

Above ground flat bottomed storage tanks: A guide to inspection maintenance and repair

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Registered and Trading Address:
EEMUA, Second Floor, 16 Black Friars Lane, London EC4V 6EB
Telephone: +44 (0)20 7488 0801
Email: sales@eemua.org
Website: www.eemua.org



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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 fourth Edition was published in 2014, which introduced several sections on repair methods.

The publication has proved an EEMUA 'best-seller', and is used as the principal basis of the EEMUA CompeTank® training scheme.

This Fifth Edition contains appendices offering additional guidance and information on how to perform assessment calculations on tank components and delves deeper into the topic of PPM. This Edition offers revised chapters on corrosion of tanks, general inspection techniques and interpretation of inspection data and floating roofs. This Edition also includes completely new chapters on mothballing, turn-around procedures, aluminium domes and operation at elevated temperatures.

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

- 147** Recommendations for 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.

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 and maintenance. However, it should be noted that some tanks in particular or unusual locations or operating situations may require additional assessment 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 philosophies 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 less safe, accelerate rates of deterioration or increase risk in general.

In addition to general inspection and maintenance guidelines, several sections on repair methods have been included. 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.

Finally, this revision has incorporated a more detailed revision of the RCM process. Together with the methodology mentioned in Chapter 17 and Appendix E this aims to give guidance on using risk based methodologies for tank inspection and operation.

1.2 Scope

This guideline 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-based and reliability-based) Preventive Maintenance (PPM) concept, and for each tank component a detailed description of inspection and repair methods and degradation limits.

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 Standard 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 then designed and constructed.

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 of 0.85, and the weld quality could only have been inspected visually during construction. These tanks were typically made from steel with an ultimate tensile strength not exceeding 420 N/mm². After 1965, medium and large sized storage tanks were often made from higher tensile steels with an ultimate tensile strength over 420 N/mm². Usually top courses of lower thickness were still made from steels with lower tensile strength.

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 radiography during construction.

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

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

1.4 Definitions and Abbreviations

May	'May' is used where alternatives are equally acceptable.
Should	'Should' is used where a provision is preferred
Shall/ Must	'Shall and must' are used where a provision is considered mandatory

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

ACFM	Alternating Current Field Measurement
AISI	American Iron and Steel Institute
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BS	British Standard
CEN	Comité Européen de Normalisation (European Committee for Standardization)
CMMS	Computerized Maintenance Management System
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
EAM	Enterprise Asset Management
EN	European Norm (CEN standard)
ETBF	Estimated Time Between Failures
FMEA	Failure Mode and Effect Analysis
FS	Floor Scan (ultrasonic thickness measurement technique)
FSL	Floating Suction Lines
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 Section 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
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.
CFRT	Covered Floating Roof Tank usually a retrospective Geodesic Aluminium dome installed above an existing External Floating Roof or Internal Floating Roof (cover)
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.
EFRT	External Floating Roof Tank
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.
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.
Floaters	Buoyancy aids for use on floating suctions
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 roof (or 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.
Membrane plates	Floor plates providing operational integrity for leak prevention of the floor
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.
Seal fabric	Part of mechanical shoe seal.
Sampling device	Device to permit product sampling.
Sand foundation	Type of foundation pad
Shoe Plates	Mechanical Seal device providing primary seal between the sealing device and shell on a Floating Roof Tank
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 <i>dipping device</i> (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

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.
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.
Corrosion allowance	The thickness of material which can safely be allowed to corrode having regard for the operating environment and applied stresses.
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.
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.)
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.
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.
Planar tilt	Out of vertical alignment measured on the storage tank

Qualitative	Qualitative is based on an expert estimate, judgement, has minimal numerical input and is subjective
Quantitative	Use of measurable, objective data to determine an outcome or probability
Semi-Quantitative	Use of experience and probabilities along with judgement but is provided as relative data
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.
Remnant 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.
Ripple	Deformation of a floating roof deck or tank floor.
Susceptibility to failure	A rating which reflects the actual (exposure to) degradation in comparison with the degradation assumed in design.
TIA	Tank Integrity Assessor
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.
Vapour Space	Internal tank area above the stored product

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 approximately 20 mbar internal pressure) or high pressure tanks (to approximately 56 mbar internal pressure) - see Figure 2-1 (values in brackets are in mbar).

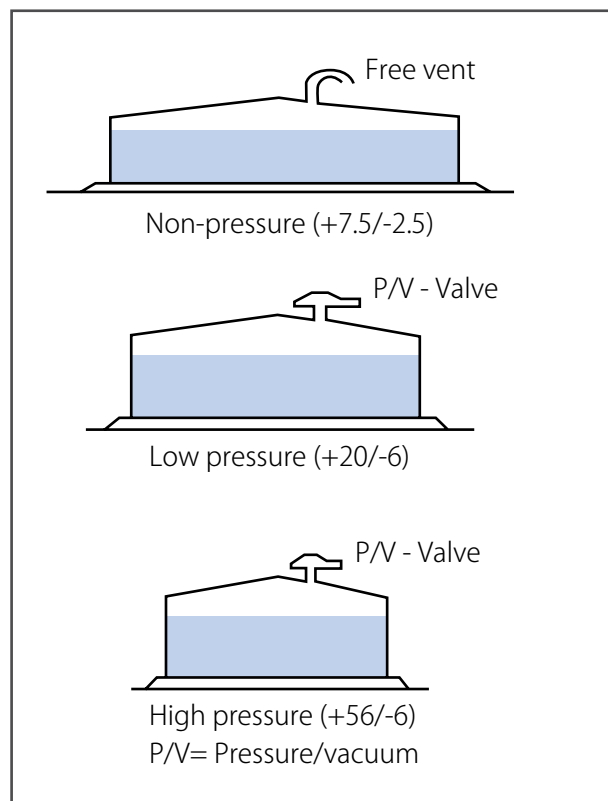


Figure 2-1 Types of fixed roof tanks

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

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

A typical fixed roof tank is shown in Figure 2-2. 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.

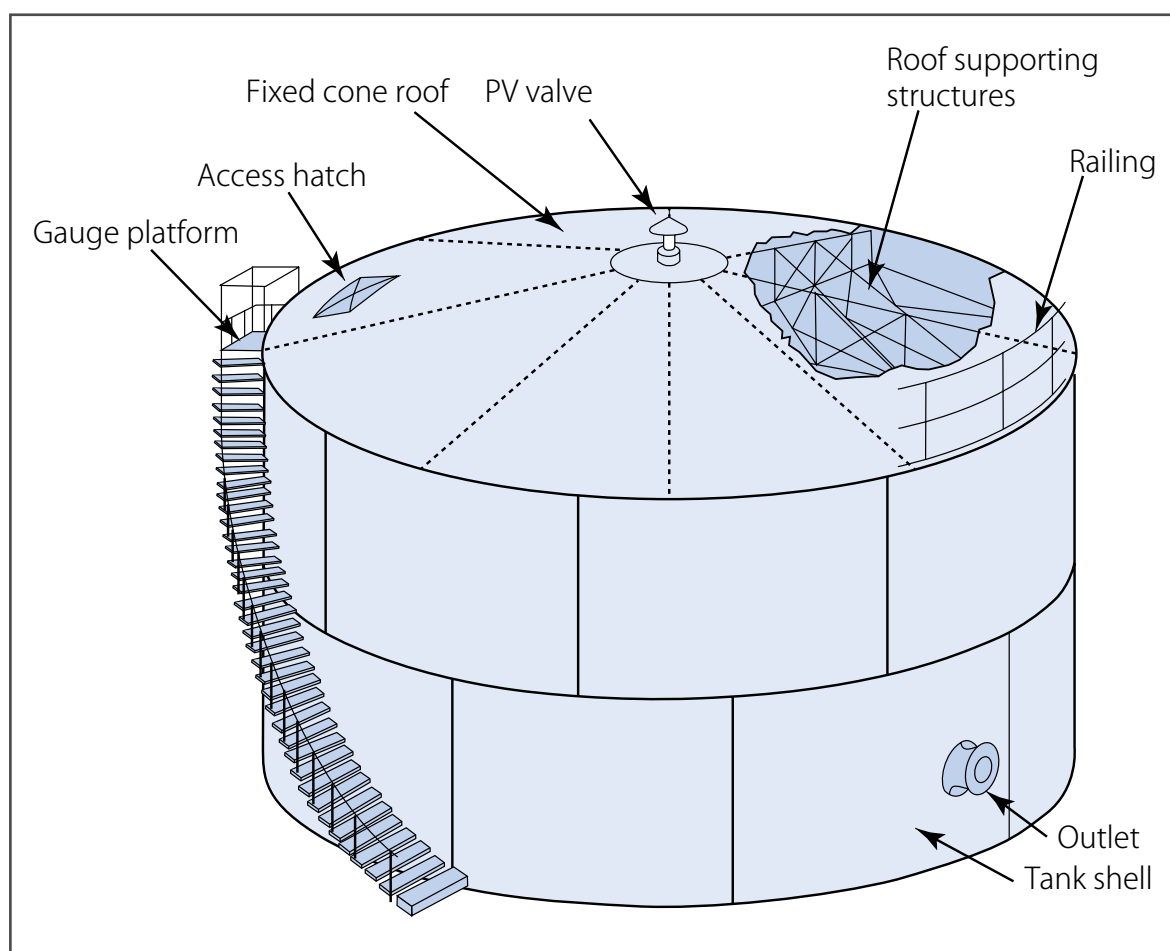


Figure 2-2 Typical fixed roof tank

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 2-1 lists the different fixed roof structures employed relative to tank diameter.

A geodesic roof is another type of self-supporting roof. A typical geodesic roof is shown in Figure 2-3. Refer to Appendix G for further information on aluminium dome roofs.

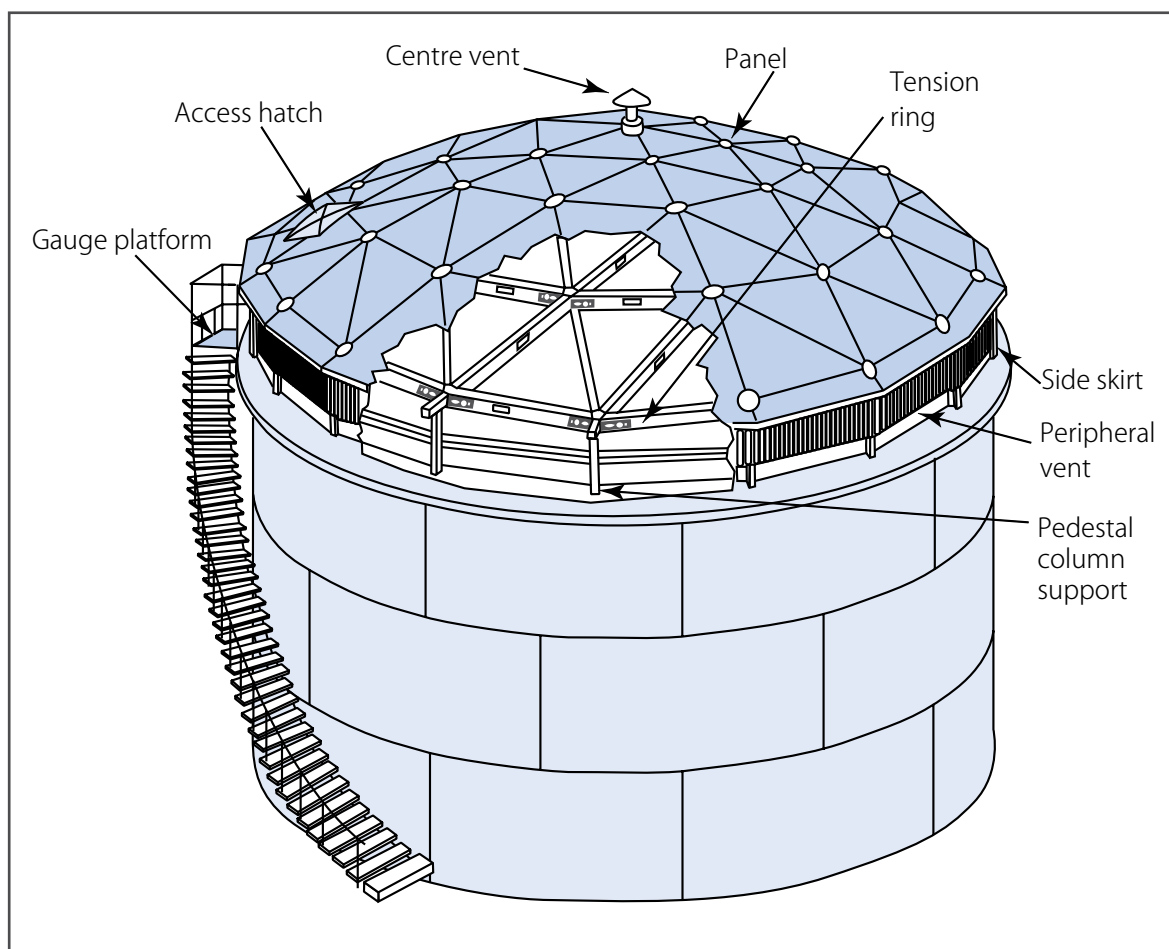


Figure 2-3 Typical open top tank with geodesic dome roof

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

Table 2-1 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 /m²	Weight	Weight /m²	Weight	Weight /m²	Weight	Weight /m²	Weight	Weight /m²	Weight	Weight /m²	Weight	Weight /m²
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 2-4)

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 2-5).

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 (for example over 50m diameter). They are structurally stronger and prevent wind problems which occur in the centre decks of large pontoon roofs.

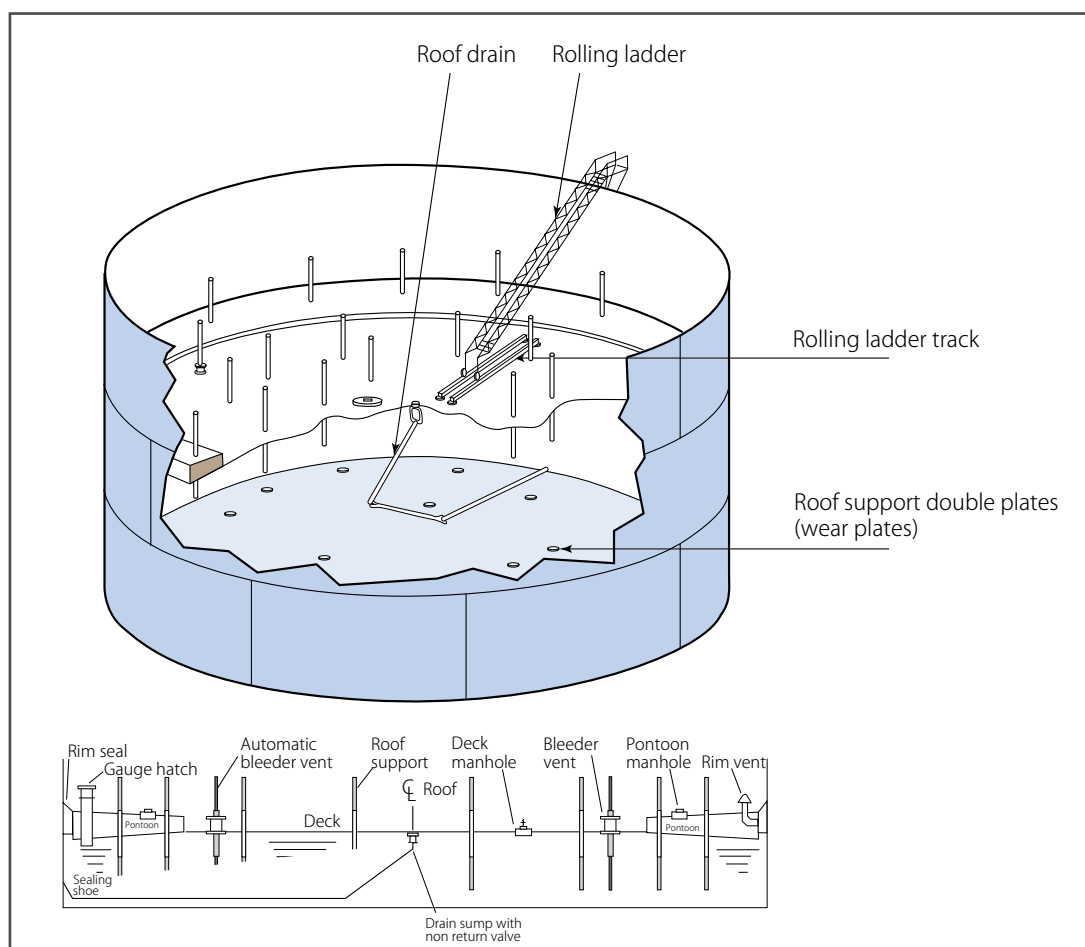


Figure 2-4 Typical floating roof tank with pontoon floating roof

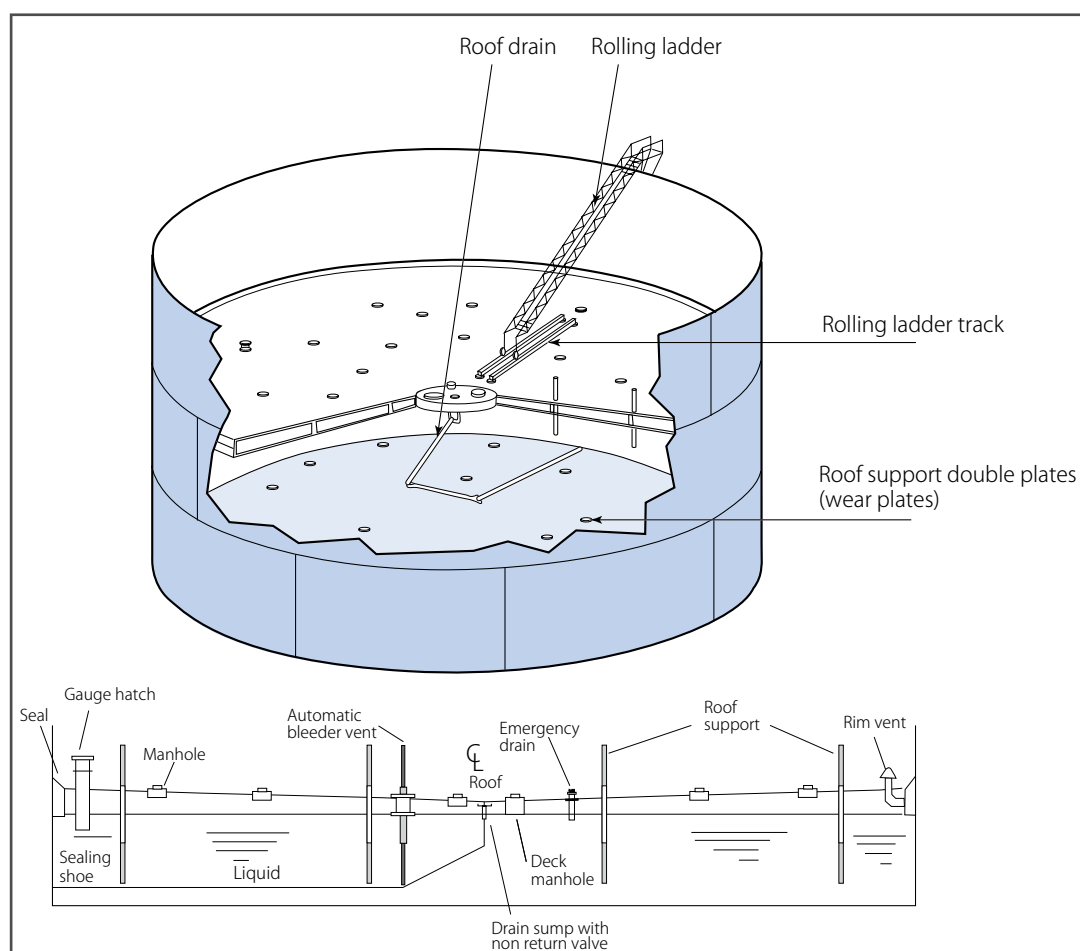


Figure 2-5 Typical floating roof tank with double deck floating roof

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 shear 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 shear 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 ever 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 have been 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;
 - Improperly applied secondary containment liner;
 - 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 the 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:
 - High temperature differential between the product and the foundation;
 - Heated products;
 - 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;
- Damaged liner underneath the tank due to (differential) settlements or water becoming trapped between the liner and the tank floor; and/or
- Jamming of floating roof structure around the 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/appendages include:

- Buckling of internal floaters due to inadequate support, induced vacuum below the roof, jamming due to guide wires or roof seal misalignment;
- 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;
- PV 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;
- Chemical compatibility;
- 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 the seal shoe plates/tank shell.

3.4 Low Cycle Fatigue failure mechanism

Low Cycle Fatigue (hereafter LCF) is a phenomenon whereby cyclic loading of high stress in material results in crack propagation. This phenomenon can occur at relatively low speed and a limited number of cycles.

When a component is subject to LCF, it is repeatedly deformed. In areas with material discontinuities this may lead to plastic deformation. In order to complete a full LCF cycle a part needs to be loaded in tension until it is deformed and subsequently be unloaded. Please note that these local stresses and residual stresses may exceed the design stresses and are not covered in normative design load conditions.

3.4.1 Storage tanks can be subject to cyclic stresses

LCF typically occurs in areas with stress concentrations. It is most common in heat affected zones close to welds. The following tank components could be subject to LCF for example: the annular plate (see Figure 3-1), nozzles under stress, floating roofs, fixed roof to shell connections and roof drain articulated pipe.

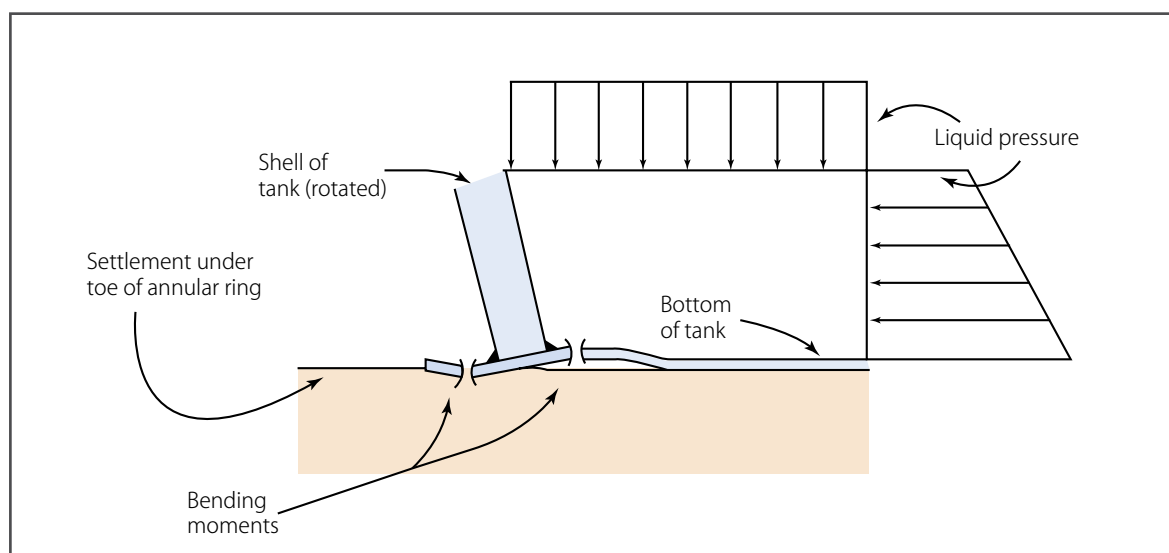


Figure 3-1 Shell to floor joint

3.4.2 Bottom-to-shell connection

The susceptibility of low cycle fatigue within the combined area of the bottom-to-shell connection in storage tanks will mainly be influenced by the following parameters:

- The density of the stored liquid;
- The maximum filling height;
- The maximum amplitude of the stress cycles (difference between stresses under maximum filling height and lowest operational level);
- The configuration of the welds between the shell and bottom plates;
- The used weld procedure (and welding electrode material)
- The operational temperature;
- The material quality and grade of the lowest shell course (which must be identical to that of the annular section of the bottom plates);
- Degradation such as thinning, settlement etc;
- The stiffness of the supporting foundation. A "stiff" (concrete) foundation is more susceptible to LCF than a "soft" foundation made from sand or crushed rock.

Studies performed on large diameter tanks (>80m and liquid levels >20 m), mild steel (leading to high stress levels) and other non-favourable parameters, showed increased probability of LCF after 1300 full cycles of product levels in elevated temperature service (>120 degrees Celsius). However, evaluations of other studies into LCF probability in the shell to bottom connection using the best possible values of the above mentioned contributing parameters, showed much higher values of stress cycles (even reaching as much as 10,000 cycles) before this could lead to the initiation of fatigue cracks in the bottom-to-shell connection.⁽¹⁰⁾

3.4.3 Floating roofs

Cracks on single deck floating roof tanks have been attributed to LCF. The cyclic loads could have been induced by high wind forces, frequent landing of floating roofs or ballooning due to vapours underneath the floating roof deck.

3.4.4 Articulated pipe of roof drain systems

In some cases for high tanks, the pipe sections of the roof drain system become too heavy and LCF cracks can be initiated. This is most likely to occur at the point where two pipes are connected through a chain. These locations should be reinforced and appropriate NDT conducted.

3.5 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.

3.6 Microbial Induced Corrosion (MIC)

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.).

The main concerns about MIC:

- Understanding by operating personnel is critical for the steel components of storage tanks;
- Having 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) is 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 of 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.

Where deposits or tubercles form, an aggressive environment with significantly higher corrosion rates can be formed.

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

- Visual inspection;
- 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 the following methodologies:

- Application of biocides (dependent upon product implications);
- Removal of dead legs;
- Preventing contamination of stored product with potential MIC containing products such as rainwater, slops;
- Water management in tank;
- Review process data; and
- Perform operational analysis of drain lines/dead legs.

Results can vary dependent upon process requirements and applicability.

4 Corrosion of tanks

4.1 General

A general definition of corrosion is the degradation of a material through environmental interaction. This chapter focuses on the corrosion of carbon and low-alloy steels used in storage tanks.

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

The reason behind the mechanism of corrosion can be found in the manufacturing process. A significant amount of energy is put into a metal when it is extracted from its ores, placing it in a high-energy state. During its use, a material always seeks the lowest energy state.

In other words; most metals are thermodynamically unstable and will tend to seek a lower energy state, which is an oxide or some other compound. The process by which metals convert to the lower-energy oxides is called corrosion.

Corrosion is the combined effect of oxidation (anodic reaction) and reduction (cathodic reaction). The location where the metal is being oxidized, is referred to as the anode. At this site, direct electric current (defined as a positive flow of charge) flows from the metal surface into the electrolyte as the metal ions leave the surface. These current flows in the electrolyte to the site where oxygen, water, or other elements is being reduced. This site is referred to as the cathode.

There are four necessary components of a differential corrosion cell:

1. There must be an anode.
2. There must be a cathode.
3. There must be a metallic path electrically connecting the anode and cathode (Normally the tank component itself).
4. The anode and cathode must be immersed in an electrically conductive electrolyte (aqueous product, water or moist soil).

4.2 Types of corrosion

The main types of corrosion phenomena related to steel tanks are;

- Uniform & Pitting corrosion;
- Crevice / under deposit corrosion;
- Galvanic corrosion;
- Stress Corrosion Cracking (SCC); and
- Microbiological Induced Corrosion (MIC).

4.2.1 Uniform corrosion

Uniform or general corrosion is defined as a type of corrosion attack (deterioration) that is more or less evenly distributed over the entire exposed metal surface. Uniform corrosion also refers to the corrosion that proceeds at approximately the same rate over the exposed metal surface. Steel plate corrodes uniformly when exposed to open atmospheres, soils and natural waters, leading to a rusty appearance.

4.2.2 Pitting corrosion

Pitting Corrosion is the localized corrosion of a metal surface confined to a point or small area, that takes the form of cavities. The danger of pitting corrosion lies in the fact that;

- Pitting depth and the number of pits is difficult to quantify;
- Corrosion rates can be very progressive, un-predictable and difficult to determine;
- A single pit can result in leakage. Loss of containment (compromising operational integrity).

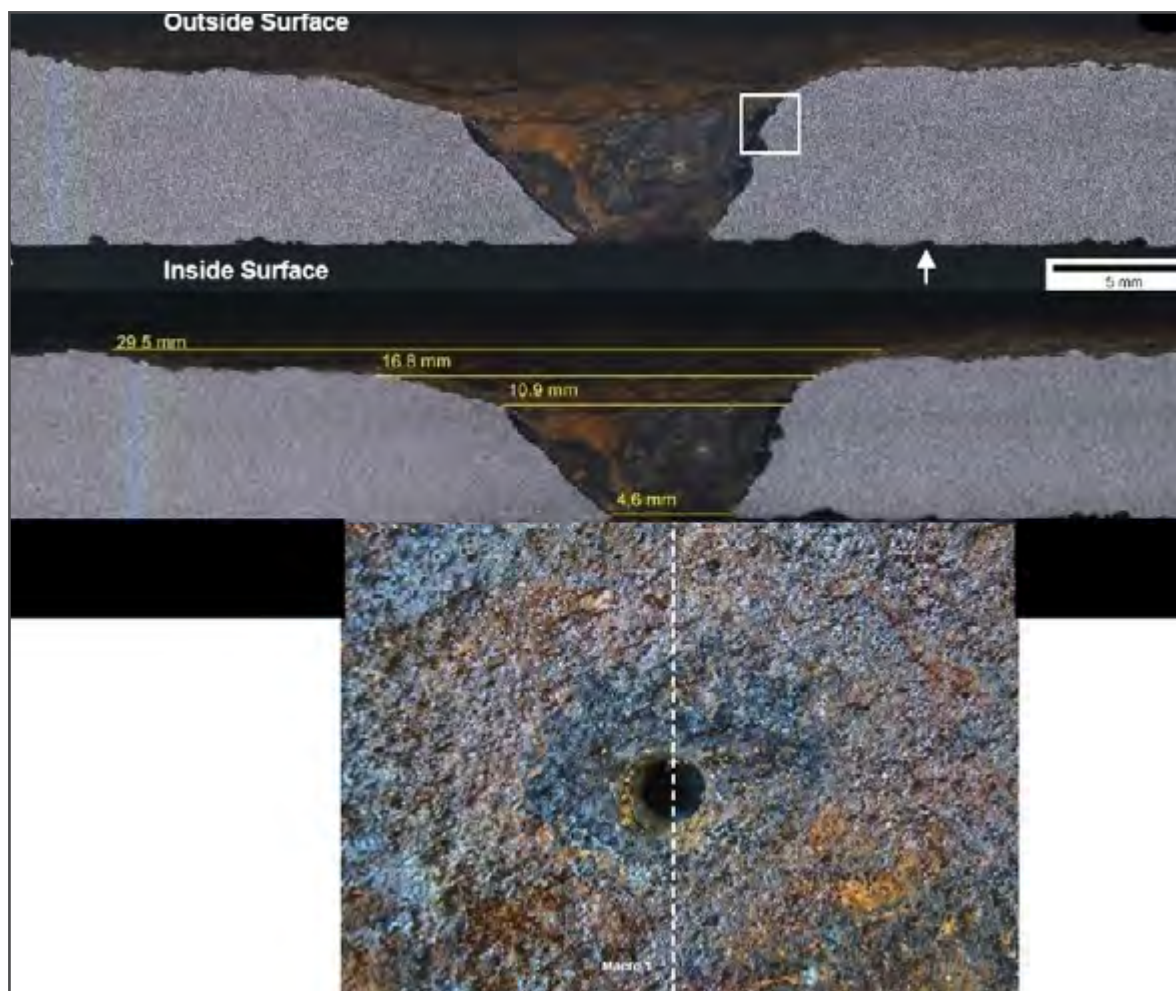


Figure 4-1 Pitting Corrosion

4.2.3 Crevice / under deposit corrosion

Within crevices and other shielded areas on metal surfaces exposed to corrosives, intensive localized corrosion often occurs. This type of corrosion attack is usually associated with small volumes of stagnant moist/liquid as a result of holes, gasket faces, spaces between lap weld joints, deposits and crevices under bolts and rivet heads or in spaces between roof plates and the roof supporting structure see Figure 4-2. Therefore, this type of corrosion is referred to as Crevice corrosion or “under deposit corrosion”.



Figure 4-2 Crevice corrosion between roof supporting structures and roof plates in the vapour space of a tank that progressed to the top side of roof plates, even leading to holes

Examples of deposits that may result in crevice corrosion or under deposit attack, are sand, dirt, condensate of contaminated product vapours, corrosion scale/scabs and other solids. The deposit acts as a shield which creates a stagnant condition underneath. Contact between metal and non-metallic surfaces can cause crevice corrosion as in the case of a gasket. Wood, rubber, concrete, fabrics and wax are examples of materials that can cause this type of corrosion.



Figure 4-3 Corrosion at flange surfaces

In order to function as a corrosion site, a crevice must be wide enough to permit liquid entry but sufficiently narrow to maintain a stagnant zone.

Methods and procedures to prevent crevice corrosion are;

- Use welded butt joints. Sound welds and complete penetration are required to avoid porosity and crevices on the inside (welded from single side);
- Close crevices in existing lap joints by continuous (seal) welding or caulking;
- Design with complete drainage, avoid sharp corners and stagnant areas. Prevent solids/sediments settlement on horizontal surfaces (tank bottom);
- Inspect and remove deposits frequently;
- Prevent/remove solids in suspension early in process or product flow;
- Provide homogenous environments;
- Use solid, non-absorbent gaskets wherever possible.



Figure 4-4 Under deposit corrosion tank annular projection

4.2.4 Galvanic corrosion

Galvanic corrosion or “Bimetallic Corrosion” as it is sometimes called, is defined as the accelerated corrosion of a metal because of an electrical contact (including physical contact) with a more noble metal or non-metallic conductor (the cathode) in a corrosive electrolyte.

Examples of galvanic corrosion with tank component can be found where stainless steel nuts, bolts and/or flanges are installed with carbon steel nozzles or tank appurtenances, for instance the grounding connection.

Different metals & alloys have different electrochemical potentials in the same electrolyte. The potential difference (i.e., the voltage) between two dissimilar metals is the driving force for the corrosion on the active metal (anode). Current flows through the electrolyte to the more noble metal (cathode) and the less noble (anode) metal will corrode. The conductivity of electrolyte will also affect the degree of degradation. The cathode to anode area ratio is directly proportional to the acceleration factor, where this can be somewhat controlled by design and material selection.

4.2.5 Stress corrosion cracking (SCC)

Stress Corrosion Cracking is the cracking induced from the combined influence of tensile stress and a corrosive environment. The required tensile stresses may be in the form of directly applied stresses or in the form of residual stresses from welding.

Welding, heat treatment, machining and grinding of tank components can introduce residual stresses. The magnitude and importance of such stresses is often underestimated. The residual stresses set up as a result of welding operations tend to approach the yield strength. The build-up of corrosion products in crevices can also generate significant stresses and should not be overlooked.

Low alloy carbon steel tanks are specifically prone to SCC in ethanol blends and anhydrous ammonia service.

4.2.6 Microbiologically induced corrosion (MIC)

Microbiologically induced corrosion (MIC) is corrosion resulting from the presence and activities of micro-organisms, including bacteria and fungi. Bacterial and fungal colonies can grow up to macroscopic proportions.

Bacteria may be mobile, capable of migrating to more favourable conditions or away from less favourable conditions, that is, toward food sources or away from toxic materials. Bacteria have specific receptors for certain chemicals which allow them to seek out higher concentrations of those substances that may represent food sources. Organic nutrients are generally in short supply in most aquatic environments, but surfaces, including metals, adsorb these materials, creating areas of relative plenty. Organisms able to find and establish themselves at these locations will have a distinct advantage in such environments. Micro-organisms can withstand a wide range of temperatures (at least -10 to 99 °C), pH (about 0–10.5) and atmospheric oxygen concentrations (0 to almost 100%).

4.2.6.1 MIC mechanisms

Most aggressive MIC takes place in the presence of microbial consortia in which many physiological types of bacteria, including metal-oxidizing bacteria, sulphate-reducing bacteria (SRB), acid-producing bacteria (APB), and metal-reducing bacteria (MRB) interact in complex ways within the structure of biofilms.

MIC does not produce a unique form of localized corrosion. Instead, MIC can result in pitting, crevice corrosion, under deposit corrosion and selective dealloying, in addition to enhanced galvanic and erosion corrosion. The principal effect of bacteria under aerobic conditions is to increase the probability that localized corrosion will be initiated. Bacteria can set up the proper conditions for pitting or crevice corrosion. Once localized corrosion has been initiated, microbial reactions can maintain proper conditions (e.g., low oxygen) for continued pit/crevice growth. The rate at which pits propagate can be governed by organic acid production by fungi in aerobic environments and by certain bacteria in anaerobic environments. Under anaerobic reducing conditions, aggressive MIC is observed when there is some mechanism for the removal or transformation of corrosion products (i.e., there are switches from stagnation to flow or from anaerobic to aerobic conditions). The following discussion about individual MIC mechanisms will be related directly to carbon steel.