameter of nozzle d_n (mm)	Minimum shell nozzle body thickness e_n (mm)	
	Carbon and carbon manganese steel	Stainless steel
$80 \leq d_n \leq 100$	7.5	6.0
$100 \leq d_n \leq 150$	8.5	7.0
$150 \leq d_n \leq 200$	10.5	8.0
$200 \leq d_n$	12.5	9.0
Flanges should conform to EN 1759-1 ⁽³²⁾ Class 150 or EN 1092-1 ⁽³³⁾ PN 25		

² = original pipe thickness less corrosion allowance specified by the tank owner

Table 11 Minimum design thickness of roof nozzles

Nominal diameter of nozzle (mm)	Outside diameter of nozzle d_n (mm)	Diameter of hole in roof plate d_n (mm)	Minimum height of nozzle h_n (mm)	Minimum nozzle wall thickness e_n (mm)	
				Carbon and carbon manganese steel	Stainless steel
25	34	40	150	3.4	2.7
50	60	66	150	3.9	2.7
80	89	95	150	5.5	3.0
100	114	120	150	6.0	3.0
150	168	174	150	7.1	3.4
200	219	230	150	8.2	3.7
250	273	284	200	9.3	4.0
300	324	336	200	9.5	4.5

Note 1 Flanges should conform to Class 100 of EN 1759-1 or PN 25 of EN 1092-1
Note 2 See Figure 19

In the above tables, it is assumed that all nozzles are equipped with reinforcing plates around the nozzles. However, nozzles having diameters less than 80mm may – in accordance with present available design codes – be executed without such reinforcing plates. These type of nozzles can be evaluated whilst using Table 12.

Table 12 Minimum design thickness of roof and shell nozzles with diameters < 80 mm, executed without reinforcing plates

Outside diameter of nozzle d_n (mm)	Minimum shell nozzle body thickness e_n (mm)	
	Carbon and carbon manganese steel	Stainless steel
$d_n \leq 50$	5.0	3.5
$50 < d_n < 80$	5.5	5.0

Note: the above evaluation considers that no lateral forces nor any induced moment will be taken up by the nozzle assembly. In case this cannot be assessed for sure, appropriate finite element calculations should be performed under full liquid level in the tank (to cater for a maximum rotation of the tank shell under maximum liquid load) to assess the actual rejection limit of the nozzle bodies of roof and shell nozzles.

12.2 Floating suction lines

The use of Floating Suction Lines, (FSL), has become a more widely used process.

Most operators use this system to ensure good product quality control, particularly in the use of aviation fuels. The suction is taken from the top of the liquid level rather than the normal low point operation.

12.2.1 Design

Design differences may vary, (including the use of chains and roller tracks). The system is used in both fixed and external floating roof tanks. Extra precautions may be necessary for internal floating roof operation, in particular for non-steel roofs.

In the case of light-weight internal roofs, the use of FSL is discouraged due to structural, weight integrity and buoyancy forces.

Most systems are shop manufactured and users should ensure that the density values are applicable to the product stored in order to ensure successful operation. Many FSL have been, or are being, installed to tanks that have been in operation for many years. It is important to understand any corrosion mechanisms, (i.e. roof thickness), that may affect installation or future operation.

It is therefore recommended that a full engineering review is completed, as modification to the roof may be necessary. Failure to do so could lead to a short operation period.

12.2.2 Operational experiences

On single deck floating roof tanks, previous experiences occurred where operation of the FSL can be affected by gassing, caused by either temperature, filling rates or process operations. This has seen a ballooning effect on the centre deck, lifting the FSL away from the product, thereby not maintaining contact with the product that created a failure to discharge the product.

Some users have experienced adverse effects on the hydraulic performance of product pumps.

12.2.3 Inspection

During internal tank inspection periods, the FSL should become a part of the written inspection scheme of examination.

The examination, both visual and with NDE, should include any degradation, (pitting, cracking, leakage or damage), pivots, floats, the line and its supports. Particular attention should be paid to swivels and ball joints ensuring adequate integrity, lubrication and functioning.

It is important that the user ensures the equipment will be fit for service until the next inspection due date, for example, joint inspection guidelines.

12.3 Ladders, stairways, platforms/railings and lighting

Access to the top of a tank and the roof may be required at any time. It is therefore important to keep all items necessary for such access in good condition.

The design of stairways, platforms, walkways and associated hand railings vary considerably. Therefore reference to the appropriate original standard should be made. The quality of the corrosion protection applied also varies considerably. Tanks are often located near the sea or adjacent to plant where the environment is likely to be corrosive.

Many components are difficult to check, however there are usually substantial safety margins built in, and the general state of the steelwork will provide a good indication of integrity. Usually stair treads, gratings and handrails are the most critical items. Handrails constructed from tubular sections are particularly vulnerable. Horizontal surfaces may act as traps for rain and debris.

It is essential to ensure protective coatings are intact and serviceable. It is particularly important to check areas where stairways and ladders are attached to the tank shell. Any corrosion or weakness in these areas may jeopardise the integrity of the stairway or ladder.

Where deemed necessary, lighting facilities should be provided for safety access of ladders, stairways etc. Preferably, lighting poles should be mounted on intermediate or top platforms (or landing areas of rolling ladders). When installed, sound electrical bonding should be provided to the earthing grid system of the tank.

Large diameter floating roof tanks often have a substantial upper or primary wind girder. This often serves a dual purpose of wind girder and walkway. It should be remembered that its prime function is that of a wind girder, and the assessment of any observed deterioration (loss of section) should take this into account.

12.4 Side entry mixers

Side entry mixers are installed for mixing the product and to prevent settlement of sediment. There are two types of motorised side entry mixers: fixed, and variable angle. Variable angle mixers are used to ensure coverage of the entire bottom area and prevent stagnant regions. A location not reached by the circulating currents induced by the mixer may suffer from extra corrosion due to the sediment and collected water at that spot. Areas where there is preferential settlement of sediment should receive attention when a tank is opened for internal inspection. The movable parts of the side entry mixers should also be inspected for leakage.

Side entry mixers should never be switched on when a floating roof is closer than 2.5m from the circle described by the impeller. Side entry mixers switched on with the floating roof in a lower position may easily damage the roof, particularly the seal. This also applies when floating covers are installed in fixed roof tanks (See 11.4, last paragraph, 3rd bullet).

12.5 Tank instrumentation

12.5.1 General/records

A complete instrumentation record file should be kept containing five types of record:

- basic data;
- continuous record;
- loop diagrams;
- field notes;
- electrical safety certification.

Basic data should include item number, manufacturer's serial number, model number, and all technical data necessary to determine the function and physical description of the equipment. This data, together with the manufacturer's drawings and instruction sheets, complete a permanent record file. The **continuous record** should include a history of all inspections performed on the equipment; the date and type of inspections performed, repairs made, materials used, and any other pertinent information helpful in determining future inspection requirements and equipment retirement.

Loop diagrams should be complete enough so that anyone with this information alone would be able to understand how one part of the system interacts with the rest of the system. Loops should be regularly checked to ensure continued compliance with **electrical certification**.

Inspection should include checking transmission systems, power supplies, seals, purges, panels and other associated equipment. Measurement and control systems can be relied upon only if they are inspected periodically and serviced by competent personnel who are familiar with both process requirements and instrument functions. Particular attention should be given to those instruments that affect safety and continuity of operation. All level alarm switches should be easy to test, with procedures that duplicate an actual alarm situation as closely as possible. High level alarm systems for tank overfill should be tested in the same manner; however, the test should not require filling the tank above its normal fill level.

Procedures for testing, inspecting and maintaining a high level alarm switch and system should take account of manufacturers' recommendations. Some electronic level switches can be tested electrically, but this may not ensure that they will operate in alarm conditions.

Additional tests and maintenance procedures may be required by local government regulations.

Liquid level measurement equipment should be given a careful visual inspection. For float type gauges, the float should be examined for corrosion or cracks to ensure that it does not contain liquid. Cables and chains should be inspected for corrosion and wear. Sheaves and pulleys should be inspected to see that they turn freely and are properly lubricated. Guides should be examined to ensure that they are free and not plugged.

Binding or friction can be detected by manually bumping the gauging system and observing its operation. Many companies install servo gauges which can be tested by push button operation from the control room, or radar gauges with no moving parts.

If a pressure gauge is used on a tank, it should be checked to ensure that the pipe connection to the gauge is not plugged, that the gauge is operative, and that its reading is accurate. For ordinary uses, the gauge can be checked for reasonable accuracy by connecting it to a suitable source of pressure along with a gauge known to be accurate. For test purposes, a deadweight tester or a calibrated test gauge should be used.

Flow instruments should be calibrated to within 0.1% or less for custody transfer applications.

In general, corrosion of instrument parts that contact process fluid is not a serious problem because these parts are normally made of corrosion resistant materials or are suitably protected by using seals or purge systems. The effects of corrosion are usually apparent from visual inspection. Obvious signs are pitting and rust formation.

12.5.2 Instrument and component failure due to external corrosion

Deterioration resulting from attack by moisture, salt, air, fungi, or corrosive vapours in the atmosphere is the most common form of external corrosion. In hot, humid climates, these factors are the major causes of instrument component failure. This type of deterioration is especially prevalent in electronic instrument components. Oxide or salt formation on metal surfaces subject to such corrosion can usually be detected visually.

In addition, electrical components may also show symptoms of corrosion such as fungal growths. A leaking or distorted capacitor is usually a sure sign of such deterioration.

12.5.3 Electronic instruments

Most capacitance or conductivity probes and probe insulators should be free of deposits and dirt, and the probe should not touch any part of the vessel in which it is suspended. The action of relays may be checked by shorting the probe to earth or by actually varying the liquid level in the equipment. The manufacturer's literature generally outlines specific troubleshooting and checking procedures, and should be referred to when inspecting the instrument.

12.5.4 Tank cooling and fire protection system

The need for a well-equipped and maintained tank cooling/fire protection system in a storage tank facility cannot be overemphasised. Most areas of a tank farm will be equipped with a fixed firewater monitor system, the capacity and type of which depend on tank size and type of product stored. Testing and maintaining these systems are the only guarantee that they will actually and adequately work when required.

There are a number of cooling systems and foam protection systems (or combinations) in use, some of which are fixed, semi-fixed or portable. The choice of system depends on the recognition of potential scenarios that can occur. Typical scenarios are: rim seal fire, spill-on-roof fire (cracks in skin, or flammable vapours escaping through a vent or roof fitting), a full surface fire (open pool fire), a bund fire, or an explosion in a pontoon, or confined space (air being pulled into the vapour space under the roof when landed on its legs).

Fire fighting systems should be designed in accordance with local legislation as a minimum, but also taking into account company policies, owner/operator requirements, and international codes and standards (e.g. EI Model Code of Safe Practice Part 15).

The tank operator is responsible for demonstrating that all reasonable measures to minimise risk are being taken. Consideration should be given to the regular maintenance of fire detection and alarm systems, and proving the protection

effectiveness. Good pre-planned incident management is important; however, a prescriptive requirement cannot be universally applied and adopted as each facility operates under different nationally recognised standards and conditions.

For storage tanks, maintenance plans should focus on equipment immediately attached to the tanks (e.g. cooling systems, foam chambers, risers, detection and alarm systems etc). Manufacturers' recommendations should be used to determine the preventive maintenance schedules, while the complete systems should be regularly tested to determine levels of deterioration and ensure the availability of the systems.

13 Tank coatings

13.1 Introduction

Paint coatings are usually applied for corrosion protection and/or aesthetic reasons.

In addition, highly reflective external coatings may be used to reduce evaporative losses, and high integrity internal coatings to protect product quality. Detailed coating requirements may be found in publications such as those produced by NACE or the ISO organisations. However, making reference to these publications does not replace the need for the development and use of detailed coating specifications, as the publications merely aim to indicate in general terms what some companies have found to be satisfactory and good practice.

Coatings should be applied by suitably competent personnel and independently inspected during application by a suitably qualified third party.

13.2 External coating systems

13.2.1 General

The selection of exterior coatings to protect against atmospheric corrosion, to improve appearance and to reduce evaporative losses will depend upon many factors. These include:

- **environment:** coastal/industrial location, ambient temperatures, humidity;
- **access:** should not be under estimated i.e. scaffold requirements, ease of access;
- **life:** future maintenance policy;
- **cost:** type of surface preparation, paint system, paint thickness;
- **expertise:** availability of coating applicators;
- **time:** weather window for painting, need to have the tank in service;
- **regulatory:** local safety regulations for volatile organic compounds (VOCs), lead, sandblasting etc.

(References: *API Manual of Petroleum Measurement Standards*, Chaps 19.1 (for effect on evaporative losses) and 19.2)

In all cases the following will result in improved coating performance:

- Good design of structural details to minimise corrosion, e.g. seal welding of stitch welded components such as wind girders prior to painting, eliminating catchment areas where water can collect;
- Removal of sharp corners, excessively rough weld ripples, temporary construction aids, etc., where the surface tension effects will result in areas of inadequate paint thickness. Premature failure of coatings at such locations is very common;
- Standard of cleanliness prior to and in between paint film layers;
- Specification of an additional stripe coat by brush to all welds, corners and edges to ensure that coating thickness is adequate;
- All coatings should be applied strictly in compliance with the manufacturers' data sheets and accepted good coating practice. Primer

coats should be applied by the most appropriate method taking into consideration that spray application may be prohibited or undesirable due to the location or safety issues; and

- Inspection is a most important aspect of coating work. Surveys have shown that almost 80% of all premature coating failures are due to poor surface preparation or paint application. Therefore, inspection should be an integral part of the work, beginning with surface preparation and covering all aspects of coating application, film thickness, workmanship, ambient conditions etc.

13.2.2 Bottom

As described previously, there may be grounds for lifting the entire tank to allow proper inspection and foundation repair. If the condition of the bottom allows, it is a good opportunity to shot blast and apply a paint coating in accordance with Appendix C.5. However, the source of the external bottom corrosion should be eliminated as well.

Only when the cause of the external corrosion is eliminated should restoration of the tank bottom integrity by internal laminate repair be considered (see Section 13.3.2 2).

13.2.3 Shell and roof

The operating temperature of the tank should be considered when selecting a paint system. Typical paint systems for the tank shell and tank roof are presented in Appendix C.5.

For spot repair and renovation, the selected paint systems should be the same as, or compatible with, the existing coating systems.

Epoxies and polyurethanes should only be applied on top of alkyd paints in exceptional cases, and only after a thorough investigation has been conducted into the softening and adhesion of the proposed coating system. In such cases the paint manufacturers should be consulted.

Silicate-based paints should not be applied on top of organic coatings or organic shop primers as there would be insufficient inter-coat adhesion.

13.3 Internal coating systems

13.3.1 General

Coatings may be applied only to those parts of the internal surfaces that need particular protection from corrosion, or to all surfaces, i.e. bottom, shell, roof, support columns etc. For the storage of some products, even low corrosion rates may allow too much iron to contaminate the contents. Thus it is common for complete internal coatings to be specified for tanks storing jet fuel and gasoline.

Coatings applied for ensuring stock purity may require special testing and approval to ensure that the coating itself does not contaminate the contents. This may mean that paints containing metallic zinc are not acceptable. Internal coating system selection depends upon many of the factors previously listed for external coatings. In addition, the following should be considered:

- For internal shell coatings on floating roof tanks, good resistance to abrasion is necessary in the area swept by the tank roof seal. Zinc silicates have given good performance in this duty. Glass flake pigmented epoxy or polyester coatings may be suitable, but these coatings may result in excessive wear on the seals;
- For tanks which regularly contain a water bottom (a layer of water on which the stored product floats), a high integrity system suitable for immersion service should be specified. Such systems include either glass flake or glass fibre reinforced epoxies or vinyl esters. In the case of glass fibre reinforced coatings, these may be applied in thicknesses of several millimetres by hand or by special spraying equipment. These thicker coatings are particularly useful where tank bottoms have suffered extensive corrosion, as they provide additional security against the risk of leaks;
- A surface blasted with high quality abrasive, which will not leave any dust/debris residues which could influence the lining material or subsequent contents of the storage tank, is strongly recommended for all such internal coatings. Control of volatile organic compounds and humidity is important. Adequate ventilation is necessary to allow intercoat and final coat curing;
- Condensation or penetration of rainwater should be avoided during paint application, since dampness can adversely affect the effectiveness of the finished paint coating. Special consideration should be given to ensure rain/water does not enter the interior of the tank between the shell and roof seals typically found on floating tank roof areas;
- For roughened and pitted surfaces it is imperative that all corrosion deposits, salts etc., are removed from the bottoms of pits before the coating is applied;
- Inspection of internal coatings is even more important than for external ones. An additional check is necessary to ensure that the coating is fully cured prior to the tank being returned to service. Depending upon the choice of lining material, solvent swab tests are usually more reliable than the use of hardness checks;
- The lining should be checked for discontinuities (holidays, pinholes and thin spots) using either a low voltage wet sponge or high voltage (spark) detection test method, which would be determined by the lining thickness and recommendations of the material manufacturer. The relevant parameters should be detailed in the description of the works, lining specification and agreed between all parties to avoid the possibility of an inappropriate test method being used;

- It is important to extend the tank floor coating a short distance up the shell, so that the shell-to-floor weld and the lower part of the shell are protected against any corrosive water phase which may collect at the bottom of the tank;
- Thick, one coat systems should be avoided. Systems having a minimum of two coats are preferred; and/or
- For glass fibre reinforced coatings, it is essential that all glass is thoroughly saturated with resin. The use of surfacing veils and the application of gel coats is good practice. This prevents glass fibres protruding through the surface, promoting 'wick action' (capillary action with water moving into the coating along the fibres).

13.3.2 Bottom

Non-metallic coatings and paint may be applied to prevent corrosion.

13.3.2.1 Coatings

If internal corrosion is observed to the extent that the corrosion allowance is almost completely used up, the need for expensive repairs in the future can be reduced considerably by coating the bottom internally: see Appendix C.5.

13.3.2.2 Laminates

If serious internal corrosion is observed but not to the extent that the tank's structural integrity is compromised, the application of glass fibre reinforced plastic (e.g. reinforced epoxy (GRE), vinyl ester, or polyester) may be considered if the costs involved are economically justifiable when compared with those of bottom renewal. The laminate should span the entire bottom and extend about 1 metre up the shell. A detailed description and typical example of an installation procedure are given in Appendix C.5.

Before deciding on bottom repair by means of laminated plastic, the annular plates should also be checked to determine whether they are seriously corroded on the underside. If that is the case, replacement will be necessary since these plates are highly stressed when the tank is full.

13.3.3 Shell and Roof

The coating and lining material needs to be compatible with the stored fluids to which it is exposed, over the full design temperature range, so that the mechanical, physical and chemical properties of the coating and lining system satisfy the design requirements throughout its intended life. Suppliers' data needs to be checked to ensure this.

13.4 Repair/modification methods - some typical examples

Appendix C.5 presents some typical paint systems for application on storage tanks.

14 Tank insulation

The requirement of insulation prevents easy inspection of the tank surfaces and a coating application should be applied prior to installation of the insulation system as the primary corrosion barrier. The tank shell, roof and all welded attachments should be dry, free from grease and loose particulates prior to coating application. The coating system to be utilised is to be agreed by the vendor. If the roof is to be insulated, two coat applications are recommended. If shop priming is employed, defects and/or blemishes should be rectified during site erection. In all cases of coating application, rigid QC/QA procedures should be applied to ensure recommended coating life is achieved.

The user should consider the impact on roof frangibility with reference to the insulation support, hand rails piping steel work. Reference should be made to EEMUA 180 to evaluate the impact on roof frangibility.

In the case of in situ spraying or foaming, the paint system should be compatible with the foam system and unaffected by any foaming reaction or in-service condition. Where foam insulation is used with fire retardant formulations, protection against the possibility of halogen-induced accelerated corrosion should be considered.

When selecting insulation materials reference should be made to CINI-Manual⁽³⁴⁾, BS 5970⁽³⁵⁾, BS 5422⁽³⁶⁾ and EN 14015 App Q. Chloride content within the insulation material should be reviewed and confirmed as non-detrimental to substrates being insulated.

A challenge to insulation requirement on both shell and roof of individual tanks should be submitted during the specific service life, with the object to remove the CUI degradation. Any permanent insulation removal should be assessed, documented, and recorded as part of a management of change review.

Materials used to insulate tanks in all service conditions include phenolic foams, polyurethane, calcium silicate and mineral wools. These materials are porous, retain moisture, are applied with a seal coat designed to prevent the ingress of water. Mastic sealed aluminium zinc sheet cladding is a widely used seal coat material. However, it is not uncommon for these surfaces to be damaged and mastic sealant at expiry/end of functional life, will allow rainwater to penetrate into the insulation, enable water ingress and the proliferation of CUI. Prevent water ingress to minimise the CUI potential (See Section 4.6).

These materials can create a wicking action over time, and for this reason it is recommended that insulation be cut back to approximately 150mm above the annular plate. This will prevent ground water from being drawn in via capillary action.

Sealing of insulation capping at the top of the tank below the curb is essential to prevent water ingress. Insulation capping below wing girders require design consideration to prevent water ingress into the insulation from drainage cut outs or 'rat holes' on vertical seams.

All cladding penetrations should be weather sealed to prevent water ingress, with a sealed sleeve design applied to nozzles, to prevent insulation contact with the nozzles. This will prevent accelerated corrosion at these locations.

Associated piping should also be considered for inspection as part of the tank CUI evaluation, with special attention afforded to PV/EV nozzles that are traced and insulated due to process considerations.



Figure 93 Examples of Corrosion Under Insulation (CUI)

Even with good design and installation, over time, the weatherproofing is unlikely to be completely effective. To minimise the risk of corrosion under insulation (CUI) such as in Figure 93, the substrate should be prepared and painted prior to application of the insulation system. In general single coat primer systems have been found to be insufficient to prevent CUI. The substrates should be prepared and painted to the same standard as un-insulated steel, with the exception of a final/top coat application to exposed steelwork for UV protection. General corrosion rates increase with rise in temperature. Hot tanks and adjacent pipework operating at 60 - 120°C are particularly at risk from CUI.

Under certain operating conditions, particularly at elevated temperature, some organic foams can release species, which are aggressive to carbon and low alloy steels. If the foam manufacturer cannot provide relevant information for the intended operating temperatures, then laboratory tests should be carried out to ascertain the risks.

Where the insulation system is found to be damaged and water ingress may have occurred, the affected area of insulation should be removed, the metal below cleaned, inspected, the affected redressed area and insulation re-instated with adequate weather sealing. These locations should be documented for future monitoring.

Methods of attaching insulation to tank shells and roofs vary considerably. BS 2654 Appendix B6 provides recommendations for the design and application of insulation and describes various methods of fixing.

Inspectors should always ascertain details of the insulation system used and the particular method of fixing adopted for any tank under examination. The arrangement and components used in fixing should always be checked as part of

the examination to ensure their integrity. Any weaknesses identified should be rectified.

Attachments used for supporting insulation may create water traps (i.e. insulation support rings); giving rise to localised corrosion if the supports are not properly designed. They should contain drain holes, or be discontinuous to prevent water accumulation or designed to have a stand off from the substrate. Whilst the deliberate removal of insulation for inspection is not normally recommended, the overall condition of a tank should be considered when determining whether sample areas should be stripped for examination. Inspection should focus on areas of insulation/cladding disrepair, mastic sealant expiry, susceptible areas, and cladding/seal coat penetrations.

Inspection tools are available as an aid to focus and target inspection areas. These include:

- Infrared thermography to identify areas of wet insulation and locations where further inspection and maintenance may be required;
- PEC tool (Pulsed Eddy Current) screening.

It must be noted that insulation removal will be required as part of the ONL or OFL inspection event, to enable UT WT monitoring as identified on Table 13 of this Guide. The surfaces can be evaluated at this time for evidence of water ingress (i.e. corrosion particulate or water salts staining). Any wall loss should be evaluated, actioned accordingly, and recorded for monitoring and scheduling purposes. Insulation re-instatement is to be fully sealed, weather proofed, and scheduled for regular inspections or maintenance to maintain integrity.

Coatings for thermal insulation are available but these should be compared with traditional tank thermal insulation systems.

Coatings for thermal heat insulation purposes can be considered when a heat loss calculation proves that the insulation function is sufficient. The heat conservation is achieved by preventing heat convection and heat radiation loss.

Heat conserving coatings need to be reviewed on a case-by-case basis for effectiveness. In some cases it can only be used for personal protection. In other cases it does conserve sufficient heat though rigid quality control should be applied similar to that of traditional coatings.

15 Hydrotesting

15.1 General

BS 2654 requires that every storage tank shall be filled to the top of the shell with water for testing.

The most important reasons for a hydrotest are as follows:

- To demonstrate that the tank is strong enough to satisfactorily withstand the liquid pressure during service. A hydrotest is usually also an overload as the specific gravity of water is higher than of most of the products stored;
- To demonstrate that there are no leaks in the shell or bottom of the tank;
- To demonstrate that the tank foundation can satisfactorily carry the load of the tank and its liquid content;

Note: Before testing, the external shoulder of the foundation should be installed in accordance with the foundation design. Testing the tank without the foundation shoulder in place could cause a foundation slip failure during test.

- To allow most of the soil settlement to occur before the tank is put into service;
- To allow plastic yielding at locations of stress peaks in the tank at a temperature above the brittle-ductile transition temperature. This will increase the safety factor against brittle fracture during service;
- To demonstrate that floating roofs can move up and down with the liquid level without problems.

15.2 Hydrotesting after repair and modification

See Figure 94 which makes reference to the points in Sections 15.2.1 to 15.2.4 below.

15.2.1 Full hydrostatic test

A full hydrostatic test should always be carried out after the following repairs or modifications have been made:

- (a) – partial or complete replacement of bottom annular plates (and partial (sequential) jacking to allow for annular plate replacement);
- any repair or replacement of the internal shell-to-bottom fillet weld;
- installation of new shell plates or insert plates, except as exempted under (j), 15.2.4;
- installation of shell nozzles or shell manholes, except as exempted under (j), 15.2.4;

- installation of a flush type clean-out door, a flush type nozzle (API 650, 3.7.8) or a D-type sump (BS 2654, Figure 32);
- (b) partial or complete replacement of bottom plates;
- (c) complete jacking of tank shell;
- (d) new foundation or major foundation repairs including the installation of a membrane or clay mats under the tank;
- (e) installation of internal floating cover in an existing fixed roof tank (tank should be filled to maximum fill height to test operation of internal floating cover);
- (f) floating roof seal or drain replacement.

15.2.2 Partial hydrostatic test

A partial hydrostatic test should be carried out after the following repairs or modifications have been made:

- (g) weld repairs to floating roof (roof should be floated and checked for leaks);
- (h) installation of external intermediate shell stiffener in upper part of shell to stiffen corroded shell against buckling due to wind and/or vacuum (tank should be filled to 500mm above stiffener location and checked for leaks).

15.2.3 No hydrostatic test

No hydrostatic test is required after the following repairs or modifications have been made:

- (i) partial or complete replacement of roof plates and roof framing (fixed roof tanks), provided steps are taken to protect the tank bottom from damage (a thorough visual inspection of the tank bottom should be made after the work is completed);
- (j) local repairs to tank bottom by means of patch plates;
- (k) minor repair to foundation shoulder.

15.2.4 No hydrostatic test (API 653 exemptions)

- (I) A full hydrostatic test is not required for major repairs and major alterations when the conditions set out in 12.3.2 of API 653, except as amended in extract, are satisfied. Numeration is as in API 653.

EXTRACT from API 653

12.3.2.2 Shell Repair

For welds to existing metal, develop welding procedure qualifications based on existing material chemistry actual tank material

12.3.2.2.2 New materials used for the repair shall meet the requirements of the current edition of API 650 requirements or of an equivalent internationally recognised standard.

12.3.2.3 Bottom Repair Within the Critical Zone

Repairs within the critical zone are only acceptable without hydrostatic test when no repairs have been made to the tank foundation within the critical zone, and when there is no history of differential tank bottom settlement or of tank jacking. Only tanks founded on properly constructed concrete or crushed stone ring walls can be exempt from hydrostatic test after repairs within the critical zone.

12.3.2.3.1 a. Meet the requirements of 12.3.2.2.2 and 12.3.2.2.2 as modified above, and 12.3.2.2.3 a and b. (12.3.2.2.3 c is not valid for stress in the critical zone.)

12.3.2.4 Shell-to-bottom weld repair

Repair of the weld attaching the shell to the annular ring or the shell to the bottom plate shall meet the following requirements:

- *A portion of the inner or outer weld may be removed and replaced as long as the replaced weld is not greater than 300mm in length and the total, cumulative length for each weld does not exceed 1000mm around the circumference. Removed lengths of weld shall not be closer than 300mm to each other, including repairs on the opposite side of the shell;*
- *The replaced weld shall meet the size requirements of API 650, 3.1.5.7.*

15.3 Requirements for hydrotesting

15.3.1 Pipe connections

No pipes should be connected to the tank during the water test except the one used to fill the tank with water. Product lines should not be connected to the tank until after the water test to ensure that they are not affected by any settlement occurring during the test.

15.3.2 Water quality

Fresh, clean water should be used for the hydrostatic test if possible. At locations where clean water is not available in sufficient quantity or where the cost of using such water is prohibitive, river water, dock water or seawater may be used. In such cases a water chemistry test should be performed to determine pH, chloride content and the presence of other potentially corrosive substances. The analysis will provide an indication of the corrosiveness of the water. A pH of between 6 and 8.3 is acceptable, while a lower or higher pH would increase corrosiveness.

Whenever unclean water is used for testing, the length of time that the water is kept in the tank should be kept as short as possible. The corrosiveness of the water will determine the maximum time that it should remain in the tank. If the time limit is unacceptable, corrosion inhibitors may need to be added to the water. Immediately after draining the test water, the tank interior should be hosed down using fresh, clean water.

Where an aluminium internal floating cover is fitted in the tank, it is necessary that clean water be used.

15.3.3 Test temperature

The hydrotest subjects the tank to its heaviest load. Locations with stress peaks can yield. The ability to accommodate yielding is influenced by the toughness of the material. The toughness is lowest at low temperatures. It is therefore essential that hydrostatic testing be carried out at a temperature of 4°C or above. A higher temperature may be necessary due to plate thickness and material toughness. BS 2654 (Amd 1997), Figure1, gives guidance on minimum test water temperature.

15.3.4 Filling rates

15.3.4.1 General

Filling rates and the need for intermediate hold periods should take into account the soil conditions and foundation design.

Tanks built on a stable foundation with no predicted settlement, e.g. rock or a piled concrete slab, can be filled at a rate of up to 1.5m/hour.

Tanks built on foundations where significant settlement during filling is predicted, should have filling rates limited such that the subsoil layers under the tank get sufficient time to absorb the settlements without problems. The filling rates, holding times and frequency of settlement monitoring should be laid down in the hydrostatic test procedure. Where remedial work has been carried out on the tank foundation, measurements of settlement should be taken during intermediate and final hold periods: see 15.4 below.

Filling rates should be such that they do not cause the venting capacity of the roof vents to be exceeded.

When filling a fixed roof tank, it is necessary to ensure that sufficient venting capacity is available. It will usually be adequate if all the roof vents plus at least one 600 DN (24 inch diameter) roof manhole are fully open.

When filling a tank having an external floating roof or internal floating cover, a low filling rate of not more than 0.25 m/hour should be used until the roof/cover is afloat. Thereafter, the filling rate may be increased to the specified maximum filling rate.

15.3.4.2 Procedure

A recommended filling procedure is set out below. 'H' is the final filling height; 'a', 'b', 'X' etc., will depend on the factors discussed in Section 15.3.4.1 and on the limits imposed in the procedure. Monitoring during the filling and holding periods for each stage is covered in Section 15.4.

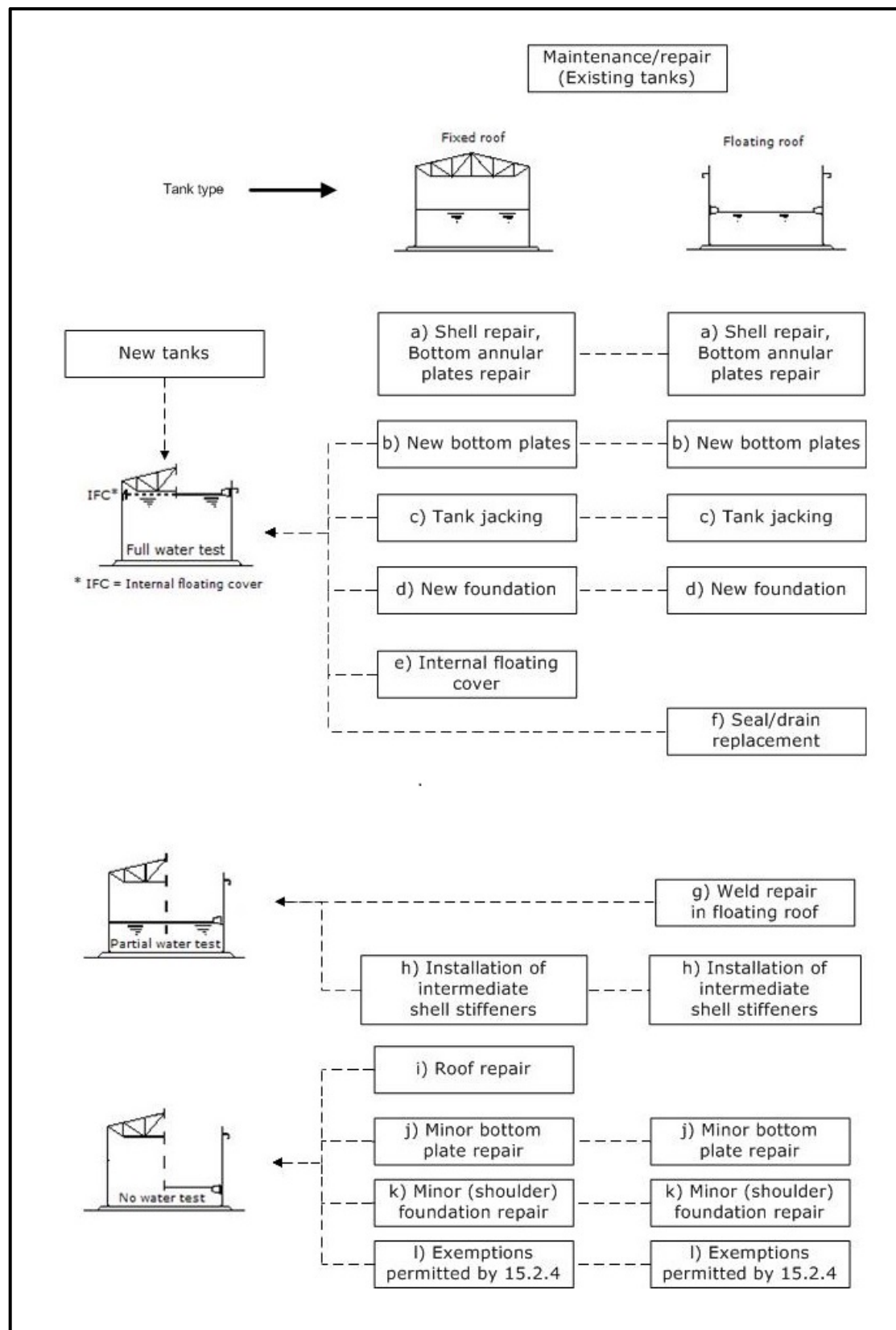


Figure 94 Selection diagram for hydrostatic testing of vertical tanks

Stage 1

Fill the tank to 0.5H at a maximum rate of '**a**' m/day. The filling period in any 24 hour period should not be less than 3 hours, nor more than 18 hours.

At the end of stage 1, there should a holding period of settlement and monitoring for '**X**' hours before the commencement of stage 2.

Stage 2

Recommence filling to 0.67H at a maximum rate of '**b**' m/day. The filling period in any 24 hour period should not be less than 3 hours, nor more than 16 hours.

At the end of stage 2, there should a further holding period of settlement and monitoring for '**Y**' hours before the commencement of stage 3.

Stage 3

Fill to 0.83H at a maximum rate of '**c**' m/day for between 3 and 16 hours, with a further holding period of '**Z**' hours before stage 4.

Stage 4

Fill to H at a maximum rate of '**d**' m/day for between 3 and 14 hours.

At the end of stage 4 the tank should be left full (and monitored) in accordance with 16.3.6.

15.3.5 Maximum filling height

The tank should be filled to the top of the shell, or to the overflow designed to limit the liquid level. For tanks with an external floating roof, the maximum filling height should be limited to 300mm below the top of the shell. For tanks with an internal floating cover, the hydrostatic test provides a unique opportunity to enter the tank above the cover while it is floating near the top (of course under stringent safety measurements since this area is a confined space). This will permit the exact maximum fill height to be established based on a minimum clearance of 150mm between the highest point on the internal cover and the lowest point of the fixed roof framing or other internal member.

The tank should not be overfilled. Overfilling of a fixed roof tank will cause an upward pressure against the underside of the roof plates, which could result in the top angle and roof supporting trusses being buckled. Overfilling a tank with an internal floating cover can seriously damage and possibly sink the internal cover.

15.3.6 Holding time

For tanks with no settlement, a minimum holding period of 24 hours is recommended. This is the time required for small leaks to show up. If there is rain during the holding period, the period may need to be extended to observe the tank under dry conditions.

For tanks with predicted settlement, the holding time should be 48 hours or longer until settlement monitoring gives a clear indication that the rate of settlement is diminishing (see 15.4 below).

15.3.7 Emptying after hydrotest

When the hydrotest is finished, emptying under gravity is sometimes used to reduce the time taken. The vacuum relief capacity of the roof vents of fixed roof

tanks should be checked to ensure it is adequate for the proposed emptying rate. If insufficient, the roof and shell could buckle. This can be avoided by opening roof manholes or dip hatches to increase relief capacity. (See also Section 10.3.3.)

When withdrawing water from an external floating roof tank, it should be ensured that the automatic bleeder vents are pinned in the same position as the roof supports. Also, the withdrawal rate needs to be reduced when the roof approaches its landing position. Floating roofs should be landed gently to avoid damage. The same applies to fixed roof tanks with internal floating covers.

15.4 Settlement monitoring

A settlement monitoring programme is an essential part of the hydrostatic test. Monitoring frequency depends on soil conditions and expected settlement. For tanks with no predicted settlement, shell level measurements should be taken with the tank empty, 67% full, 100% full, and when empty again. For tanks with predicted settlement, the monitoring frequency shown in Table 13 may be employed (the 'stages' referred to are as defined in Section 15.3.4.2).

Shell settlement readings should be taken at all reference points along the circumference. Guidance on the number of reference points is given in Section 6.3.7. The readings should be evaluated by calculating the total tilt and the deviation from the uniform tilted plane (see Section 6.5).

Measurement of the tank bottom profile should be done before starting to fill the tank, and again when the tank is nearly empty. When draining the test water, leave a level of about 0.25m in the tank to ensure that the tank bottom is in full contact with its foundation profile. The tank bottom profile should then be measured.

Table 13 Frequency of monitoring relative to filling stages

	Filling stage	Monitoring
A	Before filling starts	Take levels around shell circumference
B	With 0.25m water in tank	Measure bottom profile
C	During filling to stage 1	Take levels every 24 hours
D	While holding at stage 1	Take levels every 12 hours until rate of settlement diminishes
E	During filling to stage 2	Take levels every 12 hours
F	While holding at stage 2	Take levels every 12 hours until rate of settlement diminishes
G	During filling to stage 3	Take levels every 12 hours or more frequently depending on rate of settlement
H	While holding at stage 3	Take levels every 12 hours until rate of settlement diminishes
I	During filling to stage 4 (full)	Take levels every 12 hours or more frequently depending on rate of settlement
J	While holding at stage 4 (full)	Take levels every 12 hours until rate of settlement diminishes
K	Nearly empty, with 0.25m water remaining	Measure bottom profile to establish total bottom settlement
L	Completely empty	Take levels to establish total shell settlement

16 Re-siting of vertical tanks

16.1 General

Tanks may be lifted and moved to new positions without dismantling. This can be done using a crane with spreader beams, on rail tracks, by the air-cushion method or by self-propelled trailers. Where the terrain is suitable and a sufficient supply of fresh water is available, the tank may be moved by floating. Generally, the methods described in Sections 16.2, 16.3, 16.4 and 16.6 are preferred.

Before carrying out any moving operation, the tanks should be thoroughly cleaned, gas freed, inspected for leaks, and repaired where necessary.

16.2 Moving using a crane with spreader beam

This method is normally used for smaller diameter tanks.

16.3 Moving on rail tracks

To move a tank on rail tracks, it first has to be lifted clear off its foundation by means of jacks see Appendix C. A system of steel rails supported on timber sleepers to spread the load is then laid under the tank. The rails should be well greased, be adequately supported along their entire length. Steel bogies are placed on the rails to support the tank during moving.

The tank is lowered by means of the jacks until it rests on the bogies and is hauled by winch and pulley or by tractor. At the new site the tank is again jacked up, the rails are removed and the tank is lowered on to the new foundation. Tank movement should be closely controlled. In windy weather, operations of this nature should be suspended and the tank adequately restrained by steel guy wires.

16.4 Moving by air-cushion method

An air-cushion under the tank bottom is provided by means of mobile compressors. A special skirt is placed around the shell at the bottom to contain the air which will support the tank during movement. The tank is then towed to its new location. The tank is floating on air and any wind can move the tank off line. It is important to check that the area over which the tank has to be moved is free from unacceptable irregularities, as these may cause air leakage and consequently loss of support during the move. The tank can only move up a slight slope, the skirt will fold under and release the air.

16.5 Moving by floating

Another method of moving tanks is to build earth dikes around the route between sites and flood the area with water to a depth suitable for floating the tank off its foundation. The floating tank can then be hauled to the foundation prepared at the new site and allowed to settle by releasing the water contained within the dikes.

Experience has shown that this method of moving may result in a run-off of water to other areas in plants and refineries, and should therefore be carefully evaluated. Once the water has been drained the area has to dry out.

The depth of water required to float a tank is small. For instance, a tank of 36m diameter and 12m high will float in approximately 600mm of water. Once a tank is floating it can be hauled by winch or tractor, using a separate system of cables to steady and control it.

Before launching, fixed roof tanks should be pressurised to their maximum pressure rating, bearing in mind that the limit for atmospheric tanks is 200mm water gauge. The pressure should be maintained during the moving operation as this will reduce the flotation stresses on the bottom plates.

In order to keep the shell of the floating tank vertical, the weight of stairways etc. should be counterbalanced by placing sandbags on the tank bottom.

Tanks have been moved over distances of several miles by floating when tank sites are adjacent to a river, lake or the open sea, and the banks are suitable for the tank to be moved to the water's edge for launching. A small tug or motor launch can be used for towing a tank in open water. Rails are laid at the new site and the tank is hauled out of the water and moved on the rail tracks into position above the new foundation.

This method of moving tanks should not be used during windy weather.

16.6 Moving by self-propelled trailers

Self-Propelled Modular Trailers (SPMTs) may be used for the relocation of storage tanks. After the tank has been jacked up, SPMTs are moved under the annular plates (directly under the shell).

This method of relocation is also suitable when there is a difference in elevation between the existing and new tank foundation. The maximum gradient of the roadway between the two locations should be checked by a specialist transport consultant/contractor, but in general should not exceed about 0.7%.

The specially designed temporary steel structure inside the tank is required to allow the tank to be jacked up to about 2.5m above its foundation level, and the load to be transferred from the jacking points onto the SMPTs.

For large floating roof tanks, it is essential that the temporary steel structure is designed to accommodate any uneven load distribution resulting from level differences/deformations within the roof structure. Moreover, the difference in stiffness between the roof structure and the supporting structure needs to be considered to ensure an equal load distribution onto the jacks and trailers.

Only experienced contractors should be engaged for the jacking and relocation operations, and they should be required to decide at an early stage of the project the design principles and execution method.

The temporary roadway needs to be designed and constructed to allow for the high, concentrated wheel loads of the SPMTs. Adequate subsoil drainage should be provided for the roadway in areas with high rainfall.

The temporary, heavy duty road structure is also required to be built on top of the existing tank foundation after the tank is jacked up to about 2.5m above the tank pad.

For the new tank foundation, heavy duty road structures should be extended to a minimum of 3m all around the tank pad shoulder to avoid any damage to the foundation.

This temporary road structure may be removed after the load has been transferred from the SPMTs onto the jacking points, and before lowering the tank onto its new foundation.

Finally, the leak management/detection system, and final sand-bitumen layer and levels should be checked and accepted by the owner/operator before the tank is placed on its new foundation.

16.7 Testing requirements

After a tank has been moved to a new location, the following tests should be carried out:

- vacuum box test of all bottom welds;
- magnetic particle examination of the inside shell-to-annular fillet weld;
- full hydrostatic test including settlement survey (Chapter 15).

17 Probabilistic preventive maintenance (ppm) for tanks

17.1 Introduction

The application of risk- and reliability-based techniques for optimising inspection and maintenance activities follows the trend in industry, worldwide, to move away from a time-based maintenance approach to a condition-based maintenance approach. Risk and reliability are measures based on the application of probability theory. These probabilistic techniques have already been proven to work for static refinery equipment, e.g. heat exchangers, pressure vessels, piping etc.

Recently, it has been recognised that the techniques can be usefully applied to the total maintenance approach for conventional storage tanks.

This Chapter is intended as a guide to how the risk- and reliability-based maintenance approach - the probabilistic preventive maintenance (PPM) approach - should be used within the total philosophy of tank maintenance. The PPM approach as here described is a tool for developing proactive (preventive) maintenance plans and risk-based inspection plans. It is based on two existing underlying methodologies: risk based inspection (RBI) and reliability-centred maintenance (RCM).

The actual structure of the user's PPM plans is for him to determine and implement. The guidance herein does not preclude the use of commercially available risk-based programs and systems.

This Chapter is set out as follows:

- 17.2 provides a general description of Risk Management, RBI and RCM;
- 17.3 contains a description of the PPM process;
- 17.4–17.5 describe RBI and RCM methodologies adopted by EEMUA, which may be used if no such tools are already available to the user. The implementation of any RBI/RCM tools can only be successful when a qualified Tank Integrity Assessor (see 17.6.2) is available to the organisation;
- 17.6 focuses on the PPM implementation process.

Note on terminology used in this Chapter

- 1 The terms *rating* (e.g. 'risk rating') and *class/classification* are used synonymously.
- 2 The terms *degradation/failure mechanism* and *failure mode* are defined in 2.2.

17.2 Risk management

17.2.1 Introduction to risk management

Risk-based decision making processes have become increasingly important as tools for managing a company's activities, processes, products and services. PPM is one such risk-based tool for determining the preventive maintenance tasks required to achieve necessary tank availability with optimal maintenance effort.

PPM as described in this Chapter is based on existing maintenance and inspection methodologies. It incorporates the interconnected but essentially independent methodologies of RBI and RCM:

- RBI is a process for ensuring that the integrity, including safety, of equipment is properly addressed, whilst improving availability. Its application will safeguard tank integrity;
- RCM is a process for determining, in a cost effective manner, the optimum maintenance requirements of the asset. Its application will safeguard tank functionality.

The main deliverables of such an integrated concept are:

- development of a preventive maintenance plan;
- setting up an inspection/monitoring plan;
- development of a test plan (if applicable).

These are illustrated in Figure 95 below.

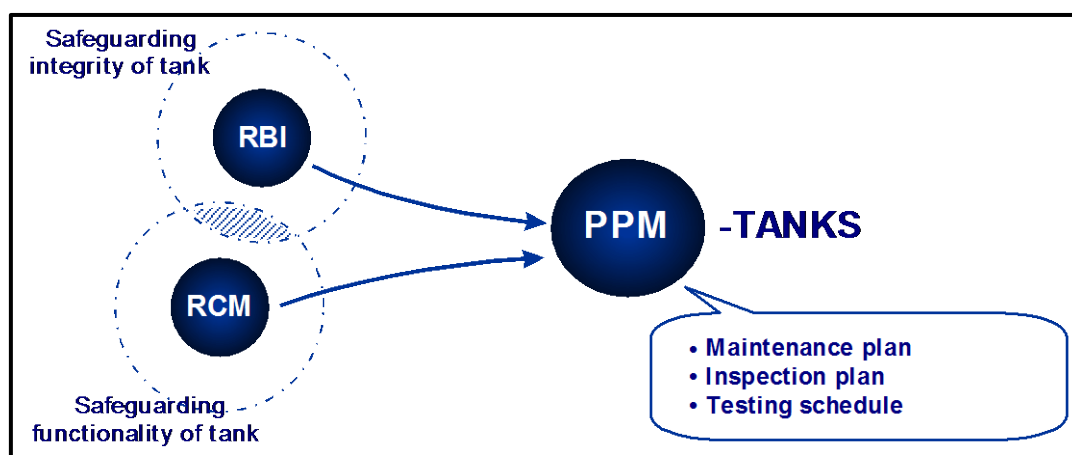


Figure 95 Deliverables of PPM tanks: an integrated approach

The main benefits of having such an integrated approach for the maintenance of conventional storage tanks are:

- optimal tank reliability and availability;
- reduction in maintenance costs;
- integrity ensured;
- compliance with changing safety, health and environmental (SHE), including legal, requirements; and
- all tank-related items/components are covered with a maintenance plan, an inspection plan and (if applicable) a test plan.

Additionally, PPM allows tank maintenance effort to be both qualified and quantified in a transparent and structured manner.

The sub-sections that follow describe the minimum requirements for applying the PPM approach and what the outcome should be.

It is important to appreciate that the value of risk-based strategies can only be discerned as the tank owner begins to use the tools on an everyday basis. These strategies are also referred to as evidence-based strategies. As evidence is

gained, and the application continually improved as more historical data is obtained and documented, it provides additional knowledge of the suitability for service of a given tank item or component. The user is therefore able to continually refine his knowledge of the risk associated with keeping the tank in service.

Before describing the PPM methodology in more detail, the independent methodologies RBI and RCM will be described (Sections 17.2.2 and 17.2.3).

17.2.2 Risk Based Inspection (RBI)

17.2.2.1 Introduction

RBI replaces time-based inspection systems with flexible inspection programmes. This is achieved by employing risk assessments based on operational, design, materials, and environmental considerations. As previously stated, it is a methodology for improving the availability of an asset whilst ensuring that its integrity is properly addressed.

There are two aspects of integrity, technical integrity and the operational integrity:

- A tank has *technical integrity* when, under specified conditions, the risk of failure endangering the safety of personnel, the environment or the asset value, is as low as reasonable. (Important factors would be, e.g., corroded roof/shell/bottom, edge settlement);
- A tank has operational integrity when it is being operated as intended, such that it can achieve storage targets without undue risk to personnel, environment or to the tank itself (e.g. the risk of overfills).

Both the technical and the operational integrity should be maintained, or better safeguarded, by the RBI method used. This can be achieved by monitoring and inspection using suitable techniques, with an appropriate inspection scope covering critical locations at an optimised inspection frequency. These inspection techniques can be applied when the tank is in or out of service. It is recognised that conventional RBI methods are mainly focused on the metal parts of the asset. But for tanks in general, it is recommended that the foundation also be included (with regard to potential problems such as tilting or settlement) within the RBI process. Such 'trendable' degradation mechanisms, which could endanger tank integrity, are particularly suited to the RBI approach.

Independent of the RBI method in use, the final deliverable of RBI should be a complete and thorough inspection and (degradation) process monitoring plan for the entire tank, or for those tank components under consideration. The main steps of a RBI process are given in Figure 96.

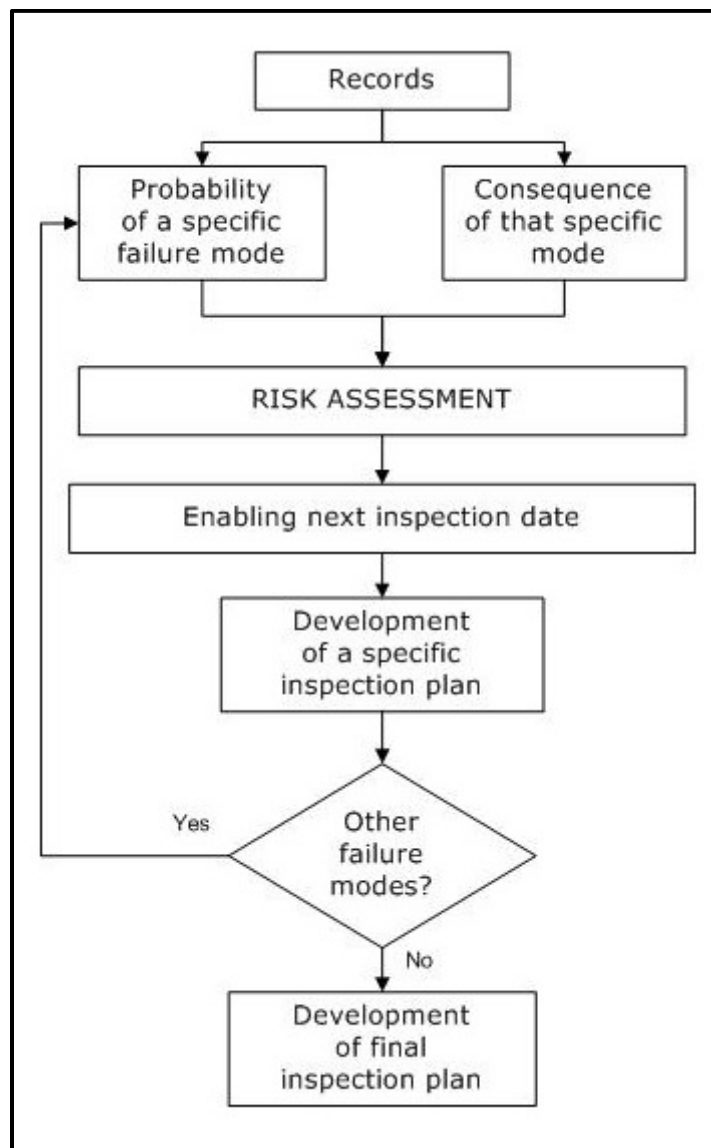


Figure 96 General concept of a RBI process

16.2.2.2 Probability of a Specific Failure Mode

The cornerstone of RBI is the assessment of an item's risk classification, since the RBI methodology is risk-based. Generally, risk is defined as the probability of occurrence (likelihood) of harm (failure) and the consequences of that harm. Figure 97 illustrates how risk can be quantified for a particular failure.

Within most known RBI methodologies, an item's risk classification is assessed in a semi-quantitative way by estimating a probability and a consequence class which, combined in a matrix, leads to the (semi-) quantitative risk class.

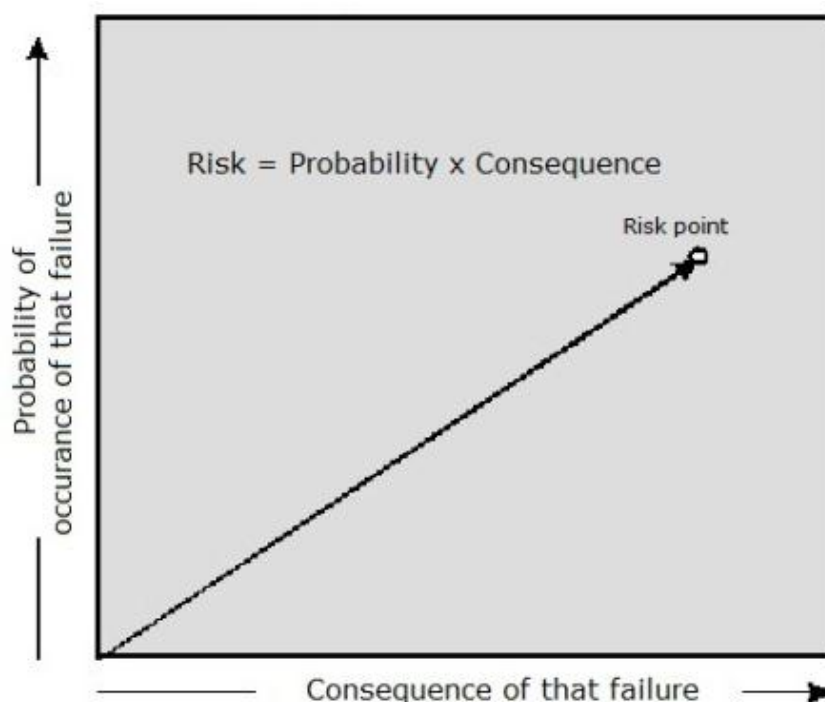


Figure 97 Risk plot when using (semi-) quantitative methods

As a first step within the RBI process, the probability of a failure mode occurring is estimated in the steps leading to the quantification of the risk. Within RBI, the probability of a specific failure mode, or better of failure due to a specific degradation mechanism, is a relevant measure. The probability or likelihood of an occurrence, is often established by using lists of actions taken or 'features' that affect the rate of progress of a particular degradation mechanism (e.g. the effect of CP on reducing corrosion rate).

Probability Rating Example:

Component/degradation mechanism: *foundation/edge settlement.*

Excessive edge settlement:

- | | | | |
|--------------------------|------------|----------|---|
| • High probability | High | score is | 4 |
| • Medium probability | Medium | | 3 |
| • Low probability | Low | | 2 |
| • Negligible probability | Negligible | | 1 |

Available RBI methods differ, with respect to the particular features considered and the final probability rating. It is the purpose of this sub-section to guide the user to a self-implementation of RBI, for which they may use commercially available programs or systems. This document does not recommend any particular supplier or system.

Generally, the RBI method takes into account those degradation mechanisms affecting the tank during normal operations (corrosion, fatigue etc.). However, failures as a result of excursions outside the defined operating window should also be considered.

Many degradation mechanisms are time-dependent (e.g. general corrosion, settlement). Where recorded measurements are few, a graphical plot may indicate a constant degradation rate: see Figure 99. In reality the degradation rate may vary over time. This aspect should be considered, and 'worst case' assumptions made to provide acceptable safety margins. Through inspection, the average rates of degradation may become better defined.

Some degradation mechanisms are independent of time, and occur when there are specific conditions present. These conditions may not have been predicted in the original assessment. For this reason RBI should be applied on a single or individual basis, where tank history and specific experiences with the particular tank are taken into account within the whole RBI process.

17.2.2.3 Consequences of a specific failure mode

After assessing the probability of occurrence of a specific failure mode, the *consequences* of that failure mode should be established.

As a minimum, EEMUA recognises three *consequence categories*, which can be considered for a failure mode: *economic*, *health/safety* and *environmental*. Consequence assessment should accordingly be carried out by a skilled team ensuring input by all areas of expertise, including the operating personnel of the tank to be assessed, to enable the team to make sound judgements on these aspects.

Within most known RBI methodologies, a *consequence rating* is assessed by using a consequence-of-failure list of relevant aspects, for each category, that influence or determine consequence.

Consequence Rating Example:

Physical result/consequence : Leaking tank bottom/economic (repair cost)
Total repair cost (total of labour, material, non-availability, product loss, etc.) **is**

• >50% of capital cost (new tank)	High	score is	4
• 10–50% of capital cost	Medium		3
• Less than 10% of capital cost	Low		2
• Negligible total cost	Negligible		1

On completion of the consequence assessment, the consequence ratings (output) should be entered into the tank record system.

17.2.2.4 Risk rating

Quantification of the risk is generally assessed in a semi-quantitative way by estimating the probability of a (specific) failure mode and a consequence rating for that failure mode which, combined in a risk matrix, leads to a risk class or rating.

Most RBI and RCM methodologies use a **risk assessment matrix** (RAM), of the type commonly applied in the industry for assessing SHE risk, as a basis for assessing risk rating. The size of these RAMs may vary from a simple 3x3 matrix to a more detailed and complex 5x5 matrix. Figure 98 shows a 4x4 matrix.

After quantification of the probability of a specific failure mode and the overall consequence class, the risk classification of the item is determined by the intersection of the relevant probability row and consequence columns as illustrated in Figure 98. An item can have multiple risk ratings, one for each possible failure mode.

For assets with low risk, the inspection interval derived from the RBI procedure may be longer than the existing chosen time-based interval which, in turn, may be prescribed by local legislation. In such cases the results of the RBI study should be discussed with the local statutory authorities to make the new insights regarding RBI more widely understood and obtain optimum inspection intervals.

RISK ASSESSMENT MATRIX							
Probability class	H	High					
	M	Medium					
	L	Low					
	N	Negligible					
Consequence class			N	L	M	H	

Figure 98 Example of a 4x4 PPM risk matrix

The main purpose of risk rating is to focus attention on the high risk items, with little or no attention devoted to the low risk items, with respect to inspection and mitigation.

It is recognised that many risks cannot be adequately reduced by inspection alone.

Examples where inspection may not be sufficient to reduce risks to acceptable levels are:

- where an item is nearing the end of its life/service;
- where the risk is consequence driven (e.g. water bottom^{*} for a leaking tank).

In such cases, mitigation actions (such as reduced filling height) may be the only appropriate measures that can be taken to reduce the risk to an acceptable level.

There may be several factors that will change the actual risk and make it prudent to conduct a RBI reassessment (e.g. external influences such as product change).

17.2.2.5 Determination of next required inspection date

One of the difficult aspects in RBI is to estimate the next inspection date. A balanced approach is necessary.

^{*} Water may be introduced into a leaking tank so that the product floats above the 'water bottom' and only leakage of water occurs.

The assessment of the remaining life of an item or component is essential for inspection planning. This is done by using the degradation rate and the degradation allowance, as derived from the relevant design and repair codes and operating conditions. Remaining life is defined as:

$$\text{remaining life} = \text{degradation allowance} \div \text{degradation rate}$$

A diagrammatical representation of this is given in Figure 99.

Where the remaining life of an item cannot be determined by measurement of thickness (e.g. in case of fatigue), it is determined from the design life of the component, minus the elapsed service life. Where an item or component may be susceptible to a degradation mechanism with a potentially high degradation rate, e.g. stress corrosion cracking, the remaining life estimation should be sufficiently conservative to allow for uncertainties in predicting the rate. If evidence is available on the risk of such degradation mechanisms, it is recommended to implement a corrective maintenance plan or a change in operational conditions.

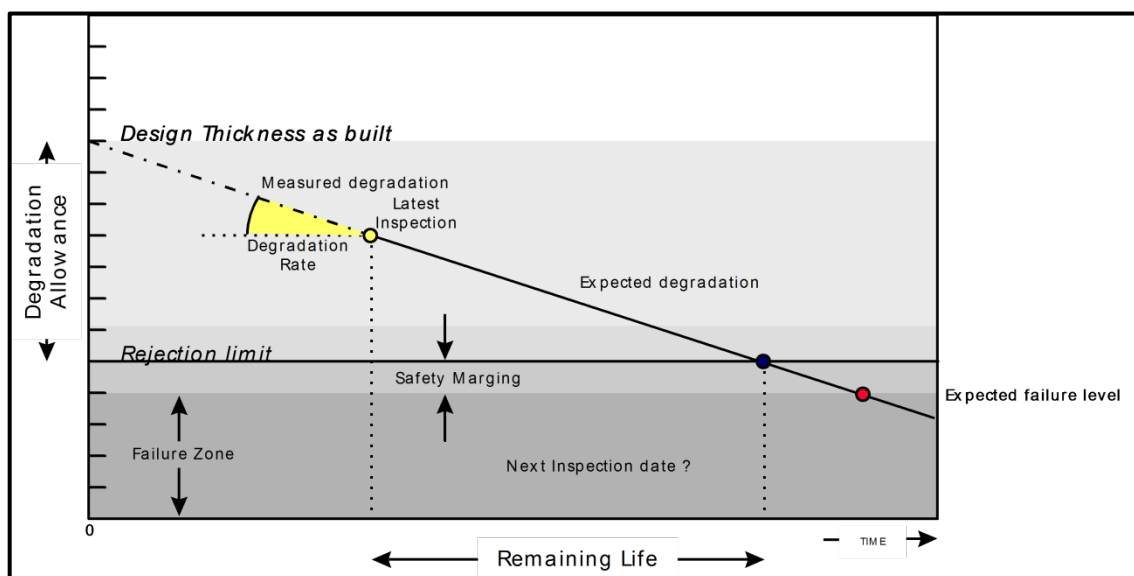


Figure 99 Expected degradation of a specific failure mode

While the degradation rates, e.g. due to corrosion, of the shell and roof can be established quantitatively during in-service inspections, the bottom requires a more cautious approach.

In general, the risk rating derived from the assessment process of an item is used to determine the next inspection date as a fraction of the remaining life.

$$\text{Inspection interval} = K \times \text{remaining life}$$

where the *confidence rating factor* K ($0 < K \leq 1$) reflects the confidence the RBI team has in the assessment of remaining life. K is dependent on:

- actual risk rating of the particular tank component (outcome from Figure 109);
- judgement regarding the stability of the degradation mechanism and the methods for its control;
- number of inspections carried out;

- previous inspection interval;
- quality of previous inspection data;
- quality of the inspection/monitoring techniques to be used for future; (in-service) inspections (which includes establishing degradation rates); and
- whether preventive measures are in place.

K needs to be determined by a qualified engineer or TIA. Generally, in order to allow sufficient flexibility, no fixed formulae are used in its determination. By conducting case studies, a first indication can be obtained of the value of K ; but when a tank is being assessed and a new inspection interval established, a thorough analysis is needed each time to determine the value of K .

Example of a RBI assessment on bottom plates

Given: A tank built in 1985 has been inspected every 5 years. The inspections so far (in 1990, 1995 and 2000) reveal a corrosion rate of 0.1mm/year for the bottom plates. During the 1990 inspection all corrosion spots were repaired. All inspection results are well documented.

Calculate: The next planned inspection date for this tank component based on the current condition – Figure 100.

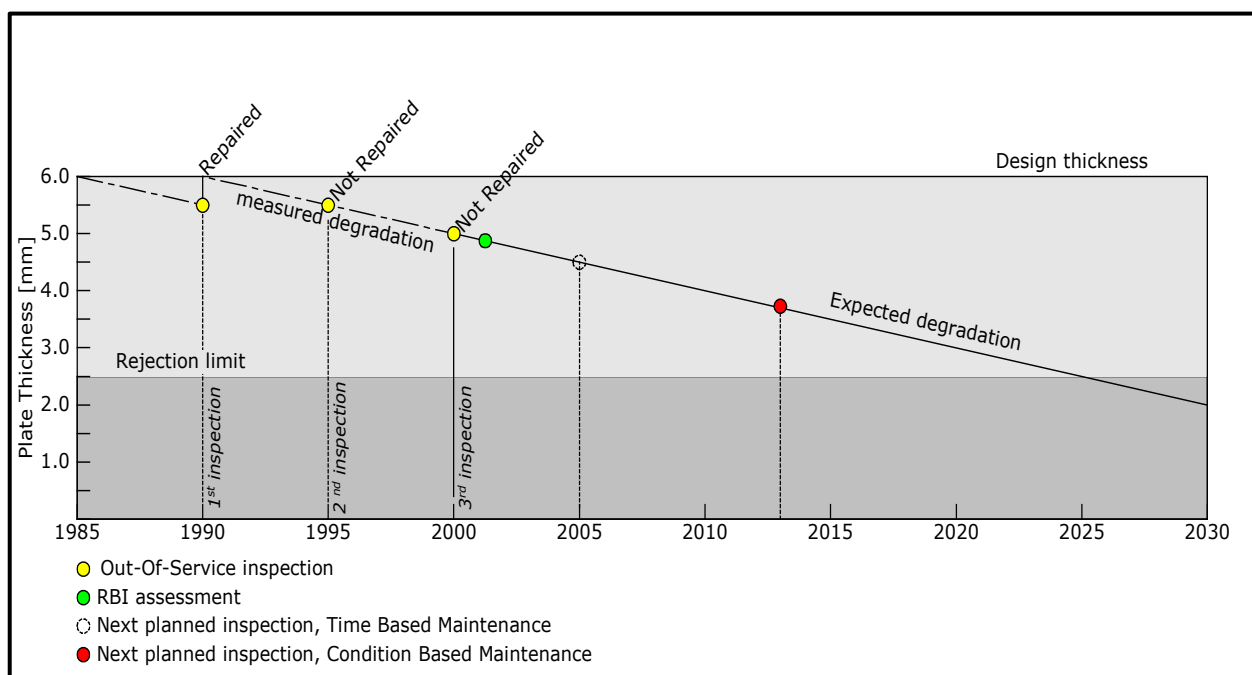


Figure 100 Degradation plot (bottom plate thickness vs time)

Answer: Based on the results of the 2000 inspection, the calculated remaining life is

$$RL = (\text{current nominal plate thickness} - \text{rejection limit}) \div \text{corrosion rate}$$

$$= (5 - 2.5) \div 0.1 = 25 \text{ years.}$$

Thus in 2025 the bottom plates should be rejected (see Figure 100).

Assuming that a confidence rating factor $K = 0.5$ has been established from the risk assessment matrix (see 17.4.5), then the next out-of-service inspection, based on current conditions, should be planned before: $2000 + 0.5 \times 25 = 2013$. Some RBI methods will give values for K , some will specify a predefined next inspection interval according to the risk classification, and some just give recommendations.

17.2.2.6 Inspection plan

Inspection activities will increase the available information on the condition of the equipment. When inspection activities have been performed, the results should be reviewed to determine if a RBI reassessment is needed.

The primary objective of a RBI effort should be an inspection plan for each item evaluated. The inspection plan should give details about the remaining risk related to current operation. For a risk level considered unacceptable, the plan should contain the mitigation actions for reducing the risk to an acceptable level.

As a minimum, the inspection plan should cover the following:

- scope of inspection;
- inspection coverage;
- technique to be used for inspection;
- date of specified inspection.

Ranking of the items or components by the risk level allows users to assign priorities to the various inspection tasks. The level of the risk should be used to evaluate the urgency for performing the inspection.

17.2.3 Reliability Centred Maintenance (RCM)

17.2.3.1 Introduction

Over the past twenty years there have been many changes in the way that maintenance activities are planned and carried out. These changes are due to a huge increase in the number and variety of physical assets which have to be maintained, much more complex design, new maintenance techniques and changing views on maintenance organisation and responsibilities. In general the thrust of the changing world of maintenance is towards:

- improving the reliability and availability of assets;
- optimising maintenance effort and cost;
- selecting appropriate and cost-effective proactive (preventive) techniques and maintenance tasks;
- a proactive rather than a reactive maintenance regime.

But in all cases these changes should never be permitted to jeopardise the SHE requirements or technical/operational integrity of the asset.

The relationship between RCM and other maintenance options is illustrated in Figure 101 below.

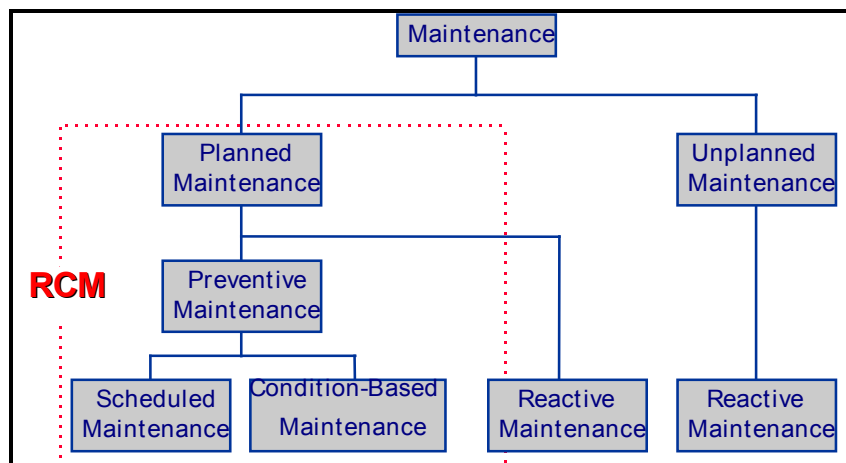
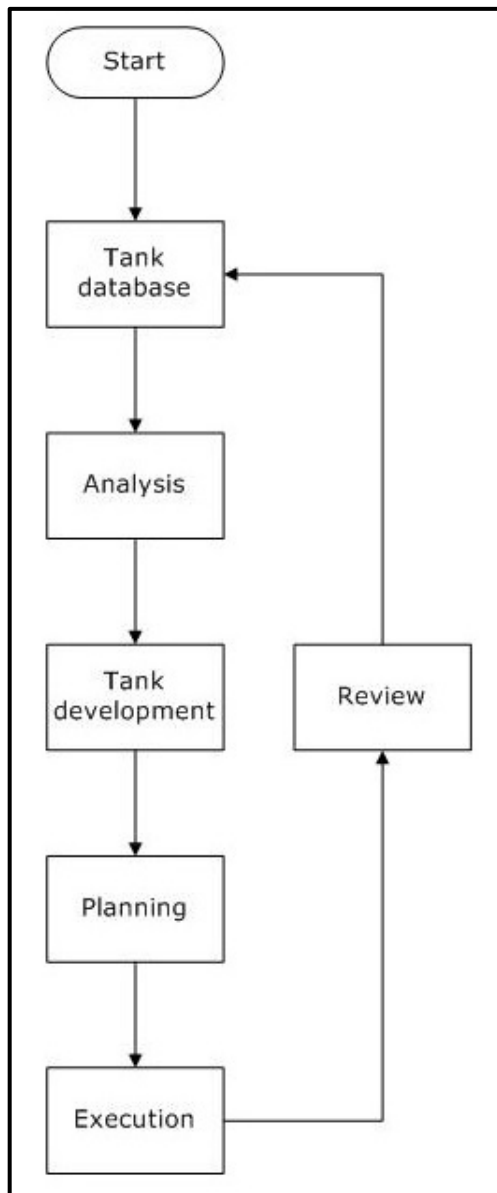


Figure 101 Relationship of RCM with other maintenance options

It is not the intention of this Section to go into great detail, but to give a general overview of the 'classical' RCM process. More details of this process can be found in *Reliability-centered Maintenance*, 2nd edition 1997, by John Moubray⁽³⁷⁾.

Originally developed in the aeronautical industry, the RCM methodology entails a structured decision support process used to determine and document (the optimum) maintenance requirements of any physical asset in its operating context. RCM applies failure mode and effect analysis (FMEA) in determining the failures that affect the functionality or performance of equipment under consideration through quantification of the consequences of those failures. The final products of the analysis are (cost-effective) preventive maintenance tasks to be executed at certain intervals; these tasks are based on actual operating experience and best practices.

RCM is one of the cornerstones of the PPM process for conventional storage tanks. The overall objective of RCM is to optimise the overall reliability, availability and profitability of the entire tank through optimising maintenance efforts by entering into a more proactive (preventive) maintenance mode, rather than a reactive mode.



The main steps of a RCM process are given in Figure 102. The first phase is the initial RCM analysis. It consists of a study to select proactive maintenance tasks, and gives (redesign) recommendations. The second phase integrates the initial analysis with the existing maintenance process. Tasks are scheduled in a planning system. By analysing reactive and proactive maintenance tasks and improving them, the maintenance process will be optimised leading to improved reliability and availability.

The RCM analysis process consists of a number of distinct steps, each with its own purpose. Each main step in the process will be described in more detail in the sub-sections that follow.

The main benefits and deliverables of RCM are:

- understanding, sharing and acceptance of identified consequences and decisions;
- better communication, teamwork and ownership of the results;
- understanding how the tank should operate and how it can fail;
- development of preventive maintenance tasks;
- definition of a consistent scope of work for shutdowns;
- elimination of mismatched and non-value added maintenance effort;
- identification of 'bad actors' and requirements for investigations and redesigns.

Figure 102 RCM process

17.2.3.2 Preparatory Steps

The first step is to identify the items or components to be analysed. This needs to be done in an appropriate sequence to ensure that the correct priority is given to the item or component which has the highest impact on the overall business.

For the analysis of all items or components and the quantification of the failure consequences, it is required that all relevant data be collected. This information is either data which has been recorded, or information gained from the experience of experts. Therefore, it is essential that the RCM team consists of people with a good cross-section of expertise and experience; see also Section 17.5.2

17.2.3.3 Description of the RCM Analysis

The classical RCM process is centred around failure mode and effect analysis (FMEA). The FMEA process is used to determine what must be done to ensure development of optimal maintenance tasks for the asset or item under consideration. In general, the FMEA process requires answers to the following questions:

1. What are the functions and associated performance standards of the item in its present operating context?
2. In what way(s) can it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to predict or prevent each failure?
7. What should be done if a suitable preventive task cannot be found?

The first step in the analysis is to define the function(s) of the item, and the operational window in which the selected item should perform as determined by the user. Let us consider the pressure/vacuum (P/V) relief valve in the example illustrated in Figure 103 below.

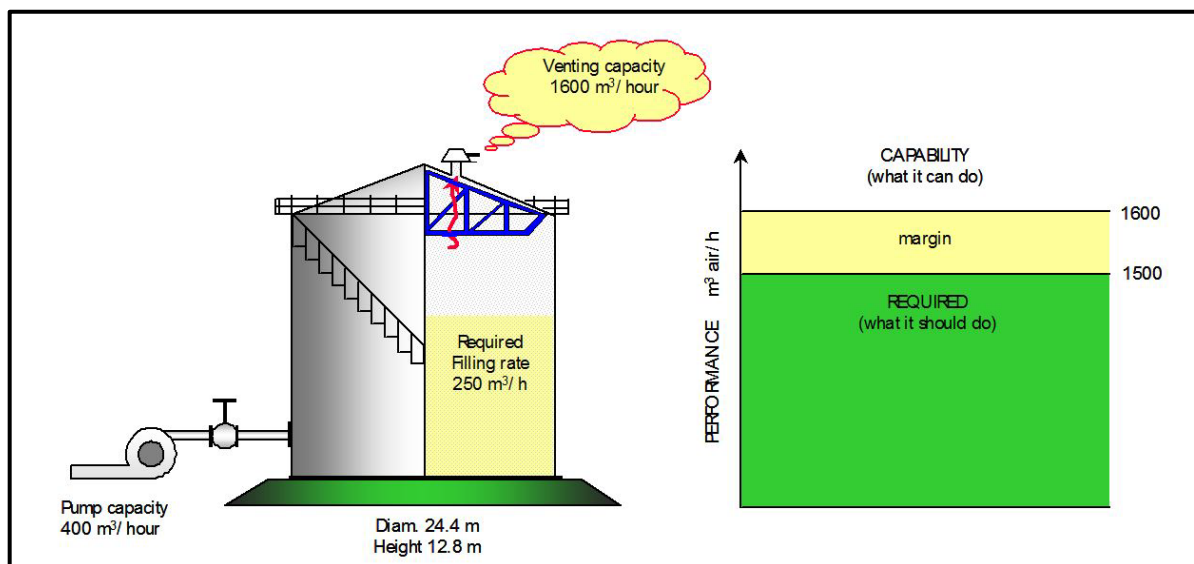


Figure 103 Example of a P/V valve and its functionality

One function of the P/V valve is to relieve excess pressure above a certain pressure setting by permitting out-breathing of the tank. Let us assume that this P/V valve is selected for relieving 1600 m³ of air per hour (standard size P/V valve).

Suppose the required maximum air flow according to API 2000 is 1500 m³/h; this means that the capability (what it can do) is approximately 100 m³/h above the desired performance (what its user wants it to do). The main objective of maintenance is to ensure that the capability stays above the level of desired performance (1500 m³/h). Maintenance on its own cannot, of course, raise the venting capability above the 1600 m³/h design value. A check should also be made that the P/V valve opens at its set pressure (above threshold level).

The P/V valve will fail to fulfil its function when it is not capable of relieving air at all, or when its venting capacity is less than the required 1500 m³/h. The next question to answer is: what event can cause the valve to get into a failed state? In RCM terminology, failed states are known as functional failures because they occur when the item is unable to fulfil its function to a standard of performance acceptable to the user.

Once each type of functional failure has been identified, the next step is to try to identify all the events that are reasonably likely to cause each failed state. These events are known as 'failure modes'. The common P/V valve failure mode is malfunction at demand or blocking, e.g. by product, debris, freezing, or nesting birds. In general it is important to identify the cause of each failure in sufficient detail to ensure that time and effort is not wasted trying to treat symptoms instead of causes. On the other hand, it is equally important to ensure that time is not wasted on the analysis itself by going into too much detail.

Care should be exercised not to confuse *failure modes* (e.g. leaking, corroded bottom plate) with *failure (degradation) mechanisms* (corrosion in this case) as used in RBI terminology. It should be noted that failure modes are defined for a given operating envelope of the items or components and the system. Should the operating window change, the previous list of failure modes should be reviewed and modified as required. The operating window should therefore be specified. Typical failure mode descriptors for different failure mechanisms are listed in Table 14 below.

Table 14 Typical failure mode descriptors (not typical for P/V valves)

Failure Mechanism	Failure Mode
Wear mechanisms	Worn, corroded, eroded, seized
Mechanical failure mechanisms	Internal/external leakage, seized, loose, disconnected, fouled, contaminated, plugged, choked, blocked
Loss of structural, material or system integrity	Buckled, bent, broken, ruptured, cracked, failed to start on demand
Loss of control system integrity	Malfunctioned, failed
Abnormal instrument readings	Erratic output, drift, out of calibration, tripped, overheated

In addition to the identification of dominant failure modes, it is also important to identify and record the relevant failure pattern. The failure pattern can be visualised as a curve of the conditional probability of failure as a function of operating age. The conditional probability of failure is defined as the probability that an item will fail during a particular age interval, given that it survives to enter that interval. In modern reliability techniques, most failure patterns can be categorised as one of the six most distinct failure patterns as depicted in Figure 104 (reference *Reliability-centred Maintenance, op. cit.*).

Identification of the failure pattern is important because it will determine if and what kind of preventive maintenance tasks should be selected. For instance,

time-based maintenance is not effective at all if the failure mode is related to pattern number D, E or F.

The next step in the analysis is to define in what way the failure matters, if it occurs, or what the *failure effect* and *failure consequences* are. These descriptions should include all the information needed to support evaluation of the consequences of the failure, such as:

- what evidence is there that the failure has occurred?
- in what ways does it pose a threat to safety, health and environment?
- in what ways does it affect production or operations?
- what physical damage is caused by the failure?
- what must be done to repair the failure?

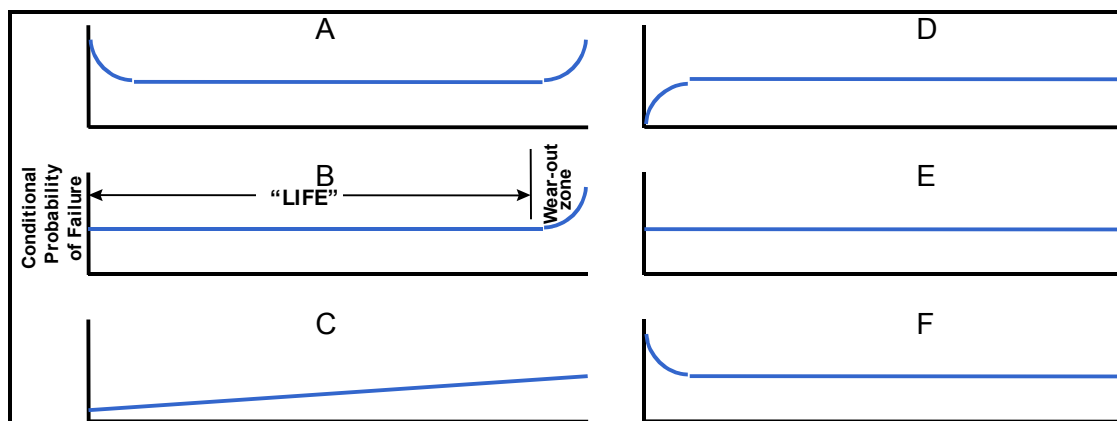


Figure 104 Six main failure patterns

illustrated by conditional probability of failure as a function of time

Example

Consider the P/V valve shown in Figure 103. Assume that instead of 1500 m³/h its relief rate is limited to 1000 m³/h (functional failure), due to partial blocking by a bird nest (failure mode). There is no other relief system present. The time to clean the vent is 2 hours and the estimated time between occurrences of this failure mode (ETBF) is 3 years.

When the tank cannot be filled with product, and thus not available to the business at that particular time, the production process will be affected (an alternative tank will have to be found) and may even have to be shut down. The cost to the organisation is assumed to be \$5000 per day for non-availability of the tank every 3 years, plus the cost of cleaning the P/V valve.

In the worst situation, the consequence of a blockage could even result in a catastrophic roof failure (internal pressure build-up). The cost of a roof repair, which could easily be in the order of \$125,000, would then be added to the above lost production cost.

The maintenance department has decided that regular checks will be carried out by a maintenance craftsman every half year and that the total time needed for the check and cleaning is 30 minutes. With an hourly rate of, say, \$35, each check will cost \$17.50. If the ETBF is 5 years, about 10 checks will have been carried out.

In other words, the cost of the checks is $10 \times \$17.50 = \$175$ every five years. In this example it is clear that the scheduled maintenance task is cost effective relative to the cost of the operational consequences to the business, and is therefore economically justified. However, one has to consider the impact and efforts in relation to the size of the tank farm.

It is the consequences which most strongly influence the extent to which we try to prevent each failure. In other words, if a failure has serious consequences, we are likely to go to great lengths to avoid it. On the other hand, if it has minor or no effect, then we may decide to do no routine maintenance beyond basic cleaning and lubrication. A great strength of RCM is that the consequences of failures are far more important than their technical characteristics. In fact, it recognises that the only reason for doing any kind of preventive maintenance is *to avoid the consequences of failure, or at least reduce them to an acceptable level*.

The main reason for starting with a FMEA analysis is to pre-empt discussions on failure mode analysis—recorded or otherwise dealt with—*after* the event. Preventive maintenance means dealing with events *before* they occur, or at least deciding how they should be dealt with when they do occur.

17.2.3.4 Maintenance task selection

The selection and development of an appropriate preventive maintenance plan and tasks are the ultimate goals of the RCM process. It is recognised that preventive maintenance has much more to do with avoiding or reducing the consequences of failure than it has to do with preventing the failures themselves.

In general, the consequences of failures are classified into three categories:

- *Safety, health and environmental (SHE) consequences.* A failure has safety consequences if it could hurt or kill someone, and environmental consequences if it leads to a spill;
- *Operational consequences.* A failure has operational consequences if it affects production or operations;
- *Non-operational, non-SHE consequences* (shortened to 'non-operational/SHE'). Failures in this category affect neither safety nor production, so they involve only to the direct cost of repair.

For failure modes which have safety or environmental consequences, a preventive maintenance task is only worth doing if it reduces the probability of the failure to an acceptable level. If such a task cannot be found to satisfy this objective, then one is dealing with a safety or environmental hazard, which cannot be adequately controlled or prevented. This means that the system must be changed in order to satisfy the SHE conditions.

The overall economic effect of any failure mode, which has operational consequences, depends on two factors:

- 1 the costs each time failure occurs, in terms of its effect on operational capability plus repair costs.
- 2 the frequency of occurrence.

In the P/V valve example above, it was already explained that for failure modes with operational consequences, a preventive maintenance task is worth doing. If a preventive task which is also cost-effective cannot be identified, then it is not worth doing any scheduled maintenance to prevent the failure mode under consideration. However, if the consequences are unacceptable, something needs to be changed in order to reduce the total costs.

For failure modes which have no operational or SHE consequences, the same cost-benefit analysis as for the operational consequences category can be used. However the economic impact of non-operational/SHE consequences is only the direct cost of repair.

Consider a similar set-up to that of Figure 103, except that an additional identical P/V valve is installed. If one valve fails, the other might be available. In this case, therefore, there would be no daily charge for unavailability (\$5000 in the previous example) nor would there be the cost for a new roof. So the only cost associated with failure of a single valve is the cost of repair and the installed (capital) cost of the additional valve.

It should be noted however that if freezing or blockage by the product is the likely cause of malfunction, then duplicating with a second, identical valve is likely to achieve negligible increased reliability. A more economic option would be to have a single installed valve with a second held in store, interchanging them periodically and overhauling the main valve as part of a planned maintenance programme.

Depending on the failure mode and mechanism, an appropriate maintenance task and interval should be chosen. Only maintenance tasks that are effective should be considered.

All maintenance tasks should be optimised by cost and effort. This could lead to new, modified, or even deleted maintenance tasks—see Figure 105 below.

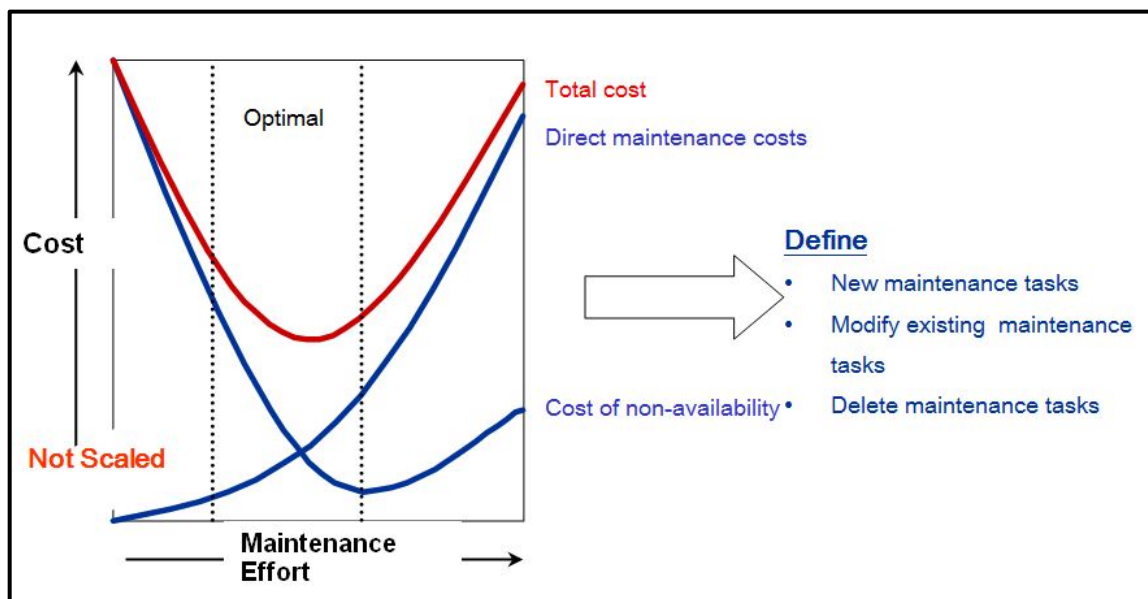


Figure 105 Optimisation of maintenance tasks by cost and effort

An item will usually have more than one dominant failure mode. Because in RCM each failure mode is analysed separately, it is good practice to review all preventive maintenance tasks selected by the RCM team. Task rationalisation should lead to a final list of (preventive maintenance) tasks for that item.

17.2.3.5 Execution

Once the results of the RCM study are implemented, the preventive maintenance tasks need to be carried out consistently at the specified maintenance intervals by the designated staff.

17.2.3.6 Review

After the initial analysis has been completed, the new preventive maintenance tasks are to be included in the existing maintenance plan. New tasks are entered in the maintenance management system where their execution will be planned and scheduled. As a task is completed, it should go through a filtering process in order to determine whether it calls for a review of the RCM analysis. Reactive maintenance tasks should be reviewed with the same objectives.

If the actual conditions revealed during the execution of preventive maintenance tasks are different from expected, or if extensive reactive maintenance is found to be required, then the initial RCM analysis should be reviewed.

17.3 The PPM process

A PPM analysis is a team exercise performed by a group of specialists from functions such as operations, maintenance, materials/corrosion, inspection, safety, electrical, and instrumentation. This group will be referred to as the PPM team.

The success of the total PPM process depends on the competence of the PPM team. The ultimate results demand a thorough evaluation with a qualified Tank Integrity Assessor (TIA) to ascertain the structural integrity of the complete tank. A detailed overview of the PPM process is presented in Figure 106, and the main steps in the process are described in more detail below.

Step 1: Select tank, set boundaries

A PPM analysis starts with selection of the tank to be analysed, and defining its boundaries precisely. The success of applying the PPM methodology for tanks can only be achieved if it starts with a visual inspection for verification of the overall tank status at the time of the review.

All equipment outside the boundaries is assumed to function properly. As a minimum, and from safety point of view, it is necessary to include the following tank items within the total PPM process - see Figure 107:

- the metal containment, including all its fittings, as the 'first line of defence';
- the leak detection/monitoring system (if installed) within the tank foundation as the 'second line of defence' (refer to EEMUA 183, Section 7);

- the bund wall, including the tank compound drain valves, and (if installed) impermeable clay mat systems over the entire bunded area, as the 'third line of defence' (refer to 7.4, *op. cit.*).

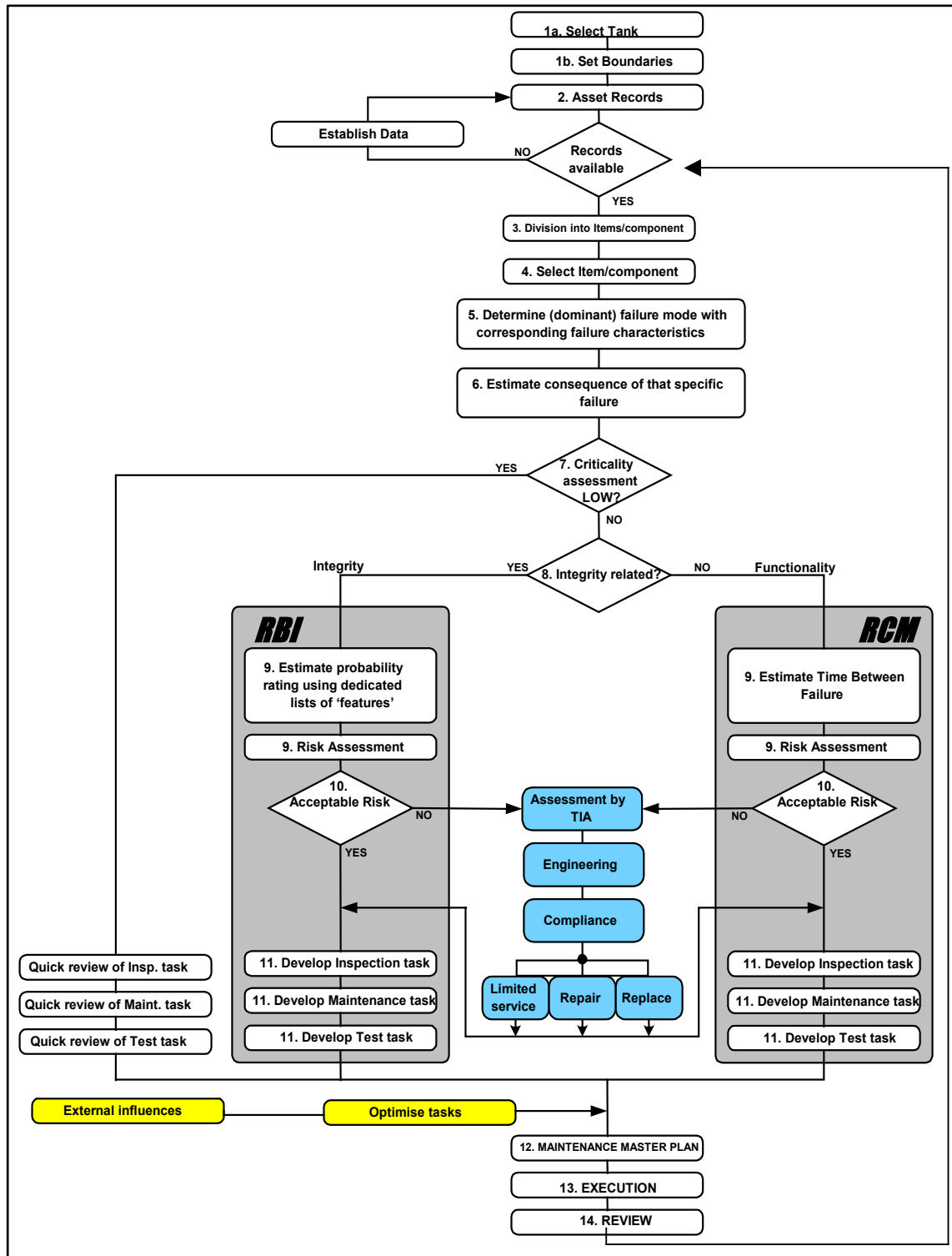


Figure 106 PPM flowchart for conventional storage tanks

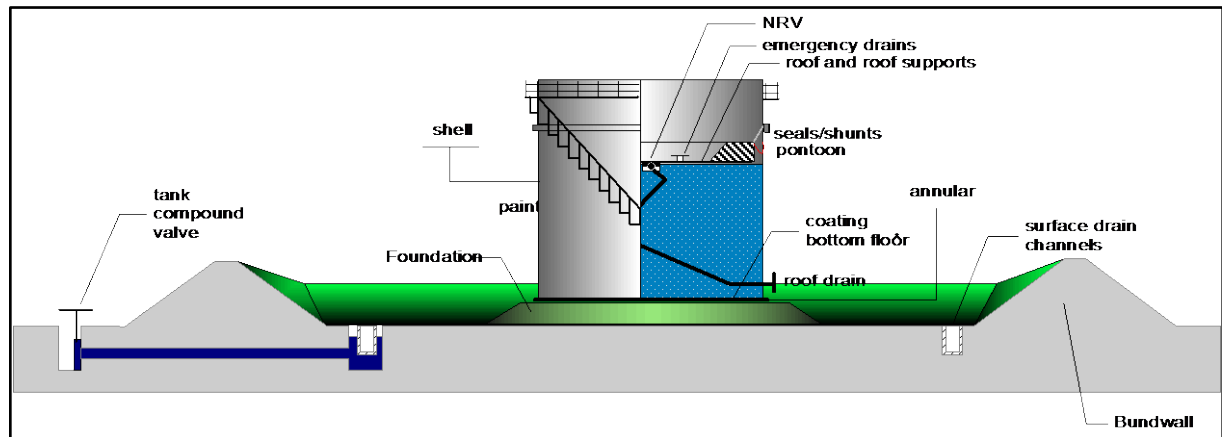


Figure 107 Tank boundaries

Step 2: Records

The next step is to gather all relevant data and information necessary for an analysis, for instance process and engineering design data, historical maintenance and inspection information etc. Note that a condition-based maintenance approach cannot be applied if a proper record system does not exist.

Appendix A includes a checklist for assessing and collecting all basic tank data and records useful for the RBI and RCM assessment process. Where records are unavailable, further investigations and/or detailed visual inspections should be conducted to provide at least a basis from which the assessment process can start.

It is also recommended to establish external influences such as envisaged operating conditions, next period of operation, etc. before the team convenes for the rest of the analysis.

Step 3: Division into items/components

Divide each tank into a list of main tank items and component items tailored for the selected tank. If the tank record file is properly structured it will reflect the tank items and main components.

Step 4: Select items/components

Selection of tank items and components for further analysis can quite often be made based on reviewing the contents of the tank record file, outcome of the visual site inspections, and reviewing the outcome and recommendations of the previous tank inspection.

Step 5: Determine dominant failure mode with corresponding failure characteristics

It is essential to determine the dominant failure mode for each item or component selected for analysis. It is possible for an item to have several failure modes. The potential risk of the dominant failure mode should be evaluated disregarding the effects of maintenance and inspection.

The basic questions to answer are:

- What are the critical parts of the selected item or component?
- What are the main drivers of the specific failure mode?
- What can go wrong?
- What are the consequences when a failure occurs? (See also next step.)
- What is the main reason for the occurrence?

The list of tank components and their typical failure modes in Appendix E.2 can be used for guidance. It is based on *long standing* experience. Local experience may differ, and should be included in the list for completeness.

Step 6: Estimate consequence of that specific failure mode

Subsequently, the overall physical consequences of any failure should be assessed and reviewed against the basic objective of no leaks and no fires. In other words, a check and balance exercise should be conducted to ensure that no consequences to the environment and other (neighbouring) facilities will occur.

Step 7: Criticality assessment

Note: On the first occasion that the PPM methodology is applied to the tank, the PPM team would have no data to justify bypassing the RBI/RCM 'boxes', and would need to proceed directly to step 8.

This phase can be regarded as a screening process for determining the criticality of the item in its operational context. On the basis of the available record system, the current condition of the selected item should be established.

The criticality assessment of each tank item/component should take the operating conditions and external influences into account. It should be based on the verification/acceptance/rejection criteria in publications such as the present document, API 653, or specific company standards. It should be based on knowledge and experience rather than on assumptions.

In order to focus on the right priorities, a distinction should be made between items ranked as 'High' compared with those indicated as 'Low' or 'Medium'.

It is recognised that evaluation of tank components in respect of ascertained 'rejection/approval' criteria is essential. The criteria for bottom and bottom annular plates, shell plates, and foundations (all main tank components) are described respectively in Sections 7.4, 8.3 and Chapter 6 of this document.

Generally, the ranking or qualification reflects the overall confidence the PPM team has in the ability to forecast any degradation of the selected item or component within a certain time-frame. The qualification rating may be defined as follows:

- 'High' indicates action is required. These items will need to undergo a further RBI or RCM assessment;
- 'Medium' indicates items have to be addressed, and a 'streamlined' approach (see below) may be sufficient for establishing the inspection and maintenance requirements;
- 'Negligible' or 'Low' indicates items may not require any significant attention during the PPM study, but a check is needed on whether or not inspection and/or maintenance would be required.

As a guideline, the following actions will be appropriate for the 'N' or 'L' ranked items:

- N = Negligible—
 - 1 continue to operate item/component as no direct action is required
 - 2 review existing maintenance and inspection tasks
 - 3 recommended review after 18 months or after a change of the operational window of the tank (e.g. product change)
 - 4 'streamline' the maintenance tasks (i.e. optimise effort by combining tasks).
- L = Low—
 - 1 continue to operate item/component
 - 2 recommended review after 12 months or after a change of the operational window of the tank (e.g. product change)
 - 3 streamline the maintenance tasks.

Referring to the flowchart (Figure 106) the recommended task/inspection plan will be, or can be, part of the maintenance master plan (step 12).

Step 8: Integrity related?

This step determines the methodology to be used.

In the context of maintenance and inspection, each methodology has a specific purpose in optimising strategies for maintenance or inspection frequencies and can be distinguished as outlined below.

RCM is predominantly used for optimising maintenance strategies, and covers mechanical, civil, electrical and instrumentation. The end result is the basis of a maintenance plan and a list of recommended improvements.

RBI is an objective tool for determining the inspection scope for the next planned shutdown and the exact part(s) of the equipment that need to be inspected. For conventional storage tanks, RBI is mainly applicable to the steel structure and foundation. Additionally, it can be used for determining the inspections to be carried out during the in-service period of the tank.

There are some overlaps in this distinction. The basic question here is: if the selected item/component fails, does the technical integrity of the tank fail? If it doesn't, the selected item/component should be assessed by the RCM methodology, otherwise the RBI methodology should be used.

Step 9: Risk assessment

A cornerstone of PPM is the assessment of an item's *risk classification or rating*, since both (RBI and RCM) methodologies are risk-based. Sections 17.2.2 and 17.2.3 describe how the underlying risk tools (RBI and RCM) deal with risk qualification.

The basic question here is: what risk level is acceptable and how can it be controlled? This question is not easily answered and can differ from case to case. But in all cases, prevention of any harm to persons, environment, asset value or production should be the aim.

There are several methods to reduce risk to an acceptable level, such as:

- (more) frequent inspections;
- improved inspection scope;
- improved inspection tools;
- utilising on-stream and robotic inspections;
- upgrading of material/coating;
- upgrade design of component that determines next inspection, or increase/improve monitoring process;
- improved maintenance performance;
- having spare equipment (mitigation measures); and
- protection/safety measures (mitigation measures).

Generally, the higher the risk class, the more effort is needed to reduce that risk. The risk classes N, L, M, H and E are described in more detail in Section 17.4.3.3.

Step 10: Acceptable risk

If the risk is unacceptable, a full tank integrity assessment needs to be carried out by the PPM team under guidance of a qualified Tank Integrity Assessor (TIA). The TIA should be capable of making a sound assessment of the integrity of storage tank and foundation in order to offer guidance on the need for repair, its urgency, and the methods of effecting such repair. It is important that the following principles are applied:

- know the risks involved;
- evaluate the level of risk acceptability;
- determine the required level of control;
- determine the reliability of the provisions, defences and necessary requirements; and
- implement the above in a management system and audit regularly to check compliance.

The monitoring of trends in the degradation mechanisms over a predetermined period of time is an important aspect of this evaluation process. The need to set up an integrated inspection and data collecting system for dimensional measurements is therefore evident. The ultimate results of the data collected and of the PPM exercise require a thorough evaluation by a TIA to ascertain the structural integrity of the complete tank in such a way that there is confidence of its fitness for purpose until the next established inspection date.

Step 11: Task development and planning

The intention here with regard to each tank item or component is to develop or review inspection, maintenance, and (if applicable) testing tasks. A rigorous approach will avoid items/components being overlooked in the total maintenance framework.

The risk classification will affect type, extent and/or frequency of the equipment's maintenance, inspection or testing tasks. The actual process in this phase is very much dependent on the methodology employed.

Step 12: Maintenance Master Plan

The result of the PPM process may lead to changes having to be made to the Maintenance Master Plan.

Step 13: Task execution

The planned and scheduled maintenance and condition monitoring (including inspection and testing) tasks are then carried out. Some of these might result in minor or major repairs. Management of these tasks lies outside the scope of this document.

Step 14: Review

After the tasks have been executed, it is important to update the tank records system. Information such as inspection and test results, condition monitoring data, and the actual condition revealed during execution of the tasks should be fed back into the records system. A review of the PPM analysis is recommended if actual conditions differ significantly from expected ones. Such a review is also required when operating conditions have changed significantly.

17.4 RBI methodology: The EEMUA approach**17.4.1 General**

The EEMUA approach to RBI methodology described below is an example that may be used if no other tools are available to the user.

17.4.2 Introduction

The RBI methodology described in this subsection focuses only on 'trendable' failure mechanisms. For bottom, shell and roof plates the dominant degradation mechanism is corrosion, and its rate is assumed to be linear with respect to the time the tank is in service.

For tank foundations the main failure mode is soil settlement. However the rate of settlement is non-linear as shown in Figure 108. It may decline exponentially over the life of the tank or may even be stepwise. It is therefore very difficult, without using the experience of specialists and computer programs, to predict when settlement will reach the rejection criterion for a particular tank. For this reason, the examples in Appendix E do not include a risk assessment model calculation for this tank component.

Other failure mechanisms to which RBI methodology can be applied and which may involve the tank components in the examples in Appendix E, should be evaluated with the help of lists of possible actions taken and 'features' which affect degradation rate for the particular failure mode and its associated risk rating.

The sub-sections that follow present only summarised explanations of the RBI approach. Reference should be made to Appendices E.3 and E.4 for more detailed information and typical examples of risk assessment calculations for bottom, shell and roof plates.

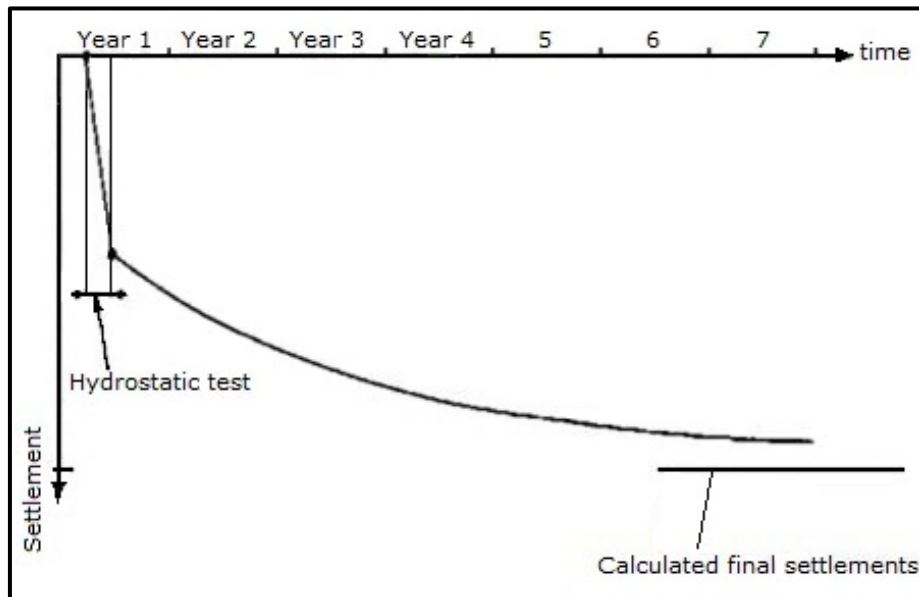


Figure 108 Typical rate of settlement of tank foundations

17.4.3 The risk assessment

17.4.3.1 Step 1: Determining probability factor and rating

The probability (of failure) rating of the occurrence of a particular failure mode for any tank component is assessed by considering actions taken or features that exist which affect the failure mode. These 'influences' are compiled in dedicated lists. Appendices E.3 and E.4 contain such lists for each of three components, namely bottom, shell and roof plates, for the failure mechanism of corrosion.

Each action or feature is assigned a value or 'score' that relates to the influence it has on the probability of the occurrence of, and hence of failure due to, corrosion. The formula used in the model calculations to calculate the *probability factor* ζ also contains further weighting factors for each action/feature to reflect their *relative* importance with regard to their influence on the probability of the occurrence of the failure mechanism.

The following probability ratings as in Table 15 can be assigned per factor ζ found:

Table 15 Relationship between probability factor ζ and probability rating

Calculated probability factor	Assigned probability rating	
$\zeta \geq 3.0$	High	H
$2.5 \leq \zeta < 3.0$	Medium	M
$2.15 \leq \zeta < 2.5$	Low	L
$\zeta < 2.15$	Negligible	N

17.4.3.2 Step 2: Determining Consequence Rating

The consequence of the failure caused by a particular failure mechanism is also assessed using dedicated lists. Three main consequence categories can be considered for a failure mode: economic, health and safety, and environmental. These are each in turn further subdivided into 'aspects', with 'scores' allocated to each. Appendices E.3 and E.4 contain such lists for each of three components, namely bottom, shell and roof plates, for the failure mechanism of corrosion. A *consequence factor* χ is calculated for each category, based on the scores, to which a *consequence rating* is assigned (Table 16). The worst case (category with the highest consequence factor) determines the *overall consequence rating* of the failure mode under consideration.

Table 16 Relationship between consequence factor χ

Consequence Factor	Assigned Consequence Rating	
$\chi \geq 3.0$	High	H
$2.5 \leq \chi < 3.0$	Medium	M
$2.0 \leq \chi < 2.5$	Low	L
$\chi < 2.0$	Negligible	N

17.4.3.3 Step 3: Determining Risk Rating

The risk rating is assessed from Table 17 below.

Table 17 Determining risk rating

From the RBI assessment, there follows a rating for:	
Probability	Outcome of Section 17.4.3.1
Consequence	Outcome of Section 17.4.3.2

The risk assessment matrix shown Figure 111 can now be used to determine the appropriate *risk rating* whose 'co-ordinates' will be the probability and consequence ratings determined above. Subsequently, the risk rating of the tank/component should be evaluated as to its acceptability.

17.4.4 Follow-up actions

Once risk rating has been determined from the RAM, the recommendations given in Section 17.3 under steps 9, 10 and 11, can be followed to set up an inspection plan.

		RBI	RCM	RISK ASSESSMENT MATRIX			
Probability rating	H	High	High	L	H	E	E
	M	Medium	Medium	L	M	H	E
	L	Low	Low	N	L	M	H
	N	Negligible	Negligible	N	N	L	M
Category	Economic			Slight Damage	Minor Damage	Local Damage	Major Damage
	Health and Safety			Slight Injury	Minor Injury	Major Injury	Single Fatality
	Environment			Slight Effect	Minor Effect	Localised Effect	Major Effect
Consequence rating				N	L	M	H

Mitigation effect:

Effect of monitoring/inspection or upgrading material or improving design:

Figure 109 Risk assessment matrix used in EEMUA PPM methodology

Note: The consequence and probability ratings are: negligible (N), low (L), medium (M) and high (H).

There are five risk ratings: N, L, M, H (with their usual meaning) and E (extreme).

17.4.5 The steps 4 and 5: Calculation of interval before next inspection

As stated in Section 17.2.2.5, the recommended interval before the next required inspection can be calculated as:

$$II = K \times RL$$

where II = inspection interval
 RL = remaining life
K = a confidence rating factor (varying between 0 and 1).

It is therefore necessary to determine the appropriate value of K. The methodology followed assigns an initial value to K depending on the risk rating. This value is then adjusted as illustrated in the examples given in Appendix E.3 and E.4.

The initial values of K, chosen from experience, are shown in Table 18.

(Comparing Table 17 with Figure 109, it will be seen that the initial values of confidence rating factor assigned to the corresponding risk ratings are: N = 0.9, L = 0.8, M = 0.7, H = 0.6 and E = 0.50).

Even for a tank component with a 'negligible' risk rating, a confidence rating factor K is defined, which results in a review close to the end of its (inherently long) derived remaining life (RL). This review should be carried out to check the need for replacement of the tank component at the end of the remaining life.

Table 18 Value assigned to confidence rating factor K from risk rating

Probability Rating	RBI	RCM	Confidence Rating Factor K			
	High	High	0.8	0.6	0.5	0.5
	Medium	Medium	0.8	0.7	0.6	0.5
	Low	Low	0.9	0.8	0.7	0.6
	Negligible	Negligible	0.9	0.9	0.8	0.7
Consequence Rating			Negligible	Low	Medium	High

Where inspection intervals are set by local or national legislation, it may be necessary to negotiate extensions with the appropriate statutory body (see Section 17.6.4).

17.5 RCM methodology: The EEMUA approach

17.5.1 General

The successful implementation of RCM requires the support and commitment of management, particularly as the initial data collection and analysis can be very costly in time.

Following completion of the RCM process, it is important that the results are fully implemented. Recommended and approved preventive maintenance tasks from the RCM process should be preferably 'loaded' into a maintenance management system. The tasks can then be planned and scheduled by that system.

17.5.2 Introduction

As for a RBI exercise, a RCM exercise is also a team effort. For this to be effective, it needs to be integrated into the overall maintenance philosophy of the company.

RCM is not a complex methodology. Nevertheless it requires a facilitator who is familiar with the RCM process and maintenance in general. The facilitator's primary role can be summarised as being to:

- 1 apply the RCM methodology.
- 2 manage the analysis.
- 3 foster understanding and teamwork.
- 4 ask a series of questions (right questions to the right persons and to understand the responses).
- 5 reassess and challenge the status quo, current practices, and proposed preventive maintenance tasks.
- 6 share and transfer best practices, experience and learning as adopted by other companies.

17.5.3 Estimated time between failures (ETBF)

Taking a tank out of service will mainly be determined by the condition of the RBI-related components such as the bottom, shell, foundation and roof. Most essential maintenance tasks will be carried out during the out-of-service period of the tank. It is recognised that ETBF is sometimes difficult to determine, or experience is missing, and for this reason a more objective approach is recommended for the risk classification. If the next calculated inspection date is established by RBI methodology, the ETBF can be classified in a relative way as shown in Table 19 below.

Table 19 Classification of estimated mean time between failures (ETBF)

Without any preventive maintenance	Likelihood (failures/yr)	ETBF (years)	Class
This component will fail annually (or more frequently)	≥ 1	≤ 1	H
This particular component fails every three to five years	0.25	4	M
It is considered possible that this component will fail before the calculated next inspection date for the tank	0.10	10	L
Component is highly unlikely to fail before the calculated next inspection date for the tank	< 0.05	> 20	N

The risk class of the specific item can be established using the RAM. The question to be considered is what risk level is acceptable and how is it to be controlled.

17.5.4 Risk analysis

In order to determine the risk class without maintenance intervention to the equipment under its operating conditions, the ETBF for the failure mode under consideration should be established. ETBF is the estimated time between failures if no maintenance is performed. No maintenance in this context means that the equipment is left in service without any human observation or intervention.

ETBF should be the probability parameter for the risk assessment. Determination of ETBF should be based on hard data, sound engineering judgement, and experience.

A risk assessment matrix showing the relationship between ETBF and consequence class is presented in Figure 110 below.

			RISK ASSESSMENT MATRIX			
ETBF	H	High				HIGH RISK
	M	Medium				
	L	Low				
	N	Negligible	LOW RISK			
Consequence class			N	L	M	H

Figure 110 Risk assessment matrix: relation between ETBF and consequence

17.5.5 Preventive maintenance plans and tasks

These are plans and tasks to be developed and carried out before a failure occurs, and to prevent the subject component from getting into a 'failure state' (the wear-out zone shown in diagram B of Figure 104).

The basic question to be considered is: **what can be done to predict or prevent a failure?** (see also question 7 under Section 17.2.3.3) so as to define what is to be done, how and when, and who will do it. The tasks are mainly done on-stream, i.e. when the tank is in normal service.

A good example of an on-stream activity that is a preventive maintenance task is inspection and maintenance of the P/V valve on a fixed roof tank (see Section 17.2.3.3).

Another example of a preventive maintenance task is the regular check on the performance of floating roof rim seals. On-stream adjustment in respect of the lateral (inward/outward) movement of the seals at a 6 - 12 month interval will not only prevent emission (product loss) but also reduce the risk of the seals jamming.

17.6 PPM implementation

17.6.1 Introduction

The objectives of introducing PPM should be determined prior to developing the PPM scheme into a practical tool. Introducing a PPM approach costs time and money (e.g. due to the introduction of more costly inspection techniques such as floor scan and acoustic emission), and benefits versus costs needs to be properly assessed.

The benefits of the PPM approach are many. Some examples are:

- increased inspection interval thereby reducing inspection and maintenance costs and also increasing revenue due to a better availability of the tank for product storage;
- reduction of unwanted events, such as bottom leakage, and all associated costs;
- better understanding of the integrity of all assets, which will result in better master planning for the location;
- Implementation also means making visible the gap, if any, between current inspection and maintenance philosophies and working practices, and the desired situation.

The implementation plan should address:

- identification of the required resources (personnel and data);
- the required knowledge of the inspection, maintenance and operations staff who will work with the scheme once it has been properly introduced (training requirements need to be established over time);
- critical success factors and potential bottlenecks.

17.6.2 Resources

As previously stated, PPM requires teamwork, with a good mix of people from operations, inspection and maintenance. Where a company does not employ its

own inspectors, well-qualified and experienced inspectors should be hired for inclusion in the PPM team.

Effective teamwork will lead to better co-operation between all the disciplines, and provide a better insight into all factors influencing the storage tank's degradation mechanisms. Good application of the PPM process will lead to insight and commitment to maintenance management, and the identified risks will then become a general management responsibility.

The key requirements for successful application of PPM are organisational (tasks, responsibilities, and qualifications of inspection personnel and staff involved with the application of PPM, RBI and RCM techniques) and technical (determination of review limits and rejection criteria, determining degradation mechanisms etc.). Technical qualifications for inspectors vary between companies and between countries, but irrespective of the local requirements and practices, it is recommended that the organisation includes a qualified Tank Integrity Assessor (TIA) (see note below). The TIA will assist in making a sound assessment of the integrity of storage tank and foundation to provide guidance on the need for repair, its urgency, and the methods of affecting such repair.

Note: EEMUA oversees a series of training courses on integrity assessment of vertical atmospheric storage tanks.

Based on the present publication as well as on API 653, the course covers the need for inspection, the interpretation of the results, and the determination of safe courses of action. It describes key features of design and the common problems that are found in service, and identifies actions that may be taken to avoid their recurrence or to remedy their adverse effects. Moreover, it imparts knowledge of design and 'fit-for-purpose' calculations necessary for carrying out integrity assessments. The CompeTank™ scheme consists of three levels of course; prospective participants should contact EEMUA for more information.

17.6.3 Minimum requirements for PPM

The following minimum requirements are recommended for the successful use of PPM.

17.6.3.1 Tasks, authorities and responsibilities

It should be recorded which department functional group is responsible for:

- making an inventory of the potential degradation mechanisms, drawing up the necessary actions with respect to control of the dominant mechanism(s);
- establishing suitable NDT techniques for detecting the potential degradation mechanisms;
- drawing up periodic inspection plans and annual inspection programmes;
- carrying out inspections and evaluating their results;
- drawing up annual maintenance programmes;
- operating the storage tanks;
- evaluation of operational factors (e.g. switching between different crude oils) which may result in variations in the degradation rate of the dominant mechanism thereby affecting the interval before the next required inspection;

- evaluating incidents with respect to integrity;
- management of tank records system.

The same department or functional group can look after one or more of the above tasks if supervision and execution remain separate.

17.6.3.2 Required expertise

It is necessary that the departments/functional groups involved in the PPM approach together provide expertise for:

- Establishing the potential failure mechanisms, the interactions between them, the critical locations, the dominant failure mechanisms and modes and the necessary actions to control the dominant factors. There should be sufficient expertise in the fields of corrosion control, operations, inspection and maintenance;
- Establishing the inspections to be carried out either by company staff or third parties with sufficient expertise in the field of corrosion and inspection;
- Carrying out inspection activities;
- Evaluating inspection results and performing engineering tasks and calculations to establish whether tank, item or component is 'fit-for-purpose';
- Evaluating incidents with the aim of ensuring direct monitoring of technical integrity. There should be expertise in the fields of operations and inspection. The inspection engineer is responsible for providing feedback for RBI analysis in the PPM plan.

Regular training of dedicated operations personnel in PPM assessment techniques needs to be given, particularly in the case of new personnel, and when there are changes of the facilities. The frequency of training should be determined by the responsible manager and recorded in the quality system. The factors arising from storage tank operation that determine integrity, the measurement of this, and the consequences of exceeding the set boundary values need to be known and understood by the operations personnel of the facility.

17.6.3.3 Monitoring of operations

The factors which determine the integrity of the facilities in question—the dominant failure mechanisms and modes—and which can be influenced by the operational factors, should be registered. Any breaching of the 'boundary values' (the previously calculated intervals before the next required inspections) of the integrity determining factors needs to be detected at an early stage and reported to the responsible functional group or department.

17.6.3.4 Changes in operation

Changes in operation should be done in accordance with a written procedure agreed in advance. This procedure should include an evaluation of the possible consequences of the change with respect to the integrity of the facilities in question as well as the way in which authorisation takes place.

17.6.3.5 Modifications and repairs

Modifications and repairs to the facility in question should take place in accordance with a written procedure. The procedure should also include a requirement to evaluate the possible consequences of the modification or repair with respect to the integrity of the modified or repaired facility and its surroundings.

17.6.3.6 Management of documentation (tank records)

There should be an accessible written overview of changes, repairs and incidents as well as the results of the inspections carried out. This should give up-to-date information on the status and history of the installation under consideration.

17.6.4 Involvement of regulatory bodies and local authorities

In certain countries, national, regional or local authorities may have a direct regulatory function with regard to the operation and maintenance of storage facilities. In such circumstances, it is recommended that the close involvement of the regulatory bodies be sought, as early as possible, when a user proposes to introduce PPM methodology. Quite often the requirements of local rules and regulations will need to be incorporated in the PPM plan. If necessary, and depending on the experience of the authorities with PPM or RBI techniques, training courses should be considered and the aims and benefits of the new philosophy explained. It would be frustrating if the regulatory authorities reject the PPM approach due to their lack of knowledge of the subject. In this respect, it may be useful to cite other locations where PPM has been successfully implemented.

A schematic representation of the composition of the entire PPM team and its internal and external interrelationships is shown in Figure 111.

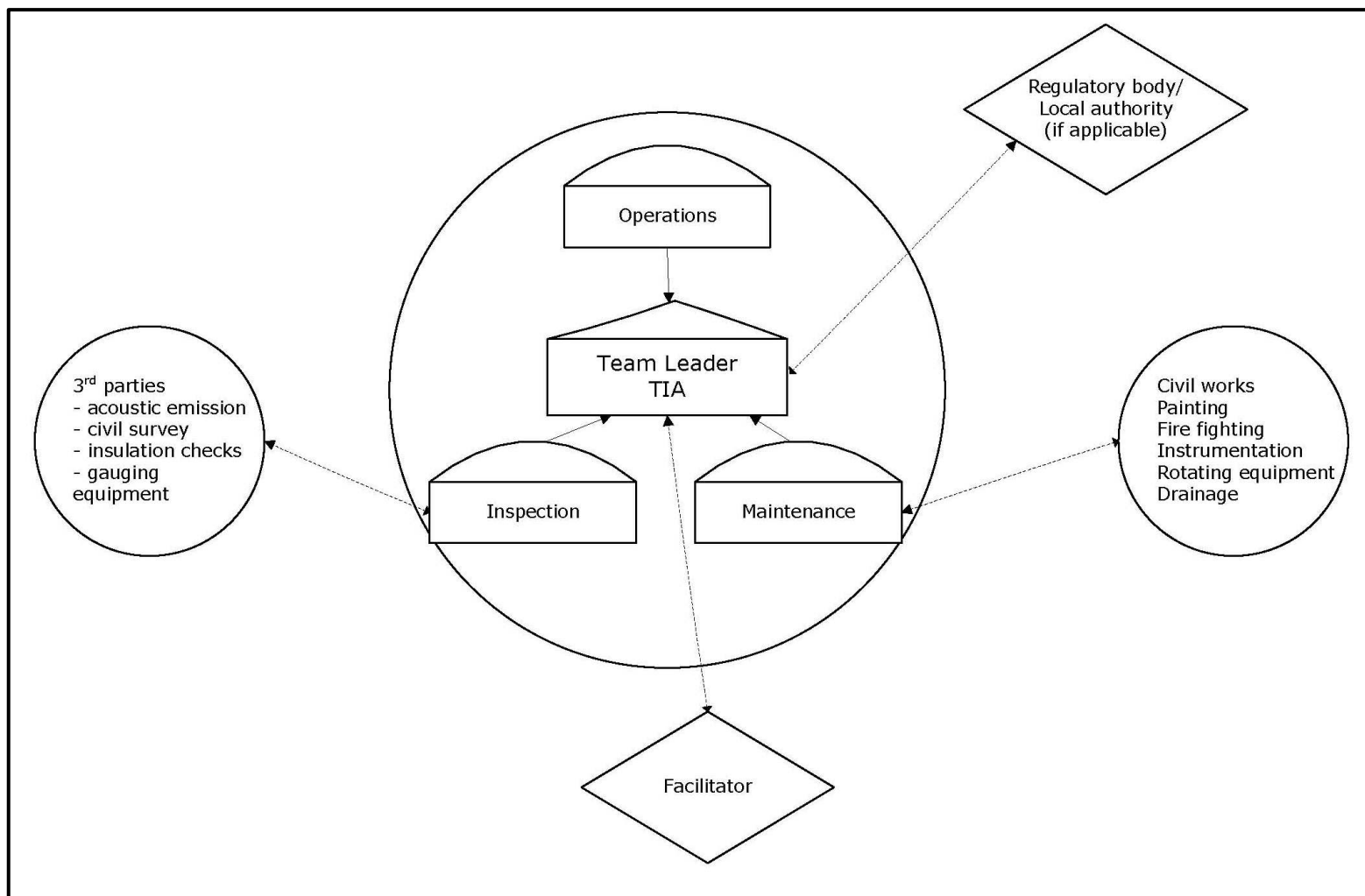


Figure 111 PPM team: composition and relationships

Appendix A Tank assessment, records and reports

A.1 Tank records

There should be a record system on site that contains at least the following information for all tanks and their appurtenances:

Storage tank

Data sheet that contains, with other pertinent information:

- date of construction;
- name of builder;
- dimensions;
- original and current safe filling height for water;
- current safe filling height for product;
- specifications for materials of construction, and materials certificates;
- welding details, including welder qualification certificates;
- drawing references;
- details of tank piping;
- drain system;
- details of ancillaries; and
- as-built drawings.

Leak detection system (if applicable):

- Product side coating/liner in tank if installed;
- leak detection system in foundation, including geo-textile flexible membrane if installed;
- cathodic protection system;
- double bottom (with or without vacuum control);
- (other measures set out in EEMUA 183).

Bunded area:

- Volume of spill wall area (single tank) or entire bunded area (more than one tank in area);
- height of bund wall(s);
- bunded area sealed with liner or impermeable layers.

Other equipment:

- Type of equipment—seals/vents/drains/mixers/heating systems (steam coils);
- materials of equipment;
- age of equipment.

Foundation:

- Soil data—type/depth of water table;
- foundation data - type (see EEMUA 183)/shoulder width/height of pad above grade etc.

Other necessary data

Operating records:

- product the tank contains;
- number of turnovers per year;
- transfer rate;
- volume transferred per loading/unloading;
- control of transfer (pumping in/out) rates to prevent overpressure/excessive vacuum;
- change of product - type, when, why.

Monitoring/detection systems:

- Spill detection;
- water table monitoring wells;
- leak detection system sump;
- tank gauging systems;
- automatic level readings;
- operator surveillance;
- overfill alarms/instrumentation.

Inspection reports:

- all completed in-service inspection checklists as per Appendix B;
- reports following out-of-service inspections as per Appendix B;
- any other, interim reports;
- reports on any work done on ancillaries;
- other data:
 - NDT data (shell, bottom, and roof plates); trends;
 - types of inspection: methods used/calibration of apparatus used/coverage (spot/gridline/full);
 - hydrostatic testing:
 - full/partial/none;
 - when, medium used;
 - functioning of equipment/instruments;
 - foundation level readings - uneven settlements (local)/planar tilt (periphery) etc.

Maintenance reports:

- details of all maintenance work carried out on the tank:
 - what, when, where, how repaired/replaced and by whom (contractor references);
 - limited service restrictions;
- manpower employed/equipment used/materials used;
- time taken/costs.

A.2 Minimum allowable thickness and shell-to-edge projection of annular plates

Guidance on the minimum (corroded) thickness and shell-to-edge projection of annular bottom plates is given in Figure 112 (see also Section 7.4.2).

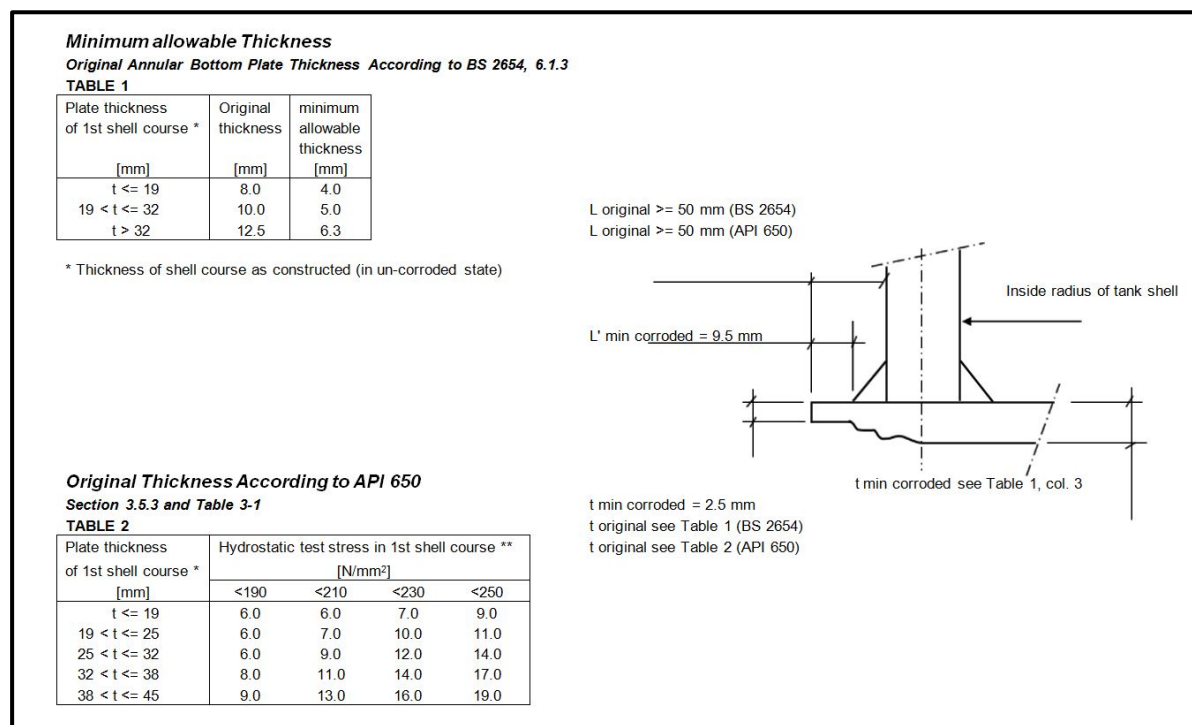


Figure 112 Minimum allowable thickness and shell/edge projection of bottom plates

Appendix B Inspection checklists and frequencies

B.1 Inspection frequencies

Table 20 Inspection frequencies

Group	Service conditions	INSPECTION FREQUENCY						
		Maximum operational external routine visual (Months)	EXTERNAL Detailed visual including ultrasonic thickness measurements of the shell, roof & external annular (Years)			INTERNAL Detailed visual including ultrasonic thickness measurements of bottom, shell & annular (Years)		
			Climate code (see below)					
			A	B	C	A	B	C
1	Slops; corrosive or aggressive chemicals, raw water, brine.	3	1	1	1	3	3	3
1A	Same as Group 1 except where internally protected as in Appendix C.5.3	3	5	5	7	10	10	10
2	Bio-fuels, Palm Oil	3	1	1	5	5	5	5
2A	Same as Group 2 except where internally protected as in Appendix C.5.3	3	5	5	7	10	10	10
3	Crude Oil (unprotected)	3	5	5	5	10	15	15
3A	Crude oil (internally protected)	3	5	5	7	15	20	20
4	Gas Oil, Lube Oil, Diesel Oil, Caustic soda, inert or non-aggressive chemicals, Ethanol, Methanol, air foam liquid, non-heated fuel oil.	3	5	5	5	15	20	20
5	Jet A1 (fully internally protected)	3	5	5	5	15	20	20
6	Light products, Kerosene, Gasoline, Cracked distillates, treated water, (not internally protected)	3	5	5	5	10	15	15
7	Heated & Insulated tanks	3	5	5	5	6	10	10
7A	Sulphur	3	3	3	3	6	10	10
8	De-min Water	3	5	5	5	10	15	15
8A	Fully protected de-min	3	5	5	5	15	20	20
9	Products with unknown corrosion rates	3	3	3	3	5	5	5

Climate codes

A = Warm and humid, e.g. tropical and subtropical areas.

B = Temperate climate with frequent rain and wind.

C = Warm and dry, e.g. desert locations.

Operational inspections

Follow procedure using Table 15.

In the case of adverse weather conditions, such as heavy rain, snow or high winds, external inspection should become more frequent.

External and internal inspections by TIA

Follow procedure using Table 16.

Note: The inspection frequencies indicated above are for guidance only. Process systems, products not covered in the table above, (including corrosion rates and product temperatures), foundation conditions and as stated above, climate, can vary considerably from site to site. Inspection frequencies could be determined by risk assessment.

Local authorities or national legislation may also require a different inspection period.

For example, many Jet A1 tanks are required to be removed from service on more frequent basis for process cleanliness inspections. This can often be taken as an "opportunity inspection" for the tank integrity examination at the same time.

After each detailed external or internal inspection, The Tank Integrity Assessor, (TIA) should determine the date for the next inspection. This date should ensure that the rejection limits stated elsewhere in this publication are not exceeded.

If the inspection results indicate a more rapid deterioration due to corrosion or settlement, other similar tanks may need to be inspected earlier. On the other hand, if the inspection results are favourable, an extension of the inspection interval, (to the inspected tank), may be considered.

For protected, See Appendix C5.

Heated tanks

Elevated temperatures above ambient to the boiling point of water may require additional inspection based on CUI and/or annular corrosion (See EEMUA 183 Section 4.4.4.).

B.2 Tank inspection checklist

Table 21 Three monthly visual inspection checklist

Check list for three monthly visual inspections by operators				
Location:		Type:	Date of inspection:	
Tank Number:		Class:	Report Number:	
Diameter:		meters	Name of inspector/operator:	
Height:		meters		
Appendix B1, Table 20, requires every three months to perform visual inspections by operators to the current status of the tank, its foundation and other important components External Inspection (clearly describe fouling, corrosion, mechanical damage, actions required etc.)				
Tank foundation shoulder				
Condition of cover material				
Drainage				
Tell-tale drains				
Edge settlement				
Out of verticality				
Painting system				
Outer edge of bottom plates				
Shell				
Roof				
Stairs and hand railing				
Nozzles				
Anchor chairs (if present)				
Insulation				
Shell				
Roof				
Floating roof (if present)				
Rim seal				
Shunts (number and contact to shell)				
Roof plates				
Rim vents				
Automatic bleeder vents				
Rolling ladder and rail track				
Landing legs and sleeves				
Connecting pins to sleeves of landing legs				
Sampling hatches				
Roof drain				
Earthing cable connections				
Fixed roof (if present)				
Roof plates				
Top curb angle				
Pressure/ vacuum relief vents				
Emergency relief vent (if present)				
Sample hatches				
Platforms, walk ways				
Tank connections				
Nozzles				
Mixer systems				
Piping connections				
Supports of piping close to tank				
Anchor bolts and anchor chairs				

Table 22 In-service tank inspection checklist

B.1.1 FOUNDATION	
	Measure foundation levelness and bottom elevations (see Chapter 7 for extent of measurements)
B.1.1.1 Concrete ring	
a.	Inspect for broken concrete, spalling and cracks, particularly under backup bars used in welding butt welded annular rings under the shell.
b.	Inspect drain openings in ring, back of waterdraw sump and top surface of ring for indications of bottom leakage.
c.	Inspect for cavities under foundation and vegetation against bottom of tank.
d.	Check that runoff rainwater from the shell drains away from tank.
e.	Check for settlement around perimeter of tank.
B.1.1.2 Asphalt	
a.	Check for settling of tank into asphalt base which would direct runoff rainwater under the tank instead of away from it.
b.	Look for areas where leaching of oil has left rock filler exposed, which indicates hydrocarbon leakage.
B.1.1.3 Oiled dirt or sand	
a.	Check for settlement into the base which would direct runoff rain water under the tank rather than away from it.
B.1.1.4 Site drainage	
a.	Check site for drainage away from the tank and associated piping and manifolds.
b.	Check operating condition of dike drains.
B.1.1.5 Housekeeping	
	Inspect the area for build-up of trash, vegetation and flammable material.
B.1.2 SHELLS	
B.1.2.1 External inspection	
a.	Visually inspect for paint failures or disbonding, pitting and corrosion.
b.	Clean off the shell to bottom area and inspect for corrosion and thinning on plate and weld.
c.	Inspect the bottom-to-foundation seal, if drip plate not fitted.
d.	On cone up bottoms, closely inspect and gauge the depth of metal loss on the lower 100mm of the shell (area of standing water).
e.	Measure depth of pitting on each shell course.
f.	Check connection of earthing cables to lugs.
B.1.2.2 Internal (floating roof tank)	
	Visually inspect for grooving, areas of rubbing, corrosion, pitting, and coating failures.
B.1.2.3 Riveted shell inspection	
a.	Inspect external surface for rivet and seam leaks.
b.	Locate leaks by sketch or photo (location will be lost when shell is abrasively cleaned for painting).
c.	Inspect rivets for corrosion loss and wear.
d.	Inspect vertical seams to see if they have been full-fillet lap welded to increase joint efficiency.
e.	If no record exists of vertical riveted seams, dimension and sketch (or photograph) the rivet pattern - number of rows, rivet size, pitch length - and note whether the joint is butt riveted or lap riveted.
B.1.2.4 Wind girder (floating roof tanks)	
a.	Inspect wind girder and handrail for corrosion damage (paint failure, pitting, corrosion product build up, water ponding), especially where it occurs at welded

	junctions, and for broken welds.
b.	Check support welds to shell for pitting, especially on shell plates.
c.	Note whether supports have reinforcing pads welded to shell and check for cracks and pitting.
B1.3 SHELL APPURTENANCES	
B.1.3.1 Manways and nozzles	
a.	Inspect for cracks or signs of leakage on weld joints at nozzles, manways, and reinforcing plate including checking vents on compensation plates for signs of leakage.
b.	Inspect for shell plate dimpling around nozzles, caused by excessive pipe deflection.
c.	Inspect for leaks on flange joints or around bolting.
d.	Inspect for excessive bolt corrosion on all shell fittings and nozzles.
e.	Inspect any shell overflow for corrosion and adequate screening.
f.	Check that location of any shell overflow is not above any tank valves or equipment.
B.1.3.2 Tank piping manifolds	
a.	Inspect manifold piping, flanges, and valves for leaks.
b.	Inspect fire fighting system components.
c.	Check for anchored piping which would be hazardous to the tank shell or bottom connections during earth movement.
d.	Check for adequate thermal pressure relief of piping to the tank.
e.	Check operation of regulators for tanks with purge gas systems.
f.	Check for damage and test the accuracy of temperature indicators.
g.	Check welds on shell-mounted davit clips above valves.
B.1.3.3 Autogauge system	
a.	Inspect autogauge tape guide and guide sheaves for damage and freedom of movement.
b.	Inspect tape and tape cable for twisting and fraying.
c.	Inspect autogauge head for damage.
d.	Bump the checker on autogauge head for proper movement of tape.
e.	Ask operator if tape tends to hang up during tank roof movement.
f.	Compare actual product level to the reading on the autogauge (maximum variation is 50 mm).
g.	On floating roof tanks, when the roof is in the lowest position, check that no more than two feet of tape are exposed at the end of the tape guide.
h.	Inspect condition of board and legibility of board-type autogauges.
i.	Test freedom of movement of marker and float.
B.1.3.4 Shell-mounted sample station	
a.	Inspect sample lines for function of valves and plugging of lines, including drain or return-to-tank line.
b.	Check circulation pump for leaks and operating problems.
c.	Test bracing and supports of sample system lines and equipment.
B.1.3.5 Heater (shell manway mounted)	
	Inspect condensate drain for presence of oil, indicating leakage.

B.1.3.6 Mixer	
a.	Inspect for proper mounting flange and support.
b.	Inspect for leakage.
c.	Inspect condition of power lines and connections to mixer.
B.1.3.7 Floating/swing line operation	
a.	Non-floating: raise, then lower the swing line with the winch, and check for cable tightness to confirm that swing line operating properly.
b.	Floating line: with tank half full or more, raise the floating line and check for cable tightness, then let out cable and check cable has gone slack, indicating that the floating line is operating properly.
c.	Indicator: check that the indicator moves in the proper direction (floating line indicators show a lower level as cable is wound upon the winch; non-floating swing line indicators show the opposite).
d.	For non-stainless steel cable, check for corrosion over entire length.
e.	All cable: check for wear and fraying.
f.	Check all cable guides for corrosion, wear or damage.
B.1.3.8 Swing lines: identify ballast varying need	
	Inspect the counterbalance assembly on swing line for corrosion and freedom of operation.
	Check for significant difference in product specific gravity since previous inspection.
B.1.3.9 Swing lines: product sample comparison	
	Check for water or gravity differences that would indicate a leaking swing joint.
B.1.3.10 Swing lines: target	
	Target should indicate direction of swing opening (up or down) and height above bottom where suction will be lost with swing on bottom support.
B1.4 ROOFS	
B.1.4.1 Deck plate internal corrosion	
a.	For safety, before accessing the roof, check with ultrasonic instrument or lightly use a ball peen hammer to test the deck plate near the edge of the roof for thinning. (Corrosion normally attacks the deck plate at the edge of a fixed roof and at the rafters in the centre of the roof first.)
b.	For floating roof tanks ultrasonically examine or hammer test the top of roof pontoon and vertical edge of pontoons especially where pontoons join well deck if single deck roof.
c.	Inspect for cracks or signs of leakage on weld joints at nozzles, manways, and reinforcing plate including checking vents on compensation plates for signs of leakage
d.	Inspect for leaks on flange joints or around bolting.
e.	Inspect for excessive bolt corrosion on all roof fittings and nozzles.
B.1.4.2 Deck Plate External Corrosion	
a.	Visually inspect for paint failure or disbonding, holes, pitting, and corrosion product on the roof deck.
b.	Check all clips, brackets and braces welded to the roof deck plates or to reinforcing pads and see that they have not broken or cracked.
B.1.4.3 Roof Deck Drainage	
a.	Look for indication of standing water. (Significant sagging of fixed roof deck

	indicates potential rafter failure. Large standing water areas on a floating roof indicate inadequate drainage design or, if to one side, an unlevel roof with possible leaking pontoons.)
B.1.4.4 Level of Floating Roof	
a.	At several locations, measure distance from roof rim to a horizontal weld seam above the roof. A variance in the readings indicates an unlevel roof with possible shell out-of-roundness, out-of-plumb, leaking pontoons or hang up. On small diameter tanks, an unlevel condition can indicate unequal loading at that level.
B.1.4.5 Gas Test Internal Floating Roof	
	Test for explosive gas on top of the internal floating roof. Readings could indicate a leaking roof, leaking seal system, or inadequate ventilation of the area above the internal floating roof.
B.1.4.6 Roof Insulation	
a.	Visually inspect for cracks or leaks in the insulation weather coat where runoff rainwater could penetrate the insulation.
b.	Inspect for wet insulation under the weather coat.
c.	Remove small test sections of insulation, and check roof deck for corrosion and holes near the edge of the insulated area.
B.1.4.7 Floating Roof Seal Systems	
a.	Measure and record maximum seal-to-shell gaps:
	at low pump out,
	at mid-shell,
	at high liquid level.
b.	Measure and record rim gap at 10 m intervals (minimum of 4 quadrants) around roof and record. Measurements should be taken in directly opposite pairs.
	Opposite pair 1
	Opposite pair 2
	etc.
c.	Check if seal fabric on primary shoe seals is pulling shoes away from shell (fabric not wide enough).
d.	Inspect fabric for deterioration, holes, tears, and cracks.
e.	Inspect visible metallic parts for corrosion and wear.
f.	Inspect for openings in seals that would permit vapour emissions.
g.	Inspect the rim mounted seal bolting bar for corrosion and broken welds.
h.	Pull seal systems back all around the shell to check operation of seal and ensure it is maintaining contact with shell.
i.	Inspect for protruding bolt or rivet heads on seal contacting the shell.
j.	While checking seal operation visually inspect area of shell hidden by seal.
k.	Inspect secondary seals for signs of buckling or indications that their angle with the shell is too shallow.
l.	Inspect wedge-type wiper seals for flexibility, resilience, cracks, and tears.
m.	Inspect anti rotation devices for operability, damage and corrosion.
B.1.5 ROOF APPURTENANCES	
B.1.5.1 Sample Hatch	
a.	Inspect condition and functioning of sample hatch cover.
b.	On tanks governed by air quality monitoring rules, check for the condition of seal inside hatch cover
c.	Check for corrosion and plugging on thief and gauge hatch cover.
d.	Where sample hatch is used to reel gauge stock level, check for marker and tab stating hold-off distance.
e.	Check condition of reinforcing pad where sample hatch pipe penetrates the roof deck.

f.	On floating roof sample hatch and recoil systems, inspect operation of recoil reel and condition of rope.
g.	Test operation of system.
h.	On ultra-clean stocks, check for presence and condition of protective coating or liner inside sample hatch (preventing rust from pipe getting into sample).
i.	On fixed roof tanks with internal floating roof: When equipped with a fabric seal, check for automatic sealing after sampling.
j.	On fixed roof tanks with internal floating roof: When equipped with a recoil reel-opening device, check for proper operation.
B.1.5.2 Gauge well	
a.	Inspect visible portion of the gauge well for thinning, size of slots and the cover condition.
b.	Check for a hold-off distance marker and tab with hold-off distance legible.
c.	On floating roofs, inspect condition of roof guide for gauge well, particularly the condition of the rollers for grooving and free movement.
d.	On floating roofs inspect condition of seal system between roof and gauge well.
e.	If accessible, check the distance from the gauge well pipe to the tank shell at different levels.
f.	If tank has a gauge well washer, check valve for leakage and for presence of a bull plug or blind flange.
B.1.5.3 Fixed-Roof Scaffold Support	
a.	Inspect scaffold support for corrosion, wear, and structural soundness.
B.1.5.4 Autogauge: Inspection Hatch and Guides (Fixed Roof)	
a.	Check the hatch for corrosion and missing bolts.
b.	Look for corrosion on the tape guide's and float guide's wire anchors.
B.1.5.5 Autogauge: (Floating Roof)	
a.	Inspect for corrosion on float well cover on floating roof tanks.
b.	Check tape cable for wear or fraying caused by rubbing on the cover.
B.1.5.6 Gauging Platform Drip Ring	
a.	On fixed roof tanks with drip rings under the gauging platform or sampling area, inspect for plugged drain return to the tank.
B.1.5.7 Roof Mounted Vents (Fixed Roof Tank)	
a.	Check condition of mesh screens on vents and P&V's.
b.	Inspect pressure/vacuum vents. (Setting should be high enough to prevent chattering of breather during normal operation. See breather manufacturer's guide.)
c.	Check condition of emergency vents including sealing, pivot pins or safety retaining chain.
d.	Inspect liquid seal hatches for corrosion, and proper liquid level in the seal.
B.1.5.8 Roof Drains	
a.	On closed drain system inspect roof sump for thinning and pitting.
b.	On closed drain system inspect protective coating (topside).
c.	On closed drain system inspect basin cover or screen for corrosion.
d.	On closed drain system test operation of check valve.
e.	On emergency drain system inspect vapour plugs for emergency drain; check that seal fabric discs are slightly smaller than the pipe ID and that fabric seal is above the liquid level.
B.1.5.9 Floating Roof Legs	
a.	Inspect the sealing system on the two-position legs and the vapour plugs in the fixed legs for deterioration of the gaskets.
b.	Inspect for reinforcing gussets on all leg openings located in a single roof plate for corrosion and broken welds.

c.	Where roof legs are stored on the roof of a floating tank inspect the leg rack supports.
B.1.5.10 Vacuum Breakers	
a.	Report size, number and type of vacuum breakers. Inspect vacuum breaker seals are sealing. Check stem for thinning. If roof legs are set to high position, check for setting of mechanical vacuum breaker is in high leg position.
B.1.5.11 Rim vents	
a.	Check condition of the mesh screen on the rim vent cover.
b.	Check rim vent for pitting and holes
c.	Check for plating off or removal of rim vents where jurisdictional rules permit removal.
B.1.5.12 Pontoon Inspection Hatches	
a.	Open pontoon inspection hatch covers and visually check inside each pontoon for signs of product leakage or rain water. Do not enter pontoon unless adequate access/egress and suitable rescue plan in place.
b.	Test for explosive gas (an indicator of vapour space leaks).
c.	If pontoon hatches are equipped with locked down covers, check for vent tubes. Check that vent tubes are not plugged by running a light wire through the gooseneck vent.
d.	Inspect lock down devices for condition and operation.
B.1.6 ACCESSWAYS	
See Table B.2, item B.2.12.	

Table 23 Out-of-service tank inspection checklist

B.2.1 OVERVIEW	
a.	Check that tank has been cleaned, is gas free and safe for entry.
b.	Check that the tank is completely isolated from product lines, all electrical power, and steam lines.
c.	Check that roof is adequately supported, including fixed roof structure and floating roof legs.
d.	Check for presence of falling object hazards, such as corroded-through roof rafters, asphalt stalactites and trapped hydrocarbons in unopened or plugged equipment or appurtenances, ledges, etc.
e.	Inspect for slipping hazards on the bottom and roof decks.
f.	Inspect structural welds on accessways and clips.
g.	Check surfaces needing inspection for heavy scale build-up, and check weld seams and oily surfaces where welding is to be done. Note areas needing more cleaning, including blasting.
B.2.2 TANK EXTERIOR	
a.	Inspect appurtenances opened during cleaning such as lower floating swing sheave assemblies and nozzle interiors (after removal of valves).
b.	Ultrasonically or hammer test the roof.
c.	Enter and inspect the floating roof pontoon compartments.
B.2.3 BOTTOM INTERIOR SURFACE	
a.	Using the bottom plate layout as a guide, visually inspect and ultrasonically inspect all annular plates and sketch plates for corrosion.
b.	Measure the depth of pitting and describe the pitting appearance (sharp edged, lake type, dense, scattered, etc.).
c.	Mark areas requiring patching or further inspection.
d.	Identify areas of underside corrosion and remove isolated areas for further investigation
e.	Check tank construction records for the presence of crushed rock under the steel bottom usually results in severe underside corrosion. Perform additional bottom plate examination (ultrasonic, hammer-testing or turning of coupons).
f.	Inspect all welds for corrosion and leaks, particularly the shell-to-bottom weld.
g.	Locate and mark voids under the bottom.
h.	Record bottom data on a layout sketch using the existing bottom plates as a grid. List the number and sizes of patches required.
i.	Vacuum test the bottom lap welds.
j.	Ultrasonically examine or hammer test any slightly discoloured spots or damp areas.
k.	Check for reinforcing pads under all bottom attached clips, brackets, and supports.
l.	Inspect floating roof leg pads for pining or cutting, and excessive dimpling (indicating excessive loading).
m.	Check the column bases of fixed roof supports for adequate pads and restraining clips.
n.	In earthquake zones, check that roof support columns are not welded down to the tank bottom, but are only restrained from horizontal movement.
o.	Check area beneath swing line cable for indications of cable cutting or dragging.
p.	Mark old oil and air test connections for removal and patching.
q.	Identify and report low areas on the bottom that does not drain adequately.
r.	Inspect coating for holes, disbonding, deterioration, and discoloration.
B.2.4 SHELL SEAMS AND PLATE	

a.	On cone up bottoms, closely inspect and gauge the depth of metal loss on the lower 100 mm of the shell (area of standing water).
b.	Measure the depth of pitting on each course.
c.	Inspect and estimate the amount of metal loss on the heads of rivets and bolts.
d.	Inspect shell-to-bottom riveted lap joints or weld for corrosion, cracking or damage
e.	Check for vertical grooving or areas of rubbing on the inside of shell where floating roof or internal floating roof exists (indicating too much pressure by the seal assembly shoes or inadequate annular space).
f.	Inspect existing protective coatings for damage, deterioration and disbonding.
g.	Visually inspect the shell plates and seams for indications of leakage.
h.	If the shell has riveted or bolted seams, record the leak locations by film or chart in case the locations are lost during surface preparation for painting.
i.	Survey the shell to check for roundness and plumb.
B.2.5 SHELL MOUNTED OVERFLOWS	
a.	Inspect overflow for corrosion and adequate screening.
b.	Check that location of overflow is not above any tank valves or equipment.
B.2.6 ROOF INTERIOR SURFACE	
B.2.6.1 General	
a.	Visually inspect the underside surface of the roof plates for holes, scale build-up, and pitting.
b.	Ultrasonically examine to check for thin areas, particularly in the vapour space of floating roofs and at edge of roof on cone roof tanks, hammer test as necessary.
c.	Check all clips, brackets, braces, etc. welded to the roof deck plates for welded reinforcing pads and see that they have not broken free.
d.	If no reinforcing pad is present, penetrant test for cracking of the weld or deck plate.
e.	Inspect the protective coating for breaks, disbondment, and deterioration.
f.	Spark test the interior surface coating if recoating is not planned.
B.2.6.2 Fixed Roof Support Structure	
a.	Inspect the support columns for thinning in the upper two feet.
b.	On API columns (two channels welded together) check for corrosion scale breaking the tack welds, unless the joint between the channels is completely seal welded.
c.	Check that the reinforcing pad on the bottom is seal welded to the tank bottom, with horizontal movement restraining clips welded to the pad.
d.	Determine if pipe column supports are concrete filled or open pipe. If open pipe, check for a drain opening in the bottom of the pipe and that it is clear.
e.	Inspect and gauge rafters for thinning, particularly near the centre of the roof; report metal loss.
f.	Check for loose or twisted rafters.
g.	Inspect girders for thinning, and check that they are attached securely to the top of the columns.
h.	Report if the columns have cross bracing in the area between the low pump-out and top of the shell (for future internal floating roof installation).
i.	Inspect and report presence of any roof-mounted swing line bumpers.
j.	Photograph the roof structure if no rafter layout drawing exists.
B.2.7 FIXED ROOF APPURTENANCES	
B.2.7.1 Inspection and Hatches	
a.	Inspect the hatches for corrosion, paint and coating failures, holes, and cover

	sealing.
b.	On loose hatches, check for a safety chain in good condition.
c.	On light hatches over 750 mm across, check for safety rods.
d.	Inspect the condition of the gaskets on bolted or latched down hatch covers.
B.2.7.2 Staging Support Connection	
	Inspect the condition of the staging support for corrosion.
B.2.7.3 Roof Mounted Vents	
a.	Inspect condition of mesh screens on vents and P&V's.
b.	Inspect and service pressure/vacuum valves. (Setting should be high enough to prevent chattering of breather during normal operation. See breather manufacturer's guide.)
c.	Check condition and service emergency vents including sealing, pivot pins or safety retaining chain.
d.	Inspect liquid seal hatches for corrosion, and proper liquid level in the seal.
B.2.8 FLOATING ROOF	
B.2.8.1 Roof Deck	
a.	Check that either the roof drain is open or the drain plug in the roof is open in case of unexpected rain.
b.	Ultrasonically examine the area between roof rim and shell (hammer test any areas of concern if necessary).
c.	Ultrasonically examine underside of roof pontoons or complete roof if double deck type roof (hammer test any areas of concern if necessary).
d.	In sour water service, clean and test all deck plate weld seams for cracking unless the lower laps have been seal welded.
e.	On flat-bottomed and cone-down bottom roof decks, check for a vapour dam around the periphery of the roof. The dam should be continuous to prevent escape of vapours to the seal area from under the centre of the roof.
B.2.8.2 Floating Roof Pontoons	
a.	Open pontoon inspection hatch covers and visually check inside each pontoon for signs of product leakage or rain water. Do not enter pontoon unless adequate access/egress and suitable rescue plan in place.
b.	If pontoon hatches are equipped with locked down covers, check for vent tubes. Check that vent tubes are not plugged by running a light wire through the gooseneck vents.
c.	Inspect lockdown devices on each cover for condition and operation.
d.	Check and report on design of each pontoon. Do not enter pontoon unless adequate access/egress and suitable rescue plan in place.
	(1) vapour tight (bulkhead seal welded on one side, on bottom, sides, and top)
	(2) liquid tight (seal welded on bottom and sides only)
	(3) unacceptable (minimum acceptable condition is liquid tight).
B.2.8.3 Floating Roof Cutouts	
a.	Inspect underside of cutouts for mechanical damage.
b.	Inspect welds for cracks.
c.	Inspect plate for thinning, pitting and erosion.
d.	Measure mixer cutouts and record plate thickness for future mixer installation or replacement.
B.2.8.4 Floating Roof Supports	
a.	Inspect floating roof legs for thinning.
b.	Inspect for notching at bottom of legs for drainage.
c.	Inspect for leg buckling or bellling at bottom.
d.	Inspect pinhole in roof guide for tears/elongation.

e.	Check plumb of all legs.
f.	Inspect for adequate reinforcing gussets on all leg openings on roof plate.
g.	Inspect the area around the roof legs for cracking if there is no internal reinforcing pad or if the topside pad is not welded to the deck plate on the underside.
h.	Inspect the sealing system on the two-position legs and the vapour plugs in the fixed low leg for deterioration of the gaskets.
i.	On shell mounted roof supports, check for adequate clearance based on the maximum floating roof movement as determined by the position of the roof relative to the gauge well end or counter rotational device.
B.2.9 FLOATING ROOF SEAL ASSEMBLIES	
B.2.9.1 Primary Shoe Assembly	
a.	Remove for inspection four sections of foam log (foam filled seals) at 90° intervals and inspect foam for liquid absorption and deterioration.
b.	Inspect hanger attachment to roof rim for thinning, bending, broken welds, and wear of pinholes.
c.	Inspect clips welded to roof rim for thinning.
d.	Inspect shoes for thinning and holes.
e.	Inspect condition of metal parts, bolts, clips and attachments for corrosion and wear.
f.	Visually inspect seal fabric for deterioration, cracking, stiffening, holes and tears that would allow vapour emissions.
g.	Measure length of fabric from top of shoe to roof rim, and check against maximum anticipated roof rim gap as roof operates.
h.	Inspect any modification of shoes over shell nozzles, mixers, etc., for clearance.
i.	Inspect shoes for damage caused by striking shell nozzles, mixers, etc.
B.2.9.3 Rim-Mounted Secondary Assembly	
a.	Inspect the rim-mounted bolting bar for corrosion and broken welds.
b.	Measure and chart seal-to-shell gaps.
c.	Visually inspect seal from below, looking for holes as evident by light.
d.	Inspect fabric for deterioration, cracking, stiffening, holes and tears.
e.	Inspect for mechanical damage, corrosion, and wear on tip in contact with shell.
f.	Inspect for contact with obstructions above top of shell.
B.2.10 ROOF APPURTENANCES	
B.2.10.1 Roof Manways	
a.	Inspect walls of manways for pitting and thinning.
b.	On tanks with interface autogauges, check seal around gauge tape cable and guide wires through manway cover.
c.	Inspect cover gasket and bolts.
B.2.10.2 Rim Vent	
a.	Check rim vent for pitting and holes.
b.	Check vent for condition of mesh screen.
c.	On floating roof tanks where the environmental rules require closing off the vent, check the vent pipe for corrosion at the pipe-to-rim joint and check that the blinding is adequate.
B.2.10.3 Vacuum Breaker, Breather Type	
a.	Service and check operation of breather valve and condition of the mesh screen.
b.	Check that nozzle pipe projects no more than 15 mm below roof deck (minimise vapour under the roof).
c.	Inspect reinforcing pad and pad welds.

B.2.10.4 Vacuum Breaker, Mechanical Type	
Inspect the condition of the seal and the stem for thinning. Measure how far the vacuum breaker cover is raised off the pipe when the roof is resting or high or low legs.	
B.2.10.5 Roof Drains: Open Systems including Emergency Drains	
a.	Check liquid level inside open roof drains for adequate freeboard. Report if there is insufficient distance between liquid level and top of drain.
b.	On emergency drain system inspect vapour plugs for emergency drain; check that seal fabric discs are slightly smaller than the pipe ID and that fabric seal is above the liquid level.
c.	If emergency drain is not at the centre of the roof, check that there are at least three emergency drains.
B.2.10.6 Closed Drain Systems: Roof Sump	
a.	Inspect roof sump for thinning and pitting.
b.	Inspect protective coating (topside).
c.	Inspect roof sump cover or screen for corrosion.
d.	Test operation of check valve.
e.	Check for presence of check valve where bottom of roof sump is below product level.
f.	Inspect roof sump(s)-to-roof deck welds for cracking.
g.	Check roof sump(s) outlet pipe for adequate reinforcement to roof deck (including reinforcing pad).
B.2.10.7 Closed Drain Systems: Fixed Drain Line on Tank Bottom	
a.	Hammer test fixed drain line on tank bottom for thinning and scale/ debris plugging.
b.	Inspect supports and reinforcing pads for weld failures and corrosion.
c.	Check that pipe is guided, not rigidly locked to supports, to avoid tearing of tank bottom plate.
B.2.10.8 Closed Drain Systems: Flexible Pipe Drain	
a.	Inspect for damage to exterior of pipe.
b.	Check for obstructions that pipe could catch on.
c.	Inspect shields that protect pipe from snagging.
d.	Inspect results of hydrotest on flexible roof drain system.
B.2.10.9 Closed Drain Systems: Articulated Joint Drain	
a.	Hammer test rigid pipe in flexible joint system for thinning and scale/debris plugging.
b.	Inspect system for signs of bending or strain.
c.	Inspect results of system hydrotest.
d.	Inspect landing leg and pad.
B.2.10.10 Autogauge System and Alarms	
a.	Inspect autogauge head for damage
b.	Inspect sheaves for freedom of movement.
c.	Test operation of checker.

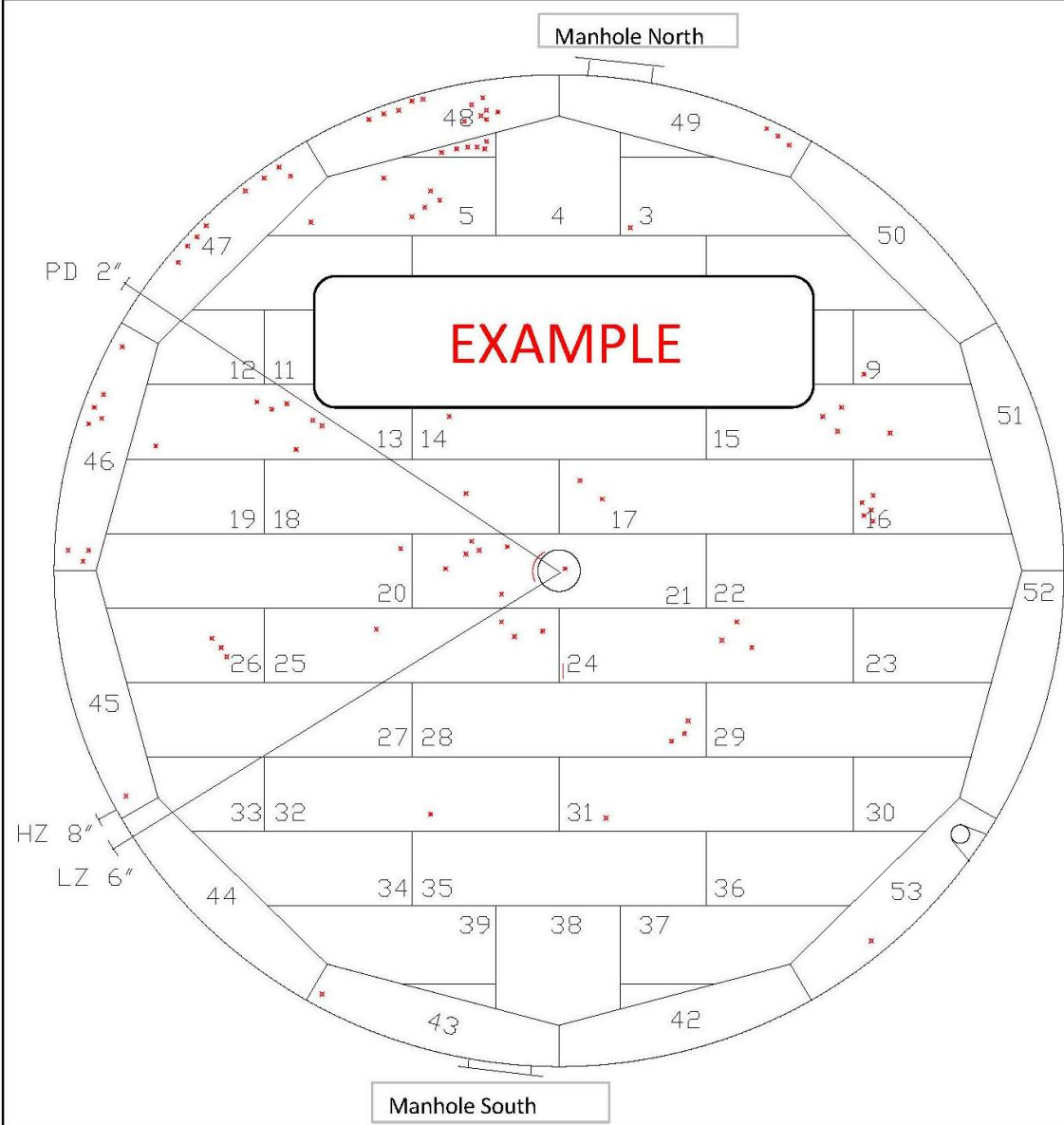
d.	Inspect tape and tape cable for twisting and fraying.
e.	Test the tape's freedom of movement through guide sheaves and tape guide pipe.
f.	On open-top tanks, check that gate tapes with cables have no more than one foot (305 mm) of tape exposed with float at lowest point.
g.	Check float for Leakage.
h.	Test float guide wire anchors for spring action by pulling on wire and releasing.
i.	Inspect float wells in floating roofs for thinning and pitting of walls just above the liquid level.
j.	Check that the autogauge tape is firmly attached to the float.
k.	Inspect the tape cable and float guide wire fabric seals through the float well cover.
l.	Inspect the bottom guide wire attachment clip: inspect for a temporary weighted bar instead of a permanent welded down clip.
m.	Inspect board-type autogauge indicators for legibility, and freedom of movement of indicator.
n.	On floating roof tanks measure and record distances below to determine whether seal damage will occur If tank is overfilled:
	(1) from shell top angle to underside of tape guide system.
	(2) from normal liquid level on floating roof to top of secondary seal.
o.	Identify floating roofs where the tape is connected directly to the roof.
p.	Inspect tank overfill prevention alarm switches for proper operation.
B.2.11 COMMON TANK APPURTENANCES	
B.2.11.1 Gauge Well	
a.	Inspect gauge well pipe for thinning at about two-thirds distance above the bottom: look for thinning at the edge of the slots.
b.	Check for corrosion on the pipe joint. Check that sample cords, weights, thermometers etc., have been removed from the pipe.
c.	Check for cone at bottom-end of pipe about 300 mm above the bottom.
d.	Check condition of well washer pipe and that its flared end is directed at the near side of the hold-off pad.
e.	Check that supports for gauge well are welded to pad or to shell and not directly to bottom plate.
f.	Check operation of gauge well cover.
g.	Check that gauge well pipe is vertical.
h.	Check presence of a hold-off distance marker in well pipe and record hold-off distance.
i.	Identify and report pipe size and schedule, and whether pipe wall is solid or slotted. Report slot size.
j.	Check that the hold-off distance plate is seal welded to the bottom, and that any gauge well supports are welded to the plate and not directly to the bottom.
k.	Inspect vapour control float and cable.
l.	Check for presence and condition of gauge well washer.
m.	Check for bull plug or plate blind on gauge well washer valve.
n.	Inspect gauge well guide in floating roof for pitting and thinning.
o.	Inspect the guide rollers and sliding plates for freedom of movement.
p.	Inspect condition of gauge well pipe seal system.
q.	On black oil and diesel services, if gauge well is also used for sampling, check for presence of a thief- and gauge-type hatch for avoiding spillage.
r.	Visually inspect inside of pipe for pipe weld protrusions which could catch or

	damage vapour control float.
B.2.11.2 Sample System: Roof Sample Hatches	
a.	Inspect roof mounted sample hatches for reinforcing pads and cracking.
b.	Inspect cover for operation.
c.	For tanks complying with Air Quality Monitoring District rules, inspect sample hatch covers for adequate sealing.
d.	Check horizontal alignment of internal floating roof sample hatches under fixed roof hatches.
e.	Inspect the sealing system on the internal floating roof sample hatch cover.
f.	Inspect floating roof sample hatch cover recoil reel and rope.
B.2.11.3 Shell Nozzles	
a.	Inspect shell nozzles for thinning and pitting.
b.	Inspect hot tap nozzles for trimming of holes.
c.	Identify type of shell nozzles.
d.	Identify and describe internal piping, including elbow-up and elbow-down types.
B.2.11.4 For Nozzles Extended into the Tank	
a.	Inspect pipe support pads welded to tank bottom.
b.	Inspect to see that pipe is free to move along support without strain or tearing action on bottom plate.
c.	Inspect nozzle valves for packing leaks and damaged flange faces.
d.	Inspect heater steam nozzle flanges and valves for wire cutting (by trace heating wires).
e.	Report which nozzles have thermal pressure relief bosses and valves.
f.	Internal elbow-down fill line nozzles: inspect the wear plate on the tank bottom.
g.	On elbow-up fill lines in floating roof tanks: check that opening is directed against underside of roof, not against vapour space. Inspect impact area for erosion.
B.2.11.5 Diffusers and Air Sparging Systems	
a.	Inspect diffuser pipe for erosion and thinning.
b.	Check holes in diffuser for excessive wear and enlargement.
c.	Inspect diffuser supports for damage and corrosion.
d.	Check that diffuser supports restrain, not anchor, longitudinal line movement.
e.	Inspect air spiders on bottom of lube oil tanks for plugging, and damaged or broken threaded joints.
B.2.11.6 Floating/Swing Line	
a.	Inspect flexible joint for cracks and leaks.
b.	Scribe the flexible joint across the two moving faces and raise end of swing line to check the joint's freedom of movement, indicated by separation of scribe marks.
c.	Check that flexible joints over 150 mm are supported.
d.	Inspect the floating/swing pipe for deep pitting and weld corrosion.
e.	Loosen the vent plugs in the floats and listen for a vacuum. Lack of a vacuum indicates a leaking pontoon.
f.	Check the results of air test on floats during repairs.
g.	Inspect the floats for pitting.
h.	Inspect the pull-down cable connections to the swing line.
i.	Inspect the condition of the bottom-mounted support, fixed roof limiting bumper, or shell mounted limiting bumper for condition, weld and bolt corrosion and seal welding to bottom or shell.
j.	Inspect safety hold-down chain for corrosion and damaged links.

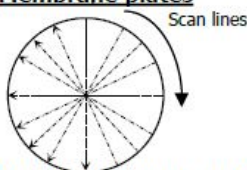
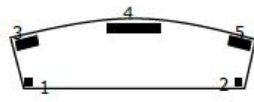
k.	Check that there is a welded reinforcing pad where the chain connects to the bottom.
l.	If the floating swing in a floating or internal floating roof tank does not have a limiting device preventing the swing from exceeding 60 degrees, measure and calculate the maximum angle possible with the roof on overflow. (If the calculated angle exceeds 65 degrees, recommend installation of a limiting bracket.)
m.	Inspect pull down cable for fraying
n.	Inspect for three cable clamps where cable attaches to end of swing line (single-reeved) or to roof assembly (double-reeved). Inspect sheaves for freedom of movement.
o.	Inspect winch operation and check the height indicator for legibility and accuracy.
p.	Inspect bottom-mounted sheave assembly at end of pontoon for freedom of rotation of sheave.
q.	Inspect shell-mounted lower sheave assembly for freedom of rotation of sheave, corrosion thinning, and pitting of sheave housing.
r.	Inspect upper sheave assembly for freedom of movement of sheave.
s.	Inspect the cable counterbalance assembly for corrosion and freedom of operation.
B.2.11.7 Manway Heater Racks	
a.	Inspect the manway heater racks for broken welds end bending of the sliding rails.
b.	Measure and record the length of the heater and length of the track.
B.2.11.8 Mixer Wear Plates and Deflector Stands	
a.	Inspect bottom and shell plates and deflector stands.
b.	Inspect for erosion and corrosion on the wear plates. Inspect for rigidity, structural soundness, corrosion and erosion of deck plates and reinforcing pads that are seal welded to the bottom under the deflector stand legs.
c.	Measure for propeller clearance between the bottom of deflector stand and roof when the roof is on low legs.
B.2.12 ACCESS STRUCTURES	
B.2.12.1 Handrails	
a.	Identify and report type (steel pipe, galvanised pipe, square tube, angle) and size of handrails. Inspect for pitting and holes, paint failure.
b.	Inspect attachment welds.
c.	Identify cold joints and sharp edges. Inspect the handrails and midrails.
d.	Inspect safety drop bar (or safety chain) for corrosion, functioning, and length.
e.	Inspect the handrail between the rolling ladder and the gauging platform for any hazardous opening when the floating roof is at its lowest level.
B.2.12.2 Platform Frame	
a.	Inspect frame for corrosion and paint failure.
b.	Inspect the attachment of frame to supports and supports to tank for corrosion and weld failure.
c.	Check reinforcing pads where supports are attached to shell or roof.
d.	Inspect the surface that deck plate or grating rests on, for thinning and holes.
e.	Check that flat-surface to flat-surface junctures are seal welded.

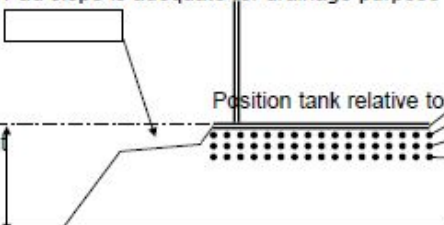
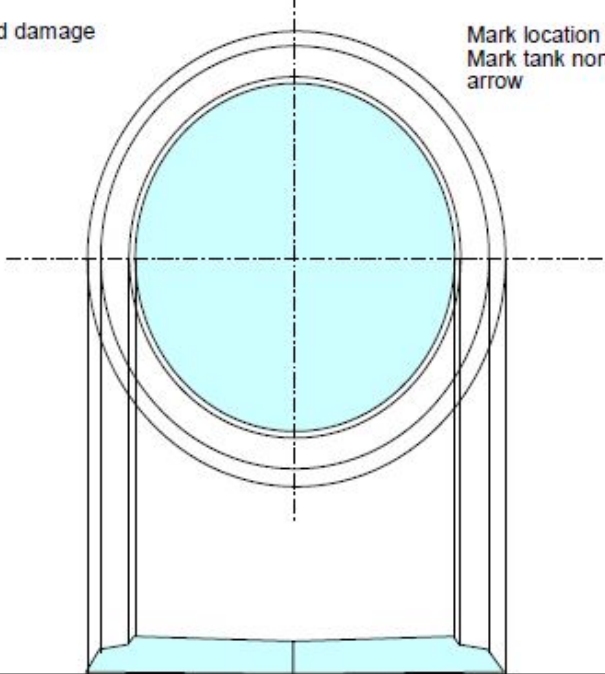
B.2.12.3 Deck Plate and Grating	
a.	Inspect deck plate for thinning or holes (not drain holes) caused by corrosion, and paint failure.
b.	Inspect plate-to-frame weld for rust scale build-up.
c.	Inspect grating for thinning of bars and failure of welds caused by corrosion.
d.	Check grating tie-down clips. Where grating has been retrofitted to replace plate, measure the rise of the step below and above the grating surface and compare with other risers on the stairway.
B.2.12.4 Stairway Stringers	
a.	Inspect spiral stairway stringers for corrosion, paint failure and weld failure. Inspect attachment of stairway treads to stringer.
b.	Inspect stairway supports-to-shell welds and reinforcing pads.
c.	Inspect free standing accessways to tank for corrosion, paint failure and weld failure.
d.	Inspect steel support attachment to concrete base for corrosion.
B.2.12.5 Rolling Ladder	
a.	Inspect rolling ladder stringers for corrosion.
b.	Identify and inspect ladder fixed rungs (square bar, round bar, angles) for weld attachment to stringers and corrosion, particularly where angle rungs are welded to stringers.
c.	Check for wear and corrosion where rolling ladder attaches to gauging platform.
d.	Inspect pivot bar for wear and secureness.
e.	Inspect operation of self-levelling stairway treads.
f.	Inspect for corrosion and wear on moving parts.
g.	Inspect rolling ladder wheels for freedom of movement, flat spots, and wear on axle.
h.	Inspect alignment of rolling ladder with roof rack.
i.	Inspect top surface of rolling ladder track for wear by wheels.
j.	Inspect rolling ladder track welds for corrosion.
k.	Inspect track supports on roof for reinforcing pads seal welded to deck plate
l.	Check by dimensioning, the maximum angle of the rolling ladder when the roof is on low legs.
m.	If rolling ladder track extends to within 1.5 m of the edge of the roof on the far side, check for a handrail on the top of the shell on that side.

B.3 Example NDT inspection sheets

Bottom lay-out	
Location: Tank No.: Type: CR Class: Date of examination: Diameter: metre Report number: Height: metre Name of inspector: tnom Membrane: 0.0 mm tnom Annular: 0.0 mm Schematic lay-out bottom plates + numbering of plates	
	

1000

Ultrasonic inspection tank bottom																
Location:		Type:		Class:		Date of inspection:										
Tank No.:		metre				Report No.:										
Diameter:		metre				Name of inspector:										
Height:																
Membrane plates  Scan lines Annular plates  Per measuring point: report minimum measured value.																
Membrane plates: UT thickness measurements on grid line system according to table 5, section 5.3.4 (connect the points at the shell to each other and measure along the these lines at the following points (see section 5.3.5.b): 25 mm inwards of the tank shell; 300 mm inwards of the tank shell; 750 mm inwards of the tanks hell and further at distances not in excess of 3 m from each other. Include in the UT measurement scope all zones found by the floor scan technique which are marked by the operator of the MFL-equipment (see section 5.3.5.a) Annular plates: perform UT inspections at the areas 3, 4 and 5 covering zones of 500 long and 250 mm wide. Perform UT inspections at the areas 1 and 5 covering zones of 250 long and 250 mm wide. Record the least minimum thickness found at these locations. When excessive thickness losses (by pitting corrosion) are found extent the areas 3, 4 and 5 by performing UT measurements to 100% of the circumferential length over an inwards zone of 250 mm.																
Plate nr.	M/A plate?	1	2	3	4	5	Comments		Plate nr.	M/A plate?	1	2	3	4	5	Comments
1																
2																
3																
4																
5																
6																
7																
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to																
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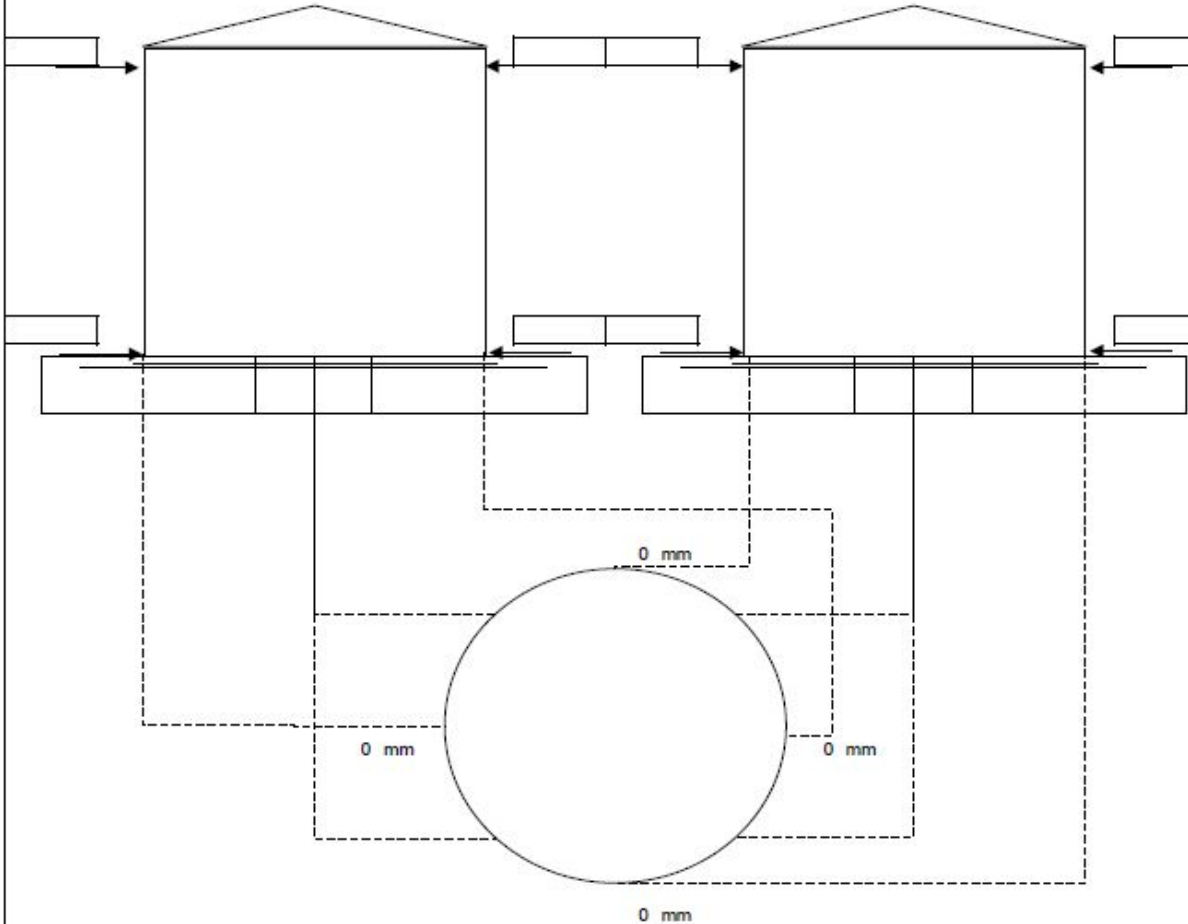
Inspection foundation shoulder																			
<table style="width: 100%; border: none;"> <tr> <td style="width: 25%;">Location:</td> <td style="width: 15%;">Type:</td> <td style="width: 15%;">Class:</td> <td style="width: 45%;">Date of inspection:</td> </tr> <tr> <td>Tank No.:</td> <td>metre</td> <td></td> <td>Report number:</td> </tr> <tr> <td>Diameter:</td> <td>metre</td> <td></td> <td>Name of inspector:</td> </tr> <tr> <td>Height:</td> <td></td> <td></td> <td></td> </tr> </table>		Location:	Type:	Class:	Date of inspection:	Tank No.:	metre		Report number:	Diameter:	metre		Name of inspector:	Height:					
Location:	Type:	Class:	Date of inspection:																
Tank No.:	metre		Report number:																
Diameter:	metre		Name of inspector:																
Height:																			
<table style="width: 100%; border: none;"> <tr> <td style="width: 30%;"><u>Pad finish</u></td> <td style="width: 30%;">Leak detection sump present?</td> <td style="width: 40%;">If yes: mark presence of liquid in sump</td> </tr> <tr> <td>Tiles: ☐</td> <td>Yes : ☐</td> <td>☐ yes ☐ no</td> </tr> <tr> <td>Asphalt: ☐</td> <td>No: ☐</td> <td></td> </tr> <tr> <td>Concrete: ☐</td> <td></td> <td>Substance found</td> </tr> <tr> <td></td> <td></td> <td>☐ product ☐ water</td> </tr> <tr> <td></td> <td></td> <td>☐ mixture product/water</td> </tr> </table>		<u>Pad finish</u>	Leak detection sump present?	If yes: mark presence of liquid in sump	Tiles: ☐	Yes : ☐	☐ yes ☐ no	Asphalt: ☐	No: ☐		Concrete: ☐		Substance found			☐ product ☐ water			☐ mixture product/water
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Asphalt: ☐	No: ☐																		
Concrete: ☐		Substance found																	
		☐ product ☐ water																	
		☐ mixture product/water																	
Pad slope is adequate for drainage purpose Position tank relative to pad Pad height  ☐ Position tank base higher than pad level ☐ Slight settlement ☐ Tank base reached same level of pad top ☐ Tank base is lower than pad top (no drainage possible)																			
Note any pad damage Mark location of manhole Mark tank north position by means of an arrow 																			

Planar tilt measurement with use of laser level tool					
Location:	Type:	Class:	Date of inspection:		
Tank No.:	metre		Report number:		
Diameter:	metre		Name of inspector:		
Height:					

West ←

South

Planar tilt measurement:
 Measure on number of measurement points (to be established by the formula: $N = D/3.05$ with a minimum of 8 points and maximum distance of 10 m between measuring points).
 Locate measuring points starting from spiral stair or liquid level measuring device:
 1 position as low as possible at tank base
 1 position as high as possible near compression area or top curb angle



Minimum no. of survey points = 8

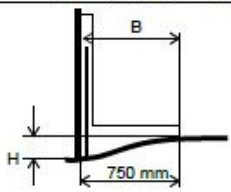
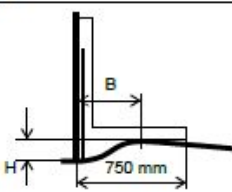
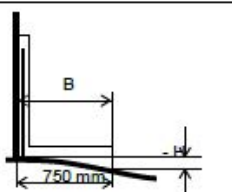
Edge settlement measurements					
Location: Tank No.: Type: CR Class: Diameter: metre Height: metre t nom Membrane: 0.0 mm t nom Annular: 0.0 mm Date of inspection: Report number: Name of inspector:					
   <u>Factor of Edge Settlement (FES)</u> $FES = H/B$ $RZF_{max} = 0.167$					
Measure on number of measuring points (to be established by the formula: $N = D/3.05$ with a minimum of 8 points and maximum distance of 10m between measuring points). See section 6.5.2 for maximum distance of B and required reduction of distance B when deformation in annular shows a summit at a distance smaller than 750 mm inwards of the tank shell					
Plate No.	Measurement No.	H	B	FES	Result
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	etc.				

Plate No.	Measurement No.	H	B	FES	Result
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	etc.				

Plate No.	Measurement No.	H	B	FES	Result
	1				
	2				
	3				
	1				
	2				
	3				
	1				
	2				
	3				
	1				
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	1				
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	3				
	1				
	2				
	3				
	etc.				

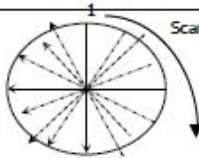
Uneven circumferential settlement					
Location:	Type: CR	Class:	Date of inspection:		
Tank No.:			Report number:		
Diameter:	metre		Name of inspector:		
Height:	metre				

The diagram illustrates the measurement setup for uneven circumferential settlement. It shows a circular cross-section of a tank with diameter D . Measurement points are distributed around the circumference at regular intervals of 10 meters. The vertical distance between two adjacent measurement points is denoted as $dH_{\max}$. A horizontal dimension line indicates a maximum distance of 300 mm between points. A vertical dimension line shows a height of 100 mm from the base to the first measurement point.

Measurements:
 Measure on number of measurement points (to be established by the formula: $N = D/3.05$ with a minimum of 8 points and maximum distance of 10 m between measuring points). See Section 6.3.7.
 Locate measuring points starting from spiral stair or liquid level measuring device:

Criteria:
 dH between 2 adjacent points max. 100 mm.
 $dH_{\max}$ For floating roof tanks equipped with -X/+3X seals:
 between $H_{\max}$ en $H_{\min}$, according to graph.
 $dH_{\max}$ for floating roofs equipped with -X/+X seal

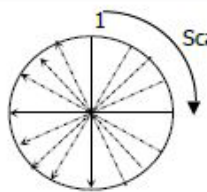
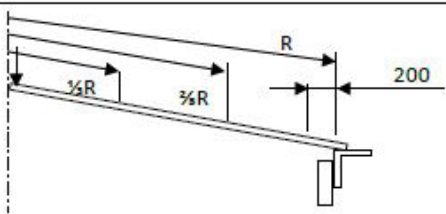
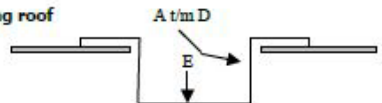
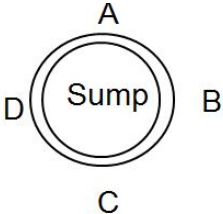
Point	Value	Correction	dH [mm] interval 10 m	Result	Remarks
etc.					

Bottom sag measurements with use of laser level tool																																																																																																																																																																																									
Location: Tank No.: Diameter: Height:	Type: metre metre	Class:	Date of inspection: Report number: Name of inspector:																																																																																																																																																																																						
 <u>Number of scan lines:</u> Number of scanlines according to formula: $N = D/3.05$ with a minimum scan 8 lines and a maximum distance between scan lines of 10 m. See Section 6.3.7.			<u>Bottom sag measurements:</u> The required minimum number of scan lines should be spaced equally over tank base. Measure the height over the length of the scan line, every 2 metre, starting and ending against the tank shell. "M" = level measurement "C" = difference in height between highest point per scan line and point under consideration																																																																																																																																																																																						
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Diameter No of scan lines $D < 20$ 4 $20 \leq D \leq 36$ 8 $D > 36$ Max. 15 m interval See Section 5.3.4				Thickness measurements tank shell: Locate minimum required scan lines equally over circumference of tanks As a minimum: measure plate thickness, per scan line, on each shell course at 3 locations $\frac{1}{3}h$, $\frac{2}{3}h$ and 30 mm above lowest horizontal weld seam of each course. OR (preferably) Use automatic UT crawler and measure each 100																																																																																																																																																																																																			
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Ultrasonic inspection Tank Roof (single deck floating roof)			
Location:	Type:	Class:	Date of inspection:
Tank No.:	metre		Report number:
Diameter:	metre		Name of inspector:
Height:			

Scan lines

Thickness measurements roof plates:

Divide scan lines equally over tank circumference.
3 measurements per scan line on $\frac{1}{3}R$, $\frac{2}{3}R$ and $(R-3m)$ from centre of roof

See Section 5.3.4.

Diameter:

$D < 20$ 4
 $20 \leq D \leq 36$ 8
 $D > 36$ Max. 15 m distance between points along circumference

Number of scan lines:

scan line	$\frac{1}{3}R$	$\frac{2}{3}R$	$R-3m$
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

scan line	$\frac{1}{3}R$	$\frac{2}{3}R$	$R-3m$
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			

scan line	$\frac{1}{3}R$	$\frac{2}{3}R$	$R-3m$
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			

scan line	$\frac{1}{3}R$	$\frac{2}{3}R$	$R-3m$
31			
32			
33			
34			
35			
36			
37			
38			
39			
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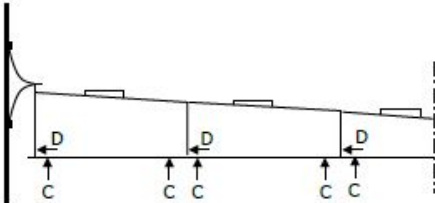
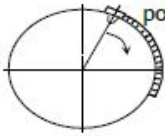
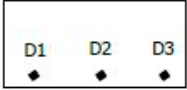
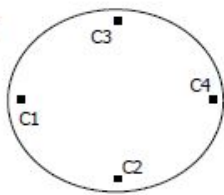
Sump floating roof

Measurement	A	B	C	D	E	Min
Plate thickness						0.0

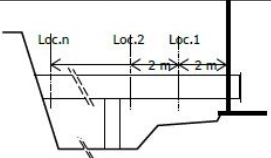
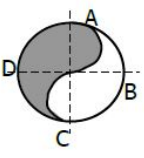
Bottom plates near Sump	A	B	C	D

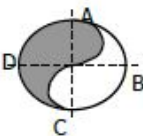
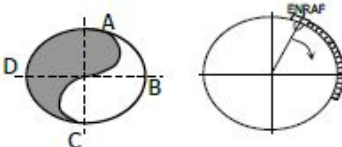
Ultrasonic inspection pontoons (single deck floating roof)													
Location: Tank No.: Diameter: Height:		Type: meter meter		Class:		Date of inspection: Report number: Name of inspector:							
				<u>Pontoons:</u> Numbering of pontoons from guide poles:- measuring point 'E' at height of liquid level, measuring point 'A' at 200 mm away from outer-rim edge. Measuring point 'B': 25 mm above the connecting weld of the centre membrane to the inner rim plate of the pontoon. Measuring points 'C1', 'C2', 'C3' and 'C4': 50 mm away from, respectively the outer or the inner rim plates of the pontoons and 50 mm away from the bulkhead plates. Measuring points 'D1', 'D2' and 'D3': 25 mm above the weld of the lower deck plates of the pontoons.									
Bottom deck pontoon		Outer-rimplate		Inner-rimplate		Top deck pontoon							
Point	Measurement positions												
	A	B	C1	C2	C3	C4	D1	D2	D3	E1	E2	E3	
1													
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etc.													
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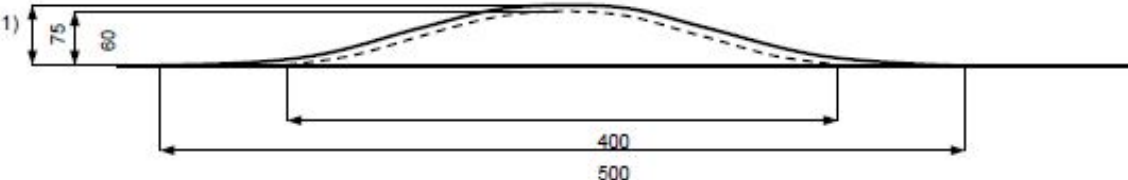
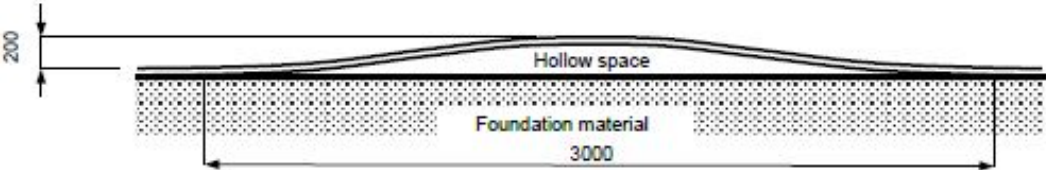
Ultrasonic inspection tank roof (double deck floating roof)																																																																																																																																																																																			
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Ultrasonic inspection Pontoons (double deck floating roof)												
Location: Tank No.: Diameter: Height:		Type: metre metre	Class:	Date of inspection: Report number: Name of inspector:								
				 Pontoons: Numbering of pontoons from Guide pole Measuring points A and B in a double deck floating roof are to be deleted Measuring points 'C1', 'C2', 'C3' and 'C4': 50 mm away from, respectively the outer or the inner rim plates of the pontoons and 50 mm away from the bulkhead plates Measuring points 'D1', 'D2' and 'D3': 25 mm above the weld of the lower deck plates of the pontoons								
 Bottom deck plate		 Outer rimplate		 Bottom deck plate (centre pontoon)								
Pont.	Measuring positions											
			C1	C2	C3	C4	D1	D2	D3			
1												
2												
3												
etc.												
etc.												

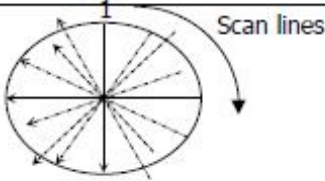
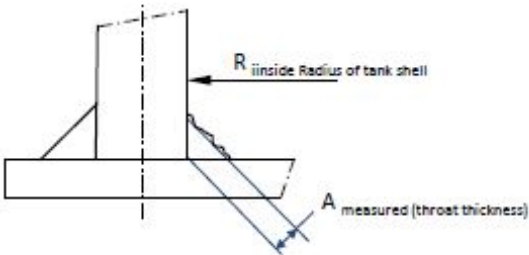
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Ultrasonic inspection internal pipeline systems										
Location: Tank No.: Diameter: Height: Type: metre metre Class: Date of inspection: Report number: Name of inspector:										
							Tank piping: Start numbering of measurement points from tank to bund wall Measure along length of pipe line every 2 metres on 4 points Per measurement location record thickness at A t/m D according to figure.			
No.	Line identification:	Diameter	Schedule	Loc. No.	Elbow	measurement position				Min.
						A	B	C	D	
1										
2										
3										
etc.										
etc.										

Ultrasonic thickness measurements										
Location: Tank no.: Diameter: Height:					Type: metre metre		Class:		Date of inspection: Report number: Name of inspector:	
					Shell Nozzles 4 UT wall thickness measurements. Start position A at 12 o'clock position top side of nozzle Any nozzle not measured or not accessible or insulated nozzles please mark as not measured					
Nozzle No.	Diameter	Schedule	Description	A	B	C	D	Min.	Remarks	
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										
					Roof Nozzles 4 UT wall thickness measurements. Start position A at 12 o'clock position from tank North/South line Any nozzle not measured or not accessible or insulated nozzles please mark as not measured					
Nozzle No.	Diameter	Schedule	description	A	B	C	D	Min.	Remarks	
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										
11										
12										

Visual inspection tank bottom (ripples and bulges)																																																									
Location: Tank no.: Diameter: Height: Type: metre metre Class: Date of inspection: Report number: Name of inspector:																																																									
When, during visual inspections, ripples or bulges are found, the dimensions of these defromations should be measured in accordance with EEMUA 159. 1) For ripples (fully supported by foundation materials) see Section 6.5.5 H/W ration should be > 0.15 2) For plates that are not supported by the foundation materials and that have void spaces below them see section 7.5, figure 48																																																									
 1) <i>Exampe: the maximum allowable height of a ripple with a width of 400 mm should be $0,15 \times 400 = 60$ mm</i> Figure 7.5.5-1 Maximum ripple dimensions <table border="1" style="margin: 10px auto; border-collapse: collapse; text-align: center;"> <thead> <tr> <th>No.</th> <th>Measured height [mm]</th> <th>Measured width [mm]</th> <th>Ratio</th> </tr> </thead> <tbody> <tr><td>1</td><td>75</td><td>500</td><td>0.150</td></tr> <tr><td>2</td><td>75</td><td>490</td><td>0.153</td></tr> <tr><td>3</td><td>60</td><td>480</td><td>0.125</td></tr> <tr><td>4</td><td></td><td></td><td></td></tr> <tr><td>5</td><td></td><td></td><td></td></tr> <tr><td>6</td><td></td><td></td><td></td></tr> </tbody> </table>  <table border="1" style="margin: 10px auto; border-collapse: collapse; text-align: center;"> <thead> <tr> <th>No.</th> <th>Measured height [mm]</th> <th>Measured width [mm]</th> <th>Ratio</th> </tr> </thead> <tbody> <tr><td>1</td><td>200</td><td>3000</td><td>0.067</td></tr> <tr><td>2</td><td>190</td><td>3000</td><td>0.063</td></tr> <tr><td>3</td><td>210</td><td>2950</td><td>0.071</td></tr> <tr><td>4</td><td></td><td></td><td></td></tr> <tr><td>5</td><td></td><td></td><td></td></tr> <tr><td>6</td><td></td><td></td><td></td></tr> </tbody> </table>		No.	Measured height [mm]	Measured width [mm]	Ratio	1	75	500	0.150	2	75	490	0.153	3	60	480	0.125	4				5				6				No.	Measured height [mm]	Measured width [mm]	Ratio	1	200	3000	0.067	2	190	3000	0.063	3	210	2950	0.071	4				5				6			
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Appendix C Typical repair solutions

C.1 Tank jacking

C.1.1 Engineering

Engineering calculations are required to safely lift the tank without damage or injury to personnel working on the tank:

- job safety analysis should be performed for each job task;
- ground conditions around the tank should be tested. To lift 20 tons, the ground must support 20 tons;
- ground suction may require adding additional equipment to protect the tank shell;
- timbers stacks are engineered to support the tank load;
- the tank shell must be protected from being overstressed;
- the tank bottom must be protected from being overstressed;
- the tank must be protected from overturning or sliding during winds.

C.1.1.1 Application

Jacking is a very important technique for making repairs or modifications to tank foundations and bottoms. Tanks are jacked up by using hydraulic jacks or air-bags, which lift the tank 2 to 2½m above the foundation, and supported on timber stacks as shown in Figure 115. The 2 to 2½m free height allows small earth-moving equipment to operate under the tank.

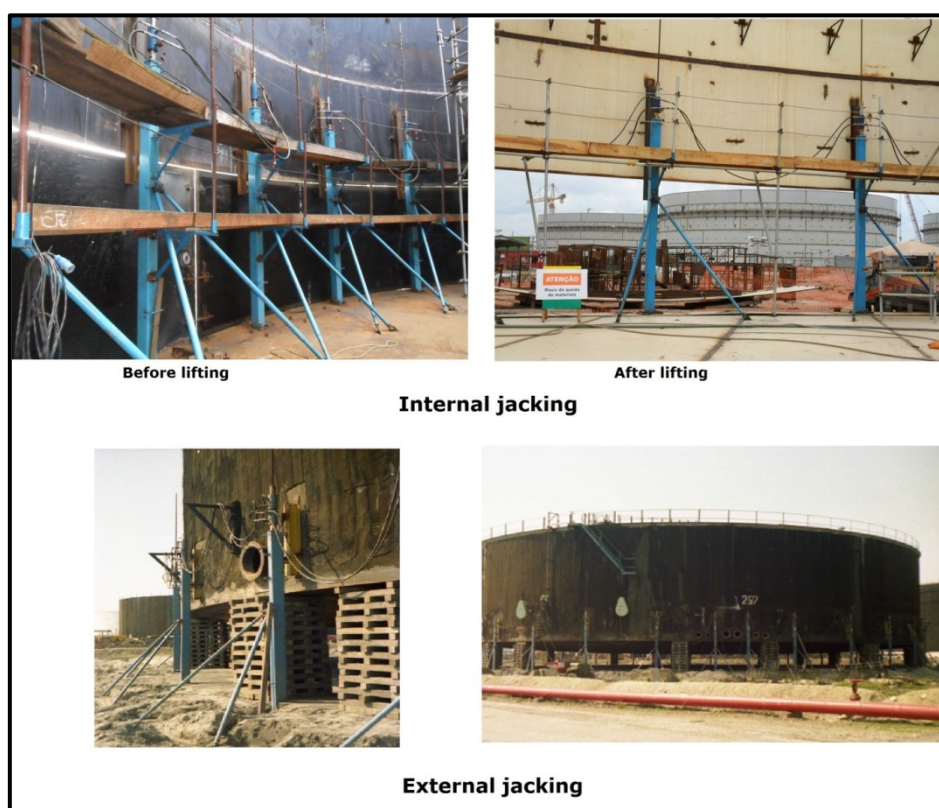


Figure 113 Examples of tank jacking

More specifically, jacking is often used to:

- correct unacceptable foundation settlement;
- remove contaminated soil caused by bottom leakages, and restore the foundation;
- install a high density polyethylene (HDPE) membrane under the entire tank together with a leak detection system or leak detection and management system;
- ensure safe replacement of the tank bottom if the foundation is contaminated;
- inspect the tank bottom for underside corrosion; if necessary, the underside of the tank bottom can be blasted and coated after the inspection;
- install a cathodic protection system under the tank bottom; and
- for relocation of tanks.

C.1.2 Types of jacks

The capabilities and requirements of the two commonly used jacking devices are outlined below.

- **Hydraulic jacks.** High capacity (up to 60 tons per jack) but heavy to move around. Lifting lugs need to be welded to the outside of the shell, or large excavations are required to position the jacks directly under the shell. Such large excavations are undesirable;
- **Air-bags.** Lower capacity (up to 70 tons per air-bag) but easy to handle and move around. Air-bags require a small excavation under the shell, about 60mm high, to insert an empty bag. On small tanks usually, two excavations are required to lift part of the shell to allow the insertion of additional air bags at adjacent locations.

C.1.3 Jacking methods

C.1.3.1 One-stage method using hydraulic jacks

This method requires an excavation into the tank pad shoulder to place hydraulic jacks directly under the shell on a temporary foundation of hardwood blocks laid on a well compacted gravel base (Figure 114).

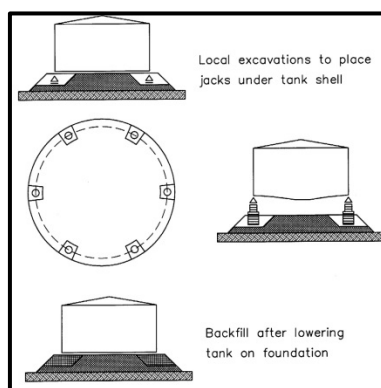


Figure 114 One stage jacking

When the jacks have been positioned, the tank is jacked in lifts of 100mm each time, this being the effective stroke length of the hydraulic jacks. The 100mm gap is then filled with hardwood blocks laid in a special configuration to ensure adequate load transfer and stability, and allow the hydraulic cylinder to be retracted and the jack repositioned for the next lift. This way, the tank is jacked to about 2 to 2½m above its foundation.

After the repairs/modifications have been completed, the tank is jacked down onto its foundation in the reverse sequence. When the tank is resting on its foundation, the jacks and temporary foundation are removed, and the excavation backfilled and well compacted.

The backfilling and compaction of the foundation directly under the shell and annular plate are critical operations because of the risk of local uneven settlement. In addition, this method creates a major complication when an HDPE liner with leak detection system needs to be installed.

It should be noted that the one-stage method using hydraulic jacks cannot be used on tanks supported on a concrete ring wall or concrete raft. In such circumstances a two stage jacking method as described below is used.

C.1.3.2 Two-stage method using hydraulic jacks

For this method, special steel brackets are installed equally spaced around the circumference and welded to the bottom shell course. When lifting lugs are welded to the side of the tank shell then the welding on each lifting lug should be tested. This method requires lifting the tank off centre of the tank shell and stress in the tank shell may occur. Hydraulic jacks are located directly below the special brackets. When lifting lugs are welded to the side of the tank shell then the welding on each lifting lug should be tested. The jacks are placed on temporary hardwood foundations on top of the existing tank pad shoulder. Initial jacking is carried out in 100mm lifts to an elevation adequate to place other jacks on hardwood foundations directly underneath the shell/annular plate and on top of the exposed tank foundation. (See Figure 115)

After the load transfer from the initial, 'external' jacks to the jacks underneath the tank, the second stage jacking can commence and the tank jacked in 100mm lifts to approximately 2 to 2½m above its foundation.

After the repairs/modifications have been completed, the tank is jacked down in two stages onto its foundation in the reverse sequence. Once the tank is resting on its foundation, the special brackets, jacks and hardwood foundation are removed.

C.1.3.3 Combined air-bag–hydraulic jack method

This jacking method uses both air-bags and hydraulic jacks. On small tanks two shallow excavations, about 60mm deep, are made under the shell to allow insertion of an empty air-bag at each excavation. A small section of the shell is lifted with these two air-bags so that additional air-bags can be inserted next to the first two air-bags. This sequential lifting continues all around the tank. The tank is then jacked uniformly up to a level of 300 to 400mm above the foundation, at which point hydraulic jacks are installed directly under the shell to complete the jacking operation.

The combined method has the advantage of not requiring large excavations or special brackets welded to the shell. If there is a concrete ring wall, one or two external lifting points are needed to lift the shell just enough to insert the first air-bag.

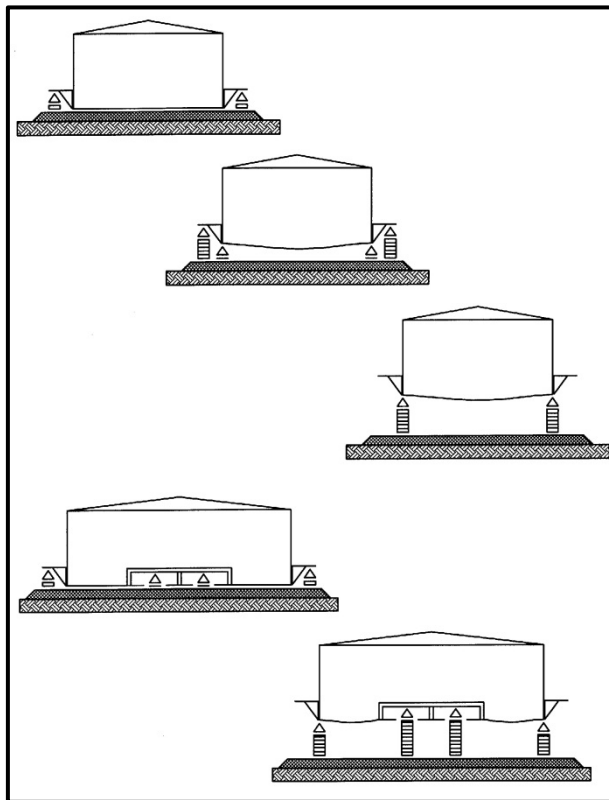


Figure 115 Two stage jacking

C.1.3.4 Airbag method

Shallow excavations, about 60mm deep, are made under the shell to allow insertion of an empty air-bag at each excavation. The tank is lifted 160mm using the airbags and 150mm tank support wood is placed directly underneath the shell/annular plate and on top of the exposed tank foundation. The tank is jacked in 150mm lifts to approximately 2 to 2.5m above its foundation.

C.1.3.5 Sequential Jacking

Sequential jacking is similar to the method described in C.1.3.3, where the tank is lifted a short distance off its foundation, starting at one point and moving around from there. Timbers are placed between the tank and the foundation, and the jack is released and moved to the next location (leapfrogging) (See Figure 116). This method is frequently used for the replacement of annular plates for which the shell needs to be about 100mm above the foundation. Special attention needs to be given to how much the tank can be jacked at a single point without causing shell distortions. Considerable experience is already available with this method, which works well provided small lifts are made at a time. Air-bags are particularly suitable for this method because of their flatness and light weight.

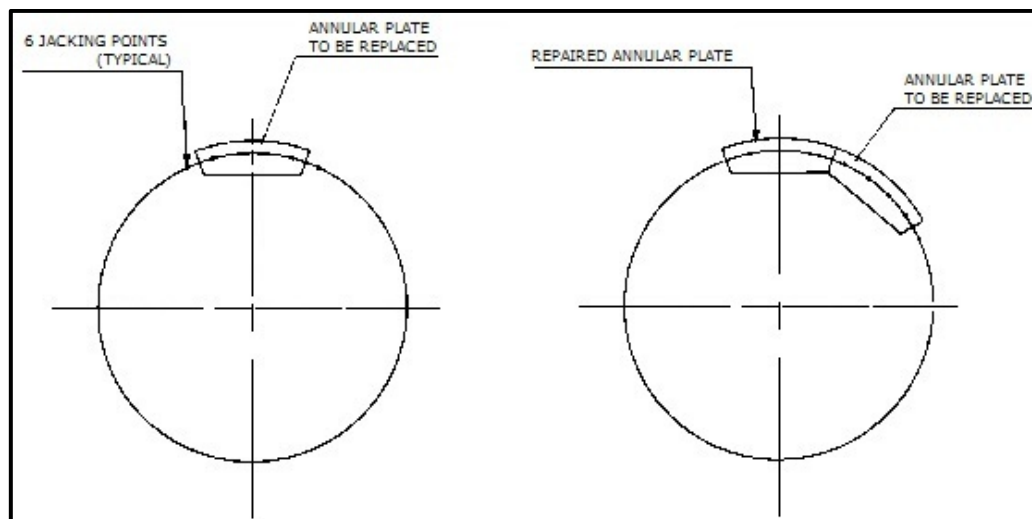


Figure 116 Sequential tank jacking

C.1.3.6 Tank Re-levelling

Tank re-levelling, which requires the tank to be empty and clean, consists of local jacking at tilted or depressed sections of the shell/bottom perimeter, using hydraulic jacks or air-bags, to bring the sections back up to their proper, horizontal level. Provided the gaps formed between tank bottom and pad are less than 50mm, they can be packed with clean sand and adequately sealed with sand-bitumen mix. Where gaps are greater than 50mm, filling should be done with crushed graded stone with a thin sand top layer. The tank pad shoulder should be finished with a slope as in EEMUA 183, Appendix VII, Figure I-2.

C.1.4 Number of jacks required

The number of jacks required needs to be adequate to lift the weight of the entire tank, allowing for the additional force needed to overcome adhesion between tank bottom and foundation. The jacks need to have adequate reserve capacity to perform this task and the maximum lifting capacity of each jack should be verified.

The maximum spacing between jacks is determined by the stiffness of the shell. If the spacing is too great, the bending stresses in the shell can cause deformations in the upper shell courses. The maximum spacing between two support points (jacks or timbers) should be 6m or more when it is proved to be safe and verified by means of calculations; special care should be taken. For tanks with a severely corroded shell, and or severely corroded annular section of the bottom a closer spacing may be required.

C.1.5 Jacking of fixed roof tanks

Jacking of a fixed roof tank with a self-supporting roof structure up to a diameter of approximately 34m can be done with jacks equally spaced around the circumference.

Jacking of a fixed roof tank with a self-supporting roof structure greater than 34m diameter requires guy wires installed from the roof-shell connection to the tank

bottom to control the sag of the latter. With the guy wires installed, the tank can be lifted with jacks equally spaced around the circumference.

Jacking of a fixed roof tank with a column-supported roof structure requires a cutout to be made in the tank bottom and jacks placed under the columns. These column jacks need to be operated in concert with the shell jacks. Methods exist for supporting the columns with guy wires, but great care needs to be exercised with such a system as the framing can easily become unstable with the possibility of 'corkscrewing' down.

C.1.6 Jacking of floating roof tanks

C.1.6.1 Pontoon floating roof

Jacking of pontoon type floating roof tanks with a diameter up to around 34m can be done with jacks equally spaced around the circumference. The limited sag of the bottom of the lifted tank ensures sufficient support for the roof legs, and keeps the roof deflection within allowable limits.

Jacking of pontoon type floating roof tanks over 34m diameter requires special measures to support the roof structure. Triangular support brackets are attached to the inner surface of the first shell course to form a horizontal sliding support for the roof edge. The support brackets should be placed under the pontoon bulkhead plates. (See Figure 117)

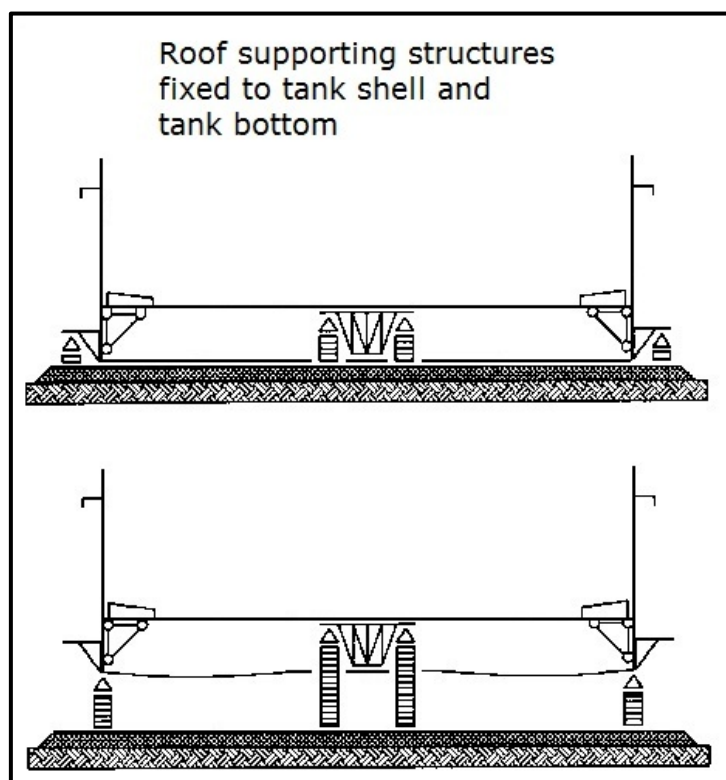


Figure 117 Two stage jacking of floating roof tank

Besides attaching triangular support brackets to the shell, the deflection of the roof and bottom plates needs to be controlled by temporary lattice girders

connecting the roof and bottom plates. These temporary support structures are located in between extra jacking supports, which are equally spaced in a ring around the roof centre. In this way the tank shell, bottom and roof are jacked simultaneously. It should be noted that the centre jacking supports require a temporary opening through the tank bottom plate.

C.1.6.2 Double-deck floating roof

For double-deck floating roofs, the jacking procedure is, in principle, identical to the jacking of a pontoon roof. For tanks larger than approximately 34m diameter, additional supports are also required around the roof centre. The space between top deck and bottom deck should be packed with wood directly above the jacking positions.

C.1.6.3 Radially reinforced floating roof

Jacking of radially reinforced floating roof tanks, normally with a diameter over 50 m, is similar to that for tanks with a pontoon type floating roof. However, special attention should be given to maintaining the downward slope of the roof and radial beams during the jacking operation and when placing the tank on its new foundation.

C.1.7 General requirements

The general requirements for ensuring a safe and successful jacking operation are:

- selection of an experienced jacking contractor;
- jacking contractor to perform site survey including level measurements;
- jacking contractor to submit detailed method including calculation of overturning stability under wind conditions. In addition, the contractor should demonstrate by means of calculations that the tank integrity (shell and roof structure) will be maintained during jacking. Special attention should be given to tanks with corroded shell plates, i.e. more jacking points may be required to reduce vertical bending stresses;
- after jacking, a vacuum box test of the tank bottom and internal shell-to-bottom fillet weld should be performed, followed by a full hydrostatic test;
- maximum ground load of 125 kN/m² per jack shall not be exceeded;
- jacking operation should be stopped immediately when excessive ground settlement under jacks occurs;
- adequate roof draining should be assured during and after jacking a floating roof tank under all circumstances.

C.1.8 Acceptance criteria after jacking

Tolerances on level and verticality should be in accordance with Section 7.5.1, and on roundness in accordance with Section 12.9.3.

C.2 Typical repair solutions for tank foundations

C.2.1 Erosion of shoulder

The shoulder of elevated tank pad should be well maintained to prevent damage or erosion by rain or wind, particularly rain flowing down the tank which can penetrate into the foundation. Any damage to the surface of the sealing coat, or breakdown of the sand-bitumen mix of that part of the foundation, which projects beyond the base of the tank, should be repaired before the underlying foundation becomes damaged.

C.2.2 Minimum width of shoulder

The shoulder should have sufficient width to provide lateral support for the foundation material under the tank. The width of the shoulder will depend on tank height, tank diameter and elevation of tank pad above grade. An insufficient shoulder width may cause the shoulder to slip away when the tank is fully loaded, creating a very serious safety risk.

C.2.3 Minor edge settlement

Even with relatively minor settlement, the outer edge of the bottom plates of a vertical tank will settle at a level below the surface of the sealing layer of the foundation shoulder. This results in the formation of a channel around the periphery of the tank in which rainwater collects. In such cases, the surface of the projecting part of the foundation should be trimmed, and a new sealing layer of sand-bitumen mix laid with a surface sloping away from the toe of the tank bottom to provide proper drainage.

C.2.4 Major edge settlement

With major edge settlement, the level of the tank bottom may sink until access to connections in the bottom course of the shell becomes difficult, and proper drainage of the foundation becomes impossible. If such a settlement occurs, it may be necessary to restore the level of the tank bottom by lifting the tank and building a new shoulder to the original (and satisfactory) design, to prevent future major edge settlements.

C.2.5 Differential settlement along periphery

When differential settlement or tilting of the shell has reached the limit specified in Section 6 (main text), it will be necessary to make the foundation and tank level again. This is done by jacking the tank and repairing the foundation. It will usually mean raising the elevation of the foundation under the shell to the level of the highest point. It is recommended that the entire tank is jacked to a level of 2 to 2½m above the tank foundation to permit proper placement and compaction of the fill material.

C.2.6 Deformations of bottom due to settlement

Deformations of the tank bottom, as described and illustrated in Section 6, need to be made good when the acceptable limits are exceeded. In some cases the foundation may need to be reshaped; in other cases, additionally, parts of the bottom may need to be replaced. Repairs can be made from inside the tank by

removing some of the bottom plates or by jacking the tank to repair the foundation.

C.2.7 Installation of impervious membrane

The installation of an impervious membrane requires the tank to be jacked to a level of 2 to 2½m above the foundation.

C.2.8 Test requirements

A full hydrostatic test is always required after jacking the tank and/or major foundation repairs (see Chapter 15).

C.3 Typical repair solutions for tank bottoms

C.3.1 Local repairs by welding and/or with welded-on patch plates

The description below is in line with API 653, except for patch plates welded on in the critical zone.

Widely scattered pits can be repaired by filling them with weld material. However, they may be ignored if allowed under Section 7.4.

The patch plates covered by this subsection are welded-on patch plates (see Figure 118).

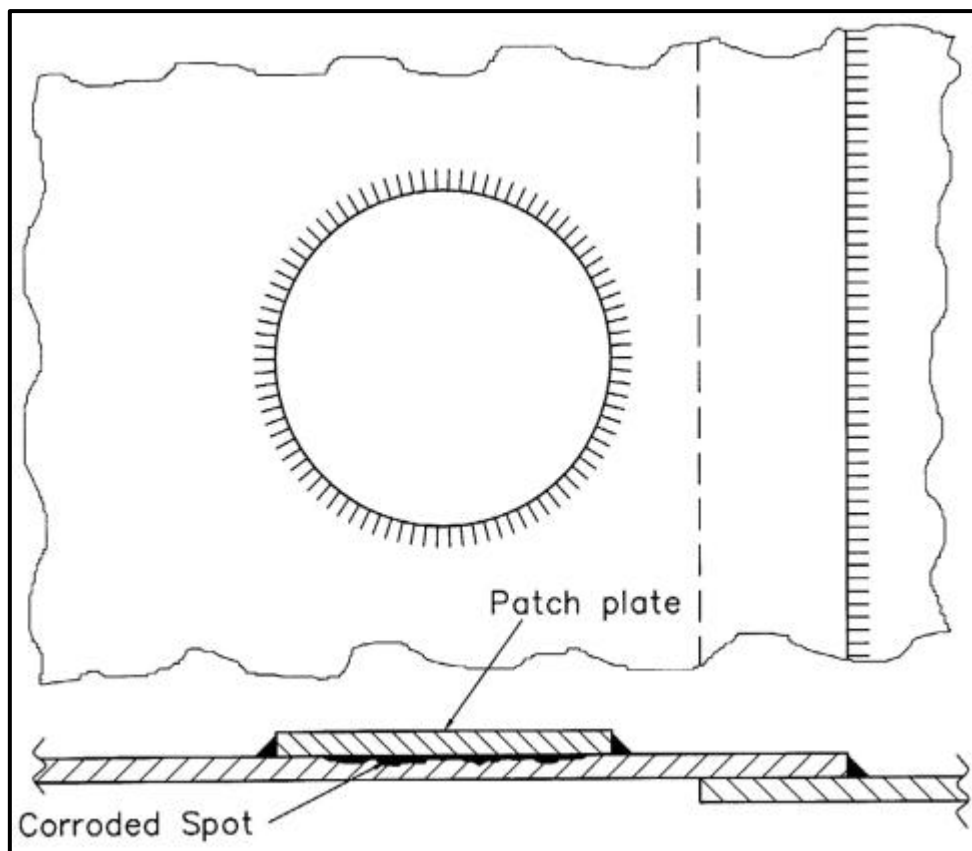


Figure 118 Typical welded-on patch plate

Patch plates can be used for small, corroded spots inside the tank. The shape can be circular or rectangular. In the latter case, rounded corners are recommended.

Patch plates should have the same thickness as the bottom plates. The dimension (diameter/side) must not be less than 300mm. Patch plates may be placed over existing patches.

Patch plates should not be welded on at locations that show local or global deformation due to settlement. This means that welding patch plates to tank bottoms still undergoing settlement is not recommended.

It is important that patch plates are not used within the critical zone, i.e. in the peripheral area 75mm radially inwards from the tank shell.

The thickness of the bottom plate under the perimeter of a patch-plate should meet the requirements of Section 7.4 (main text). The use of patch plates that do not meet those requirements may be permitted provided that the repair method has been reviewed and approved by a qualified and experienced Tank Integrity Assessor. The review needs to consider brittle fracture, stress due to settlement, stress due to shell-bottom discontinuity, metal temperature, fracture mechanics and the extent and quality of non-destructive examination.

The above also applies to the repair of sumps located within the critical zone.

C.3.2 Replacement of an annular plate segment

The method described below can be followed using the sequential jacking method (see C1.1.3.4 above):

- 1 Determine the location and extent of the annular plate segment that is to be replaced. Mark the location of the radial cuts to be made, and determine the required circumferential length and radial width of the replacement segment. Its circumferential length should be made 1mm longer than that of the segment to be cut out, to allow for weld shrinkage.
- 2 Remove the existing corner welds between the tank shell and annular plate over the length of plate to be replaced, plus an additional 500mm at either end.
- 3 Where the radial weld seams of the new segment cross the tank shell, the bottom of the shell plate should be welded to the annular plate with a full penetration 'K' weld over a length of approximately 150mm. The weld preparation should be made by air gouging, in accordance with Figure 119.
- 4 Remove all existing welds between the bottom plate and the existing annular plates, either by air gouging or grinding. Flame cut away the existing annular plate segment exactly on the radial lines marked for the new seams, and prepare these cut edges with 45° weld preparation.

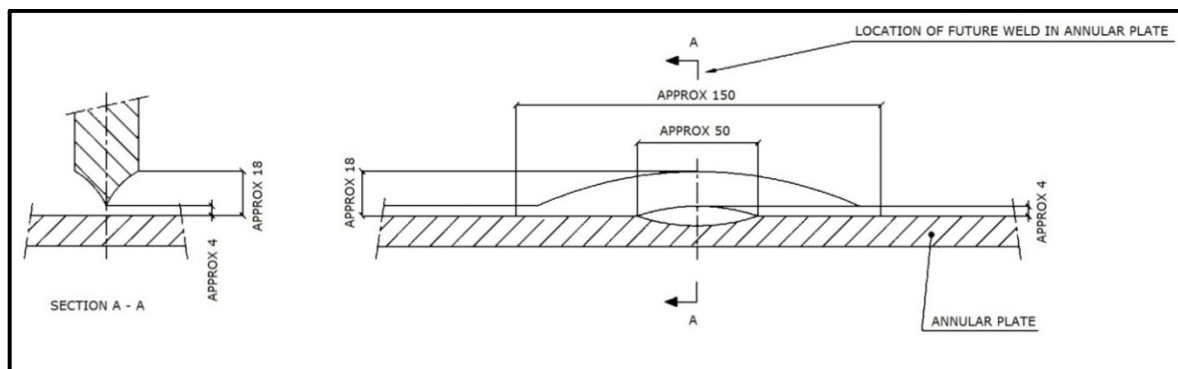


Figure 119 'K' seam where new annular plate radial welds cross tank shell

- 5 Fit the new annular plate segment, which may be equipped with backing strips at the new radial weld seams to allow for one-sided welds. Since the inserted segment is 1mm longer than the cut segment, it will not lie flat until weld shrinkage has taken place.
- 6 The welding sequences to be employed for the various welds of the new annular plate segment are as shown in Figure 120.

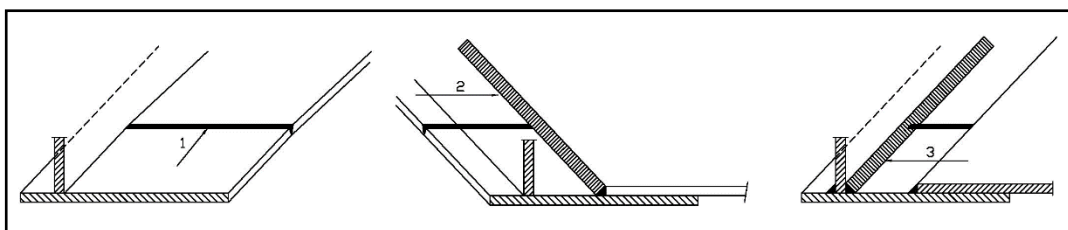


Figure 120 Welding sequence for annular plate replacement

- 7 When welds 1 and 2 (Figure 123) have been completed (including NDT), the new corner welds between the tank shell and the annular plate should be restored, including the special 'K' welds where the shell crosses the annular plate radial seams.
- 8 Welding of the new corner plate should be made according to a block sequence as specified in the scheme illustrated in Figure 121. This scheme is designed to balance weld shrinkage and avoid distortion of the annular plate. The first and second weld layers are made from the inside of the tank by two welders working simultaneously from either end of the inset plate towards its centre. Then the third and fourth weld layers are made from the outside of the tank. In this case they are made by the two welders working together, one from one end and the other from the centre of the insert as illustrated in Figure 121. This latter method is repeated inside and out, sequentially, according to the number of weld layers required in the procedure to reach the specified throat thickness. Figure 122 gives a pictorial view of the welding sequence.

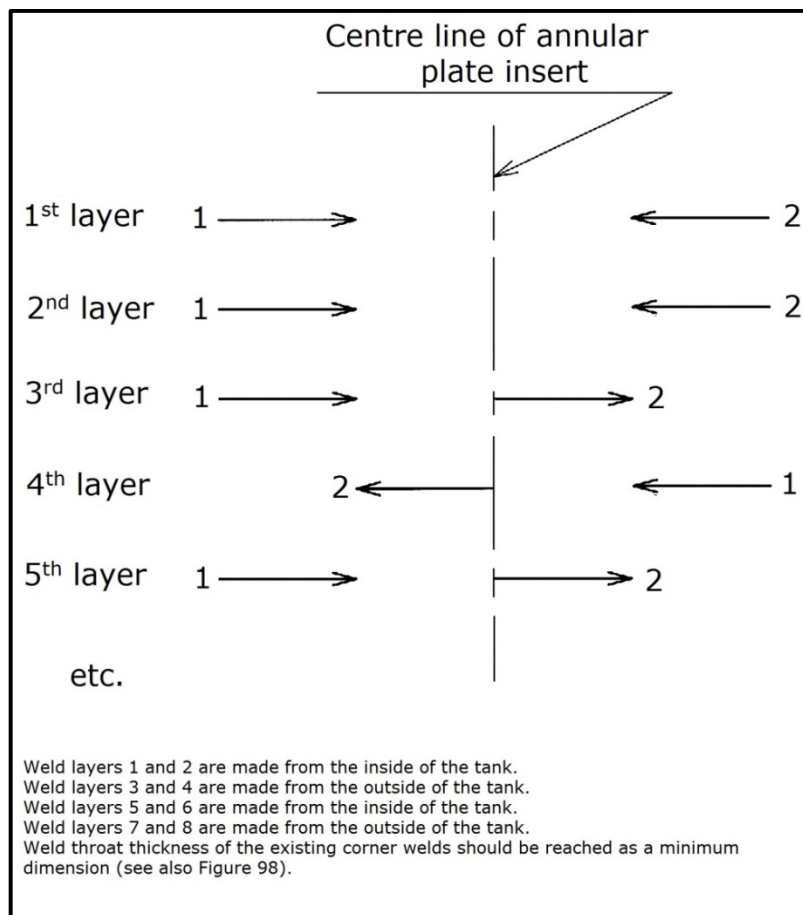


Figure 121 Welding sequence for shell-to-bottom junction

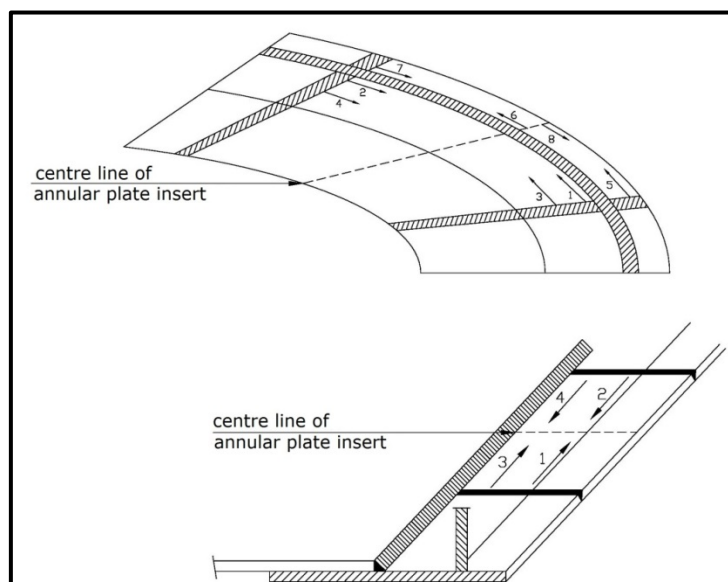


Figure 122 Explanation of welding sequence for shell-to-bottom junction

C.4 Typical repair solutions for tank shells

C.4.1 General

Each spot showing excessive corrosion should be evaluated for a proper repair. The way a corroded area is repaired should be based on international standards. The repair flowchart, Figure 63 will be of assistance for establishing a proper repair procedure for each corroded spot; see also Figure 125.

When repair of a buckled tank shell is deemed necessary, this should always be done using insert plates. Because buckled areas are generally larger in size than corroded spots, the shell needs to be supported by extra beams when a buckled area is repaired. Sometimes large indentations can be repaired by filling the tank with liquid where there has been no major plastic deformation.

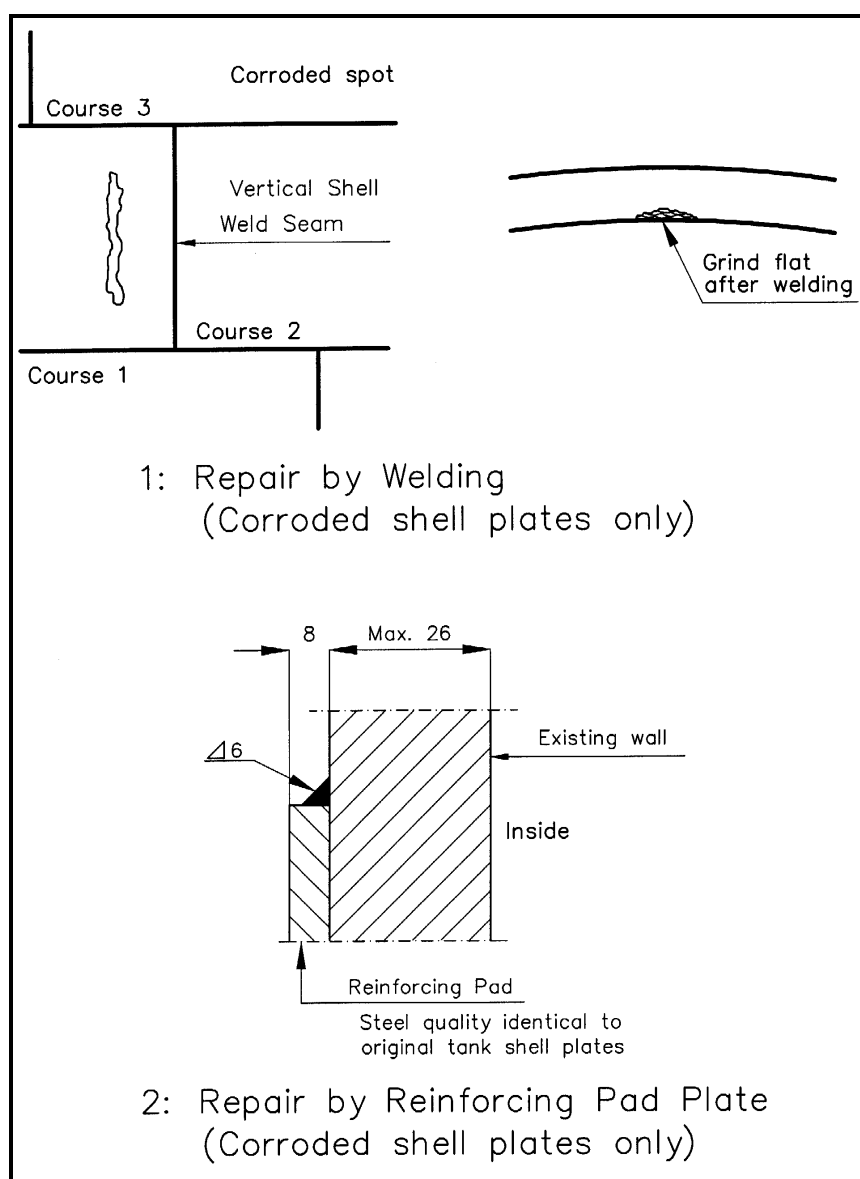


Figure 123 Repair solutions for shell plates
(continued next page)

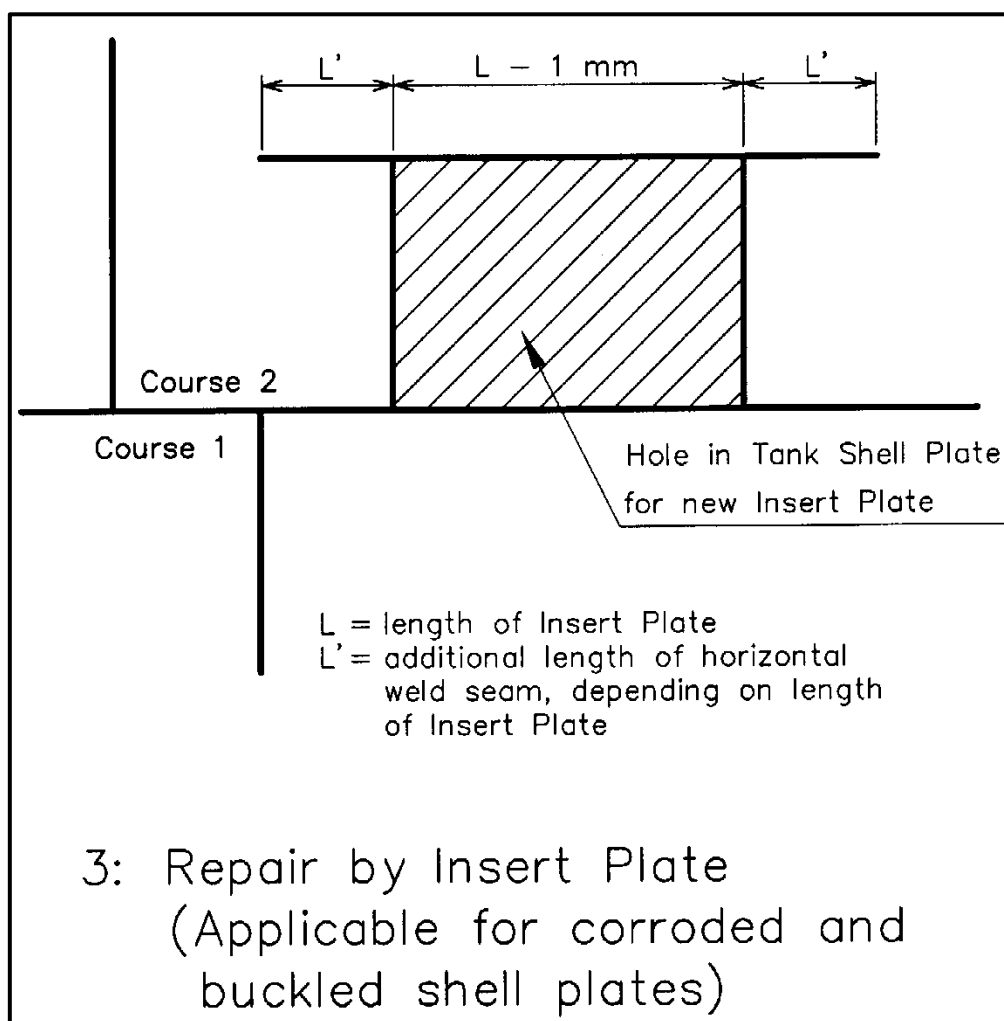


Figure 123 Repair solutions for shell plates
 (continued from previous page)

C.4.2 Repair procedure using insert plates

C.4.2.1 General

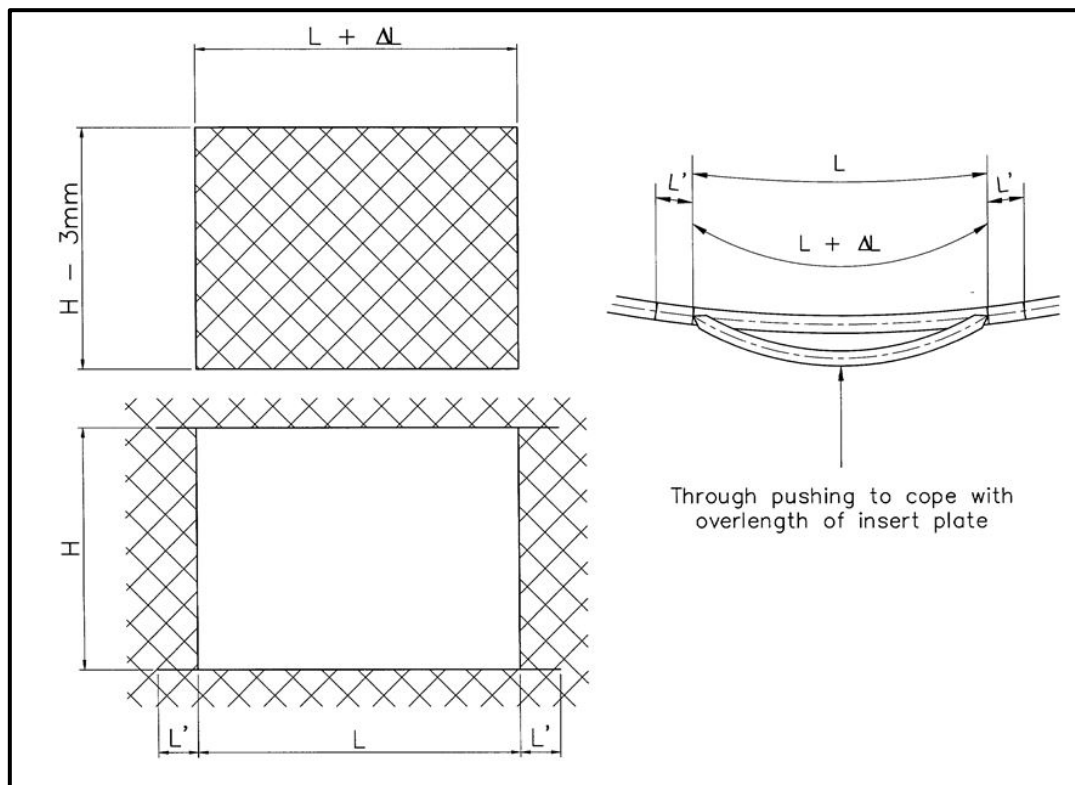
For repair welding and welding of insert plates, the procedure below is recommended:

- 1 The edges of the hole need to be of undamaged material. Normally a distance of 300mm is maintained between the visible damage and the cuts. The cuts are extended in the horizontal direction, and the insert plate is made with an 'overlength', to cope with shrinkage due to welding. See Table 24 below for the values of the extension and the overlength.

Table 24 Overlength of insert plates

Length of Insert Plate (L) [m]	Extended Length (L') (mm)	'Overlength' (ΔL) (mm)
1	150	0.5
2	250	1.0
3	350	1.5
4	450	2.0
etc.	etc.	etc.

- 2 In the vertical direction, the insert plate is cut approximately 3mm smaller than the hole, depending on the welding details.
- 3 The vertical seams of the insert plate are welded first, whilst pushing the insert plate into the opening (see Figure 124).
- 4 For material equivalent to S355 (see Section 2.4.1) exceeding 20mm in thickness, the locations of welding should be preheated to approximately 75°C.

**Figure 124 Sizes of cuts and insert plates**

C.4.2.2 Removing the damaged shell plate

Once the dimensions of the section to be cut out have been determined, the bottom horizontal seam is cut first. Then the two vertical seams are cut, working upwards from the bottom. Finally the upper seam is cut, starting from the edges and working towards the centre.

C.4.2.3 Welding sequence for insert plate

The vertical seams are welded first, followed by the horizontal seams. The sequences shown in Figure 125 should be followed.

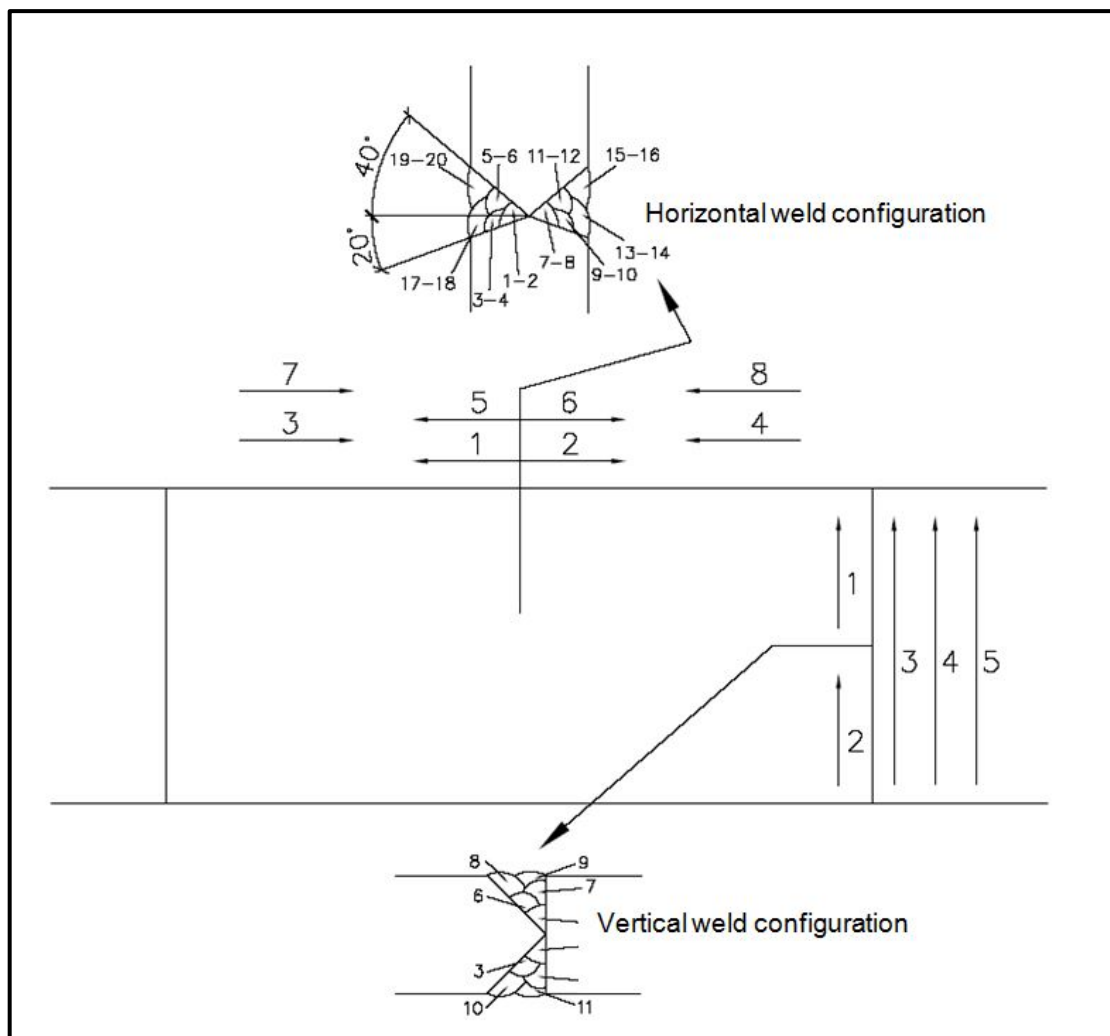


Figure 125 Welding sequences for horizontal and vertical welds

Note 1 After finishing weld layers 3-4 in the vertical weld, the backside is to be gouged and ground before welding layers 5 etc.

Note 2 After finishing weld layers 5-6 in the horizontal weld, the backside is to be gouged and ground before welding layers 7-8 etc.

C.5 Tank coating and lining

C.5.1 Paint systems

This subsection presents typical paint systems for storage tanks. Other coating systems may also be suitable for use (e.g. when in accordance with coating manufacturers' recommendations). Tables 25 to 27 give data of proposed coating repairs following major tank repairs, i.e. replacement of bottom and/or shell

plates, and following smaller repairs to damaged paint surfaces. Table 26 gives further details with respect to tank contents.

The requirements are slightly different for smaller paint coating repairs: see Table 25, which assumes a surface condition not worse than ISO 4628-3 Ri 3 (1% of area rusted) or Ri 4 (8% of area rusted). Note the differences between the surface preparations recommended in Tables 26 and 27.

Note that references are made to ISO 4628-3⁽³⁸⁾ that gives guide lines how to interpret the current stage of degradation of a paint system. Figure 128 shows different degradation stages and its relevant degradation reference number that is used to assess that appropriate repair work that is to be executed, in order to bring the paint system back to its original duty: protection of the relevant tank component from further corrosion attack.

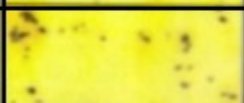
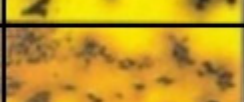
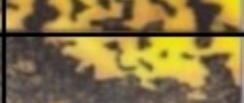
	EN	ISO	
	RE 1	Ri 1	No Anomaly
	RE 2	Ri 2	No Anomaly
	RE 3	Ri 3	No Anomaly
	RE 4		
	RE 5	Ri 4	Low Criticality Anomaly
	RE 6		
	RE 7	Ri 5	Medium Criticality Anomaly
	RE 8		
	RE 9		

Figure 126 Degradation stages and reference numbers
Reproduced from ISO 4628-3

C.5.2 Paint maintenance

Periodic removal of all contaminants, e.g. salts, dirt, grease, oil, etc., by hosing with fresh water is sufficient if the coating is contaminated but no breakdown or

corrosion is observed (i.e. no Ri stage can be allocated). If needed, a concentrated detergent may be used. If conducted regularly this will reduce the impact from the environment and result in longer maintenance intervals.

If the paint film, apart from local rusted areas, is sound and adequate (Ri 3 = no anomaly), the areas that are corroded should be spot cleaned, and touched up to full film thickness. All corrosion products should be removed and the interface between the sound coat and the cleaned areas properly prepared.

For renovation (Ri 4 = low criticality anomaly and R1 5 = medium criticality anomaly), spot repair should be carried out to the existing coating, and a full top coat applied. The existing coating system should be sound and adequate and the new top coat would enhance the corrosion inhibition. In some cases a complete renovation may be needed for reasons of a change of colour or to prevent increased dirt retention.

The degree of blistering should be evaluated in accordance with ISO 4628-2⁽³⁹⁾. This standard characterises blistering in terms of size and frequency as shown in Figure 126.

When blistering frequency observed on a coating becomes 'medium', the nature of the blisters should be studied in order to establish the need for maintenance.

If the area underneath the blisters is dry and the blisters are raised by gas (e.g. from trapped solvent) the repair is urgently required. This is also the case if the blisters are filled with liquid even if there is little or no corrosion underneath.

Blisters with both liquid and corrosion product underneath indicate that corrosion has been initiated on the substrate and, therefore repair is necessary. In this case the repair requires complete removal of the blisters, since experience has shown that on equipment repaired once (locally) and put back into service, blistering is rapidly renewed. Consequently, the only satisfactory procedure is to blast-clean the surface thoroughly, which means a repair procedure similar to that for rust scale M1 to M4, as given in Table 27.

Table 25 Typical painting requirements for storage tanks

ITEM		OPERATING TEMP (°C)	SUBSTRATE	PAINT SYSTEM No.	
				Table 26	Table 27
CRUDE OIL TANKS BOTTOM and LOWEST SHELL COURSE	INTERNAL Non-corrosive	< 80	Carbon and low alloy steel	2	N.A.
	INTERNAL Corrosive	< 80	Carbon / low alloy steel	1	Ri 3–Ri 4: M1
CRUDE OIL TANKS ROOF and SHELL	INTERNAL	< 80	Carbon and low alloy steel	2	N.A.
	EXTERNAL	< 80	Carbon and low alloy steel	4	Ri 3–Ri 4: M2
OTHER STORAGE TANKS	INTERNAL	< 120	Carbon and low alloy steel	2	N.A.
	EXTERNAL	< 120	Carbon and low alloy steel	4	Ri 3: M2 Ri 4: M3
		50 – 220	Stainless steel	5	M4
	INTERNAL Chemical resistant	< 60	Carbon and low alloy steel	3	Ri 3: M5 ⁽¹⁾ Ri 4: M6
	INTERNAL Industrial water ⁽²⁾	< 80	Carbon and low alloy steel	1	Ri 3–Ri 4: M7

⁽¹⁾ Use M6 where maximum chemical resistance is required.⁽²⁾ For industrial water tanks, the use of primer is optional.**Table 26 Typical paint systems for storage tanks - replaced plates**

Replaced bottom and/or shell plates

System No	Surface Preparation	Paint System		
		Primer	Inter-coat	Top Coat
1	Sa 2½	Polyamide-cured epoxy DFT 75 microns (µm)	—	Solvent free high build, amine cured epoxy DFT 500 microns (µm)
2	Sa 2½	Zinc rich epoxy DFT 25 microns (µm)	—	—
3	Sa 2½	Amine cured epoxy DFT 100 microns (µm)	Amine cured epoxy DFT 100 microns (µm)	High build, amine cured epoxy DFT 100 microns (µm)
4	Sa 2½	Alkyl zinc silicate DFT 75 microns (µm)	High build epoxy sealer DFT 75 microns (µm)	High build, aliphatic polyurethane DFT 75 microns (µm)
5	Light sweep blast (if not possible steam clean)	Heat resistant aluminium silicone DFT 75 microns (µm)	-	Silicone acrylic DFT 25microns (µm)

DFT = dry film thickness (more than one application may be required to achieve the required film thickness)

Table 27 Typical paint systems for storage tanks: repair of painted surfaces

System No	Surface Preparation	Paint System		
		Primer	Inter-coat	Top Coat
M1	Sa 2	Polyamide-cured epoxy DFT 75 microns (µm)	-	Solvent free amine cured epoxy DFT 300 microns (µm)
M2	St 2	Surface tolerant, Aluminium pigmented high solids amine cured epoxy DFT 75 microns (µm)	-	High build MIO pigmented polyamide cured epoxy DFT 100 microns (µm)
M3	Sa 2	Surface tolerant, Aluminium pigmented high solids amine cured epoxy DFT 75 microns (µm)	High build MIO pigmented polyamide cured epoxy DFT 75 microns (µm)	High build, aliphatic polyurethane DFT 75 microns (µm)
M4	St 3	Surface tolerant, high solids amine cured epoxy DFT 75 microns (µm)	Amine adduct cured epoxy DFT 100 microns (µm)	High build amine adduct cured epoxy DFT 100 microns (µm)
M5	Light sweep blast (if not possible steam clean)	Silicone-acrylic DFT 25 microns (µm)	-	Silicone acrylic DFT 25microns (µm)
M6	Sa 2	Amine cured epoxy DFT 100 microns (µm)	Amine adduct cured epoxy DFT 100 microns (µm)	High build amine adduct cured epoxy DFT 100 microns
M7	St 3	Zinc rich epoxy DFT 25 microns (µm)	-	Solvent free high solids amine cured epoxy DFT 500 microns (µm)

DFT = dry film thickness (more than one application may be required to achieve the required film thickness)

MIO = micaceous iron oxide

C.5.3 GRP bottom liner

Glass fibre reinforced linings can be used successfully to protect the tank bottom and first course of the tank shell against internal corrosion, but an internal lining does not stop external corrosion. Once external corrosion has perforated the steel plate, the internal lining will only be able to prevent product leakage for a limited period of time. As the external corrosion continues to eat away at the tank bottom, the unsupported area will increase in size until the liner fails. There is also a risk that moisture will start to separate the lining from the steel bottom around the perforation.

Consequently, if corrosion is mainly external, an internal lining should not be used. If corrosion is mainly internal, then an internal lining is a suitable means of protecting the bottom. However, since a high quality internal lining is expensive, the cost of this should be evaluated against that of complete bottom replacement before a decision is taken. In arriving at a decision, consideration should be given to the condition of the tank bottom and the annular plates vis-à-vis their rejection criteria.

A laminate repair typically involves the following steps:

- clean and grit blast (Sa 2½) the steel surface of the tank bottom as well as the first metre of the lowest shell course;
- apply primer to the freshly blasted surface;
- with a resin based putty, fill holes, provide a gradual slope around the tank annular and at (lap welded) plate overlaps, cover any rivets, to give a smooth surface on which to apply the laminate without bridging;
- patch any severely pitted areas with laminate;
- apply laminate consisting of at least two layers of chopped strand mat and surfacing tissue;
- allow laminate to cure (check using the Barcol test method);
- test for porosity and repair as required (HV holiday detection – check with manufacturer the appropriate test voltage to be used);
- apply pigmented seal coat if required.

Note:-

The density of the laminate layers may differ between suppliers, but should, preferably, not be less than 0.4 kg/m².

The number of laminate mats used may differ between suppliers.

The supplier's instructions for the application of the lining should be adhered to.

The typical painting requirements for storage tanks is shown in the following Table 28.

Table 28 Typical painting requirements for storage tanks relative to stored product

Location (See top diagram)	Corrosion Evaluation Criteria	Products Stored	Paint System to be Applied ⁽¹⁾	
			General Corrosion	Pitting
1 Tank Bottom Topside	A	Crude	1	1
	A	Slops	1	1
	A	Intermediates	2	2
	A	Gasolines	2	2
	A	Kerosines	2	2
	A	Gas Oils	2	2
	N	Fuel Oils	2	2
			Repair/Replace	Replace
2, 2A ⁽²⁾ Inside Tank Shell	A	Crude	1	1
	A	Slops	1	1
	A	Intermediates	2	2
	A	Gasolines	2	2
	A	Kerosines	2	2
	A	Gas Oils	2	2
	N	Fuel Oils	2	2
			Repair/Replace	Replace
3 Vapour Space 3A Seal Rim Space	A	Crude	2	2
	A	Slops	1	1
	A	Intermediates	2	2
	A	Gasolines	2	2
	A	Kerosines	2	2
	A	Gas Oils	2	2
	N	Fuel Oils	2	2
			Repair/Replace	Replace
4, 4A ⁽²⁾ Roof Structure	A	Crude	2	2
	A	Slops	1	1
	A	Intermediates	1, 2 ⁽³⁾	1, 2 ⁽³⁾
	A	Gasolines	1, 2 ⁽³⁾	1, 2 ⁽³⁾
	A	Kerosines	1, 2 ⁽³⁾	1, 2 ⁽³⁾
	A	Gas Oils	1, 2 ⁽³⁾	1, 2 ⁽³⁾
	N	Fuel Oils	1, 2 ⁽³⁾	1, 2 ⁽³⁾
			Repair/Replace	Replace
5 ⁽⁴⁾ Tank Bottom Underside	A		Jack-up, apply coating (it is unlikely that a tank will be jacked up primarily to apply coating). Replace	
	N			

⁽¹⁾ For paint system see Table 25.⁽²⁾ For outside tank see Tables 25 and 26.⁽³⁾ Choose system 1 or 2 depending on corrosiveness of tank contents; if in doubt choose 2.⁽⁴⁾ Eliminate corrosion source before applying coating: coating is not a substitute for structural integrity of bottom plates.

A Acceptable (or limited service).

N Not acceptable.

Appendix D Sample calculations

D.1 Stability of corroded tank

D.1.1 Tank data

Tank stability for corroded shell is checked in three steps:

- check hoop stress condition (see Section D.1.2);
- check buckling condition (see Section D.1.3);
- check uniform roof load condition (see Section D.1.4).

Assume that the tank was designed, based on the following data:

Design code	= BS2654:1989 (including Amdt No 1, 1997)
Type of tank	= Low pressure cone roof tank
Climate	= Temperate (LODMAT* = 10°C)
Shell material	= EN 10 025, S275
Material yield stress	= 275.00 N/mm ² for t ≤ 16mm
Allowable design stress	S = 183.33 N/mm ²
Joint efficiency	E = 1.00
Tank diameter	D = 33.00 m
Tank height	= 14.60 m
Maximum fill height	= 14.60 m
Design pressure	p = 20.00 mbar (ga)
Design vacuum	v _a = 6.00 mbar (ga)
Design wind speed	V _w = 54.00 m/s (3-second gust)
Corrosion allowance	c = 0.00 mm
Minimum thickness	= 8.00 mm
Specific gravity product	w = 1.00 (min. required for shell design)
Specific gravity steel	= 7.85
Number of shell courses	= 6

* LODMAT = least one-day mean ambient temperature

Top angle is 200mm angle, lap welded to shell and extending 20mm above shell.

Using formula in BS2654, Section 7.2.2 (modified to include joint efficiency)

$$t = \frac{D}{20.S.E.} * [98 * w * (H - 0.3) + p] + c$$

Table 29 Minimum shell coarse thicknesses

Course Number	Course Height (mm)	H (mm)	t (calculated, excl. corr. allowance) (mm)	Selected course thickness (mm)
1	2430	14 600	12.79	12.80
2	2430	12 170	10.65	10.70
3	2430	9740	8.51	8.60
4	2430	7310	6.36	8.00
5	2430	4880	4.22	8.00
6	2430	2450	2.08	8.00
Top angle	20			

Minimum shell course thicknesses t are calculated, and are shown in Table 29 with selected thicknesses below (H = distance from max. fill level to bottom of course under consideration).

The results of stability calculations (see BS 2654, Section 7.3.2.7) are summarised in Table 30 below.

The factor $K = 6.20$. Note that 2.5mbar must be added to the design vacuum (see BS 2654, Section 7.3.2.6) so that v_a (in the BS formula) becomes 8.5.

Table 30 Minimum thickness from stability calculations

Course Number	Course Height, h (mm)	t selected, excl. corr. allow (mm)	H_e (m)
1	2430	12.80	0.750
2	2430	10.70	1.175
3	2430	8.60	2.028
4	2430	8.00	2.430
5	2430	8.00	2.430
6	2250	8.00	2.250
Top angle	0		
Transformed shell height		$H_E = \sum H_e =$	11.063
Maximum permitted spacing (see step 5 of calculation)		$H_p =$	5.920
No. of secondary wind girders required		$=$	1

Note: Transformed shell taken to underside top angle; course 6 reduced accordingly (by 180 (= 200 – 20)).

The secondary wind girder is located as high as permitted by the calculation results, which is at ($H_E - H_p$) below the top angle.

Location of secondary wind girder (transformed shell)	$=$	5.143	m (below top angle)
Transposed location on actual shell	$=$	5.143	m (below top angle)
Check clearance to nearest hor. weld seam	$=$	0.463	m below 4–5 horizontal weld seam, so OK
Size of secondary wind girder	$=$	angle	125 x 75 x 8mm

The transformations of the 'as built' tank shell with the secondary wind girder are illustrated in Figure 127.

D.1.2 Check hoop stress condition for corroded shell

Assume: The tank has been in operation for 5 years storing light products. The first detailed external inspection (including ultrasonic thickness measurements) has been completed and the corroded shell now needs to be evaluated in accordance with Chapter 8.

Refer to D.1.1 for data not mentioned here.

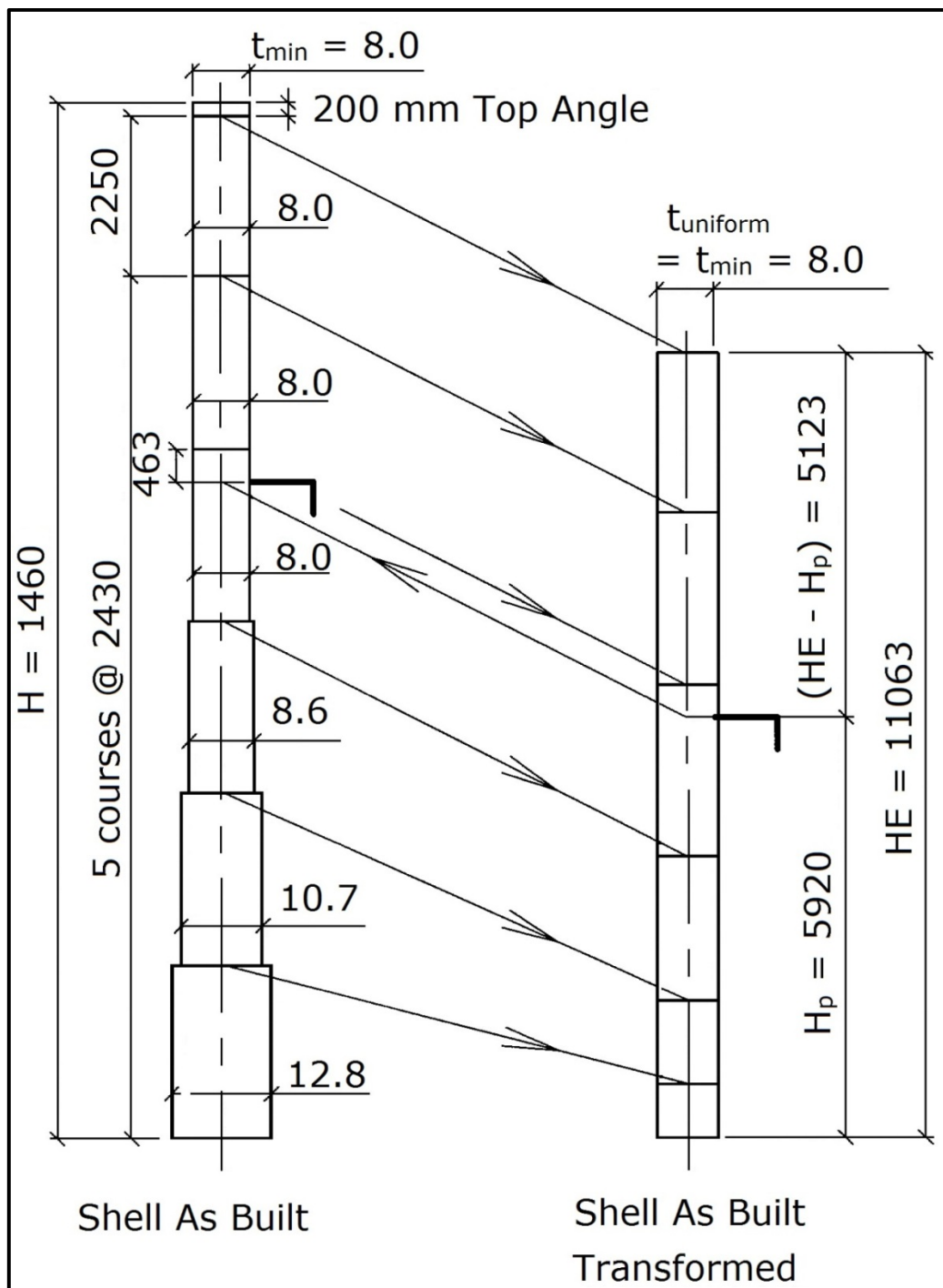


Figure 127 'As-built' tank shell transformations

The required shell thickness is re-calculated, but with a different design stress, now termed 'allowable stress'. However, the minimum shell thickness may not become less than 50% of the original (excluding corrosion allowance).

Minimum thickness	= 4.00	mm, rejection limit
Allowable stress	= 220.00	N/mm ² (= 0.8 x material yield stress)
SG product	= 1.00	(chosen to accommodate future hydrostatic test)
Paint thickness	= 0.50	mm

Table 31 Acceptable hoop stress

Course Number	Course Height (mm)	H (mm)	Plate Thickness t (mm)			Acceptable for hoop stress condition?
			As built	Measured (less paint)	Calculated rejection	
1	2430	14600	12.80	12.5	10.66	Yes
2	2430	12170	10.70	10.5	8.87	Yes
3	2430	9740	8.60	8.3	7.09	Yes
4	2430	7310	8.00	7.4	5.30	Yes
5	2430	4880	8.00	7.0	4.00	Yes
6	2250	2450	8.00	6.8	4.00	Yes
Top-angle	0					

From Table 31 it is seen that the tank shell deterioration due to corrosion is not a problem with respect to hoop stress.

D.1.3 Check buckling condition for corroded shell

The buckling resistance of the corroded shell is now calculated and summarised in Table 32 (Use formula in BS 2654, Section 7.3.2.7 to calculate H_e ; refer to D.1.1 and D.1.2 for data used; see also Figure 128).

The minimum thickness of the tank shell is 6.8mm (top course)

Table 32 Minimum thickness from buckling calculations

Course Number	Course Height (mm)	Measured thickness (less paint) t (mm)	H_e (corroded) [m]
1	2430	12.5	0.530
2	2430	10.5	0.820
3	2430	8.3	1.476
4a	1967	7.4	1.592
4b	463	7.4	0.375
5	2430	7.0	2.260
6	2250	6.8	2.250
Top-angle	0		
Transformed shell 1-4a		$H_{Ea} =$	4.419
Transformed shell 4b-6		$H_{Eb} =$	4.885
Transformed shell 1-6		$H_E =$	9.304
Max permitted spacing		$H_p =$	3.940

Conclusion:

Since H_p is smaller than both H_{Ea} (below stiffener) and H_{Eb} (above stiffener), the tank shell is not stable and further corrosion cannot be accommodated. For required reinforcements see Figure 128.

Note: The calculation indicates that the section below the existing stiffener would need an additional stiffener 592mm below the existing one. However, since that dimension is less than 1m, the advice would be to refrain from reinforcing this

section. The upper section needs to be reinforced with an additional stiffener as per the figure.

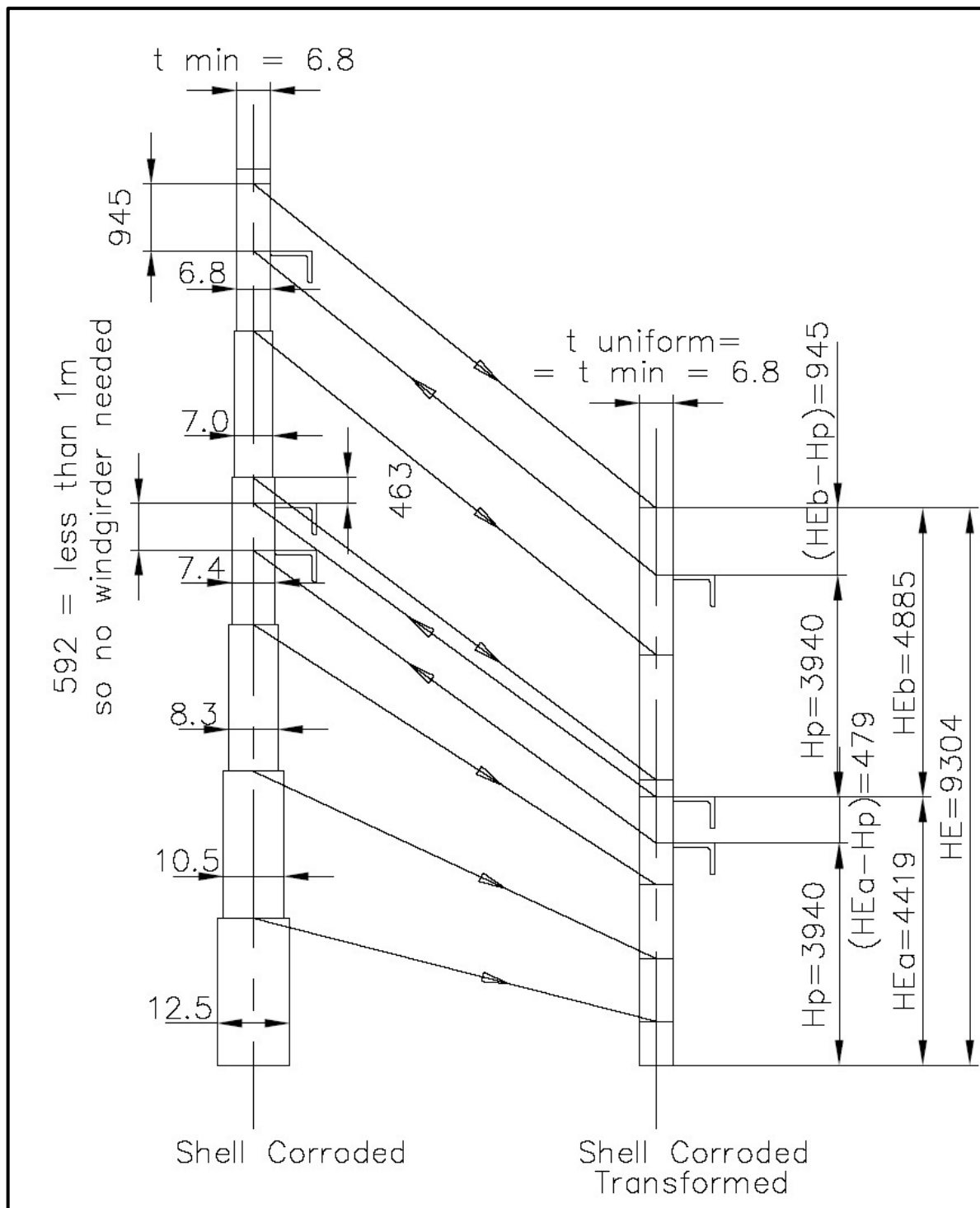


Figure 128 'Corroded' tank shell transformations

D.1.4 Check uniform roof load condition for corroded shell

Superimposed load (BS 2654, 5.3)	=	1200 N/m ²	=	9.90N/mm (of circumference)
Weight roof plates (5mm)	=	400 N/m ²	=	3.30N/mm
Weight roof framing	=	300 N/m ²	=	2.48N/mm
Weight top angle	=	82 kg/m	=	0.80N/mm
Weight course 6	=	120 kg/m	=	1.18N/mm
Total weight at lower edge of course 6			q =	17.66 N/mm

Axial compression at lower edge of course
($q \div t = 17.66 \div 6.8$) $f_a = 2.60 \text{ N/mm}^2$

Allowable compression (API 620, 3.5.4.2)
 $S_{cs} = 1.8 \times 10^6 (t/R) \text{ lb}_f/\text{in}^2 \times 6.895 \times 10^{-3} =$
 $= 12411(t/R) \text{ N/mm}^2$ $F_a = 5.11 \text{ N/mm}^2 (> f_a, \text{ so OK})$

D.2 Venting**D.2.1 Valve sizing and selection procedure for normal and emergency venting**

This sample calculation demonstrates the valve sizing and selection procedure for normal and emergency venting in accordance with the API standard 2000.

Tank data:

Description	SI units	US customary units
Diameter [D]	30 m	98.43 ft
Height [H]	15 m	49.21 ft
Type roof	Cone with 1:5 slope	Cone with 1:5 slope
Code	Low pressure	Low pressure
Design pressure	20mbar (ga)	8.0 inch water gauge
Design vacuum	6mbar (ga)	2.4 inch water gauge
Product	Class II (IP code classification)*	Class II
Flash point	Below 37.8 °C	Below 100 °F
Max. pump-in rate	600 m ³ /hour	3773 barrels/hour
Max pump-out rate	300 m ³ /hour	1887 barrels/hour
Tank insulated	No	No

* IP Model Code of Safe Practice Pt 15 (Class II: flash point 21–55°C, boiling range 150–240°C).

Calculate venting requirements:

(1) Calculate tank capacity (volume of cylindrical shell):

$$V = (\pi D^2 H)/4 = 10,603 \text{ m}^3$$

$$V = 10,603 \times 6.29 = 66,693 \text{ barrels.}$$

(2) Normal outbreathing (pressure relief) requirements:

- (a) Required venting capacity for normal pressure relief due to pumping in (API 2000, 4.3.2.3.1 for products with flash point below 100 °F):
required pressure relief capacity = $12 \times 3773 = 45,276$ scfh (standard cubic feet per hour) of air;
- (b) Required venting capacity for normal pressure relief due to thermal outbreathing (API 2000, 4.3.2.3.2, Table 2A, column 4 for products with flash point below 100 °F), by interpolation for tank capacity of 66 693 barrels:
required normal pressure relief capacity = 46,677 scfh air;
- (c) Total required normal pressure relief capacity = a) + b) = 91,953 scfh air.

(3) Normal inbreathing (vacuum relief) requirements:

- (a) Required venting capacity for normal vacuum relief due to pumping out (API 2000, 4.3.2.1.1 for products with any flash point):
required vacuum relief capacity = $5.6 \times 1887 = 10,567$ scfh air;
- (b) Required venting capacity for normal vacuum relief due to thermal inbreathing (API 2000, 4.3.2.1.2, Table 2A, column 2 for products with any flash point), by interpolation for tank capacity of 66,693 barrels:
required normal vacuum relief capacity = 46,677 scfh air;
- (c) Total required normal vacuum relief capacity = a) + b) = 57,244 scfh air.

D.2.2 Capacity of free orifice vents

The capacity of a vent which consists of a free circular opening, or which is of such simple construction that it is practically a free circular opening, may be determined from the table below for openings of 200mm or smaller. For openings greater than 200mm diameter, use the following formula. This is summarised in Table 33 below.

$$\text{Venting capacity } \left(\frac{\text{m}^3}{\text{hour}} \right) = 0.01818d^2\sqrt{(\partial p)}$$

where:

- d = diameter of orifice (mm)
- (∂p) = pressure difference between inside and outside of tank (mbar)

Table 33 Venting capacities for different orifice diameters

Venting capacity (m ³ /hour)	Pressure difference (mbar)					
	2.5	5.0	7.5	70	175	350
	Orifice diameter* (mm)					
50	42	35	32	32	32	32
100	60	50	45	32	32	32
250	93	78	71	41	32	32
500	132	111	100	57	46	38
750	162	136	123	70	56	47
1000	187	157	142	81	65	54
1250	-	175	158	91	72	61
1500	-	192	174	99	79	66
2000	-	-	200	115	91	77
4000	-	-	-	162	129	108
6000	-	-	-	200	158	133
8000	-	-	-	-	182	153
10000	-	-	-	-	200	172
12000	-	-	-	-	-	188
14000	-	-	-	-	-	200

* Interpolate diameter for intermediate values of venting capacity and differential pressure.

Example: for a required capacity of 500m³/hour and a differential pressure of 7.5mbar, the minimum orifice diameter is 100mm.

D.2.3 Ambient temperature drop, sample calculation No. 1

This simplified calculation demonstrates, for each fixed roof tank category, the drop in ambient temperature that can be accommodated before the vacuum relief valve opens.

In Section 2.1 of BS 2654, fixed roof tanks are divided into standard categories as shown in Table 34 below. The larger the span between maximum pressure and maximum vacuum, the more ambient pressure and/or temperature variations the tank can accommodate without either the pressure relief or vacuum relief valve opening. As long as the pressure and vacuum relief valves remain closed there are no breathing losses. In other words, the larger the pressure span, the higher the vapour saving efficiency.

Table 34 Categorisation of fixed roof tanks

	Design Pressure (mbar (g))	Design Vacuum (mbar (g))
Non-Pressure	7.5	-2.5
Low Pressure	20	-6.0
High Pressure	56	-6.0

The calculation is based on the fundamental law of (ideal) gases:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

where:

P_1	=	initial pressure in vapour space, mbara
P_2	=	final pressure in vapour space, mbara
V_1	=	initial volume of vapour space, m ³
V_2	=	final volume of vapour space, m ³
T_1	=	initial temperature in vapour space, K
T_2	=	final temperature in vapour space, K

In this case, the volume of the vapour space remains constant (no pumping in or out), thus:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

Assume:

T_1	=	Average vapour space temperature = 20°C = 293°K
P_1	=	Pressure relief set pressure, mbar (abs)
P_2	=	Vacuum relief set pressure, mbar (abs)
Atmospheric pressure P_a = 1,013mbar (abs)		

From the data presented in the Table 35 calculation indicates that a high pressure tank can accommodate a temperature drop of 13.6°C, whereas the non-pressure tank can only accommodate a temperature drop of 2.2°C.

Table 35 Calculated temperature drops

		Non-Pressure	Low Pressure	High Pressure
Design pressure	(mbar (g))	7.5	20	56
Design vacuum	(mbar (g))	-2.5	-6.0	-6.0
Pressure relief set pressure P_1	(mbar (g))	6.0	15	45
Vacuum relief set pressure P_2	(mbar (g))	-1.5	-4.0	-4.0
Pressure relief set pressure P_1	mbar (abs)	1019.0	1028.0	1058.0
Vacuum relief set pressure P_2	mbar (abs)	1011.5	1009.0	1009.0
Average vapour space temp. T_1	K	293.0	293.0	293.0
$T_2 = T_1 \times P_2 / P_1$	K	290.8	287.6	279.4
$\Delta T = T_2 - T_1$	K or °C	2.2	5.4	13.6

D.2.4 Ambient temperature drop, sample calculation No. 2

This sample calculation, shown in Table 35, demonstrates that the API 2000 required venting capacity for thermal inbreathing (vacuum relief) may be inadequate for certain unusual climatic conditions.

API 2000 venting requirements for vacuum relief are based on the inflow of air due to product movement plus thermal inbreathing. Thermal inbreathing is caused by changes in atmospheric conditions. API 2000 requirements for thermal inbreathing are based on a mean rate of change of 100°F (56°C) per hour in the vapour-space temperature. (See Appendix A of API 2000 for further details).

This sample calculation checks the required vacuum relief capacity of an 80ft. diameter x 30ft. high tank, located in Colombo, Sri Lanka. A temperature record is available for this tank which indicates a temperature drop of no less than 30°F (from 87°F to 57°F) in 15 minutes. This sharp temperature drop occurred during a downpour after a hot and sunny day.

It should be noted that this calculation is not exact. It is presented to illustrate the effect of a rapid cool down of the vapour space.

Table 36 Sample calculation data

Tank diameter	D =	24.38m	=80.0ft
Tank height	H =	9.14m	=30.0ft
Roof tangent (cone roof)	tg =	0.20	
Tank capacity		26,855barrels	
Tank volume incl. roof space	V =	4,650m ³	=164,200ft ³
<i>Assume tank empty:</i>			
Volume of vapour space	V ₁ =	4,650m ³	
Molecular weight of gas	m =	29	
Atmospheric pressure	p =	1,013mbar	
Gas-constant	R =	0.08478litre-atm/°C/mole	
Normal vapour density	ρ _n =	1.294kg/m ³ (at 0°C)	
Vapour temperature	T ₁ =	87°F	
Vapour density at T ₁	ρ ₁ =	1.164kg/m ³	
Total mass of vapour at T ₁	m ₁ =	5,412Kg	
Vapour temperature	T ₂ =	57°F	
Vapour density at T ₂	ρ ₂ =	1.232kg/m ³	
Vapour volume at T ₂	V ₂ =	4394m ³	
Vapour contraction	δV =	256m ³ /15 min. = 1024 m ³ /hr	
		= 36 162 ft ³ /hr	
Inbreating due to temperature drop			= 36 162 scfh air
API 2000 inbreathing requirement			= 25 484 scfh air
Percentage increase over API 2000			= 42%

D.3 Floating roof seal design

Figure 131 shows a floating roof storage tank; relevant dimensions are:

Tank nominal diameter:	D _t	=	50.0m
Floating roof diameter:	D _r	=	49.6m

Furthermore:

R_n is the smallest distance between the floating roof and the tank shell. It is a construction parameter, determined only by the construction of the seal. The seal in this example has R_n = 75mm.

The working range of floating roof seals is traditionally defined as: $R (-X|+X)$, where:

$$\begin{aligned} R &= \text{the rim space, the designed average space between the floating roof and the tank shell, and} \\ X &= R - R_n. \end{aligned}$$

The rim space is determined by:

$$R = (D_t - D_r)/2 = 200\text{mm. So: } X = R - R_n = 125\text{mm.}$$

In periods of strong winds, e.g. during thunderstorms, the roof will drift to one side of the tank. This is the situation shown in Figure 129. The largest distance from tank shell to the floating roof is:

$$D_t - D_r - R_n = 325\text{mm} = 200 + 125\text{mm} = R + X.$$

Conclusion: the seal remains tight.

This, however, is only valid for tanks of perfectly circular shape. In practice, all storage tanks have a certain out-of-roundness, which is mainly caused by uneven settlement of the foundation. When a tank tilts, the shape becomes oval.

Assume now that the tank has as an oval shape; see Figure 130.

$$\begin{aligned} \text{Smallest diameter: } C_n &= 49.85 \text{ m.} \\ \text{Largest diameter: } C_x &= 50.15 \text{ m.} \end{aligned}$$

The nominal diameter D_t remains unchanged. The largest distance from tank shell to floating roof is now $C_x - D_r - R_n = 475\text{mm} > R + X = 325\text{mm}$. The seal working range $R (-X|+X)$ is no longer sufficient.

Conclusion: the seal leaks, because it lacks capability of bridging the widened gap caused by the ovality of the tank.

Note that such extreme situations often occur during thunderstorms. The vapour escaping through the leaking seal presents a considerable hazard due to the risk of a rim fire, ignited by lightning or sparks from static electricity.

The best way to reduce fire hazard is a good, tight seal. This can be achieved by modifying the seal range from $R (-X|+X)$ to $R (-X|+3X)$, with $X \geq (D_t - C_n)/2$.

In Figure 131, the dimensions of tank and floating roof are the same as in Figure 130. The minimum value of $X = (D_t - C_n)/2 = 75\text{mm}$.

With the given average rim space $R = 200\text{mm}$, the seal will have $R_n = 125\text{mm}$.

Note that R_n is no longer a construction parameter of the seal only, but has also become dependent on the nominal diameter of the tank, the diameter of the floating roof and on the ovality of the tank shell.

The largest distance from tank shell to floating roof now becomes $475\text{mm} = R + 3X$.

Conclusion: the seal remains tight, even in extreme conditions.

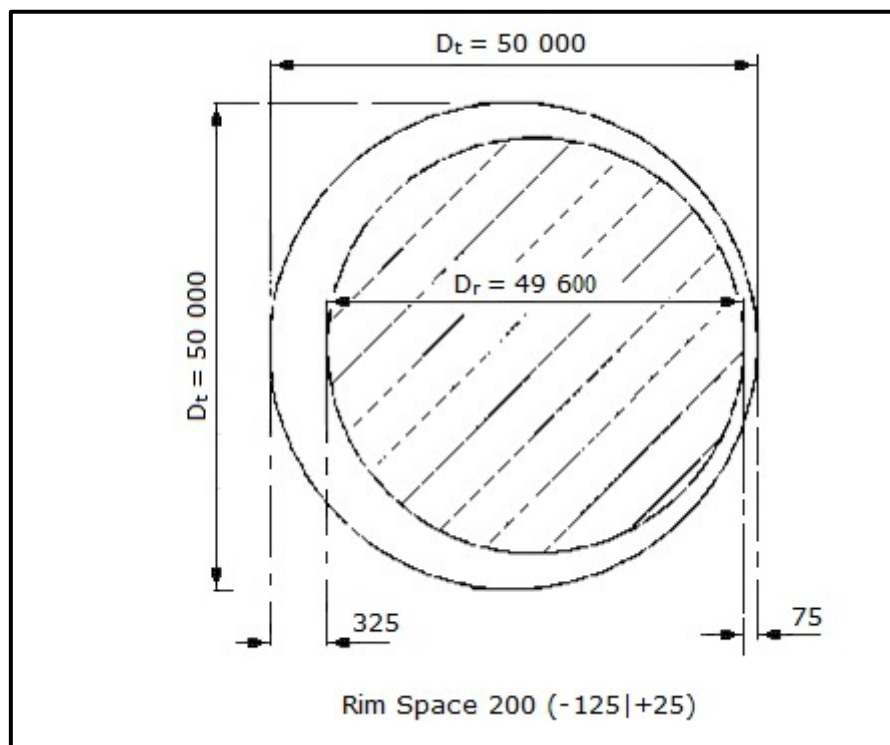


Figure 129 Perfectly round tank, rim space $200 (-125 | +125)$ mm

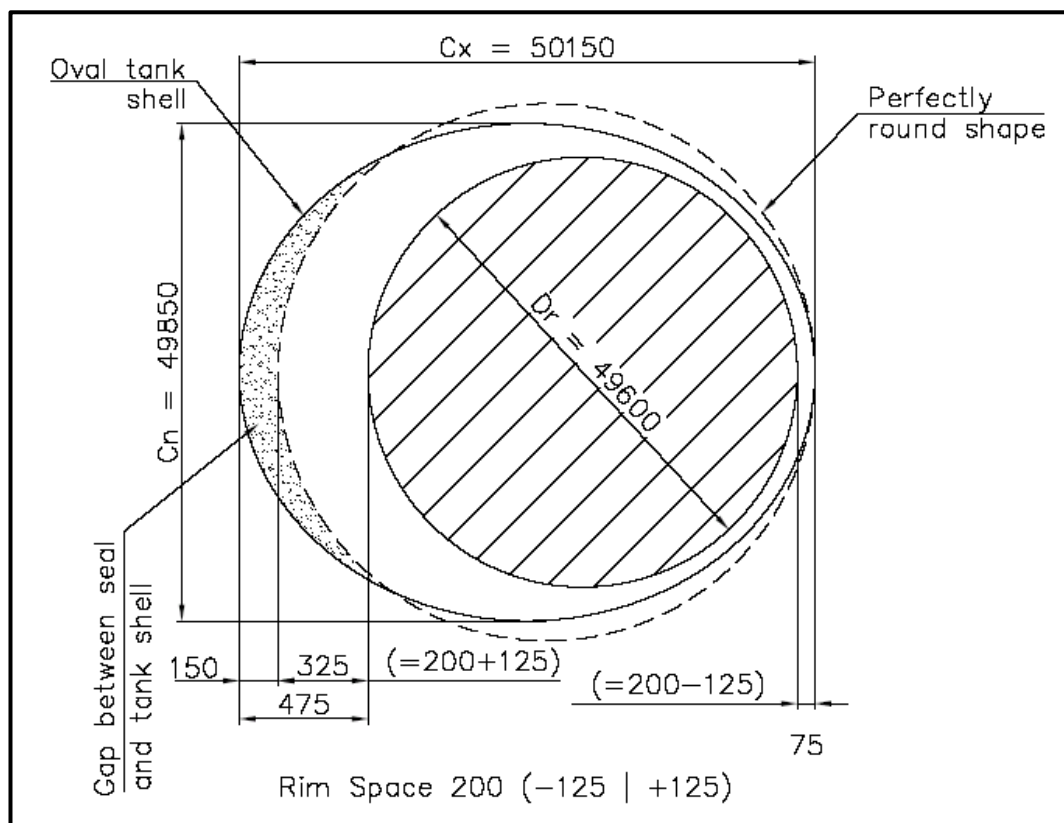
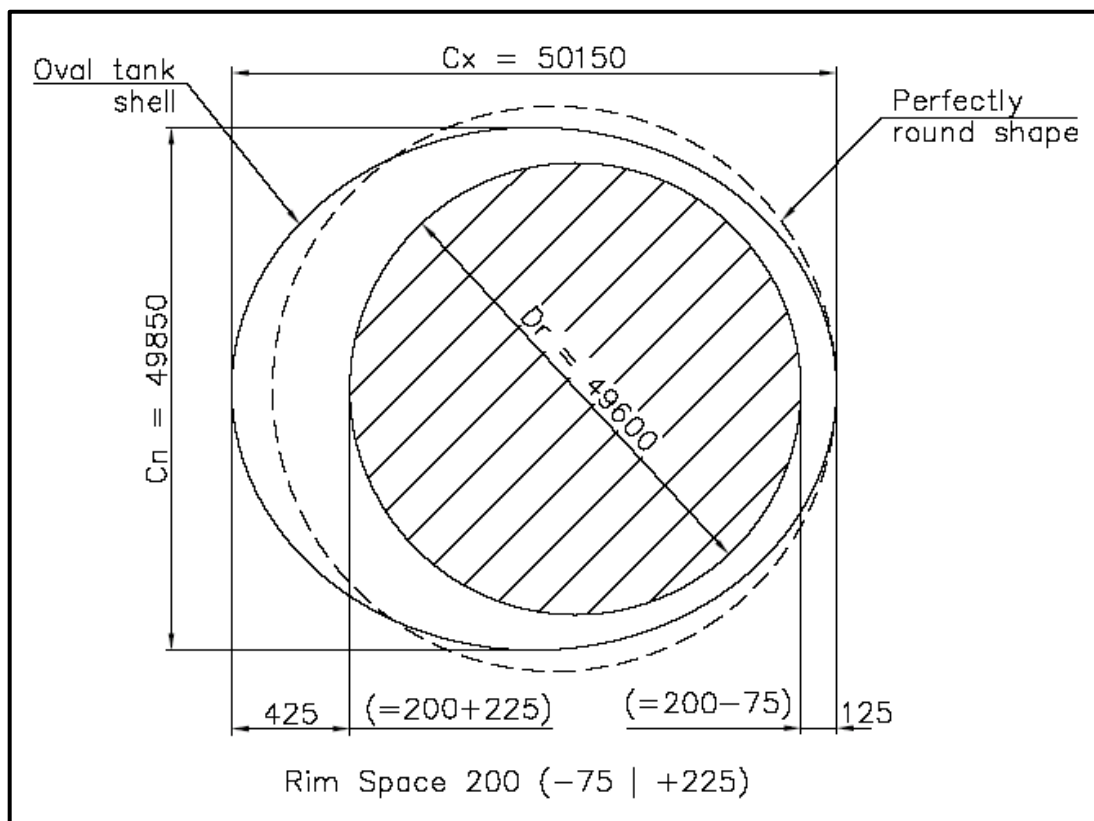


Figure 130 Oval tank, rim space 200 (–125 | +125)**Figure 131 Oval tank, rim space 200 (–75 | +225)**

D.4 Remaining life of a storage tank

Consider the following example. A storage tank was built in 1980. The tank was originally designed for storage of sweet crude. Environmental circumstances indicate that the tank may suffer high corrosion rates. The tank is therefore inspected at relatively short intervals; tank records have well been kept up-to-date. A 'corrosion trend' graph has been drawn, based on the tank records, which also show the tank's service history - see Figure 132.

This analysis deals with the shell top course, which was 10mm thick in the original design.

Product vapours are more aggressive than liquid product. The top shell courses are therefore vulnerable for corrosion, which causes decreased buckling resistance. The limit of deterioration for the subject shell course is that for shell stability. Note that the limit of thickness for the lower shell courses is determined by the shell strength, which is usually lower than for shell stability.

Analysis of the top course shows that the limit of thickness for shell stability (buckling resistance) without application of additional stiffening rings is 6.3mm. The limit of thickness for shell strength is 6.0mm

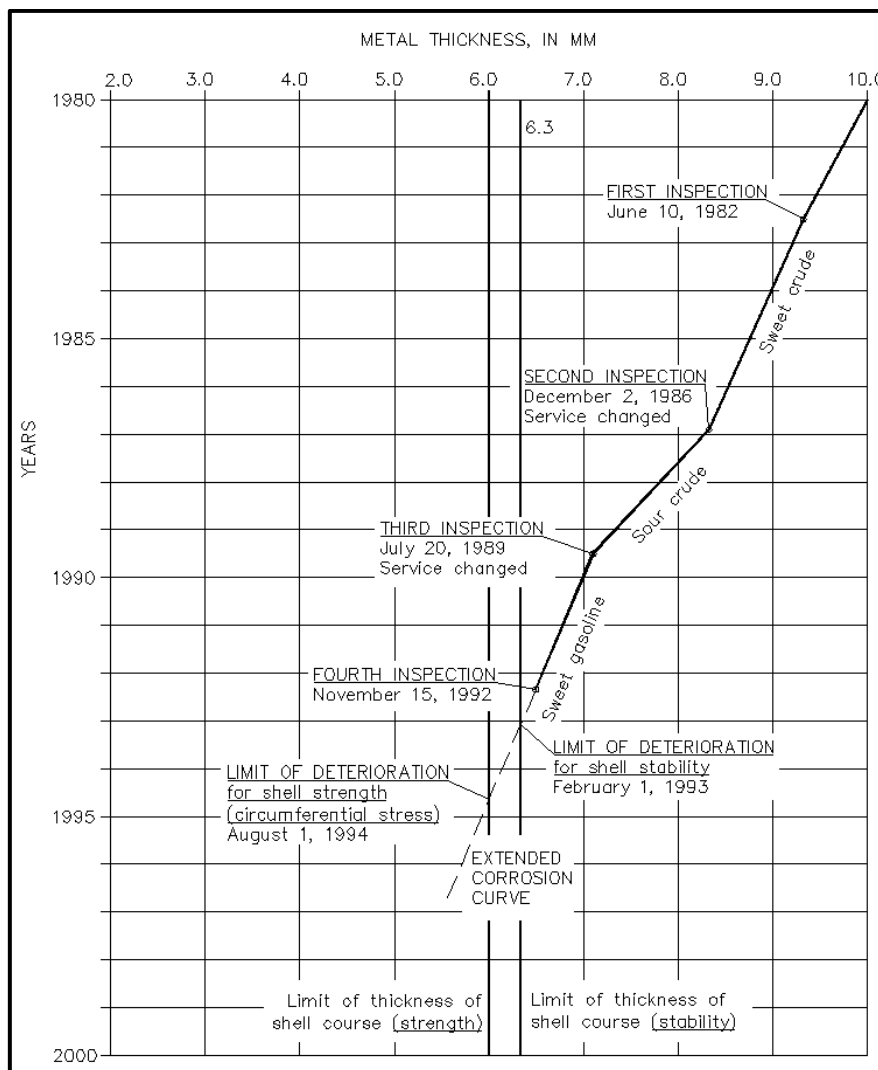


Figure 132 Corrosion rate curve

It can be derived from Figure 132 that:

- Had the tank service not been changed from sweet crude to sour crude, the tank might have remained usable until approx. June 1995 (extend product line for sweet crude to intersect limit of thickness for stability);
- As indicated at the third inspection, the change of service from sweet crude to sour crude reduces the remaining life to ca. February 1991 (extend product line for sour crude to intersect limit of thickness for stability). As sweet gasoline is less aggressive than sour crude, a service change might extend the tank's life by some years;
- The last change of service (sour crude to sweet gasoline) results in a two year extension of the expected lifetime, to ca. February 1993. Note that this conclusion can only be drawn after the fourth inspection.

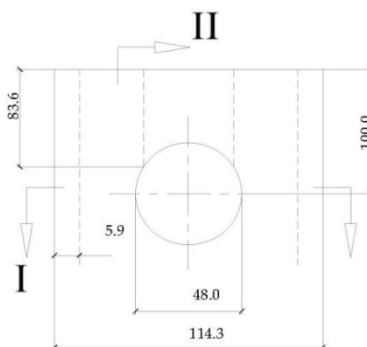
A possibility for further extension of the tank's life is to place an extra stiffening ring on the tank shell, or modify an existing one. This would move the limit of

thickness for stability to a lower figure, e.g. 5.2mm. However, the trend graph shows that the limit of thickness for circumferential stress is 6.0mm, to be reached in August 1994. The modification would extend the tank's life only by approximately 1½ years; however, such a short extension might not be economically justifiable.

D.5 Sample calculation of a corroded landing leg

Check sleeve

Ratio 1: $d_{\text{hole}} / (\pi/2 \cdot d_{\text{sleeve}})$	=	0.28	-
Ratio 2: $h_{\text{sleeve}} / (\pi/2 \cdot d_{\text{sleeve}})$	=	0.59	-
Reduction factor, K_t (see below figure 3.19)	=	4.1	-
Capacity net cross section (I - I), $F_{\text{tens;I-I}}$	=	296.0	kN
Capacity shear (II - II), $F_{\text{shear;II-II}}$	=	233.5	kN
Capacity bearing, F_{bearing}	=	127.0	kN
Capacity peak stress, F_{peak}	=	115.5	kN
Critical capacity, F_{crit}	=	115.5	kN
Vert. force sleeve self weight, N_{self}	=	46.7	kN
Vert. force sleeve live load, N_{live}	=	68.6	kN
Vertikale force sleeve total, N_{total}	=	115.3	kN



Unity check sleeve

UC	=	1.00	<	1.00	OK
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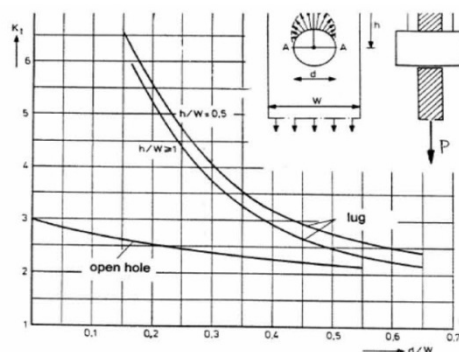
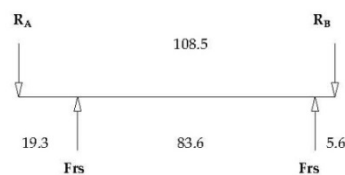


Fig. 3.19 K_t -values for a lug. Results of Frocht and Hill [8]. Comparison to an open unloaded hole.

Check pin

Surface pin, A_{pin}	=	962.1	mm ²
Section modulus pin, W_{pin}	=	4209.2	mm ³
<i>Limits pin; ultimate limit state</i>			
Shear, F_{VRd}	=	166.3	kN
Bending, M_{Rd}	=	1.5	kNm
Bearing on pin, F_{BRd}	=	65.4	kN
<i>Load pin; ultimate limit state</i>			
Vert. force leg, $F_{\text{roof support}}$	=	57.6	kN
Load point A, R_A	=	50.4	kN
Load point B, R_B	=	64.9	kN
Bending moment, M_b	=	0.97	kNm



Check pin ultimate limit state

Unity check bearing	UC	=	0.99	<	1.00	OK
Unity check shearing	UC	=	0.39	<	1.00	OK
Unity check bending	UC	=	0.65	<	1.00	OK
Unity check combination bending + shearing	UC	=	0.58	<	1.00	OK

Appendix E Probabilistic preventive maintenance (PPM)

E.1 Asset records

Appendix A.2 lists the minimum amount of tank data that should be kept maintained in a records system. The EEMUA PPM methodology for tanks described in Chapter 17 of this publication may need to make use of most of that data. Without such data it will be impossible to perform a PPM evaluation of the tank.

E.2 Tank components and their typical failure modes

Chapter 17 describes in detail the process to follow when performing RBI and RCM studies on storage tanks. In principle, the EEMUA PPM method follows the flowchart shown in Figure 106.

In order to assist the user to apply steps 1 to 7 of that flowchart, Table 37 and 38 that follow give, for tank components, examples of typical failure modes, consequences and effects of failure, and the possible causes of failure. The tables also indicate whether the particular component safeguards the integrity of the tank (inspection driven—to be evaluated using RBI methodology) or its functionality (maintenance driven—to be evaluated using RCM methodology).

Table 37 Typical failure modes for bottom and shell

Main item	Component	Main function	Failure Mode (Cause of Failure)	Failure Consequences	Failure Effects (what happens when it fails)	Causes	RBI
Bottom	Plates	To hold product within the tank	Corroded plates	Thinning, leakage	Loss of containment	Coating breakdown, corrosivity of product, water accumulation, deposits (sludge), poor drainage, high water table, poor soil conditions, settlement, tank pad height	X
	Annular plates	To hold product within the tank	Corroded plates	Thinning, leakage	Loss of containment	As above	X
		Provide rigidity to bottom-shell connection	Excessive bending of annular section	Cracking	Loss of structural integrity	As above	X
	Sump(s)	Drainage of product or water	Corroded plates	Thinning, leakage	Loss of containment	As above (except for 'poor drainage')	X
	Cathodic protection	To prevent corrosion	Part of system fails due to improper functioning	Corrosion of bottom plates	Loss of corrosion protection	Poor maintenance, soil condition (including contamination), product type	
Shell	Plates	To hold product within the tank	Corroded plates	Thinning, leakage	Loss of structural integrity (increased buckling tendency), loss of vapour and liquid containment through hole(s)	Coating breakdown, corrosivity of product, water accumulation	X
	Wind girder	To provide stability to tankshell	Corroded girders	Thinning	Loss of structural integrity (increased buckling tendency of tank shell)	Coating breakdown	
	Stairs	To provide acces to roof and sampling points	Unable to carry live load due to corroded structural components	Access denied	Loss of structural integrity	Coating breakdown (ageing, wear and tear) leading to corrosion, water trap	

Table 38 Typical failure modes for roof, fixings and other parts

Main item	Component	Main function	Failure Mode (Cause of Failure)	Failure Consequences	Failure Effects (what happens when it fails)	Causes	RBI	RCM
Roof (fixed)	Plates	Hold vapour within tank and allow access	Corroded plates	Thinning, leakage	Loss of structural integrity (increased buckling tendency), loss of vapour containment through hole(s)	Coating breakdown, corrosivity of vapour, water entrainment	X	
	Supporting structures	Give support to roof plates	Corroded supporting structures	Loss of structural integrity	Collapse of roof	As above	X	X
			Settlement of tank	Loss of structural integrity by tilting		Settlement, poor tank pad design & construction		X
	P/V valve, roof vents, emergency vents	To reduce excessive pressure and vacuum	Blocked vent	No pressure/vacuum relief	Buckling, rupture due to overpressure /implosion	Poor inspection/maintenance		X
			Operated outside operational window	Inadequate pressure/vacuum relief	As above	Poor design/operation		X
	Railings	Provide safety to staff	Corroded structure	Loss of safety	Unable to walk on tank roof	Coating breakdown		X
Aluminium dome (geodesic structure)	Total structure	To eliminate rain and wind effects	Leakage through sealant material	Fails to keep out rainwater/wind	Water in tank and product	Lack of maintenance, wrong application of sealant		X
Floating roofs (single & double decks) and internal floating covers	Plates (steel only)	Sealing of product (surface)	Corroded plates	Thinning, leakage	Loss of structural integrity (increased buckling tendency), loss of vapour containment through hole(s), loss of buoyancy due to liquid on roof	Coating breakdown, corrosivity of product, water accumulation	X	
	Supporting legs	Support to roof when landed	Buckled support due to tilting	No support	(Partial) collapse of roof	Mal-operation during landing; roof not fixed when landed, excessive bottom settlement		X

Main item	Component	Main function	Failure Mode (Cause of Failure)	Failure Consequences	Failure Effects (what happens when it fails)	Causes	RBI	RCM
Floating roofs (single & double decks) and internal floating covers			Corroded support	Thinning	Loss of structural integrity	Coating breakdown, corrosivity of product		X
	Pontoons	Provide buoyancy of roof	Corroded plates	Thinning, leakage	Loss of structural integrity (increased buckling tendency), loss of vapour containment through hole(s), loss of buoyancy due to liquid in pontoons	Coating breakdown, Corrosivity of product, water accumulation	X	X
	Rolling ladder	Access to roof	Derailed ladder	Rotation/tilting of roof	Loss of buoyancy due to product on roof, (partial) collapse of roof	Poor maintenance/house keeping, maloperation		X
	Roof drain	Water drainage	Leakage	Inadequate water drainage	Product in drainage system/product on roof/product contamination	Corrosion, cracking, wear and tear		X
			Blocked	No water drainage	Accumulation of water on roof which could lead to roof buoyancy problems (floating condition) or collapse of roof (landed condition)	Poor housekeeping, freezing, interference with roof equipment		X
Floating roofs (single & double decks) and internal floating covers (cont'd)	NRV of roof drain	To prevent product entering the roof	Leakage	Product flow onto roof (single deck)	In case of a leaking drain: accumulation of water on roof which could lead to roof buoyancy problems (floating condition)	Gasket material, wear and tear, debris, poor maintenance		X
	Roof seals	Smooth movement of roof	Restricted movement by friction along shell	Jamming of roof	Collapse of roof	Poor construction, wear (worn, corroded, eroded) of seal material (fabric, shoes, spring, weight), loosening of bolts, excessive settlement/tilting/		X

Main item	Component	Main function	Failure Mode (Cause of Failure)	Failure Consequences	Failure Effects (what happens when it fails)	Causes	RBI	RCM
						ovality of tank		
		Closing of ring gap	Leakage	Emissions	Increased likelihood of rim fires, de-centring of roof	Wear (worn, corroded, eroded) of seal material (fabric, shoes, spring, weight), loosening of bolts, excessive settlement/tilting/ovality of tank		X
	Roof shunts	To provide earthing of shoe-plates of seal	Loss of earthing	Increase of polarity differences	Increased likelihood of rim fires	Excessive settlement/ovality of tank; wear and tear, poor maintenance		X
	Rim vents	To reduce excessive pressure in rimspace (shoe mounted seals only)	Blocked vent	No pressure relief	Seal (fabric) damage, loss of seal flexibility	Poor inspection/maintenance; fouling		X
	Bleeder vents	To reduce excessive pressure and vacuum	Failed to open	No pressure/vacuum relief	Damage to roof structure	Settlement, presence of deposits (sludge), corrosion of leg.		X
Fixings	Earthing	To provide adequate grounding	Loss of earth contact	Increase of polarity differences between tank components	Fire/explosion	Poor maintenance, damage		X
	Shell penetrations (nozzles)	To connect external piping to the tank	Cracked or ruptured nozzle connection	Leakage	Leakage	Settlement, tank or pipe movement, corrosion		X
Internals	Heating coils	Heating of product	Leaking coil	Inadequate heating	Steam/water in product	Poor maintenance, corrosion		X
	Internal piping pipes	To transport product	Corroded piping	thinning	loss of functionality	As above		X

Main item	Component	Main function	Failure Mode (Cause of Failure)	Failure Consequences	Failure Effects (what happens when it fails)	Causes	RBI	RCM
	Internal pipe supports	Give structural support to piping	Corroded structure	introduction point loads on shell protrusions, bottom and piping	Collapse of piping	Poor maintenance, corrosion, settlement		X
Miscellaneous	Mixer	Prevent separation of bottom sludge and water from product	Mechanical (of impeller)	Bottom sludge and water accumulation	Excessive costs of sludge removal	Wear of mixer components, broken impeller		X
	Coating	Corrosion prevention	Coating breakdown	No corrosion protection	Corrosion of structural members	Ageing, wear and tear, mechanical damage		X
Foundation	Tank pad	To provide structural support to the tank and its contents	Soil settlement	Loss of structural integrity	Collapse of roof, shell buckling, out-of-roundness, ovality, rupture of shell-bottom joint, excessive loads on pipe connections	Poor soil conditions, improper soil improvement		X
	Tank pad shoulder	To provide rigidity to the tank pad	Eroded shoulder	Slip	Edge settlement, shell buckling, rupture of shell-bottom joint	Poor soil conditions, improper soil improvement, lack of maintenance	X	X
Leak detection system	Liner in foundation	Early detection of leakage	Inadequate drainage to collection pit due to tank settlement	No alarm	Product loss to sub-soil and/or ground water, loss of confidence in 'second line of defence'	Poor soil conditions, improper soil improvement, lack of maintenance		X
	Double bottom	Prevent leakage to soil/groudwater	Corroded bottom plates	No alarm; leakage	As above	As above, also corrosion	X	X
Bunded area	Wall/bund	To keep any spill within the bunded area (local)	Leakage through bund due to erosion or holes (e.g rabbits, or other burrowing animals)	Non-localised effect	Excessive cleaning	Poor maintenance		X

Main item	Component	Main function	Failure Mode (Cause of Failure)	Failure Consequences	Failure Effects (what happens when it fails)	Causes	RBI	RCM
	Drainage system	To drain rain and fire water to sewerage system	Blocked drainage	No adequate drainage	Water accumulation in bunded area, corrosion of tank bottom plates, loss of capacity of bunded area	Poor maintenance, poor housekeeping		X
	Drainage valve	To allow monitored drainage of the collected water in the compound	Leaking/open valve	Uncontrolled (contaminated) drainage	Loss of the functionality of the bunded area	Poor maintenance, poor housekeeping		X

E.3 Calculation of interval before next required inspection

E.3.1 Overall calculation process

Figure 133 flowchart illustrates the stepwise calculation process for determining the interval before the next required inspection for a tank component due to any 'trendable' degradation mechanism. The calculation process follows the EEMUA RBI methodology (Section 17.4). Appendix E.4 gives examples of calculations of inspection intervals applicable to **bottom**, **shell** and (fixed roof tank) **roof plates** for the degradation mechanism of **corrosion**. Corrosion has been chosen as it is the likely dominant failure mechanism for those components.

This Section E.3, gives guidance on the calculation process, and lists and discusses the various features and aspects that influence **risk rating**, **remaining life** and **consequence rating factor**, and hence the interval before the next required inspection.

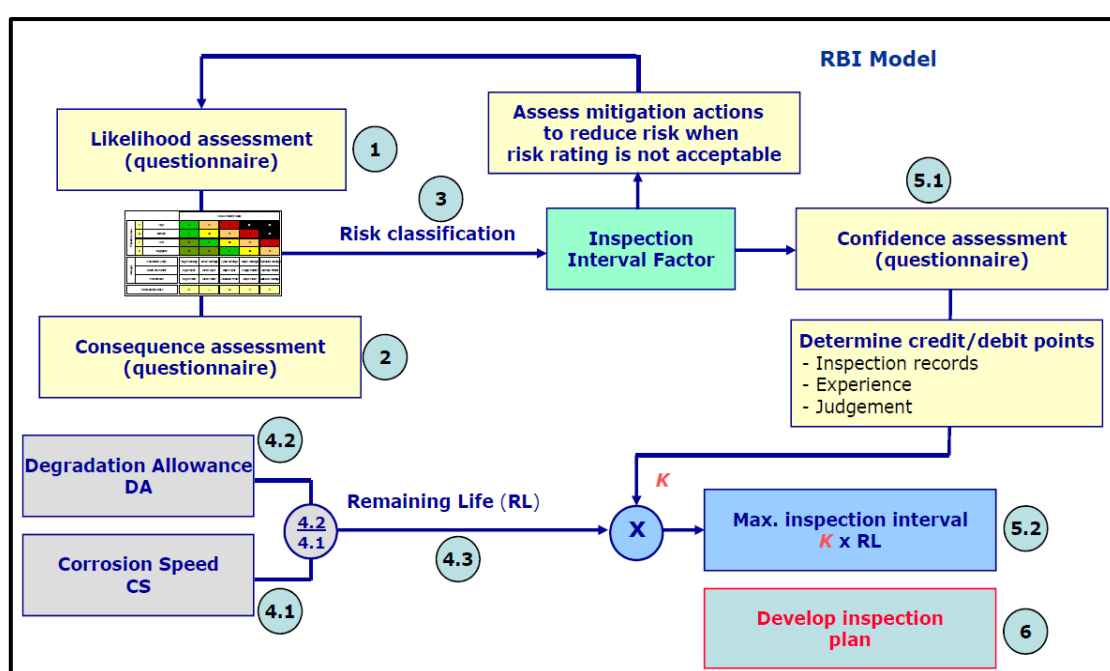


Figure 133 Calculation flowchart

E.3.2 Probability of failure by corrosion: features/actions affecting corrosion rate

E.3.2.1 Introduction

The probability of failure by a specific mechanism (in this case corrosion) is dependent on the actions taken to prevent or limit the particular degradation process, and on features that prevent, limit or encourage the process. The first step in the evaluation procedure (Figure 133) leads to the determination a *probability factor* ζ (see Section 17.4.3.1). This is done by first assessing the individual effect of each action/feature, each 'aspect' of which is allocated a 'score' (see 'Step 1' of the model calculations in Section E.4). The assigned numerical value of the score is semi-empirical, based on the evaluator's experience. Low values correspond to low probabilities of failure and vice versa. The probability factor is calculated as a weighted average of the scores, the assigned weightings also being semi-empirical, based on experience (see first box in Step 3 of the model calculations). Each tank component is subjected to this evaluation.

In the subsections that follow, the probability of failure due to corrosion of bottom, shell and roof plates is addressed.

E.3.2.2 Bottom plates

The actions and features that influence the corrosion of bottom plates are listed and discussed below.

- 1 *Actions taken to prevent or limit corrosion.* These could be the installation or application of:
 - (a) an impressed current CP system below the tank bottom or a sacrificial CP system above the bottom;
 - (b) an internal or external coating system;
 - (c) a GRE lining on the tank bottom and on the first metre of the shell.
- 2 *Features that influence the corrosion process.*
 - (a) storage conditions (product temperature);
 - (b) configuration of bottom (cone up, flat or cone down);
 - (c) heating coils in the tank;
 - (d) product corrosivity.
- 3 *Effectiveness of the drainage system in preventing water ingress under the bottom plates.* The determining features here are:
 - (a) type of foundation;
 - (b) height of foundation above the water table;
 - (c) adequacy of the drainage system in the vicinity of the tank;
 - (d) width and slope of the tank pad shoulder.

The effect on corrosion of each of the above listed actions/features is discussed below. The 'box' number refers to the corresponding numbered box in the model calculations for bottom plates in E.4.

(1a) *Cathodic protection* (see Section 6.6, EEMUA 183) [Boxes 1 & 2]

In the assessment of corrosion of the underside of bottom plates, an impressed current CP system underneath the tank bottom will have the effect of increasing the lifetime. However the effectiveness of such a CP system is proportional to the voltage reading, and the assigned factor will depend on the reading. Sacrificial CP systems can be used to prevent corrosion attack on the topside of bottom plates due to water in the product.

(1b) *Internal/external coating* (see Sections 6.2.1 & 6.2.2, op. cit.) [Boxes 3 & 4]

When an internal or external coating system has been applied, bottom plate lifetime may be prolonged. However the continuing effectiveness of such systems depends on the remaining life of the coating.

(1c) *Glass fibre reinforced epoxy resin laminate liner* (see Sections 6.2.3, op. cit.)

A GRE liner applied to the bottom plates will prevent contact with an aggressive product. The continuing effectiveness of protection will depend on the remaining life of the liner.

(2a) *Storage conditions (temperature of product)* [Box 5a]

Corrosion rates increase with temperature of stored product.

(2b) *Configuration of bottom (cone up, flat or cone down)* [Box 5b]

Especially when product is stored at elevated temperatures, cone-down bottom configurations will experience increased corrosion rates at the annular section of the bottom.

(2c) Heating coils installed [Box 5c]

When in direct contact with bottom plates, heating coils will increase corrosion rate.

(2d) Product corrosivity [Box 6]

The effect of this parameter is assessed for each product type.

(3a) Foundation type [Box 7]

The type of foundation will affect the effectiveness of drainage.

(3b) Height of tank pad above grade (see Section 2 and Appendix IV, sheet 3, op. cit.) [Box 8]

The likelihood of contact between tank bottom and groundwater is affected by the height of the foundation pad above the grade level of the surrounding bunded area. Where the pad height is low and the bottom plates are in contact with water, their life expectancy may be assumed to be low to very low.

(3c) Effectiveness of drainage (see Section 4.4.1 b) and Appendix IV, sheet 4, op. cit.) [Box 9]

When drainage is poor, or not carried out frequently enough (housekeeping), the accumulated rainwater may come into contact with the bottom plates resulting in the situation described in (3b). When rainwater is adequately drained, preventing contact with the bottom plates, their life expectancy as assessed by this feature may be assumed to be high to very high.

The slope of the tank pad shoulder will also have an effect in preventing water ingress under the bottom plates. Unevenness in the top of the pad can cause the formation of a gutter in which rainwater, debris and dead vegetation collect.

E.3.2.3 Shell plates

(The layout of this subsection follows that of the previous.)

- 1 *Actions taken to prevent or limit corrosion.* These could be the application of an:
 - (a) internal coating system;
 - (b) external coating system.
- 2 *Features that influence the corrosion process.* These could be:
 - (a) storage conditions (product temperature);
 - (b) heating coils in the tank;
 - (c) corrosivity of the liquid product;
 - (d) corrosivity of the product vapour;
 - (e) external insulation of the shell.

(1a & b) Internal and external coatings [Boxes 1 & 2]

Only sound, multi-layer coating systems are taken into account. A primer coat, normally applied during tank construction, is not by itself considered to be a coating. However the effectiveness of a coating system depends on its expected remaining life.

(2a) Storage conditions [Box 3a]

Corrosion rates increase with temperature of stored product.

(2b) Heating coils installed [Box 3b]

When in direct contact with shell plates, heating coils will increase corrosion rate.

(2c & d) Product corrosivity (liquid and vapour) [Boxes 4 & 5]

The effects of these parameters are assessed for each product type.

(2e) External insulation [Box 6]

The occurrence of CUI will increase the probability of failure.

E.3.2.4 Roof plates

(The layout of this subsection follows that of the two previous.)

- 1 *Actions taken to prevent or limit corrosion.* These could be the application of an:
 - (a) internal coating system;
 - (b) external coating system.
- 2 *Features that influence the corrosion process.* These could be:
 - (a) storage conditions (product temperature);
 - (b) corrosivity of product vapour;
 - (c) operation with an inert blanketing system;
 - (d) internal location of roof supporting structure;
 - (e) external location of roof supporting structure;
 - (f) insulation on top of roof.

(1a & b) Internal and external coatings [Boxes 1 & 2]

(As for shell plates above.)

(2a) Storage conditions [Box 3]

(As for shell plates above.)

(2b) Corrosivity of product vapour [Box 4]

The effect of this parameter is assessed for each product type.

(2c) Operation with an inert blanketing system [Box 5]

The use of an inert blanketing system within the vapour space will not only reduce the likelihood of an internal explosion—its primary function—but will also reduce the occurrence of corrosion of steel components within the vapour space.

(2d) Internal location of roof supporting structure [Box 6a]

The likelihood of crevice corrosion needs to be assessed when the roof supporting structure is below the plates.

(2e) External location of roof supporting structure [Box 6b]

When the roof supporting structure is above the plates, the adequacy of rainwater draw-off points needs to be assessed.

(2f) Insulation on top of the roof [Box 7]

The likelihood of CUI needs consideration (as for shell plates).

E.3.2.5 Probability rating

The next stage in the evaluation procedure is to establish a *probability rating*. The probability ratings assigned to the calculated probability factors are taken from Table 15, which is reproduced below. [See Boxes 16 & 17 (bottom), 13 & 14 (shell) and 14 & 15 (roof).]

Table 39 Probability rating

Calculated Probability Factor	Assigned Probability Rating	
$\zeta \geq 3.0$	High	H
$2.5 \leq \zeta < 3.0$	Medium	M
$2.15 \leq \zeta < 2.5$	Low	L
$\zeta < 2.15$	Negligible	N

E.3.3 Consequences of failure by corrosion: categories and aspects

E.3.3.1 Introduction

The consequences of failure for the three tank components under consideration - bottom, shell and roof - generally divide into three main categories, namely:

- economic;
- health and safety;
- environmental.

E.3.3.2 Economic aspects

The economic consequences of failure by corrosion are the costs of:

- cleaning up of spillage (surface water contamination, groundwater contamination, soil remediation, above-ground contamination);
- removal and replacement of insulation (if present);
- actual repair, both labour and materials;
- demolition of tank and disposal of materials if repair is not an option;
- new tank (if to be erected);
- non-availability of tank and indirect costs.

The list is not exhaustive and may be expanded to suit the circumstances.

If alternative or excess storage capacity is available, then non-availability may not be an immediate economic consideration. In such cases it is worthwhile to consider not repairing the tank, or delaying the repair (depending on predicted storage requirements).

In determining the effect of the economic category on *consequence factor* (Section 17.4.3.2), the following aspects are considered in the model calculations in Section E.4:

(1a) *Estimated time to repair* [Boxes 10a (bottom), 7a (shell) and 8a (roof)]

(1b) *Estimated cost of repair* [Boxes 10b (bottom), 7b (shell) and 8b (roof)]

(1c) *Probable magnitude of product loss* [Boxes 10c (bottom), 7c (shell) and 8c (roof)]

E.3.3.3 Health and safety aspects

The health and safety aspects resulting from failure that need to be considered, are generally as listed below. However, local legislation may dictate that more severe criteria apply to the tank under consideration, in which case the most severe criterion

should be used. If local legislation uses a combination of individual aspects, care should be taken in calculating the overall safety aspect.

The following aspects are considered in the model calculations:

- (2a) *Likelihood of injury to personnel* [Boxes 12a (bottom), 9a (shell) and 10a (roof)]
- (2b) *Product flammability characteristics* [Boxes 12b (bottom), 9b (shell) and 10b (roof)]
- (2c) *Product toxicity* [Boxes 12c (bottom), 9c (shell) and 10c (roof)]
- (2d) *Location of tank farm* [Boxes 12d (bottom), 9d (shell) and 10d (roof)]

E.3.3.4 Environmental aspects

Environmental pollution does not stop at the gate or fence. The likely severity of pollution needs to be estimated by the team that implements the PPM methodology, and should be based on the possibility and cost of cleaning.

The following aspects are considered in the model calculations:

- (3a) *Environmental hazard to soil and water* [Boxes 14a (bottom), 11a (shell) and 12a (roof)]
- (3b) *Vapour emission* [Boxes 14b (bottom), 11b (shell) and 12b (roof)]

E.3.3.5 Consequence rating

The dominant *consequence factor* (χ) (see 6.4.3.2) is the highest 'score' of the three selected categories, economic, health and safety, or environmental (see E.3.3.1). The scores assigned to each category are calculated as:

- for economic aspects, the greater of $(1a + 1b) \div 2$ or $1c$ [Boxes 10d (bottom), 7d (shell) and 8d (roof)];
- for health and safety aspects, the greater of $2a$ or $(2b + 2c + 2d) \div 3$ [Boxes 12e (bottom), 9e (shell) and 10e (roof)];
- for environmental aspects, the greater of $3a$ or $3b$ [Boxes 14c (bottom), 11c (shell) and 12c (roof)].

In other words, χ is the highest of $(1a + 1b) \div 2$, $1c$, $2a$, $(2b + 2c + 2d) \div 3$, $3a$, or $3b$.

The *consequence rating* of the particular failure mode is then obtained from Table 16, which is reproduced below.

Consequence Factor	Assigned Consequence Rating	
$\chi \geq 3.0$	High	H
$2.5 \leq \chi < 3.0$	Medium	M
$2.0 \leq \chi < 2.5$	Low	L
$\chi < 2.0$	Negligible	N

E.3.4 Rejection limits and remaining life

As already explained elsewhere in this document, the **remaining life** of a tank component depends its allowable degradation or **rejection limit**, the failure mechanism, and the data used to assess the rate of degradation.

This subsection deals with rejection limits of the components chosen for this exercise: bottom, shell and roof plates.

Section 4.2 gives examples of typical corrosion rates of bottom, shell and roof plates, based on data from several companies, for various stored products. However actual corrosion rates may well differ from those typical figures. Appendix D.4 gives guidance, by way of an example, on how to establish degradation rates or trends when thickness measurements are taken at specific locations, identified by means of a grid system at various time intervals. When such data is available it should be used in the RBI procedure instead of that in Section 4.2.

The calculation routines for establishing the allowable minimum plate thicknesses for the chosen components assume that they are attacked by general corrosion only. Pitting corrosion does not normally present a significant threat to overall structural integrity of bottom, shell and roof plates unless present in a severe form with the pits close together. The procedure outlined previously determine when pitting corrosion exceeds allowable limits. When this occurs, pitting, rather than general corrosion, will govern the predicted remaining life of the component.

Rejection limits/criteria, pertinent to the calculation examples in Section E.4, are given as follows:

- bottom plates - Section 7.4;
- shell plates - Section 8.3;
- roof plates - Section 9.3.

Remaining life (RL) is calculated as shown in Step 4 of the calculation examples in Section E.4.

E.3.5 Confidence rating factor, K , and interval before next inspection

E.3.5.1 General

Having used the probability rating and consequence rating to establish, via the RAM, the *risk rating* and (initial) *confidence rating factor K* for each component (see Sections 17.4.3.3 and 17.4.5), the interval before the next required inspection (II) can be calculated from the formula in Section 17.4.5:

$$II = K \times RL$$

where RL is the remaining life of the component.

However, before calculating II, the magnitude of K may be adjusted by adding/subtracting 'credit or debit points' whose assigned values, based on experience, depend on various 'influences'. These influences may be applicable to some or all components, or unique to a single component.

The calculations are shown in Step 5 of the Section E.4 examples.

E.3.5.2 Adjustments to K : Influences applicable to all three components

E.3.5.2.1 Reliability of Measurement of Degradation [Boxes 28 (bottoms), 24 (shell) & 26 (roof)]

With regard to plate thickness measurements, the value of the points added to or deducted from the initial value of K is dependent on the NDT method used and the extent of coverage (number of readings taken).

In ascending order of reliability, these NDT methods are:

- visual inspection with some spot US;
- US measurements using the grid line system described in 5.3.5;

- complete scans using the MFL technique supplemented by US of suspect areas;
- eddy current techniques, which may offer advantages over the previous (MFL + US) method (not considered in Step 5).

E.3.5.2.2 Inspection frequency [Boxes 29 (bottom), 25 (shell) & 27 (roof)]

It is obvious that the more the amount of data collected in the past, the more confidence there will be in the accuracy of the prediction of the remaining life of the component under consideration. The available data should be of good quality with regard to accuracy of the measurements and the extent of coverage. If no such data exists, a conservative approach will need to be adopted.

E.3.5.3 Adjustments to K: Influences unique to individual components

The box numbers below refer to the appropriate calculation example in Section E.4.

E.3.5.3.1 Bottom plates

BOX 30: Type of interconnecting welds

The assessed risk rating of bottom plates pertains to the plates only. It is assumed that the interconnecting welds and the inspection and testing thereof have been done in accordance with the applicable design and construction codes (BS 2654, API 650 etc.) and appropriate procedures. However, the better the welding technique, the lower the chance that the weld will fail earlier than the plates themselves. Existing tanks constructed to earlier editions of the said codes may have welds that are less resistant to corrosion.

E.3.5.3.2 Shell plates

BOX 26: Corrosion attack on wind girders

The formulae for establishing the minimum allowable shell plate thickness under external loads (a combination of wind loads and vacuum) assume the wind girder (if fitted) to be of sound shape and minimum cross-sectional area appropriate to the dimensions of the tank under consideration. However corrosion of the girder could weaken it, thereby affecting stability of the shell and hence its remaining life.

BOX 27: Buckles in the shell

Deformations in tank shells such as buckles, dents, weld peaking and banding, etc. can adversely affect the stability of the tank shell when under external load, particularly when the tank is empty or partially empty. A combination of external wind loading and internal vacuum can cause an empty tank to buckle due to excessive hoop compressive stress. Longitudinal compressive stresses are also present in a fixed roof tank due to the dead weight of the roof together with any live and superimposed loads on the roof. The presence of existing deformations can have an adverse influence on the stability of the shell when under these compressive loads and therefore on the remaining life (RL).

BOX 28: Shell connections

Bending moments on tank shell nozzles, induced by differential settlements between the tank structure and the supports to piping connected to the nozzles, will increase the allowable minimum thickness of the shell plates under consideration, over and above the allowable minimum if there were no bending moments. These effects cannot be easily assessed by formula, and thus have to be addressed by reducing the confidence rating factor K by means of debit points.

E.3.5.3.3 Roof plates

BOX 28: Roof connections

As for Shell connections above, K may need to be reduced by debit points to take account of allowable minimum plate thickness when roof nozzles are subjected to bending moments.

E.4 Model calculations for determining interval before next required inspection

E.4.1 Introduction

The calculations that follow illustrate the stepwise process for determining the interval before the next required inspection for bottom, shell and roof plates due to the effects of corrosion. An explanation of the steps in the calculation process relating to bottom plates is given in E.4.2 below. The other two sets of model calculations follow a similar stepwise process, and therefore do not require separate detailed explanation.

E.4.2 Model calculation for bottom plates

E.4.2.1 Step 1: Determine probability rating of failure mode

Step 1 assigns 'scores' to each 'feature', which are used in the calculation of probability factor and probability rating (Step 3, Boxes 16 & 17). The numerical values of the scores are based on experience.

BOXES 1 & 2

The tank in the example is assumed not to be protected by a CP system, hence scores are 2 for each box.

BOXES 3 & 4

The tank has no internal or external coating/lining, hence score 2 for each.

BOXES 5a, 5b & 5c

Temperature of stored product is between 40 & 85 °C: 5a score = 1. The type of bottom is only of relevance when product temperature is > 85°C, hence 5b score = 0. No heating coils are installed: 5c score = 0.

Note that the weighted score for boxes 5 is calculated as: $\{[5a] + [5b] + [5c]\}/2.5$, where [5a] is the score for box 5a (etc.). 2.5 is chosen as the denominator (instead of 3) as experience shows it to give a better weighted score. Overall score is $(1 + 0 + 0)/2.5 = 0.4$.

BOX 6

Product is very corrosive: score = 2.

BOX 7

Tank has a sand pad with a sound sand-bitumen top layer and annular ring of coarse granular material: score = $\frac{2}{3} = 0.67$.

BOXES 8 & 9

Bottom plates are not in contact with water, and slope of tank pad shoulder allows effective drainage: score = 0 in each case.

E.4.2.2 Step 2: Determine consequence rating of failure mode

E.4.2.2.1 Economic Aspects

BOXES 10a, 10b & 10c

Here it is assumed that there will be a major repair causing an outage of between 3 and 8 months (10a score = 3), the cost of repair is between 5 and 10% of the capital cost of a new tank (10b score = 2), and the possible magnitude of product loss is 5% of the tank's contents or less (10c score = 2).

BOXES 10d & 11

The consequence factor χ (10d) is either the average of 10a + 10b scores or the 10c score, whichever is greater. In this example the former is the greater:

$\chi = (2 + 3)/2 = 2.5$. From box 11 (using the table in E.3.), the consequence rating assigned to this value of χ is 'M'.

E.4.2.2.2 Health, safety and environmental aspects [Boxes 12a–15]

By a process similar to the foregoing, the consequence rating for health and safety aspects is 'M' (box 13), and for environmental aspects is 'L' (box 15).

E.4.2.3 Step 3: Determine overall risk rating

E.4.2.3.1 Establish probability rating

BOX 16

The probability factor is now calculated from the scores in Step1 in accordance with the formula:

$$\zeta = \{2 \times [1] + 1 \times [2] + 3 \times [3] + 2 \times [4] + 2 \times [5] + 4 \times [6] + 5 \times [7] + 2 \times [8] + 3 \times [9]\} \div 9$$

where: [1], [2] etc. are the scores of boxes 1, 2 etc. (Step 1), and the multipliers have been chosen from experience.

In the present example

$$\begin{aligned} \zeta &= (2 \times 2 + 1 \times 2 + 3 \times 2 + 2 \times 2 + 2 \times 0.4 + 4 \times 2 + 5 \times 0.67 + 2 \times 0 + 3 \times 0) \div 9 \\ &= (4 + 2 + 6 + 4 + 0.8 + 8 + 3.35) \div 9 = 28.15 \div 9 = 3.13 \end{aligned}$$

BOX 17

Using the table in E.3.3.5, the probability rating assigned to $\zeta = 3.13$ is 'H'.

E.4.2.3.2 Establish consequence rating

BOX 18

The highest consequence rating of the various aspects (economic, etc.—Step 2) is 'M'.

E.4.2.3.3 Establish overall risk rating

From the RAM (a simplified version of Figure 111), it is seen that the combination of a high probability rating and a medium consequence rating gives an 'extreme' overall risk rating.

E.4.2.4 Step 4: determine remaining life

BOXES 20a–26

Step 4 is a straightforward calculation based on ultrasonic thickness measurements and the interval between such measurements. The corrosion rate has been adjusted to take account of pitting (boxes 24 & 25). The calculated remaining life (RL) is 3.4 years (box 26).

E.4.2.5 Step 5: Determine interval before next required inspection

The confidence rating factor K is assigned values based on risk rating. The initial value of K is 0.5 (box 27).

K is then adjusted, as described in E.3.5, by adding/deducting 'credit/debit points' which depend on various 'influences' (boxes 28–30). In the example, the algebraic sum of the credit and debit points is 0.2 (box 31), whence $K = 0.5 + 0.2 = 0.7$ (box 32).

Interval before next required inspection (E.3.5.1) is therefore:

$$II = K \times RL = 0.7 \times [26] = 0.7 \times 3.4 = 2.38 \text{ years.}$$

E.4.3 Determine interval before next required inspection for entire tank

The results of the model calculations give the following intervals before the next required inspections of the components under consideration:

- bottoms 2.38 years;
- shell 4.84 years;
- roof 34.23 years.

Hence the interval before the next required inspection of the entire tank is determined by the requirement for the bottom; that is 2.38 years.

Note: The maximum interval between Internal inspections may not exceed 20 years, even when results of calculation models give a longer period.

Model calculation for determining corrosion rate, probability, Consequence & risk ratings, remaining life, and interval before next inspection of bottom plates under corrosion attack

See E.3. 'Scores' as given below are indicative only.

1 Impressed cathodic protection
(See 6.6, EEMUA 183) - all readings around the periphery are above 0.85 V, score = 0 - all readings around the periphery are below 0.85 V, but above 0.60 V = 1 - readings are below 0.60 V thus no effective CP existing or CP does not exist = 2

Score 2

2 Sacrificial cathodic protection (See 6.6, EEMUA 183)
- sacrificial CP available and operating = 0 - sacrificial CP not available nor operating = 2

Score 2

3 Internal Coating or lining is applied to bottom plates
See 6.2.1 & 6.2.2, EEMUA 183, and Appendix C.5 of this publication) - internal coating applied and quality is sound = 0 - internal coating applied but quality is poor = 1 - not existing = 2

Score 2

4. External coating is applied to bottom plates (other than shop primer)
- External coating applied and quality is sound = 0 - External coating applied but quality is poor = 1 - Non existent = 2

Score 2

Features that influence the failure mechanism of bottom plates

5a Storage condition temperature of product
- > 85°C = 2 - Between 40 and 84°C = 1 - Less than 40°C = 0

Score 1

5b Type of bottom
- Cone up = 0 - Flat = 2 - Cone down = 0 (Data only needed for hot tanks: T > 85 °C)

Score 0

5c Heating coils in tank?
- Yes = 1 - No = 0

Score 0

**Weighted score for 5,
use formula: $5 = (5a + 5b + 5c) / 2.5 = 0.4$**

(Data only needed when there is direct contact between heating coil and tank bottom plates)

6 Product corrosivity		
Group	Risk	Score
1	H	2
1A	M	1
2	H	2
2A	M	1
3	M	1
3A	L	0
4	L	0
5	L	0
6	L	0
7	M	1
7A	H	2
8	M	1
8A	L	0
9	H	2

Score 2

Effectiveness of drainage to prevent water ingress under bottom plates

7 Foundation type

(See Section 2, EEMUA 183)

- 'traditional' granular soil/sand type = 2
- sand pad with annular ring of coarse granular material = 4/3
- as above but with sound sand-bitumen top layer = 2/3
- concrete raft under tank = 0
- piled concrete raft = 0

Score 0.67

8. Height of foundation

(See Appendix IV, Sheet 3, EEMUA 183)

Is tank bottom free from contact with water?
(I.e. is groundwater level well below top of foundation,
and drainage of bunded area sufficiently adequate to
ensure a dry tank bottom?)

- yes = 0
- no = 2

Score 0

9. Effectiveness of drainage

(See 4.4.1 & Appendix IV, Sheet 4, EEMUA 183)

- slope of tank pad shoulder allows for adequate drainage away from tank bottom = 0
- water will remain under the tank bottom due to inadequate drainage or tank bottom is standing in water = 2

Score 0

Calculation of probability factor is shown at the beginning of Step 3.

STEP 2 Determine consequence factors & ratings for the various aspects - bottom plates (E.3.3)

10a Time to repair	Score
- internal entry required, major repair (> 8 months)	4
- internal entry required, major repair (3–8 months)	3
- internal entry required, limited repair (> 3 months)	2
- no internal entry required, limited repair, no limitation on repair time	1

Score 3

Economic aspects (E.3.3.2)

10b Cost of repair	Score
- > 50% of capital cost (new tank)	4
- 10–50% of capital cost	3
- 5–10% of capital cost	2
- negligible, or less than 5% of capital cost	1

10c Probable magnitude of product loss	Score
- > 5% of tank contents	3
- < 5% of tank contents	2
- no release of product	1

Score 2

Score 2

Consequence factor, economic aspects

10d Probable magnitude of product loss
Maximum consequence factor is score of $[(10a + 10b)/2]$ or 10c, whichever is the greater

Consequence factor χ
2.5**Consequence rating, economic aspects (E.3.3.5)**

11 Relation between consequence factor χ and assigned consequence rating		
Assigned Consequence Rating		Factor
High	H	$\chi \geq 3.0$
Medium	M	$2.5 \leq \chi < 3.0$
Low	L	$2.0 \leq \chi < 2.5$
Negligible	N	$\chi < 2.0$

Consequence rating
M

Health and safety aspects (E.3.3.3)

12a Likelihood of injury to personnel	Score	
- serious injury/fatality on site	4	Score 2
- lost time injury/medical treatment	3	
- minor injury	2	
- no injury or near miss	1	
12b Product flammability as per IP Model Code of Safe Practice in the Petroleum Industry, Part 19	Score	
- class I product	4	Score 3
- class II(2) and class III(2) product	3	
- class II(1) product	2	
- class III(1) and unclassified product	1	
12c Product toxicity	Score	
- extremely toxic substance	4	Score 4
- toxic substance	3	
- toxic substance if in contact with other substances	2	
- non-toxic substance	1	
12d Location of tank farm	Score	
- in plant area within populous area *	4	Score 1
- sloping tank farm *	3	
- flat tank farm *	2	
- tank farm within an abandoned area *	1	

* If tank is near a public fence, add 1 to the score

Consequence factor, health and safety aspects**12e**

Maximum consequence factor is score of 12a or $[(12b+12c+12d)/3]$, whichever is the greater

Consequence factor χ
2.7

Consequence rating, health and safety aspects

13 Relation between consequence factor χ and assigned consequence rating			
Assigned Consequence Rating		Factor	
High	H	$\chi \geq 3.0$	Consequence rating M
Medium	M	$2.5 \leq \chi < 3.0$	
Low	L	$2.0 \leq \chi < 2.5$	
Negligible	N	$\chi < 2.0$	

Environmental aspects (E.3.3.4)

14a Environmental hazard to soil and water has the potential to cause:	Score	
- severe damage/nuisance/pollution over large area	4	
- environmental pollution; extensive restoration required	3	
- environmental nuisance affecting neighbourhood	2	Score 2
- no or negligible environmental effect	1	
14b Vapour emission	Score	
- large (> 1000 m ³) harmful (toxic) release	3	
- small harmful (toxic) release	2	Score 1
- no or negligible harmful (toxic) release	1	

Consequence factor, environmental aspects

14c Maximum consequence factor is score of 14a or 14b whichever is the greater

Consequence factor χ
2

Consequence rating, environmental aspects

15 Relation between consequence factor χ and assigned consequence rating			
Assigned Consequence Rating		Factor	
High	H	$\chi \geq 3.0$	Consequence rating L
Medium	M	$2.5 \leq \chi < 3.0$	
Low	L	$2.0 \leq \chi < 2.5$	
Negligible	N	$\chi < 2.0$	

STEP 3 Risk assessment - bottom plates**Establish probability rating**

16 Establish probability factor ζ			Probability factor 3.13
Use formula: {2x[1] + 1x[2] + 3x[3] + 2x[4] + 2x[5] + 4x[6] + 5x [7] + 2x[8] + 3x[9]}/9 (boxes)			
[1] = value or score of Box 1 (etc.)			
17 Relationship between probability factor ζ and probability rating			
Calculated Value of Factor		Assigned Probability Rating	
$\zeta < 2.15$	Negligible		N
$2.15 \leq \zeta < 2.5$	Low		L
$2.50 \leq \zeta < 3.00$	Medium		M
$\zeta \geq 3.00$	High		H
Establish consequence rating			
18. Aspect		Rating	
Economic	M		
Health and safety	M		
Environmental	L		
Highest consequence rating	M		

Probability Rating: **H**

Consequence Rating: **M**

Establish overall risk rating

Risk assessment matrix

	RBI	Risk assessment matrix			
Probability rating	High	L	H	E	E
	Low	L	M	H	E
	Medium	N	L	M	H
	Negligible	N	N	L	M
Consequence rating		Negligible	Low	Medium	High

19. Overall risk rating

E

See 6.3 Step 9 for methods of reducing risk ratings.

STEP 4 Determine remaining life - bottom plates

Corrosion rate

20a What is the minimum thickness measured during previous inspection (PI)?	6mm
20b Period of service between previous PI and date of this inspection	38 years
Note: when 20a value is original design thickness, use elapsed time from commissioning date of tank in 20b; when 20a value is thickness known at the previous PI, use elapsed time since the previous PI in 20b.	
21a What is the measured minimum bottom plate thickness at the date of the present inspection?	2.8mm
21b What is the allowable minimum bottom plate thickness? See 8.4: - for standard type A, B & C foundations (see EEMUA 183, Section 2 & Appendix IV, Sheet 1), t (min) bottom plates = 2.5mm; - for type D and E foundations and when leak detection & management systems or double bottoms are installed (see EEMUA 183, section 7.2.1 and Appendix I, Figure I-1), t (min) bottom plates = 1.5mm; - in all cases for annular plates, t (min) = 50% of original thickness (see Appendix A.2, this Publication)	2.5mm
22 Calculate corrosion rate per year, using formula: $(20a - 21a) / 20b$	0.08mm/year
If measurement figures are not known use general figures as per Chapter 4, Vol. 1	
23 What is the average corrosion rate established from similar product tanks? (See Chapter 4)	0mm/year
Acceleration factor to take pitting into account	
24 Acceleration factor for pitting. Multiply general corrosion rate (CR) by factor: - CR $\geq$ 0.5mm/year = 1.15 0.3 $\leq$ CR < 0.5mm/year = 1.1 0.1 $\leq$ CR < 0.3mm/year = 1.05 - CR < 0.1mm/year = 1.0	1.05 factor
25 Adjusted corrosion rate use formula: (22 x 24) (measurements) or (23 x 24) (guess)	0.09mm/year If known always use 22
REMAINING LIFE (RL)	
26 Remaining life use formula: $(21a - 21b) / 25$	3.4 years

STEP 5 Determine interval before next required inspection—bottom plates

Establish confidence rating factor *K* (see Step 3, and Table 18)

Probability rating	RBI	Confidence factor <i>K</i>			
	High	0.8	0.6	0.5	0.5
	Medium	0.8	0.7	0.6	0.5
	Low	0.9	0.8	0.7	0.6
	Negligible	0.9	0.9	0.8	0.7
Consequence rating		Negligible	Low	Medium	High

27 Establish confidence factor *K* from above matrix

0.5 factor

Adjustment to factor *K* (see E.3.5.2 & E.3.5.3)

Establish credit or debit points to adjust the factor *K*

28 Credit or debit points for:

NDT method used and extent of coverage (number of readings) to establish actual bottom plate thickness

- visual + spot ultrasonic (US) = - 0.1
- US on gridline system = 0
- floor scan + US = 0.1

0.1 credit

29 Credit points for:

Frequency of internal inspections performed during service life of tank in line with Appendix B

- multiple inspections carried out, insert 0.1
- no or minimal inspection data available, insert 0

0.1 credit

30 Credit or debit points for:

Type of interconnecting bottom plate welds outside of annular section

- butt welds = 0.1
- double pass lap welds = 0
- single pass lap welds = - 0.1

0

31 Sum of credit and debit points:

use formula (**28** + **29** + **30**), but maximum allowable credit points may not exceed 0.2

0.2

32 Establish adjusted factor *K*

Use formula: (**27** + **31**)

0.7

INTERVAL BEFORE NEXT REQUIRED INSPECTION

33 Interval before next required inspection:

use formula (**26** x **32**)

$$II = K \times RL$$

2.38 years

Model calculation for determining corrosion rate, probability, consequence & risk ratings, remaining life, and interval before next inspection of shell plates under corrosion attack

See E.3. Scores as given below are indicative only.

STEP 1 Determine scores for calculating probability factor - shell plates (E.3.2.3)

Actions taken to limit internal corrosion on shell plates	
1 Internal coating is applied to tank shell plates (see Appendix C.5) - internal coating applied and quality is sound = 0 - internal coating applied and quality is poor = 1 - internal coating not existing = 2	Score 2
2 External coating is applied to tank shell plates (see Appendix C.5) - external coating applied and quality is sound = 0 - external coating applied and quality is poor = 1 - external coating not existing = 2	Score 0
Factors that influence corrosion rates	
3a Storage conditions - temperature of product > 85°C - between 40 and 85°C = 1 <40 °C = 0	Score 0
3b Heating coils in tank? - yes = 1 - no = 0 (Data needed when there is direct contact between heating coil and tank shell plates)	Score 0

Weighted score for **3a** and **3b**,
use formula: **3** = (**3a**+**3b**)/2.5 = 0

4 Product corrosivity		
Group	Risk	Score
1	H	2
1A	M	1
2	H	2
2A	M	1
3	M	1
3A	L	0
4	L	0
5	L	0
6	L	0
7	M	1
7A	H	2
8	M	1
8A	L	0
9	H	2

Score 1

5 Vapour corrosivity		
Group	Risk	Score
1	H	2
1A	H	2
2	H	2
2A	H	2
3	L	0
3A	L	0
4	L	0
5	L	0
6	M	1
7	H	2
7A	H	2
8	M	1
8A	M	1
9	H	2

Score 1

Average score for 4 and 5:
1

6 Tank shell has been insulated, and rain water may cause corrosion under insulation	
- CUI is likely to occur	2
- Tank shell is properly insulated and CUI is unlikely to occur	0
- Tank shell is not insulated	0

Score 0

Calculation of probability factor is shown at the beginning of Step 3

Step 2 Determine consequence factors & ratings for the various aspects - shell plates (E.3.3)

7a Time to repair	Score	
- internal entry required, major repair (>8 months)	4	
- internal entry required, major repair (3–8 months)	3	Score 3
- internal entry required, limited repair (>3 months)	2	
- no internal entry required, limited repair, no limitation on repair time	1	
7b Cost of repair		
- > 50% of capital cost (new tank)	4	
- 10–50% of capital cost	3	Score 2
- 5–10% of capital cost	2	
- negligible or less than 5% of capital cost	1	
7c Probable magnitude of product loss		
- >5% of tank contents	3	Score 2
- <5% of tank contents	2	
- no release of product	1	

Consequence factor, economic aspects

7d	
Maximum consequence factor is score of [(7a + 7b)/2] or 7c whichever is the greater	Consequence factor χ 2.5

Consequence rating, economic aspects (E.3.3.5)

8 Relation between consequence factor χ and assigned consequence rating			
Assigned consequence rating		Factor	
High	H	$\chi \geq 3.0$	
Medium	M	$2.5 \leq \chi < 3.0$	Consequence rating M
Low	L	$2.0 \leq \chi < 2.5$	
Negligible	N	$\chi < 2.0$	

Health and Safety Aspects (E.3.3.3)

9a Likelihood of injury to personnel	Score	
- serious injury or fatality on site	4	
- lost time injury/medical treatment	3	Score 2
- minor injury	2	
- no injury or near miss	1	
9b Product flammability as per IP model Code of Safe Practice in the Petroleum Industry, Part 19		
- class I product	4	
- class II(2) and class III(2) product	3	Score 3
- class II(1) product	2	
- class III(1) and unclassified product	1	
9c Product toxicity		
- extremely toxic substance	4	
- toxic substance	3	Score 4
- toxic substance if in contact with other substances	2	
- non-toxic substance	1	
9d Location of tank farm		
- in plant area within populous area*	4	
- sloping tank farm*	3	Score 1
- flat tank farm	2	
- tank farm within an abandoned area	1	

* If tank is near a public fence, add 1 to the score

Consequence factor, health and safety aspects

9e

Maximum consequence factor is score of **9a** or $[(9b+9c+9d)/3]$ whichever is the greater

Consequence factor χ
2.7

Consequence rating, health and safety aspects

10 Relation between consequence factor χ and assigned consequence rating

Assigned consequence rating	Factor
High H	$\chi \geq 3.0$
Medium M	$2.5 \leq \chi < 3.0$
Low L	$2.0 \leq \chi < 2.5$
Negligible N	$\chi < 2.0$

Consequence rating
M

Environmental Aspects (E.3.3.4)

11a Environmental hazard to soil and water has the potential to cause:

- severe damage/nuisance/pollution over large area
- environmental pollution; extensive restoration required
- environmental nuisance affecting neighbourhood
- no or negligible environmental effect

4

3

2

1

Score 2

11b Vapour emission

- large (> 1000 m³) harmful (toxic) release
- small harmful (toxic) release
- no or negligible harmful (toxic) release

3

2

1

Score 1

Consequence factor, environmental aspects

11c

Maximum consequence factor is score of **11a** or **11b** whichever is the greater

Consequence factor χ
2

Consequence rating, environmental aspects

12 Relation between consequence factor χ and assigned consequence rating

Assigned consequence rating	Factor
High H	$\chi \geq 3.0$
Medium M	$2.5 \leq \chi < 3.0$
Low L	$2.0 \leq \chi < 2.5$
Negligible N	$\chi < 2.0$

Consequence rating
L

STEP 3 Risk assessment—shell plates**Establish probability rating**

13 Establish probability factor ζ		
Use formula: $(3 \times [1] + 3 \times [2] + 2 \times [4+5] + [6]) / 5(\text{boxes})$		
[1] = value or score of Box 1 (etc.)		
14 Relationship between probability factor ζ and probability rating		
Assigned Probability Rating		Factor
Negligible	N	$\zeta < 2.15$
Low	L	$2.15 \leq \zeta < 2.5M$
Medium	M	$2.50 \leq \zeta < 3.00$
High	H	$\zeta \geq 3.00$
Establish Consequence Rating		
15. Aspect	Rating	
Economic	M	
Health and safety	M	
Environmental	L	
Highest consequence rating	M	

2.0

Probability Rating: N

Consequence Rating: M

Establish overall risk rating

	RBI	Risk assessment matrix			
Probability rating	High	L	H	E	E
	Low	L	M	H	E
	Medium	N	L	M	H
	Negligible	N	N	L	M
Consequence rating		Negligible	Low	Medium	High

16. Overall risk rating**L**

See 16.3 Step 9 for methods of reducing risk ratings.

STEP 4 Determine remaining life (shell)**17** Time in service between previous periodic inspection (PI) and date of this examination**38**

years

18 Course	Thickness in mm				Calculated average corr. rate (mm/yr)*	EEMUA average corr. rate†
	As built thickness	Min. thickness previous insp.	Min. thickness this insp.	Min. required thickness‡		
Bottom 1	Column A	Column B	Column C	Column D	Column E	Column F
2	31	30	27	26	0.07895	
3	28	27	23	22	0.10526	
4	25	24	21	20	0.07895	
5	19	18	15	14.4	0.07895	
6	14	13	10	9.3	0.07895	
7	11	10	7	5.3	0.07895	
8	6	6	5	4.1	0.02632	
9	6	5.3	4.8	3.4	0.01316	
Top 10	6	4.8	4.7	3.3	0.00263	

* Column 18E = (Col 18B – Col 18C)/17

† Column 18F: If 18B or 18C are unknown then in accordance with Table 2

‡ Column 18D is the maximum of 19A, 19B and 19C

Assessment of minimum required/allowable thickness (mm)

19 Course	Internal Pressure*	External pressure†	Incorporating uniform roof load‡
	Column A	Column B	Column C
Bottom 1	25	25	26
2	22	21	22
3	19	19	20
4	13	14	14.4
5	8	9	9.3
6	5	5	5.3
7	3	4	4.1
8	3	3.2	3.4
9	3	3.1	3.3
Top 10			

* See 9.3

† See 9.5 and BS 2654, 7.3.2.7

‡ See API 620, 3.5.4.2

Acceleration factor to take pitting into account

20 Acceleration factor for pitting	
Multiplying general corrosion rate (CR) by factor:	
- CR ≥ 0.5mm/year = 1.4	Factor 1.1
- 0.3 ≤ CR < 0.5mm/year = 1.2	
- 0.1 ≤ CR < 0.3mm/year = 1.1	
- CR < 0.1mm/year = 1.0	

Actual corrosion rate to be used in remaining life calculations

Use formula: [average corrosion rate (18 Col. E) or (18 col. F) x Box 20] for calculating adjusted corrosion rate

21 Remaining life calculation based on adjusted corrosion rate			
	Average corrosion rate (mm/year)	Adjusted corrosion rate (mm/year)	Remaining life (years)
Course	Column A*	Column B†	Column C‡
Bottom 1	0.07895	0.08684	11.52
2	0.10526	0.11579	8.64
3	0.07895	0.08684	11.52
4	0.07895	0.08684	6.91
5	0.07895	0.08684	8.06
6	0.07895	0.08684	19.58
7	0.02632	0.02895	31.09
8	0.01316	0.01447	96.73
9	0.00263	0.00289	483.64
Top 10			

* Column 21A = 18E; if unknown use 18F

† Column 21B = 21A x Box 20

‡ Column 21C = (18C–18D)/21B

Remaining Life (RL)

22 Governing remaining life (minimum value of Col. 21C)

6.91
years

Step 5 Determine interval before next required inspection (shell plates)**Establish confidence rating before next required inspection (shell plates)**

Establish confidence rating factor K (see Step 3, and Table 18)

Probability rating	RBI	Confidence factor K			
	High	0.8	0.6	0.5	0.5
	Medium	0.8	0.7	0.6	0.5
	Low	0.9	0.8	0.7	0.6
	Negligible	0.9	0.9	0.8	0.7
Consequence rating		Negligible	Low	Medium	High

23 Establish confidence factor K from above matrix

0.8 factor

Adjustment to factor K (see E.3.5.2 & E.3.5.3)**Establish credit or debit points to adjust factor K**

24 Credit points for NDT method used and extent of coverage (no. of readings) to establish actual shell plate thickness - visual + spot US = 0 - US on gridline system = +0.05 - crawler/beetle + US = +0.1	0.1 credit
25 Credit points for: Frequency of inspections performed during service life of tank in line with Appendix B - multiple inspections carried out, insert 0.1 - no or minimal inspection data available, insert 0	0.1 credit
26 Corrosion on wind girders will affect the tank's stability and thus the allowable minimum thickness of shell plates under external loads (wind and vacuum) - corrosion present, but no effect on the integrity of the tank shell plates = 0 - corrosion present and this induces effects on integrity of tank shell plates = -0.1 - no corrosion on wind girder = 0	-0.1 debit
27 Buckles in shell plates will affect the tank's stability and thus the allowable minimum thickness of shell plates under external loads (wind and vacuum) - buckles present but no effect on the integrity of the tank shell plates = 0 - buckles present and they induce effects on integrity of tank shell plates = -0.1 No buckles on tank shell plates = 0	-0.1 debit
28 Bending moments in shell nozzles induced by differential settlements between the tank structure and the supports of the piping to/from the tank, will affect the allowable minimum thickness of the shell plates. - moments present but no effect on integrity of tank shell plates = 0 - moments present and they induce effects on integrity of tank shell plates = -0.1 - no moments in shell nozzles or structures available which reduce nozzle loads = 0	-0.1 debit
29 Sum of credits and debits points: use formula (24 + 25 + 26 + 27 + 28), but maximum allowable credit points may not exceed 0.2	-0.1 debit
30 Establish adjusted factor K Use formula: (23 + 29)	0.7
Interval before next required inspection	
31 Interval before next required inspection: use formula (30 x 22)	4.84 years

$$II = K \times RL$$

Model calculation for determining corrosion rate, probability, consequence & risk ratings, remaining life, and interval before next required inspection of fixed roof plates under corrosion attack

See E.3 'Scores' as given below are indicative only

STEP 1 Determine scores for calculating probability factor (E.3.2.4)

Actions taken to limit internal corrosion on fixed roof plates	
1 Internal coating is applied to tank roof plates (see Appendix C.5) - internal coating applied and quality is sound = 0 - internal coating applied and quality is poor = 1 - internal coating not existing = 2	Score 2
2 External coating is applied to tank roof plates (see Appendix C.5) - external coating applied and quality is sound = 0 - external coating applied and quality is poor = 1 - external coating not existing = 2	Score 0
Factors that influence corrosion rates	
3 Storage conditions - temperature of product > 85°C = 2 - between 40 and 85°C = 1 <40 °C = 0	Score 0

4 Vapour corrosivity		
Group	Risk	Score
1	H	2
1A	H	2
2	H	2
2A	H	2
3	L	0
3A	L	0
4	L	0
5	L	0
6	M	1
7	H	2
7A	H	2
8	M	1
8A	M	1
9	H	2

Score 1

5 The tank is operated with an inert blanket system above the product - yes = 0 - no but the score of Box 3 ≤ 1, = 0 - no but the score of Box 3 > 1, = 2	Score 1
6a Roof supporting structures is located below roof plates - Crevice corrosion is likely to occur = 2 - Crevice corrosion is not likely to occur = 0 - roof supporting structure is placed on top of roof plates or the roof is of the self-supporting or membrane type = 0	Score 0
6b Roof supporting structures is located on top of the roof plates - water draw-off points are not adequate enough for preventing accumulation of rain water = 2 - water draw-off points are adequate enough for preventing rain water accumulation = 0 - if roof supporting structure is not located on top of roof plates and proper water draw-off is secured at all times = 0	Score 2

Weighted score of **6** is the greater of **6a** and **6b**

Score 2

7 Tank roof has been insulated and rain water may cause corrosion under insulation (CUI)

- CUI is likely to occur = 2
- Tank roof is properly insulated and CUI is not likely to occur = 0
- Tank roof is not insulated = 0

Score 2

STEP 2 Determine consequence factors & ratings for the various aspects – bottom plates (E3.3)

8a Time to repair	Score	
- internal entry required, major repair (> 8 months)	4	
- internal entry required, major repair (3-8 months)	3	
- internal entry required, limited repair (> 3 months)	2	Score 3
- no internal entry required, limited repair, no limitation on repair time	1	
8b Cost of repair	Score	
- > 50% of capital cost (new tank)	4	
- 10 - 50% of capital cost	3	Score 2
- 5 - 10% of capital cost	2	
- negligible or less than 5% of capital cost	1	
8c Probable magnitude of production loss	Score	
- > 5% of tank contents	3	
- < 5% of tank contents	2	Score 2
- no release of product	1	

Consequence factor, economic aspects

8d Maximum consequence factor is score of $[(8a + 8b)/2]$ or **8c**, whichever is the greater

Consequence factor χ
2.5

Consequence rating, economic aspects

9 Relation between consequence factor χ and assigned consequence rating			
Assigned Consequence Rating		Factor	
High	H	$\chi \geq 3.0$	Consequence rating M
Medium	M	$2.5 \leq \chi < 3.0$	
Low	L	$2.0 \leq \chi < 2.5$	
Negligible	N	$\chi < 2.0$	

Health and Safety Aspects (E.3.3.3)

10a Likelihood of injury to personnel	Score	
- serious injury/fatality on site	4	Score 2
- lost time injury/medical treatment	3	
- minor injury	2	
- no injury or near miss	1	
10b Product flammability as per IP Model Code of Safe Practice in the Petroleum Industry, Part 19	Score	
- class I product	4	Score 3
- class II(2) and class III(2) product	3	
- class II(1) product	2	
- class III(1) and unclassified product	1	
10c Product toxicity	Score	Score 4

- extremely toxic substance	4	
- toxic substance	3	
- toxic substance if in contact with other substances	2	
- non-toxic substance	1	
10d Location of tank farm	Score	
- in plant area within populous area *	4	Score 1
- sloping tank farm *	3	
- flat tank farm *	2	
- tank farm within an abandoned area *	1	

* If tank is near a public fence, add 1 to the score

Consequence factor, health and safety aspects

10e

Maximum consequence factor is score of 10a or [(8b+8c+8d)/3], whichever is the greater

Consequence factor χ

2.7

Consequence rating, health and safety aspects

11 Relation between consequence factor χ and assigned consequence rating			
Assigned consequence rating		Factor	
High	H	$\chi \geq 3.0$	Consequence rating M
Medium	M	$2.5 \leq \chi < 3.0$	
Low	L	$2.0 \leq \chi < 2.5$	
Negligible	N	$\chi < 2.0$	

Environmental aspects (E.3.3.4)

12a Environmental hazard to soil and water has the potential to cause:	Score	
- severe damage/nuisance/pollution over large area	4	Score 2
- environmental pollution; extensive restoration required	3	
- environmental nuisance affecting neighbourhood	2	
- no or negligible environmental effect	1	
12b Vapour emission	Score	
- large (> 1000 m ³) harmful (toxic) release	3	Score 1
- small harmful (toxic) release	2	
- no or negligible harmful (toxic) release	1	

Consequence factor, environmental aspects

12c Maximum consequence factor is score of 14a or 14b whichever is the greater

Consequence factor χ

2

Consequence rating, environmental aspects

13 Relation between consequence factor χ and assigned consequence rating			
Assigned Consequence Rating		Factor	
High	H	$\chi \geq 3.0$	Consequence rating L
Medium	M	$2.5 \leq \chi < 3.0$	
Low	L	$2.0 \leq \chi < 2.5$	
Negligible	N	$\chi < 2.0$	

STEP 3 Risk assessment—roof plates**Establish probability rating**

14 Establish probability factor ζ		
Use formula: $\{3x[1] + 3x[2] + 2x[3] + 4x[4] + [5] + [6] + [7]\}/7$ (boxes)		
[1] = value or score of Box 1 (etc.)		
15 Relationship between probability factor ζ and probability rating		
Assigned Probability Rating		Factor
Negligible	N	$\zeta < 2.15$
Low	L	$2.15 \leq \zeta < 2.5M$
Medium	M	$2.50 \leq \zeta < 3.00$
High	H	$\zeta \geq 3.00$
16 Establish consequence rating		
Aspect	Rating	
Economic	M	
Health and safety	M	
Environmental	L	
Highest consequence rating	M	

2.38

Probability Rating: L

Consequence Rating: M

Establish overall risk rating

	RBI	Risk assessment matrix			
Probability rating	High	L	H	E	E
	Low	L	M	H	E
	Medium	N	L	M	H
	Negligible	N	N	L	M
Consequence rating		Negligible	Low	Medium	High

17 Overall risk rating

M

See 16.3 Step 9 for methods of reducing risk ratings.

STEP 4 Determine remaining life—roof plates

18a What is the minimum thickness of the roof plates measured during previous inspection (PI)?	6.35mm
18b Period of service between previous PI and date of this inspection	38 years
Note: when 18a value is original design thickness, use elapsed time from commissioning date of tank in 18b; when 18a value is thickness known at the previous PI, use elapsed time since the previous PI in 18b.	
19a What is the measured minimum roof plates thickness at the date of the present inspection?	4.3mm
19b What is the allowable minimum thickness of the roof plates? (Normally 75% of 3mm)	2.25mm
20 Calculate corrosion rate per year, using formula: $(18a - 19a) / 18b$ (Only to be used if sound 'trending' measurements are available)	0.053947mm/year
If measurement figures are not known use general figures as per Chapter 4	
21 What is the average corrosion rate established from similar product tanks? (See Chapter 4)	
Acceleration factor to take pitting into account	

22 Acceleration factor for pitting. Multiply general corrosion rate (CR) by factor: - $CR \geq 0.5\text{mm/year} = 1.15$ - $0.3 \leq CR < 0.5\text{mm/year} = 1.1$ - $0.1 \leq CR < 0.3\text{mm/year} = 1.05$ - $CR < 0.1\text{mm/year} = 1.0$	1.0 factor
23 Adjusted corrosion rate use formula: (20 x 22) (measurements) or (21 x 22) (guess)	0.0539mm/year If known always use 20
REMAINING LIFE (RL)	
26 Remaining life use formula: (19a - 19b)/23	38.0 years

Step 5 Determine interval before next required inspection (roof plates)

Establish confidence rating factor **K** (see Step 3, and Table 18)

	RBI	Confidence factor K			
Probability rating	High	0.8	0.6	0.5	0.5
	Medium	0.8	0.7	0.6	0.5
	Low	0.9	0.8	0.7	0.6
	Negligible	0.9	0.9	0.8	0.7
	Consequence rating	Negligible	Low	Medium	High

25 Establish confidence factor **K** from above matrix

0.7 factor

Adjustment to factor **K** (see E.3.5.2 & E.3.5.3)

Establish credit or debit points to adjust factor **K**

26 Credit points for NDT method used and extent of coverage (no. of readings) to establish actual roof plate thickness - visual + spot US = 0 - US on gridline system = +0.05	0.1 factor
27 Credit points for: Frequency of inspections performed during service life of tank in line with Appendix B1 - multiple inspections carried out, insert 0.1 - no or minimal inspection data available, insert 0	0.1 factor
28 Differential settlements between the tank structure and the supports of the piping to/from the tank will affect the allowable minimum thickness of the roof plates: - moments present but no effect on integrity of tank roof plates = 0 - moments present and they induce effects on integrity of tank roof plates = -0.1 - no moments in the roof nozzles or structures = 0	0 number
29 Sum of credits and debits points: use formula (26 + 27 + 28) , but maximum allowable credit points may not exceed 0.2	0.2
30 Establish adjusted factor K Use formula: (25 + 30)	0.9
Interval before next required inspection	
31 Interval before next required inspection: use formula (30 x 24) II = K x RL	34.23 years

Note: may never exceed 20 years

E.5 Methodology to assess remaining service time and next maintenance period (Reliability Centred Maintenance)

E.5.1 General calculations

The flow chart in Figure 121 shows the phased way to calculate the maximum service time of a storage tank which degrades under mechanisms of which the progress cannot be measured during the use of the tank.

The method to assess the next maintenance period follows the EEMUA RCM methodology as described in Section 17.5 of the EEMUA 159. Section E.6 gives examples of calculating the periods between maintenance windows that are valid for tank components that fall under the RCM regime.

Appendix E.7, provides the method of calculation and describes the various aspects that have influence on the risk classification, the remaining in-service time of tank components and the consequence classification factor. These parameters are needed to assess the next maintenance period for such components – and, in return, also for the total storage tank.

E.6 The phrase ETBF (Estimated Time Between Failures)

E.6.1 Introduction

A successful implementation of the RCM-methodology within an organization requires support from within that organization and commitment of the management of such organization as the initial search for and gathering of the required information and data and the performing of the analyses often could be costly and absorbs time from staff involved. When a RCM process finally is fully implemented, it also is a requirement to follow-up the results and not to deviate from the tasks and time frames set. Required and determined preventive maintenance tasks, established by the RCM-process, should be followed-up by the integrated maintenance department and should be adhered to by and should be embedded within the planning (schedule) and budget (costs forecasts) of that department.

E.6.2 Implementation

Similar as required by a successful implementation of the RBI process, also the implementation of the RCM process requires the formation of a team, which is formed from members of different disciplines that work together to:

1. Assess the criticality and the importance of (tank) components for the entire (tank) system.
2. Assess and identify the dominant failure mode for such component.
3. Assess and identify the relevant pattern of the dominant failure mode (see Figure 93).

The pattern of a failure mode can be illustrated as a curve of a conditional probability of failure as a function of the "life-time" of a tank or such component. The conditional probability is defined as the chance that a component will develop a failure mode during a specific time interval, providing that the component will fulfill its function as intended during a time long enough to reach that interval. In modern reliability techniques most patterns of a failure mode can be categorized as one of the six most available patterns of failure as shown in Figure 122.

Identification of the pattern of failure is important since this determines whether

preventive maintenance tasks are to be specified and which tasks should be selected to let the component fulfil its intended function as long as required. Time base maintenance is totally not effective as the failure mode is similar as patterns D, E, of F.

E.6.3 Model calculation routine for RCM

Figure 135 flowchart illustrates the stepwise calculation process for determining the interval before the next required maintenance activity for a tank component due to any degradation mechanism, not being general corrosion and settlement. The calculation process follows the EEMUA RCM methodology (Section 17.5). Section E.4 gives examples of calculations of inspection intervals applicable to **bottom, shell** and (fixed roof tank) **roof plates** for the degradation mechanism of **corrosion**. Corrosion has been chosen as it is the likely dominant failure mechanism for those components.

This Section E.3, gives guidance on the calculation process, and lists and discusses the various features and aspects that influence **risk rating, remaining life** and **consequence rating factor**, and hence the interval before the next required inspection.

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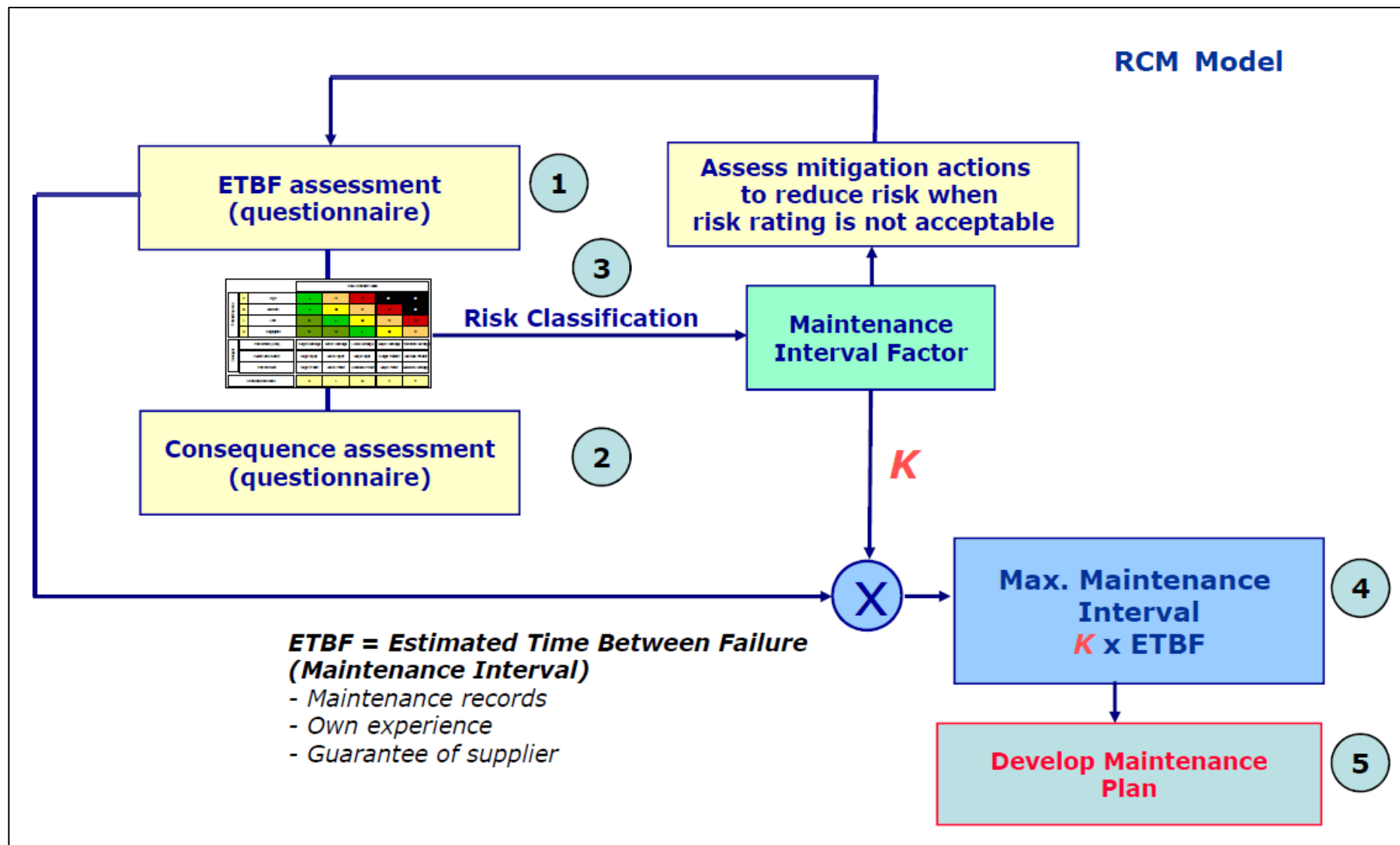


Figure 134 Flow chart of risk assessment calculation model for RCM

E.6.3.1 Step 1: ETBF classification

The ETBF can be classified in a simple way as shown in Table 40.

Table 40 Classification of the “Estimated Mean Time Between Failures”

Without preventive maintenance	Probability of a failure (failure frequency/year)	ETBF (years)	Class
The tank component will fail each year (or shows a higher frequency)	≥ 1	≤ 1	H
This tank component fails every 3 to 5 year	0.25	4	M
It is possible that this tank component will fail before the next inspection period – as determined by the RBI-process will be reached	0.10	10	L
This tank component will not fail earlier than the preset and next inspection period that was assessed by the RBI-methodology of EEMUA	< 0.05	> 20	N

E.6.3.2 Step 2: Assess the consequence classification of a failure

This step follows identical decisions that were taken during executing the calculation of the consequences performed in the RBI classification model of a tank component as described previously, i.e. identical questionnaires has been introduced for assessing the consequences of a dominant failure mechanism of a tank component.

E.6.3.2.1 Economic aspects

BOXES 2a, 2b & 2c

Here it is assumed that there will be a major repair causing an outage of between 3 and 8 months (2a score = 3), the cost of repair is between 5 and 10% of the capital cost of a new tank (2b score = 2), and the possible magnitude of product loss is 5% of the tank's contents or less (2c score = 2).

BOXES 2d & 3

The consequence factor χ (2d) is either the average of 2a + 2b scores or the 2c score, whichever is greater. In this example the former is the greater:
 $\chi = (2 + 3)/2 = 2.5$. From box 4 (using the table in E.3.), the consequence rating assigned to this value of χ is 'M'.

E.6.3.2.2 Health- & safety en environmental aspects [Boxes 4a-5]

By a process similar to the foregoing, the consequence rating for health and safety aspects is 'M' (box 5), and for environmental aspects is 'L' (box 15).

E.6.3.3 Step 3: Determine overall risk rating

The EEMUA PPM-methodology uses, for both processes RCM as well as RBI, an identical Risk Assessment Matrix (RAM), Table 41. After having assessed the ETBF-classification (vertical axis in below RAM) and the maximum consequence classification, based on the highest value established from the three different aspects of consideration – Economical aspects, Health and Safety aspects and Environmental aspects (which is expressed in the horizontal axis of the RAM) – the total risk classification of the tank component under consideration is determined. This is the point where the two axes of the ETBF- and consequence classification come together.

Table 41 Risk Matrix (RAM) for the RCM-methodology

ETBF-classification	RCM	Risk Assessment Matrix			
	High	L	H	E	E
	Medium	L	M	H	E
	Low	N	L	M	H
	Negligible	N	V	L	M
Consequence classification		Negligible	Low	Medium	High

E.6.3.4 Step 4: Assess the period to the next maintenance interval

The next maintenance period can be assessed by using the below formula:

$$\text{NMI} = K * \text{ETBF}$$

Where: NMI = Next Maintenance Interval
 ETBF = Frequency of failure occurrence within a tank component
 K = Confidence factor (vary between 0 and 1).

From the found risk location (risk classification) within the RAM of a tank component, as described in Section E.7.3.3, the value of the Confidence Factor *K* is established, based on experiences the PPM-team has with subject component and from the following Table 42.

Table 42 Values of the confidence factor relative to the risk classification

ETBF-Classification	RCM	Confidence Factor <i>K</i>			
	High	0.8	0.6	0.5	0.5
	Medium	0.8	0.7	0.6	0.5
	Low	0.9	0.8	0.7	0.6
	Negligible	0.9	0.9	0.8	0.7
Consequence classification		Negligible	Low	Medium	High

The implementation of the EEMUA RCM-methodology is further explained in the model calculation example below (see Section E.7).

E.7 Model calculation for assessing next maintenance period of a tank component

STEP 1: Assess the ETBF-value of the tank component under consideration for which the RCM-methodology is valid –

Without preventive maintenance	Probability of a failure (failure frequency/year)	ETBF (years)	Class
The tank component will fail each year (or shows a higher frequency)	≥ 1	≤ 1	H
This tank component fails every 3 to 5 year	0.25	4	M
It is possible that this tank component will fail before the next inspection period – as determined by the RBI-process will be reached	0.10	10	L
This tank component will not fail earlier than the preset and next inspection period that was assessed by the RBI-methodology of EEMUA	< 0.05	> 20	N

ETBF-value

1 ETBF value = 10 years

STEP 2 Assess the consequence factors and the consequence classifications of the different aspects –

a) Economic aspects

2a Time to repair	score	
- internal entry required, major repair (> 8 months)	4	
- internal entry required, major repair (3 - 8 months)	3	score 3
- internal entry required, limited repair (> 3 months)	2	
- no internal entry required, limited repair, no limitation on repair time	1	
2b Cost years of repair	score	
- $> 50\%$ of capital costs (new tank)	4	
- 10 – 50% of capital costs	3	score 2
- 5 – 10% of capital costs	2	
- negligible, or less than 5% of capital costs	1	
2c Probable magnitude of product loss	score	
- $> 5\%$ of tank content	3	Score 2
- $< 5\%$ of tank content	2	
- no release of product	1	

Consequence factor, economical aspects**2d**

The maximum consequence factor is score of $[(2a + 2b)/2]$ or $2c$, whichever is the greater

Consequence factor χ
2.5

Consequence classification, economical aspects

3 Relation between consequence factor χ and its assigned consequence classification	
Assigned consequence classification	factor
High H	$\chi \geq 3.0$
Medium M	$2.5 \leq \chi < 3.0$
Low L	$2.0 \leq \chi < 2.5$
Negligible N	$\chi < 2.0$

Consequence
Classification M

b) Health and safety aspects

4a Likelihood of injury of personnel	score	
- serious injury/fatality on site	4	Score 2
- lost time injury/medical treatment	3	
- minor injury	2	
- no injury or near miss	1	
4b Product flammability as per IP Model Code of Safe Practice in the Petroleum Industry, Part 19	score	
- Class 1 product	4	Score 3
- Class II(2) en Class III(2) product	3	
- Class II(1) product	2	
- Class III(1) and unclassified product	1	
4c Product toxicity	score	
- extremely toxic substance	4	Score 4
- toxic substance	3	
- toxic substance if in contact with other substances	2	
- non-toxic substance	1	
4d Location of tank farm	score	
- in plant area within populous area*	4	Score 1
- sloping tank farm*	3	
- flat tank farm*	2	
- tank farm within an abandoned area*	1	

* if tank is near a public fence, add 1 to the score

Consequence factor, health and safety aspects**4e**

Maximum consequence factor is score of 4a of $[(4b+4c+4d)/3]$, whichever is the greater

Consequence factor χ
2.7

Consequence classification, health and safety aspects

5 Relation between consequence factor χ and its assigned consequence classification		
Assigned consequence classification		factor
High	H	$\chi \geq 3.0$
Medium	M	$2.5 \leq \chi < 3.0$
Low	L	$2.0 \leq \chi < 2.5$
Negligible	N	$\chi < 2.0$

Consequence
Classification
M**c) Environmental aspects**

6a Environmental hazard to soil and water has the potential to cause	score
- severe damage/nuisance/pollution over large area	4
- environmental pollution; extreme restoration required	3
- environmental nuisance affecting neighbourhood	2
- no or negligible environmental effect	1

score
2**Consequence factor, environmental aspects**

6b Vapour emission	score
- large (> 1000 m ³) harmful (toxic) release	3
- small harmful (toxic) release	2
- no or negligible harmful (toxic) release	1

Score
1

6c
Maximum consequence factor is score of 6a or 6b, whichever is the greater

Consequence factor χ
2**Consequence classification, environmental aspects**

7 Relation between consequence factor χ and its assigned Consequence Classification		
Assigned consequence classification		factor
High	H	$\chi \geq 3.0$
Medium	M	$2.5 \leq \chi < 3.0$
Low	L	$2.0 \leq \chi < 2.5$
Negligible	N	$\chi < 2.0$

Consequence
Classification
L**Set overall consequence classification determined**

8 Aspect	Classification
Economic	M
Health and safety	M
Environmental	L
Highest consequence classification	M

Consequence classification
M

STEP 3: Assess overall Risk rating -

Risk assessment matrix

ETBF-classification	RCM	Risk assessment matrix			
	High	L	H	E	E
	Medium	L	M	H	E
	Low	V	L	M	H
Consequence classification	Negligible	V	V	L	M
		Negligible	low	Medium	High

9 Overall risk rating

M

STEP 4: Establish Confidence rating factor K -

ETBF-classification	RCM	Confidence factor K			
	High	0.8	0.6	0.5	0.5
	Medium	0.8	0.7	0.6	0.5
	Low	0.9	0.8	0.7	0.6
Consequence classification	Negligible	0.9	0.9	0.8	0.7
		Negligible	Low	Medium	High

10

K-value = 0,7
from above matrix

STEP 5: Next maintenance period of the tank component under consideration

Interval for the next required maintenance period

11 Interval to the next required maintenance period:
use formula: (Box 1 x Box 10) **NMI = K x ETBF**

7 years

E.8 Determining the required maintenance tasks belonging to dominant failure mechanisms of tank components

In following Tables 43 through 48, dominant failure mechanisms are detailed of main tank components, for which maintenance tasks are to be performed during the **in-service period** of a tank. The responsible PPM-team should determine the relevant ETBF-value, belonging to the described failure mechanism.

The tank components which need attention by the maintenance crew during the in-service periods are:

- tank foundation shoulder;
- external tank shell;
- external Floating roof;
- rolling ladder;
- rim seal; and
- instrumentation.

In following Tables 49 through 54, dominant failure mechanisms are detailed of main tank components, for which maintenance tasks are to be performed during the **out-of-service period** of a tank. The responsible PPM-team should determine the relevant ETBF-value, belonging to the described failure mechanism.

The tank components which need attention by the maintenance crew during the in-service periods are:

- tank foundation;
- tank bottom;
- internal tank shell;
- external or internal floating roof;
- rim seal; and
- instrumentation.

In many cases the ETBF-value that are used to determine the next maintenance interval may not be normative (or leading) with respect to the maximum assessed "in-service period" of a tank, which was determined by the RBI-process. However, in some cases an RCM-item may be prescriptive to determine the maximum "in-service period" of such a tank and maximum **next maintenance period** is m in that case leading for the **next inspection period**.

The ETBF value of many tank component are dependent of the maintenance of the coating/paint system that protect them from degradation by corrosion. In case such external paint system will be regularly maintained during the "in service period" of a tank, the ETBF-value should be set at level of 0.05. However, in case maintenance of the paint system is not scheduled to take place during that period, the ETBF value should be set a level of 0.1 (in case the regular maintenance of the paint system is scheduled to take place every 10 years on external tank components – like the (primary and secondary) wind girders, the tank shell, the tank roof, the tank nozzles, the top curb angle etc.) or at a level of 0.2 (in case the 5-yearly maintenance tasks to the paint system on tank components which are installed to provide access to the tank – like walk ways, spiral stairs, rolling ladder, platforms, hand railings etc. for which the safety integrity is required to maintained).

In general, it may be possible to assume that, in case all different (external) painting systems will be maintained during the normal scheduled "in-service periods" of storage tanks, all other critical maintenance tasks may be performed during the next "out-of-service period" which have been assessed by following the RBI-process on "trendable" degradation mechanisms.

"In-service" maintenance tasks are summarised in Tables 43 to 48.

"Out-of-service" maintenance tasks are summarised in Tables 49 to 54.

Table 43 "In-service" maintenance tasks: Foundation shoulder

Components of tanks to be maintained during "in-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
1	Foundation shoulder	1.1	drainage (rain)water under tank bottom instead of to bund	change form of tank pad shoulder to sloped edge to allow proper drainage of water away from tank bottom and/or relevel tank base			
		1.2	ranked vegetation between tank bottom and tank pad causes underside of bottom plates to corrode	remove ranked vegetation and seal crevice between tank bottom and foundation with water repellent sealant			
		1.3	erosion of tank pad shoulder	maintain micro asphalt on shoulder cover and make layer erosion resistant			

Table 44 "In-service" maintenance tasks: External tank shell

Components of tanks to be maintained during "in-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
2	External tank shell						
		2.1	external paint/coating system shows corrosion stains	maintain painting system			
		2.2	external corner weld bottom/shell connection corrodes	maintain painting system			
		2.3	secondary windgirder or its supports corrode	maintain painting system			
		2.4	primary windgirder or its supports corrode	maintain painting system			
		2.5	hand railing on primary windgirder corrodes	maintain painting system			
		2.6	concrete support underneath spiral stairs shows signs of settlement, differential to the tank base	re-instate supporting function by relevelling concrete block			
		2.7	gratings, stair threads and the stair components show corrosion areas	maintain paint and/or galvanisation layers			
		2.8	cable ducts and/or their supports/connecting structures to the stairs show corrosion	maintain galvanisation			
		2.9	cable connector to the cable ducts are disconnected	re-connect cables with new connecting details			
		2.10	gauger's platform, its supports, gratings and hand railing show corrosion	maintain paint and/or galvanisation layers			

		2.11	earthing cable connection to tank shell corrodes, is disconnected or is missing	re-instate grease or paint system on earthing connection detail to the tank shell, fasten or reconnect the cable to the earthing boss. Measure, at least, once per maintenance period the current resistance			
		2.12	reinforcing plates of shell nozzles show corrosion	maintain painting system			
		2.13	interconnecting welds between nozzles and reinforcing plates and/or to tank shell corrosion	maintain painting system			
		2.14	area near hole in doubling plate for pressure test shows corrosion	check cause of corrosion; plughole in reinforcing plate.			
		2.15		maintain painting system			
		2.16	top curb angle corrode	maintain painting system			

Table 45 "In-service" maintenance tasks: Floating roof

Components of tanks to be maintained during "in-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
3.	Floating roof						
		3.1	internal (radial) bottom settlement does not allow the floating roof to land in a horizontal position	remove landing legs from sleeves; measure profile of tank bottom through sleeves and adjust length of landing legs accordingly in order to enable landing of the roof in a horizontal position			before next out-of-service inspection
		3.2	accumulation of sludge on tank bottom does not allow the roof to land in a horizontal position	measure with help of a radar tool the sludge profile at bottom level through a manhole or a sleeve of a landing leg (remove landing leg first), adjust length of landing legs before landing of roof accordingly			before next out-of-service inspection
		3.3	painting system on all external components of the floating roof fail	maintain painting system			
		3.4	securing of pins between sleeves and landing legs and or the bleeder vent is missing	mount securing pins to both sides of the pins of the landing legs			
		3.5	landing legs are in operational	adjust height of all legs in			before next

			position whereas the bleeder vent is in maintenance position of reverse	identical position			out-of-service inspection
		3.6	landing legs, bleeder vents and/or their sleeves are out-of-vertical induced by deformations in deck of floating roof	add locally additional structures (or weight) onto the inner membrane in order to allow the legs to become vertical again			before next out-of-service inspection
		3.7	lids of manholes on pontoons of the floating roof lay loose or are blown away by heavy winds	replace or reconnect manhole covers			
		3.8	foam dam drainage is blocked or blocked by debris	clean rat-holes of mouse-holes in foam dam and/or increase drainage capabilities			
		3.9	seal gasket underneath bleeder vent releases vapours	improve sealing gasket or change			
		3.10	rim vent can't open adequately	pallet review and make smooth			
		3.11	rim vent pallet is disconnected	pallet review and repair guide			
		3.12	seal gasket underneath rim vent pallet releases vapours	replace gasket in vent			
		3.13	bird screen corrodes , shows holes and/or is disconnected or is missing	fasten bird screen or replace bird screen			
		3.14	water accumulation on roof	clean drain sump, grid/strainer and/or rat-holes			
		3.15		check function of drain			

		3.16		check sensors mounted on roof to automatically check horizontal position of roof on "eratic out-put"			
		3.17	product accumulation on roof	check function of NRV of check valve in drain en correct, increase functionality of NRV and/or replace NRV			
		3.18		check pit corrosion in central deck and repair			
		3.19	product accumulation in pontoons	arrange soonest emptying of tank, search for cause of leakage and repair			
		3.20	product accumulation in radial box girders	arrange soonest emptying of tank, search for cause of leakage and repair			remove product from radial box girders
		3.21	water accumulation in radial box girders	arrange soonest emptying of tank, search for cause of leakage and repair			remove water from radial box girders
		3.22	water accumulation in pontoons	check presence of manhole cover; replace cover in case missing/lose			
		3.23	cover plate of manhole on centre deck releases vapours	check bolted connections, tighten nuts and/or replace gasket			
		3.24	connection of earthing cable to earthing boss on roof or on rolling	grease earthing lug, re-connect or fasten earthing			

			ladder structure is disconnected or is missing	cable. Perform electrical resistance measurements at least once during in-service period			
		3.25	sampling hatches are left in open position, are disconnected or leak	perform visual inspection to sampling hatches, repair or replace hinge structures of hatch and/or repair or replace seal/gasket structure			
		3.26	water accumulation on roof may occur or occurs after roof has landed	remove emergency drain plugs			
		3.27	water accumulation on roof under operational conditions is possible or happens	check openings of emergency drain, clean openings and/or replace gratings			
		3.28	track of rolling ladder is not in-line with position of rolling ladder	check possible occurred rotation of roof by inspection to functionality of sleeves around the guide pole, repair or replace rollers, grease bearing structures of rollers or replace bearing structures of rollers			

Table 46 "In-service" maintenance tasks: Rolling ladder

Components of tanks to be maintained during "in-service" periods						Applicable to tank No.	Remarks
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
4.	Rolling ladder						
		4.1	structures of rolling ladder, rail track, stair treads and/or mechanism that causes stair treads to always stay in a horizontal position show signs of corrosion	maintain paint system or galvanisation system			
		4.2	wheels of rolling ladder don't turn easily, are stuck or make extreme noise when product level in tank changes	check bearing structures of wheels, lubricate bearings and/or replace bearings			
		4.3	stair treads do not stay in a horizontal position during product level changes within tank	check cause of blocking of movement mechanism, lost connection of this structure to the stair treads; repair/replace stuck parts or loose parts of the assembly			
		4.4	earthing cable may come under wheels of rolling ladder or lies on rail track of rolling ladder	check position of cable, relocate or replace cable connections and/or consider installing of a cable guide structure			
		4.5	hinge between rolling ladder and gauger's platform is stuck, does not	check function of hinge, lubricate hinge or replace			

			move without applying forces	hinge			
		4.6	earthing cable between rolling ladder and gauger's platform show signs of chafing, is disconnected or broken etc.	lubricate earthing lug connection, reconnect or retighten cable. Perform electrical resistance measurements at least once during in-service period			

Table 47 "In-service" maintenance tasks: Rim seal

Components of tanks to be maintained during "in-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
5.	Rim seal	5.1	primary seal shows gaps between seal and tank shell	check function of springs/pantograph structure, repair or replace.			possibly only an "out-of-service" job as secondary seal is placed
		5.2		check wear on seal shoe plates; repair or replace shoe plates			possibly only an "out-of-service" job as secondary seal is placed
		5.3		check excessive tilting of tank or deformations in tank shell; when required, jack and re-level tank			possibly only an "out-of-service" job as secondary seal is placed
		5.4	shunts have no contact with tank shell	check function of springs, repair or replace springs.			
		5.5		check excessive tilting of tank or deformations in tank shell; when required, jack and re-level tank			
		5.6	electrical connection between shunts and roof is disconnected, conductivity of connection between roof	check conductive properties, improve these properties or replace electrical connections between shunts and roof structure. Perform electrical resistance measurements at least once during in-service period			

			and shunts may be jeopardised				
		5.7	the distances between adjacent shunts is > 2,5 m	install additional shunts			
		5.8		check presence of loose or disconnected shunts; reconnect shunts or replace shunts			
		5.9	secondary seal shows gaps between seal and tank shell	check function of springs, repair or replace springs.			
		5.10		check wear on seal plates; repair or replace plates			
		5.11		check excessive tilting of tank or deformations in tank shell; when required, jack and relevel tank			
		5.12	primary seal shows signs of "wear" en "tear"	replace flexible cloth of seal			may only be a task during the "out-of-service" period, when secondary seal is mounted
		5.13	secondary seal shows "wear" en "tear"	replace flexible cloth of seal			
		5.14	primary seal releases vapours	check gaskets between each different shoe plate and/or connections between seal cloth and shoe[plates/outer rim plate of floating roof; repair or replace			may only be a task during the "out-of-service" period, when secondary seal is mounted

				gaskets/screws			
		5.15	secondary seal releases vapours	check gaskets between each different plate and/or connections between seal cloth and plates/outer rim plate of floating roof; repair or replace gaskets/screws			

Table 48 "In-service" maintenance tasks: Instrumentation

Components of tanks to be maintained during "in-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
6	Instrumentation connected to tank shell, to tank roof, to gauger's platform etc.	6.1	cable ducts and/or their connections to tanks structures show signs of corrosion	re-instate gavanising system or apply proper paint system			
		6.2	cable ducts and/or their fastenings to tank structures are disconnected	re-instate connections between individual ducts and between ducts and tank parts			
		6.3	level indicators, pressure indicators and/or temperature indicators and/or operational alarm systems give "erratic output"	check readings of main instruments on correct output in relation with local legislation or guidelines; perform these reading checks once during an 'in-service' period as a minimum			
		6.4	valves on tank	check spindles and or treaded			

			nozzles do not close properly or it's impossible to open them	rods, lubricate them frequently, repair or replace valves			
		6.5	valve connections to nozzle flanges are leaking	check bolted connection on proper tightening, replace bolts, replace gaskets, check valve body on any signs of cracks, check pressure loop on proper liquid tightness; replace valve/parts of valve when considered necessary			
		6.6	lights on tank, walkways, stairs etc. don't shine	check connections of electrical cables, repair or replace; replace lamps or light fixtures			

Table 49 "Out-of-service" maintenance tasks: Tank Foundation*Note: all "in-service" maintenance tasks could also apply when tank is taken 'out-of-service'*

Components of tanks to be maintained during "Out-of-service " periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
1	Tank Foundation	1.1	deformations are present in bottom plates induced by radial settlement	check deformations against limit for radial settlement; correct or repair when required			
		1.2		check supports of internal piping systems on creating excessive and additional stresses in piping or when piping is not laying properly on supports. Repair supports and/or improve horizontal position of top layer tank foundation after jacking of tank			
		1.3		check integrity of interconnecting welds between adjacent bottom plates and between bottom plates and annular plates; correct the welds, repair or replace the welds when required			

		1.4	deformation is present in annular plates by edge settlement	check deformation against limits for edge settlement and correct / replace annulars when appropriate; In case limit is bypassed by actual measured edge settlement: replacement of annular plates is the only option			
		1.5		check integrity of inner corner weld bottom/shell connection repair/replace weld when required			
		1.6	deformations in tank shell and/or toe of the annular plates outside of the tank shell, induced by differential settlements in circumferential direction and/or tilt in tank shell (ovality and/or out-of-verticality of the tank shell)	check deformation in tank components against the limits for differential circumferential settlements; repair / replace when appropriate; apply jacking and relevening of the tank			
		1.7		check rim seal of floating roof for proper abutting against tank shell or whether gaps between shoe plates and tank shell are existing; check			

				gap dimensions against limits specified; assess need for improving verticality of tank shell; otherwise prepare for jacking and relevening tank			
		1.8		check internal tank shell on signs and grooves , induced by scraping shoe plates or bumper bars against tank shell; assess need to reduce filling height, in case shell irregularities are existing at the upper regions of the tank shell; assess need to re-level and jacking of tank			
		1.9		check integrity of welds between primary- and secondary wind girders and tank shell; check wind girders on any sign of deformations; in case deformations are present, repair by relevening and jacking of tank; improve plain level tank foundation			

		1.10		check integrity of outer corner weld bottom/shell connection repair / replace weld when required			
		1.11		reduce level of water table in tank pit			
		1.12	water level in tank pit is higher than tank pad level, causing rain water to flow underneath tank bottom	Jack-up tank and increase height of tank foundation to level > 300 mm above grade level of tank pit			
		1.13		check drainage of tank pit to water treatment system; replace or repair or take adequate correcting actions			
		1.14	bottom- and/or annular plates show corrosion at lower side of bottom plates	after jacking and re-levelling of tank, check cleanliness of top layer of foundation and on existence of any debris, clay, pebbles, sand, stubs of welding electrodes etc. remove all foreign matter and properly clean top layer of foundation			
		1.15		(rain) water can flow underneath tank bottom			

				plates: see " foundation shoulder" for stated corrective actions			
		1.16	internal piping to central sump or roof drain, after landing of roof, is not in a horizontal position	check deformations against limit for radial settlement; correct or repair when required			
		1.17		check integrity of welds in piping systems repair / replace when required			
		1.18	uniform settlement creates lateral stresses and moments in tank shell nozzles from connected piping structures	compensate and reduce stresses and deformation induced by lateral forces and moments in shell and roof nozzles by the application of expansion joints, bellows, flexible joints, the introduction of spring supports or spring hangers and/or level piping structures in line with tank shell nozzles; Assess need for jacking and re-levelling of tank			

Table 50 "Out-of-service" maintenance tasks: Tank bottom*Note: all "in-service" maintenance tasks could also apply when tank is taken 'out-of-service'*

Components of tanks to be maintained during "out-of-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
2	Tank bottom						
		2.1	bottom plates corrode	repair / replace paint system; in case excessive corrosion found repair bottom plates by welding pits, by welding patch plates and/or by replacing bottom plates			
		2.2	annular platen outside critical zone area (further than 6" inwards of tank shell) corrode	repair / replace paint system; in case excessive corrosion found repair bottom plates by welding pits, by welding patch plates and/or by replacing bottom plates			
		2.3	annular plates within critical zone area (shorter than 6" inwards of tank shell) corrode	repair / replace paint system; Check possibility to apply the welding of "tomb stone" patch plates over corroded areas or replace annular plates			
		2.4	Interconnection bottom plate welds, between drain sump(s) and bottom	repair / replace paint system; check integrity of			

			plates and between normal bottom plates and annular plates corrode	welds and repair / replace welds when required			
		2.5	interconnecting welds of annular plates corrode	repair / replace paint system; check integrity of welds and repair / replace welds when required			
		2.6	inner corner weld bottom/shell connection corrodes	repair / replace paint system; check integrity of welds and repair / replace welds when required			
		2.7	drain sump(s) corrodes	repair / replace paint system; in case excessive corrosion found repair sump by welding pits and or by replacement of total sump assembly			
		2.8	"Striker" plates at landing positions of legs of floating roof corroded	repair / replace paint system; when excessive pit corrosion of general corrosion is present: repair plates by either welding pits in plates (small numbers of craters found) or replacing plates by new ones (large numbers of craters found)			
		2.9	interconnecting welds between "striker" plates at landing positions of roof and bottom plates corrode	repair / replace paint system ; check integrity of welds and correct/repair when required			

		2.10	bottom plates show irregularities in horizontal plane which are not supported by foundation materials	check profile of bottom plates against limits for unsupported dents and bulges; repair / correct when required			
		2.11	bottom plates show irregularities in horizontal plane which are properly supported by foundation materials	check profile of bottom plates against limits for ripples; repair / correct when required			
		2.12		check requirement for repair of top layer of tank foundation against limit of sag in bottom profile; repair / correct when required			

Table 51 "Out-of-service" maintenance tasks: Internal tank shell*Note: all "in-service" maintenance tasks could also apply when tank is taken 'out-of-service'*

Components of tanks to be maintained during "out-of-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
3	Internal tank shell						
		3.1	internal painting system show signs of deterioration locations or corrosion spots on tank shell plates	repair or replace painting system			
		3.2	horizontal weld in shell plates show signs of pit corrosion in HAZ	check conductivity of stored product; apply dosing of "static dissipating additives" in product to increase level of conductivity above > 50 pS/m'			
		3.3		check integrity of welds; in case required (excessive pitting corrosion) repair welds			
		3.4	vertical welds in tank shell show corrosion	check integrity of welds; in case required repair welds			

Table 52 "Out-of-service" maintenance tasks: Floating roof*Note: all "in-service" maintenance tasks could also apply when tank is taken 'out-of-service'*

Components of tanks to be maintained during "out-of-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
4.	Floating roof						
		4.1	outer rim plates of pontoons and their interconnecting welds show corrosion	apply appropriate NDT; verify deviations with design criteria and EEMUA limits under degradation; repair or replace rim plates when required			
		4.2	inner rim plates of pontoons and their interconnecting welds show corrosion	apply appropriate NDT; verify deviations with design criteria and EEMUA limits under degradation; repair or replace rim plates when required			
		4.3	bottom plates of pontoons show ripples, folded areas, dents and bulges	check with operations dept w.r.t. TVP-values of stored product, repair and/or replace			
		4.4	inner rim - / outer rim plates of pontoons show ripples, folded areas, dents and bulges	check with operation dept w.r.t. TVP-values of stored product, possible excessive water accumulation on roof during "in-service" period and verify deviations with design			

				criteria; repair or replace when required			
		4.5	load bearing capacity of landing legs is in-sufficiently guaranteed	check verticality of landing legs and correct out of plump of legs			before next out-of-service inspection
		4.6		check corrosion on landing legs, replace leg assemblies			before next out-of-service inspection
		4.7	bumper bars connected to outer rim plates of pontoons are corroded	check integrity of bumper bars and their welds; repair or replace			
		4.8	sump of roof drain(s) show corrosion	remove accumulating water from sump, apply NDT to sump components; in case corrosion levels are in excess of calculated limits of sump; repair or replace sump			
		4.9	rim vent opens/closes not adequately at levels of set-values pressure/vacuum	arrange for removal of rim vent from roof and arrange proper calibration and precise setting of opening pressures of different pallets, replace vents by using new gaskets and bolts between vent body and roof nozzle			
		4.10	functionality of roof drain is in-	check / correct functioning			

			sufficiently guaranteed	of drain assembly and/or NRV system ; apply NDT to all welds in internal piping systems; apply vacuum- and pressure test to total drain system; assess need to replace drain swivels, piping and NRV			
		4.11	outer rim plates of pontoons and their interconnecting welds show corrosion	apply appropriate NDT; verify deviations with design criteria and EEMUA limits under degradation; repair or replace rim plates when required			

Table 53 "Out-of-service" maintenance tasks: Rim seal*Note: all "in-service" maintenance tasks could also apply when tank is taken 'out-of-service'*

Components of tanks to be maintained during "out-of-service" periods						Applicable to tank No.	Remarks
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
5.	Rim seal						
		5.1	integrity of gaskets and sealant of rim seal, their bolted connections to the floating roof or the shoe plates is not guaranteed	exchange all gaskets and sealant materials; where screws are corroded: replace them by new appropriate screws according to the original design			
		5.2	hinges and springs of mechanical shoe plates show loose nuts, are disconnected, are corroding; movement mechanisms of shoe plates are disconnected, are corroding	replace rim seal springs and/or total movement mechanisms			

Table 54 "Out-of-service" maintenance tasks: Instrumentation*Note: all "in-service" maintenance tasks could also apply when tank is taken 'out-of-service'*

Components of tanks to be maintained during "Out-of-service" periods						Applicable to tank No.	
No.	Component	Failure mechanism	Description	Maintenance task	ETBF value		Remarks
6	Instrumentation connected to tank shell, to tank roof, to gauger's platform etc.	6.1	gusset plate connecting welds of supports of level indicator / stilling well to tank shell show signs of cracks	check integrity of welds by MP-inspection method; in case cracks or other non-acceptable defects are discovered: repair or replace welds			
		6.2		check out-of-plumb of level indicator / stilling well (including verticality in relation with tank shell) and correct verticality			
		6.3	gusset plate connecting details of stilling well to tank shell show signs of corrosion	repair or replace painting system			
		6.4	functionality of instruments is inadequately guaranteed	arrange proper calibration of all instruments, check functions, check accuracy and reliability of signal distributions to control room and v.v., check cable connections, consider use of vendor specialists for required maintenance tasks			

Appendix F Refrigerated storage tanks for liquefied gases

F.1 Introduction

The detailed design of refrigerated storage tanks can vary considerably depending upon the basic system of liquid containment. These are:

- single containment;
- double containment;
- full containment.

Details of these systems can be found in EEMUA 147 and BS 7777⁽⁴⁰⁾. The requirements for, and scope of, external and internal inspections should take due account of the particular system of containment under consideration.

F.2 Scope

The recommendations in the sub-sections that follow are applicable to tanks storing all refrigerated liquefied gases. Since the majority of tanks presently in service are single or double containment, the recommendations are based on experience with these types, but can be applied to other designs.

F.3 Tank data

In order to define the inspection requirements, the information listed below needs to be studied and taken into account:

F.3.1 Tank design and construction details

- i) Full tank description including detailed drawings.
- ii) Detailed data sheets containing all relevant as-built information.

F.3.2 Operating history

- i) Information concerning instances of overpressure and underpressure outside the tank design parameters.
- ii) Gas leakage or liquid spillage from fittings.
- iii) Reports of operating difficulties, sticking valves, tank overfilling, frozen and plugged pipelines etc.
- iv) Mechanical damage to the tank, its accessories and adjacent piping.
- v) Any modification or refurbishment work.
- vi) Any unusual temperature readings in foundation heating systems (where applicable).

F.4 External inspection

F.4.1 General

A thorough visual external inspection should be carried out every 12 months.

During normal tank operation, plant operators should immediately report to the inspection authority any abnormal condition or situation they observe, e.g. leakage, abnormalities with the base heating system, excessive vapour recovery, cold spots on shell or roof, instances of over- or under-pressure, etc. Any such reported abnormalities should be investigated as soon as possible.

The external inspection should be carried out with the tank in service and preferably with the tank in a 'static' condition, i.e. no fluid inflow or outflow and the tank pressure within its normal operating limits.

F.4.2 Inspection plan

F.4.2.1 Condition of Tank Foundation

- i) Carry out level survey of outer shell-to-bottom junction or the foundation. This should be compared with original level survey when tank was constructed. Examine for any signs of buckling at the base.
- ii) Check condition of ring wall or pile cap (cracked, spalled, exposed, etc.).
- iii) Check drainage away from ring wall.
- iv) Check erosion settlement and frost heave of ground around tank foundation.
- v) Check condition of grout around the outer shell.
- vi) For elevated piled tanks, check the underside of the pile cap for ice in winter. The junction of the pile to cap should be examined for spalling, cracking and traces of corrosive product from the reinforcing bar.

F.4.2.2 Foundation Heating System

- i) Examine randomly selected conduit junction boxes for damage, etc.
- ii) Check condition of fuses.
- iii) Check foundation heating controls.
- iv) Compare ammeter readings for each phase with original design values.
- v) Record voltage readings for each phase.
- vi) Check each thermocouple or remote indicating device reading used to control foundation heating. Compare with temperature indications in control room.
- vii) Check switchgear operation.
- viii) Check records of power consumption of heating system.
- ix) Check foundation heating records.

F.4.2.3 Condition of Outer Tank

- i) Check outer tank paint surface condition.
- ii) Check paint condition on shell stiffeners, stairways, structural members and nozzles.
- iii) iCheck for signs of distortion or damage to the shell or roof.
- iv) Check for corrosion or mechanical damage at the bottom plate extension beyond the shell, and at the anchor bolts and chairs.

- v) Check visually for frost or ice spots on the outer shell or roof.
- vi) Carry out a thermographic survey on the outer tank to verify the general condition of the insulation.
- vii) Check condition and integrity of insulation cladding.

F.4.2.4 Nozzles and Piping

- i) Check for frost or ice build up on thermal distance pieces.
- ii) Check the condition of any expansion bellows regarding corrosion, unusual distortions, ice build up or other damage.
- iii) Check for rotation of nozzles. Movement would indicate frost heave on the inner tank or deterioration of the foundation.
- iv) Check pipe supports connections to roof or shell.
- v) Check piping insulation.
- vi) Check condition and settings of spring supports and compare with data sheet settings.
- vii) Check trace heated nozzles and adjacent piping for localised corrosion.

F.4.2.5 Structures

Check condition of roof platforms, walkways and handrails.

F.4.2.6 Pressure and Vacuum Relief Valves and Instrumentation

- i) Check pressure and vacuum relief valves for icing, mechanical damage, corrosion and leakage.
- ii) Check and test that steam lances are functional (where fitted).
- iii) Check sources of possible liquid escape which could impinge on the tank, and check condition of any protection devices provided, e.g. mats, catchtrays, etc.

F.4.2.7 Other Fittings

- i) Check and test the condition of any fire protection device on the tank.
- ii) Check and test that steam lances are functional (where fitted).
- iii) Check sources of possible liquid escape which could impinge on the tank and check condition of any protection devices provided e.g. mats, catch-trays, etc.

F.5 Internal inspection

F.5.1 General

The decommissioning and internal inspection of RLG tanks is a potentially hazardous operation, especially for an open topped inner tank, and there exists an associated risk of causing damage to the tank and insulation system. Corrosion is known not to occur in the dry, inert, low temperature conditions inside the tank.

If the product is known not to be dry, corrosion can occur. The foundation designs used for RLG tanks do not normally suffer unacceptable tank settlement.

No technical justification for conducting routine internal inspections of RLG tanks can be provided so long as the tanks are operated within their design/ operational limitations that should be confirmed by the external inspection and the operating history.

When the operating history of a certain liquefied gas in refrigerated storage tanks indicates that the possibility of corrosion cannot be excluded, e.g. as stress corrosion has been experienced in some refrigerated ammonia tanks, it is recommended that the interval between inspections is agreed between the user and the authorities.

F.5.2 Initial inspection of suspended deck

It is important for an initial inspection of the deck to be performed to ensure its integrity is acceptable to permit a full inspection to proceed.

From the roof manway, visually examine the surface of the deck and supporting rods for signs of distress.

From the inner tank bottom examine the entire underside of the suspended deck for any unusual distortion or potential problems. When it has been established that the suspended deck is intact the full inspection of the deck may proceed.

F.5.3 Inspection from suspended deck

- i) Check that support rods are not slack.
- ii) Examine roof structure visually for any distortion or separation of roof plates from support frames.
- iii) Examine undersides of roof plates around roof nozzles and other roof attachments.
- iv) Examine the deck insulation for damage or depressed areas indicative of movement. Measure depth and compare with original.
- v) Visually examine all piping between roof and suspended deck. Particular attention should be paid to distorted or bent pipes. Where pipe is insulated check the insulation attachment to the pipe.
- vi) Check perlite level in the annular space between inner and outer shell for signs of compacting (where relevant).
- vii) Check the integrity of the seal between suspended deck and inner shell.
- viii) Check all vent openings located in the deck to ensure that they are not blocked.

F.5.4 Inner tank inspection

- i) Check for the presence of deck insulation or any other foreign matter on the bottom.
- ii) Examine the bottom plate surface and internal piping and supports for damage.
- iii) Examine visually the bottom lap welds annular plate butt welds, shell to bottom welds and any attachments welded to the bottom plates.
- iv) Visually examine shell welds and shell plate surfaces for any signs of corrosion.
- v) Examine the shell surface for any unusual buckling or distortion. Crack-detect any shell nozzle welds.
- vi) Make a level survey across four diameters. Also survey any raised or depressed areas to determine whether settlement or heave has occurred.

- vii) Survey the level of the annular plates at the shell-to-bottom junction to determine whether the shell support foundation is intact.
- viii) Leak-test the bottom and shell-to-bottom welds with a vacuum box.
- ix) Carry out ultrasonic thickness survey of the shell strakes, the annular plates and the other bottom plates.

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EN 10028 Specification for Flat Products Made of Steels for Pressure Purposes—

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EN 10137 Plates and Wide Flats Made of High Yield Strength Structural Steels in the Quenched and Tempered or Precipitation Hardened Conditions—

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- 186 A practitioner's Handbook - Electrical installation, inspection and maintenance in potentially explosive atmospheres
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155 Standard test method for comparative performance of flammable gas detectors against poisoning

138 Design and installation of On-Line Analyser systems

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