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Writer: Martin Ask	Martin Ask (Writer's signature)

Faculty supervisor: Gerhard Ersdal (UiS)

External supervisor(s): Narve Oma (Ptil), Kai Heine Sirevaag (Solvang)

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Summary

During the last decades there have been several major ship accidents, and it is believed that old ships are more unsafe than newer ships. To get a better understanding of this phenomenon the thesis is investigating different issues with ship ageing.

This thesis consists of a general description of the most important ageing issues, and the condition of sea water ballast tanks is identified as one of the most critical issue regarded to ageing on LPG-tankers.

This investigation consists of a theoretical description and evaluation of different corrosion mechanisms, fatigue, buckling and steel protection. The different rules and regulation for new build, maintenance and inspection of ballast tanks are discussed, and there have been physical inspections of some ballast tanks on some selected ships (25, 15 and 1 year old ships). A high number of ballast tanks inspection report are reviewed and used as a basis for the conclusions. To demonstrate the importance of proper steel protection, a life time evaluation of critical areas in ballast tanks are carried out.

There are five different ageing issues concerning a gas-tanker, seen through a shipping company, as listed below

- Functional ageing	Safety and environment related
- Technological ageing	
- Knowledge based ageing	
- Organizational ageing	
- Commercial ageing	Market related

Every one of the ageing mechanisms can affect the lifetime of the ship in different ways. Commercial ageing can be the most fixed ageing mechanism, where the charterer sets a maximum age on ships they will charter. The major oil and gas companies have a maximum age on gas-tankers to be 20 – 25 years old, regardless of the actual condition of the ship. Most of the oil and gas companies require the ships to be in better condition than minimum class requirement, and require ships older than 15 years old to have a Condition Assessment Program – CAP rating of 1 or 2, where CAP 1 is very good condition, CAP 3 is class limit, and CAP 4 is below class limit.

Concerning functional ageing, the sea water ballast tanks are a weak link. The ballast tanks have a very corrosive environment with sea water when filled and a humid salty environment when empty. There are (from 2006) strict requirements for coating in ballast tanks called Performance Standard for Protective Coating – PSPC, in addition cathodic protection can be used. This study shows that the top of the wing ballast tanks are the most critical area concerning heavy corrosion in case of coating breakdown. This due to:

1. Good supply of oxygen in ballast condition because the tank will in most cases not be filled to the top, and therefore no protection from the offer anodes.
2. Moist and salty environment with good supply of oxygen in loaded condition (empty for water) I.e. the cathodic protection is not effective.

Rules and regulations require the ship owner to have maintenance and inspection routines of all the important parts of the ship. In Solvang the chief officer inspects all the ballast tanks every 6th months. The ballast tank inspections that are reviewed show a varying degree of corrosion on the different ships.

The maintenance procedures have been updated lately due to problems with coating breakdown shortly after coating maintenance. From the review of the ballast tank condition it seems clear that often the identified corrosion was left unrepaired. The best practice would be to maintain the corrosion spot right away, and prevent the corrosion to expand. If not, the coating will demand more extensive maintenance later. The reasons for postponement of maintenance in ballast tanks can be many.

With regard to all the ship accidents that have happened the last 50 years, very few of them are directly caused by ageing mechanisms such as corrosion and fatigue. After MV Flare, MV Erika and MV Prestige which sank in 1998, 1999 and 2002 respectively, there have not (known to the undersigned) been any major ship disasters caused by ageing mechanisms. There have been other accidents such as groundings, collisions and collapse of hull due to bad design, but that type of accidents is not of interest in this thesis. The few accidents in the later years indicates that the rules and requirement regulating the shipping industry (IMO, IACS, class societies, flag state, port control, vetting. etc.) are showing a real effect on the accident rate concerning ageing mechanisms.

MV Flare was a bulk carrier, and MV Erika and MV Prestige were oil tankers which sank due to ageing mechanisms. No liquefied gas tankers are known (to undersigned) to sink due to ageing mechanisms. This means that the assumption that an older LPG-tanker may be more unsafe due to ageing not is the case. It is not the age, but the overall condition that decides if the ship is unsafe or not.

To evaluate the effect of coating breakdown in ballast tanks some simplified evaluations for buckling capacity and fatigue life were carried out. With localized corrosion that often appears in ballast tanks, the results found showed that the local buckling capacity may be reduced severely in a relatively short period of time. (~5 years)

Two different approaches for calculating the fatigue life have been used. The calculations show that the approach for offshore structures give approximately 50 % of the fatigue life compared to the ship rules, in corrosive environment. Both methods show that the fatigue life reduces drastically with coating breakdown.

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I would like to thank Gerhard Ersdal (academic responsible), Narve Oma (academic supervisor) and the people in the marine operation department at Solvang. With special thanks to Kai Heine Sirevaag, Halvard Benjaminsen, Trygve Knutson, Odd Magne Åsland, Ole Kenneth Idsøe, Terje Skaar and Tor Øyvind Ask.

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Symbols & abbreviations

A	Cross-section area in cm^2
C	Service life (20 years)
D	Miner sum
$D_{year,air}$	Annual miner sum, air or cathodic protection
$D_{year,corr}$	Annual miner sum, corrosive environment
E	Modulus of elasticity of the material
I_A	Moment of inertia in cm^4 about the axis perpendicular to the expected direction of buckling
L	Length of ship
L_{bp}	Length of ship between perpendiculars
$M_{Wave,hogg}$	Design wave bending moments, hogging
$M_{Wave,sagg}$	Design wave bending moments, sagging
SCF	Hot Spot Factor/K-factor
T	Fatigue life
T_{air}	Fatigue life in air or with cathodic protection
T_d	Design life of ship in seconds
T_{Total}	Total fatigue life
W_A	Time after due date
W_B	Time before due date
W_{Deck}	Midship section modulus, deck
$\bar{a}$	S-N fatigue parameter
$\bar{a}_1$	S-N fatigue parameter for $N \leq 10^7$ cycles
$\bar{a}_2$	S-N fatigue parameter for $N > 10^7$ cycles
f_e	Reduction factor on derived combined stress range accounting for the long- term sailing routes of the ship considering the average wave climate the vessel will be

f_{HT}	Reduction factor on derived combined stress range accounting for the high tensile steel quality for base material fatigue.
f_m	Reduction factor on derived combined stress range accounting for the effect of mean stresses.
h	Weibull stress range shape distribution parameter
h_0	Weibull stress range shape distribution parameter, for deck longitudinal
k	Factor
l	Length of member in m
m	S-N fatigue parameter
m_1	S-N fatigue parameter for $N \leq 10^7$ cycles
m_2	S-N fatigue parameter for $N > 10^7$ cycles
q	Weibull stress range scale distribution parameter for load condition
s	Shortest side of plate panel in m
s_1	Stress range for which change of slope of S-N curve occur
t	Thickness if plating in mm
t_k	Corrosion addition in mm
v_0	Long-term average response zero-crossing frequency
σ_c	The critical compressive buckling stress in $\mathrm{N/mm^2}$
σ_{el}	The ideal elastic compressive buckling stress in $\mathrm{N/mm^2}$
σ_f	Minimum upper yield stress of material in $\mathrm{N/mm^2}$
σ_{stw}	Stillwater induced stresses
σ_w	Wave induced stresses
$\sigma_{Wave,hogg}$	Wave induced stress, hogging
$\sigma_{Wave,sagg}$	Wave induced stress, sagging
η	Utilization factor
ψ	Factor, the ratio between the smaller and the larger compressive stress assuming linear variation
$\Delta\sigma$	Stress range

$\Delta\sigma_0$	Actual compressive stress
$\Gamma\left(1+\frac{m}{h}\right)$	Gamma function
$\Gamma(\ )$	Complementary incomplete gamma function, to be found in standard tables
$\gamma(\ )$	Incomplete gamma function, to be found in standard tables

ABS	American Bureau of Shipping
BV	Bureau Veritas
BWM	Ballast Water Management
CAP	Condition Assessment Programme
CAS	Condition Assessment Scheme
Cbm	Cubic metre
CDI	Chemical Distribution Institute
ClassNK	Nippon Kaiji Kyokai
CN	Class Note
CSR	Common Structural Rules
CTF	Coating Technical File
DNV	Det Norske Veritas
DNVGL	Det Norske Veritas – Germanisch Lloyd
DFT	Dry Film Thickness
ESP	Enhanced Survey Programme
GL	Germanisch Lloyd
IACS	International Association of Classification Societies
ICM	Increased Corrosion Margin
ICS	International Chamber of Shipping
IMO	International Maritime Organization
ISM	International Safety Management

ISPS	International Ship and Port Security
LGC	Large Gas Carrier
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LR	Lloyd’s Register
MARPOL	International Convention for the Prevention of Pollution from Ships
MV	Motor Vessel
N/A	Not Applicable
NDT	Non Destructive Test
NIS	Norwegian International Ship register
NMA	Norwegian Maritime Authority
NOR	Norwegian Ordinary Ship register
NDTF	Nominal Dry Film Thickness
OCIMF	Oil Companies International Marine Forum
PSC	Port State Control
PSP	Primary Surface Preparation
PSPC	Performance Standard for Protective Coating
Ptil	Petroleum Safety Authority Norway
PULS	Panel Ultimate Limit State
RINA	Registro Italiano Navale
RP	Recommended Practice
SCF	Stress Concentration Factor
SECA	Sulphur Emission Control Area
SIRE	Ships Inspection Reporting Program
S-N	Alternating stress amplitude / number of cycles
SOLAS	Safety Of Life At Sea
SOx	Sulphur Oxides

Star IPS	Star Information & Planning System
TSCF	Tanker Structure Co-Operative Forum
UiS	University of Stavanger
UR	Unified Requirements
UTM	Ultrasonic Thickness Measurement
VLGC	Very Large Gas Carrier
WBT	Water Ballast Tank

Table of Contents

1 Introduction

During the last decades there have been several major ship accidents, and it is believed that old ships are more unsafe than newer ships. To secure safety at sea and prevent pollution it is very important to keep the ships in good condition. Over the years accidents have happened and stricter rules and regulations have naturally been forced into the shipping industry. With the International Maritime Organization – IMO with 170 member states, adopting new rules and regulations for the shipping industry. (IMO 2014c)

Some of the latest accidents causing major oil pollution were MV Erika which sank in 1999, 24 years old and MV Prestige which sank in 2002, 26 years old. In 1998 the bulk carrier MV Flare broke in two and sank 26 years old. All accidents were related to ageing issues.

MV Erika had changed owners and classification societies frequently the last years, and the maintenance of the ship had been kept on a minimum. Before it sank, it was reported cracks in the deck-plating. This was probably caused by corrosion and fatigue. (Erika)

MV Prestige sank due to hull failure between frames 61 and 71. The American Bureau of Shipping – ABS had inspected two of Prestige’s sister ships, Alexandros and Centaur extensively during a “safe hull” program inspection in 1996. They concluded with the help of modelling tools that they would fail between frames 61 and 71 within five years, due to fatigue in the hull. These sister ships were scrapped between 1999 and 2002, but the Prestige was not, and the hull failed a little more time than five years, as predicted on the sister ships. (Prestige 2008)

MV Flare broke in two and sank 26 years old, caused by ageing issues on a voyage from Rotterdam, Netherlands, to Montreal, Quebec, causing the killing of 21 crewmembers. Four of the crew survived. The hull failure is probably caused by many factors, but some of them were improper ballasting due to steel repair carried out in ballast tanks during the voyage. The ship was highly vulnerable to slamming and pounding due to light ballast condition and shallow forward draught. Large and steep irregular waves caused severe hull whipping and vibration resulting in brittle fractures in the main deck plating, causing structural collapse and the ship to break in two. (Flare 2000)

Solvang Shipping is a Norwegian Shipping company located in Stavanger. They operate 6 semi refrigerated LPG/ethylene ships and 11 fully refrigerated LPG/ ammonia ships, which most of them are sailing worldwide. (Solvang 2014)

Solvang have/have had a fleet of ships of varying age and it is experienced that the maintenance cost on some of the ships has dramatically increased when the ship becomes older. In this thesis the ageing issues for ships will be investigated, and the most critical ageing issue will be identified.

This report consists of a general description of the most important ageing issues on LPG-tankers, gives a theoretical description of different corrosion mechanisms and steel protection. The different rules and regulation for new build, maintenance and inspection of ballast tanks are discussed. The report also includes some examples and a summary from inspections of some ballast tanks on some selected ships (25, 15 and 1 year old ships). Finally the importance of proper steel protection is demonstrated by a life time evaluation of critical areas in ballast tanks.

2 Ageing

An overview of some ageing issues on ships, and which of them that may be the most critical for the shipping company.

2.1 Ageing issues

The five main types of ageing issues concerning a ship, seen from a shipping company's perspective are seen in figure 1.

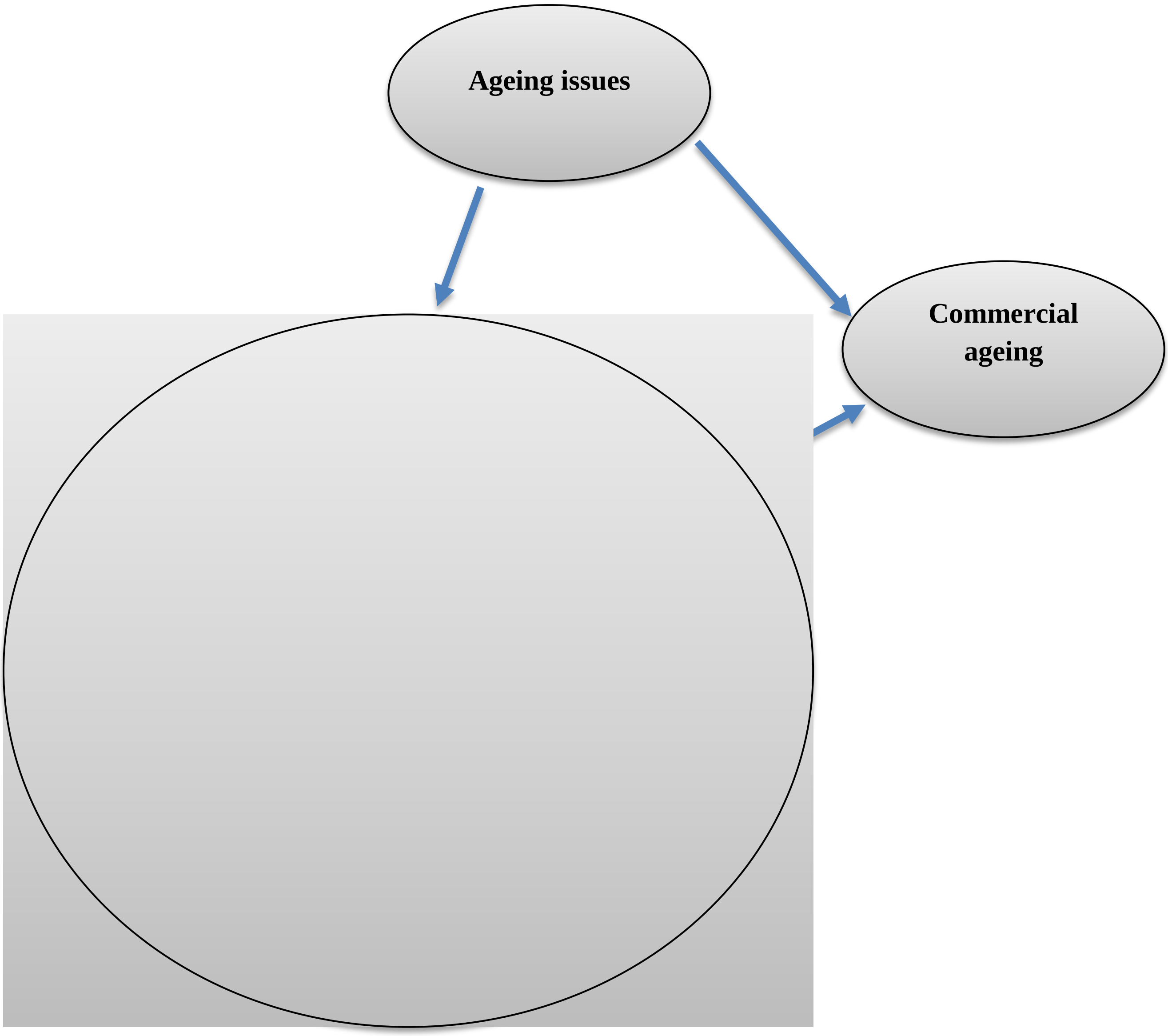


Figure 1 Ageing issues on a LPG ship

Functional ageing, technological ageing, knowledge based ageing and organizational ageing may make it difficult to secure safety at sea and prevent pollution, which is an important part of shipping. (Oma 2013)

Commercial ageing is not directly related to secure safety at sea and prevent pollution, but the oil and gas companies may have an upper age limit for ships they will allow to ship their cargo. Demand based ageing may also fit under commercial ageing, so if trading demands shifts, the oldest ships are likely to be scrapped or laid up first.

2.1.1 Functional ageing

Definition by Ersdal. G.

- The functional ability and resistance is reduced due to physical degradation, damages and changes, such as material degradation, damages, subsidence, etc. I.e. the structure or system is becoming weaker with time and less able to fulfil its function. (Ersdal 2014)

Definition of functional ageing for ships:

- The functional ability and resistance is reduced due to physical degradation, damages and changes, such as material degradation, damages, etc. I.e. the ship is becoming weaker with time and less able to fulfil its function.

On a ship functional ageing is material degradation, such as corrosion, erosion and fatigue, wear and tear, vibration etc. On a liquefied gas tanker, general corrosion and especially corrosion in sea water ballast tanks can develop into a serious problem if it is not taken care of properly.

Other systems that will experience functional ageing that may influence the life time of a ship is the condition of:

- The cargo plant with its compressors, pipes, pumps etc.
- The ballast systems with its pumps and pipes
- Main engine, and auxiliary engines
- Electronic control and monitoring systems (computers, PLS, etc)

Example

“Effective corrosion control in segregated water ballast spaces is probably the single most important feature, next to the integrity of the initial design, in determining the ship’s effective life span and structural reliability,” (GL 2014)

Indents in ships side (due to tugs, etc.) is not directly a functional ageing issue, but it may accelerate the ageing mechanisms corrosion and fatigue cracking.

2.1.2 Technological ageing

Definition by Ersdal, G.

- The present technology in the older structure or system is challenged by new technology (obsolescence), such as the technology behind the structure or structural design may become outdated compared to new technology (welding, materials, etc.), or due to compatibility issues between old and new technology or spare part availability. I.e. the structure or system is technologically outdated and hence less able to fulfil its purpose. (Ersdal 2014)

Definition of technological ageing for ships:

- The present technology in the older ships is challenged by new technology (obsolescence), such as the technology behind the ships design may become outdated compared to new technology or due to compatibility issues between old and new technology or spare part availability. I.e. the ship is technologically outdated and hence less able to fulfil its purpose.

When a ship is designed and built, it is done with the technology available at that time. Because of industry needs, research and development the technology will develop and current technology will be challenged by new technology. Examples of technology development can concern welding procedures, material properties (e.g. ultra high-strength steel), calculation methods, protection method (e.g. performance standard protective coating)

So technological ageing can be:

- outdated technology
  - navigation systems
  - control systems
  - surveillance and monitoring systems
- compatibility issues
- trouble getting spare parts

Examples:

All vessels in the Solvang fleet have the same data server technology onboard except two of the newest vessels, due to new data technology. This may cause problems with updating software etc. on the whole fleet at once, because of the different server systems onboard.

IT – systems onboard are renewed at every 5 years at docking

Fuel efficiency on gas carriers. Due to new design and hull optimization among other things, the fuel consumption has fallen dramatically the last 20 years. This can also be a major reason for replacement of old ships.

2.1.3 Knowledge based ageing

Definition by Ersdal, G.

- The original design premise is outdated due to availability of new knowledge, such as development of requirements or knowledge resulting in higher safety standards, new data, methods and models. I.e. the structure or system may by new knowledge and updated standards become less safe than required by present day standards. (Ersdal 2014)

Definition of knowledge based ageing for ships:

- The original design premise is outdated due to availability of new knowledge, such as development of requirements or knowledge resulting in higher safety standards, new data, methods and models. I.e. the ship may by new knowledge and updated standards become less safe than required by present day standards

As the time goes along, the experience and knowledge changes, and there will be new rules and regulations. The International Maritime Organization – IMO which is the top authority for shipping will constantly renew their rules and regulation applicable for shipping.

Since the start of IMO new rules and regulation steadily has been introduced due to new knowledge and experience.

Examples:

Things that were normal the earlier days, would be seen as serious environmental crime today. When oil tankers used the same tanks as both cargo and ballast tanks there was serious oil spills when the ballast water mixed with oil was pumped overboard after a ballast voyage. Segregated ballast tanks became mandatory on oil tankers delivered after 1 June 1982(MARPOL)

Due to major oil spill in collisions and groundings of oil tankers, MARPOL made it mandatory for new oil tankers to have double hull when ordered after 6 July. (IMO 2014a)

The new rules regarding Sulphur oxides (SOx) emissions will demand the older ships to either sail on more costly low sulphur fuel, or massive retrofitting of exhaust cleaning equipment or engine rebuild to run on ex LNG. (IMO 2014b)

Ballast water management BWM; due to the global trade in shipping and the use of ballast water, non-native aquatic species are spread around the world's oceans. In accordance to IMO resolution A.1005(25) adopted on 29 November 2007 the schedule for installation of ballast water treatment system on ships with ballast capacity above 5000 m^3 are shown in table 1. (DNVGL 2014a)

Table 1 Temporarily deadline for installation of ballast water treatment system for ships with 5000m3 ballast capacity (DNVGL 2014a)

Constructed year	New schedule
Before 2009	1st IOPP renewal survey after the anniversary date of delivery of ship in 2016
Between 2009 and 2011	1st IOPP renewal survey after the anniversary date of delivery of ship in 2016
After 2011	1st IOPP renewal survey after entry into force of the Convention

These examples show that new environment regulations also may affect the service life of a ship. If a rebuild of an old ship to meet new standards not is profitable, the ship will most likely be scrapped.

2.1.4 Organizational ageing

Definition by Ersdal, G.

- The organization is not able to care for the competence, information and data needed to evaluate and document the safety of the structure or system, resulting in e.g. from re-organizations, retirements, lack of knowledge transfer, change of ownership and change of information storage methods. I.e. the structure or system is not being cared for (operated and maintained) in the way it should be because of lack of information, resulting in improper use and maintenance. (Ersdal 2014)

Definition of organizational ageing for ships:

- The organization is not able to care for the competence, information and data needed to evaluate and document the safety of the ship, resulting in e.g. from re-organizations, retirements, lack of knowledge transfer, change of ownership and change of information storage methods. I.e. the ship is not being cared for (operated and maintained) in the way it should be because of lack of information, resulting in improper use and maintenance.

Organizational ageing is when the competence and information/data needed is not taken care of by the organization. It can for example be when people retire/change job, re-organizations or lack of knowledge transfer. Competence and data can also be lost if the vessel change ownership or if the information storage method is to be changed from one system to another.

Example:

If a vessel is sold, if not all the documents/data regarding the vessel history, concerning for example upgrading and replacements are transferred to the new shipping company, problems can appear.

Suppliers of equipment cannot perform service on own equipment due to organizational ageing in the suppliers organization.

2.1.5 Commercial ageing

An older ship may have more difficulties to get a long term contract. The oil and gas companies are worried for an accident with their cargo onboard, with disastrous consequences, both on the environment and the company. Therefore many oil and gas companies set an upper age limit for ships they will charter, typically 20 years old.

A way for the shipping company to get their ship judged on the actual condition rather than the age, is to get a CAP – Condition Assessment Programme. It is developed to be used on tankers and bulk carriers older than 15 years, and will rate the ship on a scale from 1 to 4. CAP 3 rating is the same as class requirement, but most of the oil companies will require a CAP rating of 1 or 2. See chapter 4.2.2.2 for more information.

In table 2 some oil and gas companies are listed with the maximal age on the ship they will charter, and which CAP rating they require on 15+ years oil and LPG vessels, and 20+ years LNG vessels. It seems like the common rule for the companies are that oil tankers are required to be younger than LPG- and LNG vessels, with LNG vessels allowed to be oldest. The max age requirement is not based on the actual condition of the vessel, it is only an upper age limit the oil and gas company sets for the vessels they charterer.

Table 2 Max age and CAP requirement set by different oil and gas companies

Company	Max age of ship			CAP Hull requirement
	Oil	LPG	LNG	
BP	20	25	40	CAP 1 or 2
Statoil	20	20	20	CAP 1 or 2
Petrobras	20	22	30	CAP 1 or 2
Conoco Phillips	20	30	30	CAP 1 or 2
Neste Oil	20 - 23	27	27	CAP 1 or 2
Preem AB	25	25	25	CAP 1 or 2
Phillips 66	20	30	30	CAP 1 or 2
ExxonMobil	-	-	-	CAP 1 or 2
ENI	25	25	25	CAP 1 or 2
Total	15	20 - 25	20 - 25	-

Info in table 2 are found from these references (BP 2014, Statoil 2014, Petrobras 2014, Conoco Phillips 2014, Neste oil 2014, Preem AB 2014, Phillips 66 2014, ExxonMobil 2014, ENI 2014, Total 2014)

Many believe that it is wrong to judge a ship only by its age.

“It is ridiculous to suggest that old ships are automatically worse than newer vessels and that a charterer should be castigated as environmentally irresponsible for the high average age of the ships he is working.
Ships are not pots of yogurt, liable to cause serious harm if used after a specified sell-by date. Quality is nothing whatever to do with the age of a ship.” (Hare 1995)

Demand based ageing are also a type of commercial ageing. If there is an excess of ships in the market, the oldest are most likely to be taken out of service first. If there is shortage of ships in the market, the oil and gas companies may charter older ships then they normally would do.

2.2 Ageing issues on ships

Based on Oil & Gas(2014)

On a liquefied gas tanker there are many systems that will age over time, among others the marine systems, including cargo system, ballast system, marine utilities, inert gas system and control system. The hull and machinery will also degrade over time.

The cargo system, including cargo pumps, piping, couplings, valves, control system, offloading system, compressors will be affected by wear, corrosion, obsolescence, cyclic stress, mechanical damage etc.

The ballast system, including ballast pumps, pipework in tanks, valves and control system will be affected by wear, corrosion, obsolescence, cyclic stress, mechanical damage etc.

The marine utilities, including fire pumps, emergency generator, sewage system, bunkering arrangement and fuel oil separators will be effected by corrosion, obsolescence etc.

The control system, including valve control, tank monitoring, flood detection, bilge system and loading control software will be affected by obsolescence and modifications.

Solvang have experienced increased dry docking costs on older ships due to steel renewal and recoating in ballast tanks because of corrosion. Corrosion in ballast tanks is seen as one of the most critical ageing issues on a LPG tanker. Therefore it was decided to investigate the problem with corrosion in ballast tanks on some of the ships in the Solvang fleet.

2.3 Ballast tanks

In SCC (2000) it is found statistics on damages on ships hull and the causes. In figure 2 it is shown that for ships with age 12 years and above, corrosion is the cause of more than half the damages recorded. Thereafter cracking causes a lot of the damages. Damages caused by vibration and other things are also listed.

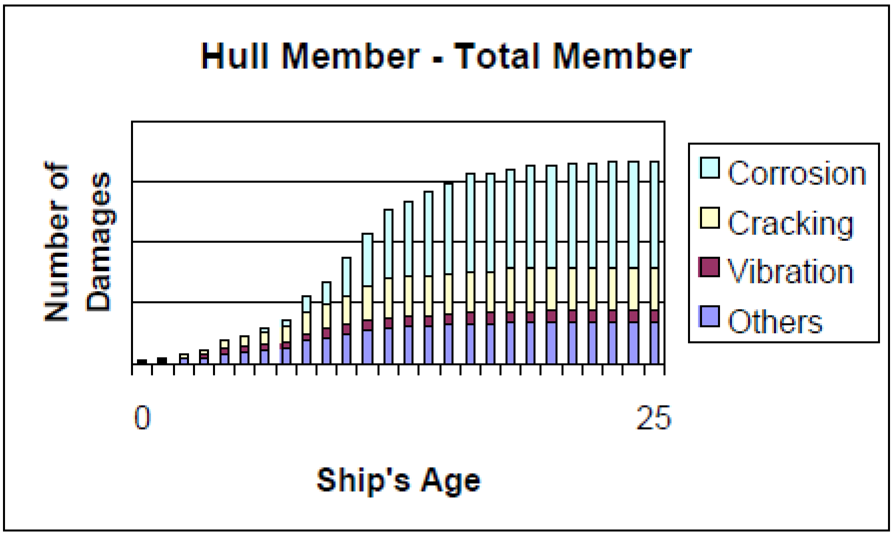


Figure 2 Relation Between Frequency of Damage to Hull Structural Members for Different Causes and Ship Age for All Ship Types (SSC 2000)

Concerning the damages caused by corrosion and fatigue, most of them appear in either the cargo holds or in the ballast tanks. See figure 3 below.

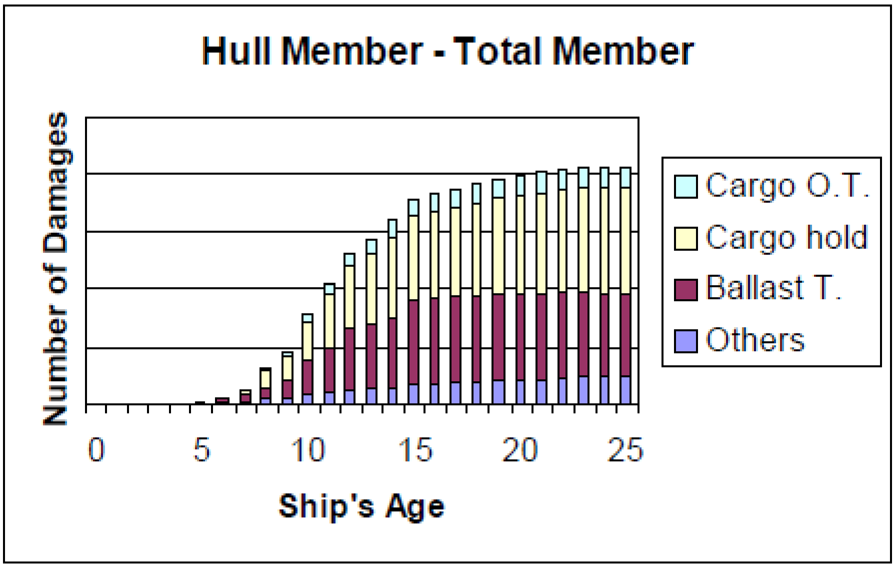


Figure 3 Relation Between Frequency of Damage Due to Corrosion and Fatigue for All Structural Members, Service Conditions, and Ship Age (SSC 2000)

Where:

Cargo O.T.	Cargo Oil tank
Cargo hold	Cargo hold for bulk carriers
Ballast	Sea water ballast tanks
Others	Other spaces

On LPG tankers corrosion in the cargo tanks does not exist, so the damages caused by corrosion and fatigue in the cargo O.T or cargo hold is not relevant for LPG tankers. From experience in Solvang the void spaces between the ballast- and cargo tanks had a major problem with corrosion and cracking on earlier ships, due to water intrusion. Due to other ship design were water intrusion in the void spaces are not possible, this is not a problem on the Solvang fleet now.

Corrosion in ballast tanks is a highly relevant theme concerning the service life of a LPG tanker. Corrosion in ballast tanks will gradually be a problem on ships. How large the problem will be and how soon it will develop depends on several factors where the following are the most important. Quality of coating and the painting work carried out at new build state at shipyard, and the quality of the maintenance work carried out in the ships lifetime.

In 2006 a new requirement regarding coating in ballast tanks was adopted by IMO, Performance Standard for Protective Coating – PSPC. (IMO 2006) Before this the coating in ballast tanks was more or less up to the owner and shipyard to decide. See Ch. 3.4.1

To get a good rating on a CAP inspection for 15 years old ships and older, the coating in ballast tanks has to be found in either good or fair condition. If the coating is found in poor condition during a CAP inspection, the ship will not get a good rating before coating maintenance are carried out. (Clipper Harald 2014) Due to this requirement ship-owners are required to take better care of their ships now than they were earlier, due to the demand from charterer to have a good CAP rating. (Ref Ch. 2.1.5)

Corrosion in sea water ballast tanks can progress in three types of ways as seen in figure 4 below; (Wang 2003)

- First there are no corrosion due to intact protective coating
- Line a, linearly increasing corrosion wastage
- Curve b, increasing and accelerating corrosion wastage over time due to flexing, and loosening “protective” scale and rust build up.
- Curve c, decreasing and decelerating corrosion wastage over time due to “protective” scale and rust build up, protecting new steel from exposure to corrosive environment.

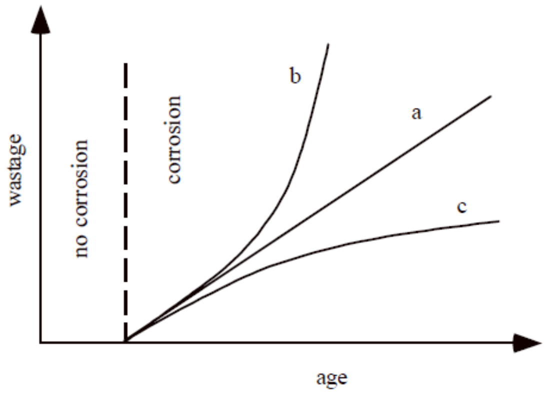


Figure 4 Different ways for corrosion to develop in ballast tank (Wang 2003)

Paik (2004) got a total of 1937 thickness measurement from ballast tanks on 11 to 27 years old ships. Measurement of renewed structural members were excluded from the study, and because it is not known how much steel that has been renewed, and how much it was corroded before renewal it will not give a total overview of how much ballast tanks will corrode. (Paik 2004)

In table 3, all the 1937 thickness measurement are presented with the ships age and the dept of the corrosion. When the corrosion depth are 2.0 mm and above it will approach the allowable limit for corrosion. (DNV 2013a) This may be a major reason for the few measurment of thickness reduction of 2.0 mm and above.

Table 3 Number of thickness measurements in the different categories with depth of corrosion in ballast tanks on 11 to 27 years old ships (Paik 2004)

Ships age (year)	**Depth of corrosion (mm)**							
	0.0-0.5	**0.5-1.0**	**1.0-1.5**	**1.5-2.0**	**2.0-2.5**	**2.5-3.0**	**3.0-3.5**	**3.5-4.0**
11.0–11.5	2	0	0	0	0	0	0	0
11.5–12.0	18	5	0	0	0	0	0	0
12.0–12.5	6	3	9	0	0	0	0	0
12.5–13.0	23	2	0	0	0	0	0	0
13.0–13.5	16	28	30	2	0	0	0	0
13.5–14.0	9	0	0	0	0	0	0	0
14.0–14.5	3	3	0	0	0	0	0	0
14.5–15.0	1	2	0	0	0	0	0	0
15.0–15.5	22	13	10	3	2	0	0	0
15.5–16.0	9	1	0	0	0	0	0	0
16.0–16.5	5	0	0	0	0	0	0	0
16.5–17.0	12	8	5	2	1	1	0	0
17.0–17.5	19	1	0	0	0	0	0	0
17.5–18.0	84	1	2	4	0	0	0	0
18.0–18.5	34	26	37	9	4	3	0	0
18.5–19.0	1	0	2	0	0	0	0	0
19.0–19.5	53	11	11	8	7	2	0	1
19.5–20.0	84	9	1	0	2	0	0	0
20.0–20.5	169	48	11	3	1	0	0	0

20.5–21.0	10	14	11	10	16	2	0	0
21.0–21.5	105	115	27	24	5	6	0	0
21.5–22.0	9	1	1	2	2	0	0	0
22.0–22.5	44	39	4	9	7	5	3	0
22.5–23.0	8	18	1	3	0	0	0	0
23.0–23.5	67	46	11	5	3	5	0	0
23.5–24.0	8	3	1	0	0	0	0	0
24.0–24.5	41	27	8	2	0	0	0	0
24.5–25.0	18	15	2	0	0	0	0	0
25.0–25.5	30	49	48	57	40	2	2	1
25.5–26.0	10	1	1	2	0	0	0	2
26.0–26.5	8	8	1	0	0	0	0	0
26.5–27.0	0	7	1	0	0	0	0	0

To get a better visualization of the collected measurement, the data are shown in figure 5. Most of the measurements are with corrosion depth of 1.5 mm and below, and nearly all measurement are below 2.5 mm corrosion depth, with very few over 2.5 mm.

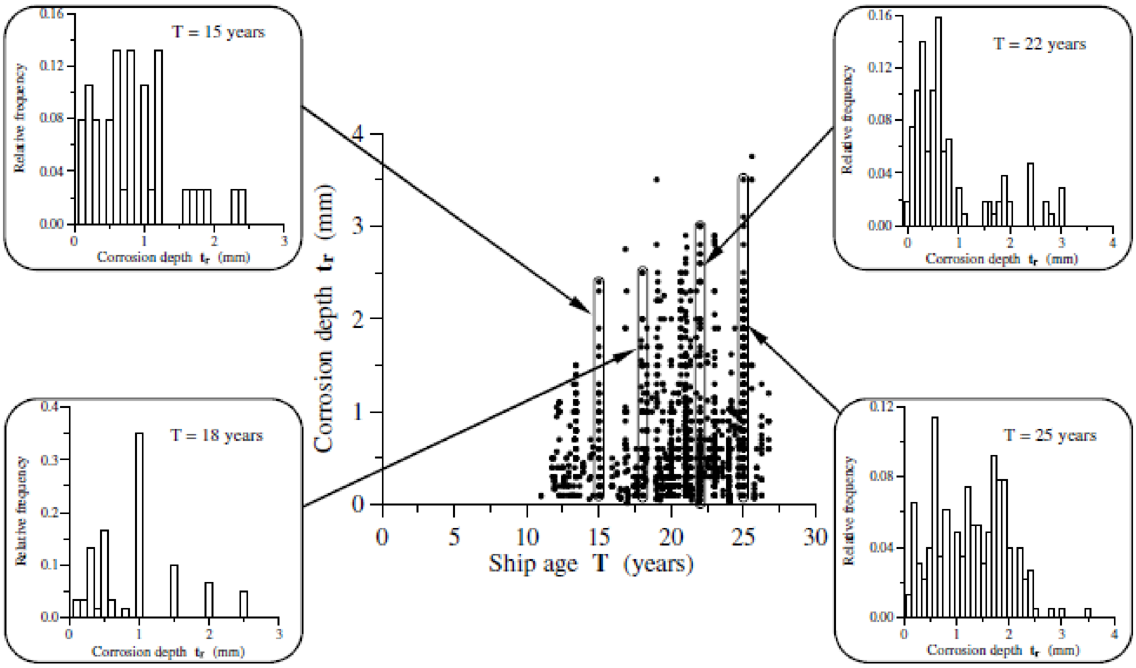


Figure 5 1937 thickness measuremets of ballast tanks (Paik 2004)

Since it is not known how much steel in the ballast tanks that are renewed, it may give a wrong impression of the corrosion rates and corrosion depth in ballast tanks. But it will give a good estimate for the corrosion rates, if the highest ratest are excluded. (Due to not known amount of steel renewal).

The corrosion rates presented in table 4 are estimated using a probabilistic model and a corrosion wastage database. The collected data is from 140 single hull oil tankers measured in the period 1992 – 2000. The ballast tanks are similar on both oil- and gas tankers, with the same corrosive environment, so the data is also relevant for gas tankers. Most of the ships were built in the 1970’s and some in the 1980’s, with a service life of 12 – 26, 32 years. A total of 110.082 measurements from ballast- and cargo tanks were used in the study. Only the data concerning ballast tanks are presented in table 4. (Wang 2003)

Table 4 Estimated mean, standard deviation and maximum values of corrosion rate for various structural members in ballast tanks on oil tankers and comparison with the range of general corrosion by TSCF (1992) (unit: mm/year) (Wang 2003)

Structure	Mean	Maximum	TSCF (1992)
Deck plating	0,055	0,277	0,1 - 0,50
Deck long web	0,047	0,444	0,25 - 1,00
Deck long flange	0,044	0,175	-
Side shell	0,043	0,573	0,06 - 0,10
Side long web	0,042	0,800	0,10 - 0,25
Side long flange	0,032	0,482	-
Bottom shell	0,049	0,320	0,04 - 0,10
Bottom long web	0,027	0,117	-
Bottom long flange	0,045	0,700	-
Bulkhead long web	-	-	0,20 - 1,20
Bulkhead long flange	-	-	0,20 - 0,60

This was before coating of ballast tanks became mandatory by requirement, so it is not known if the ballast tanks on the measured ships had coating or not. Regardless of coating or not, the corrosion rates can be representative for coated ballast tanks, because they will also corrode when the coating fails. The corrosion on spots with coating breakdown will in many cases have a higher corrosion rate than general corrosion over larger areas. The corrosion addition in ballast tanks may vary from 1 – 3+ mm, and with the maximum corrosion rates presented in table 4 it can be seen that in worst case, the reduction in steel thickness can in relatively short time (~5 years) reach the maximum allowable thickness diminution.

3 Theory, ageing issues in ballast tanks

To understand the ageing issues in ballast tanks the most relevant theory are presented in this chapter. Corrosion, fatigue, buckling, coating, cathodic protection and maintenance are studied.

Many of the pictures to illustrate the different ageing issues are taken by undersigned during tank inspections

3.1 Corrosion

Based on Ersdal (2014) and ABS (2007)

Corrosion is an electrochemical reaction where the steel reacts with the environment and forms an oxide

For corrosion to occur, three conditions have to be fulfilled

1. The metal surface has to be exposed to the environment. (The protective coating has to be damaged)
2. There has to be an electrolyte able to conduct current present. (Water containing ions)
3. There has to be an oxidant causing corrosion present. (O_2, CO_2)

Corrosion will not occur if one of these conditions is absent.

The chemistry behind corrosion is as follows: (ABS 2007)

1. $Fe \rightarrow Fe^{++} + 2e^-$
   Iron atom → Iron ion + 2 electrons
2. $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
   Oxygen + Water + 4 electrons → Hydroxyl ions
3. $Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$
   Ferrous ions + Hydroxyl ions → Ferrous hydroxide
4. $2Fe(OH)_2 + O_2 \rightarrow Fe_2O_3 2H_2O$
   Ferrous hydroxide + Oxygen → Hydrated ferrous hydroxide/corrosion

The area that becomes anode has the (1) reaction and the area that becomes cathode has the (2) reaction. See figure 6.

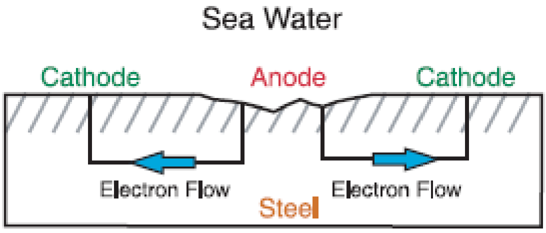


Figure 6 Anodic and cathodic area on steel surface (ABS 2007)

The (3) reaction are shown in figure 7, and when the ferrous hydroxide reacts with oxygen the (4) reaction happens and the anodic area appears with corrosion

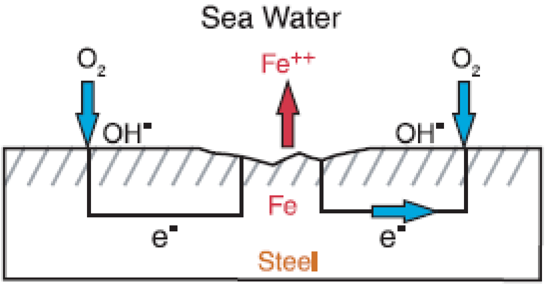


Figure 7 The steel absorbs O_2 and emits Fe^{++} (ABS 2007)

3.1.1 Types of corrosion

From the many different types of corrosion, the types known to exist in ballast tanks are presented below.

3.1.1.1 General corrosion

Based on ABS (2007)

General or uniform corrosion is a type of corrosion *where* the anodic and cathodic areas interchange to create a large uniformly corroded area. This is the least critical type of corrosion because the lifetime of the structure can more easily be predicted, than with other types of corrosion. See picture 1 for example of general corrosion in a ballast tank.

Picture 1 General corrosion in a ballast tank (Charisma 2014)

3.1.1.2 Crevice corrosion

Based on ABS (2007)

Crevice corrosion is a type of extremely localized corrosion. The steel surface in the crevice becomes anodic and the surroundings become cathodic, causing extremely localized corrosion. See fig 8.

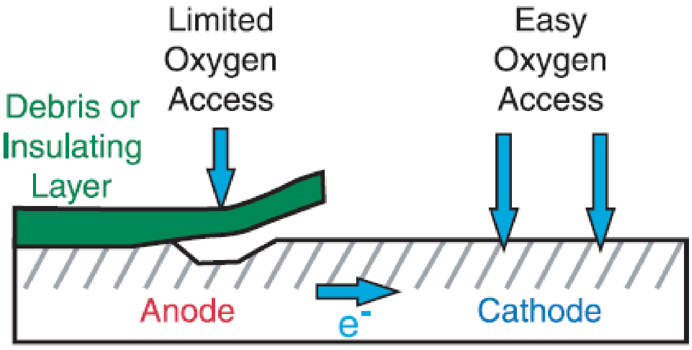
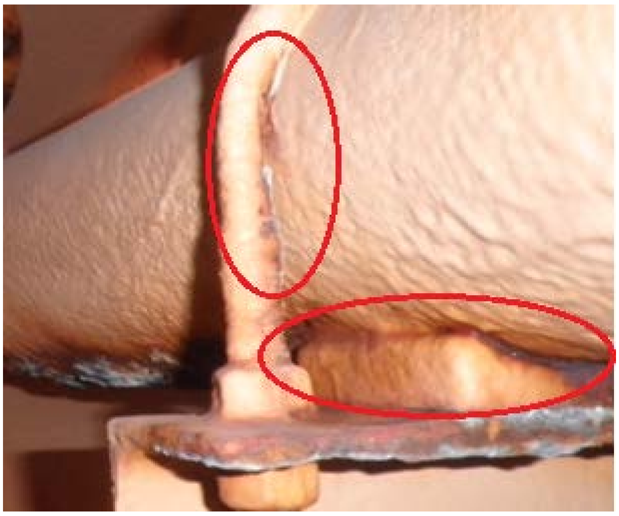


Figure 8 Crevice corrosion (ABS 2007)

Crevice corrosion in ballast tanks often appears around bolt and nuts (picture 2), and between piping and the piping clamps (picture 3)

Picture 2 Corroded bolts and nuts on a flange in ballast tank (Ask 2014a)



Picture 3 Corroded piping clamps (Ask 2014a)

3.1.1.3 Grooving corrosion

Based on DNV (2013a)

Grooving corrosion is a localized type of corrosion that typically occurs on weld seams and where the coating has been damaged.

It is a dangerous type of corrosion due to the high corrosion rate. If the coating is being damaged, the unprotected steel becomes anodic while the area with coating surrounding the damaged area becomes cathodic, causing extremely localized corrosion.

Grooving corrosion on a flat area is similar to pitting corrosion, but the groove in grooving corrosion is wider and larger than pitting. See figure 9.

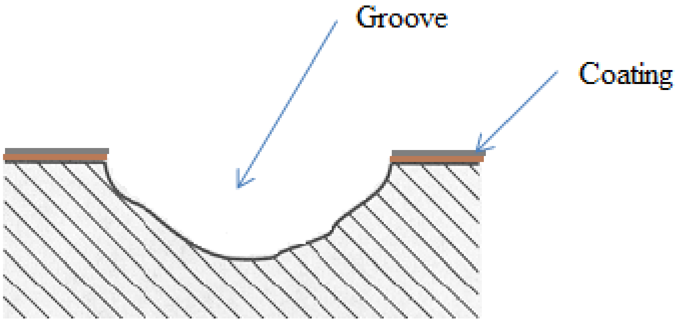


Figure 9 Grooving corrosion

An example of grooving corrosion on the side plating of a Solvang ship is shown in picture 4.

Picture 4 Grooving corrosion on ship's side after grit blasting and coating (Clipper Victory 2013)

In ballast tanks grooving corrosion is mostly occurring in the tank top of the wing tanks, due to the high level of air in the tank top when in ballast condition, and the ineffectiveness of anodes in the tank top. See figure 10.

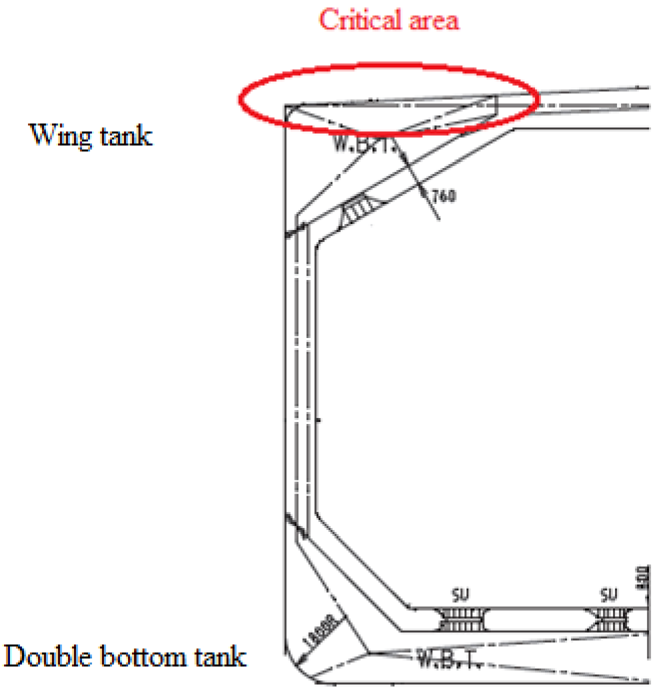


Figure 10 Critical area concerning grooving corrosion

In the weld seams connecting the longitudinal stiffeners to the deck plating in the tank top groove corrosion typically occurs. See figure 11.

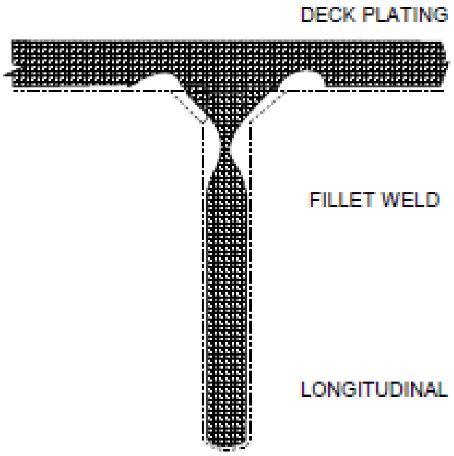


Figure 11 Grooving corrosion in weld seam between longitudinal and deck plating (DNV 2013a)

3.1.1.4 Pitting corrosion

Based on ABS (2007)

Pitting corrosion is an extremely localized type of corrosion with relatively deep penetration in relation to the surrounding area. It can penetrate the steel with a corrosion rate much larger than general corrosion. The pitting corrosion can be difficult to detect, and due to the deep penetration is one of the most dangerous types of corrosion.

Pitting corrosion can occur where the coating is poor due to mechanically damage, poor coating application or similar. The unprotected area without coating becomes anodic, and the large area with coating intact becomes cathodic, with very localized corrosion at the unprotected area as a result. See figure 12.

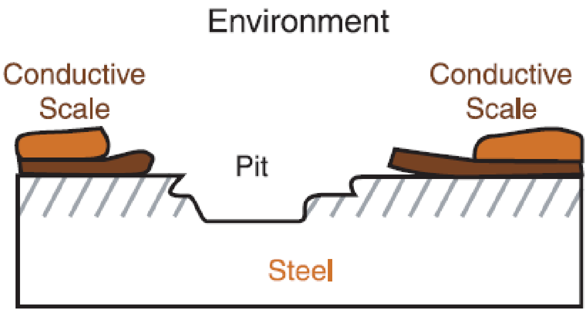


Figure 12 Pitting corrosion (ABS 2007)

See picture 5 for example of pitting corrosion on a steel surface.

Picture 5 Pitting corrosion (NDT 2002)

Different shapes of pitting corrosion can occur, with V shaped-, undercut-, saucer- and stepped pits as the most common. See figure 13.

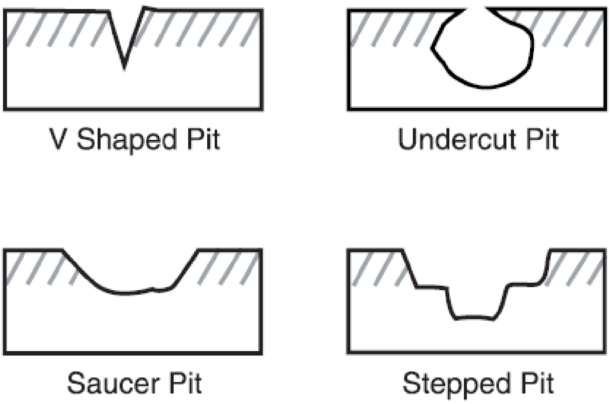


Figure 13 Different pit shapes (ABS 2007)

V shaped- and undercut pits are the most difficult to detect, and they are making the pit deep in a short period of time, and therefor the most dangerous.

The rate of the pitting corrosion is affected of the aggressiveness of the corrodent, which for ships mostly are seawater which is a very aggressive corrodent. A stagnant environment is also an environment pitting corrosion is more readily to occur.

Table 5 are showing the difference in extent for general corrosion rate and pitting corrosion rate. A lager corrosion rate of pitting are tolerable compared to general corrosion.

Table 5 Comparison of general -and pitting corrosion rate (Caproco)

	General corrosion rate	**Pitting corrosion rate**
Extent	**mm/year**	**mm/year**
Low	< 0.025	< 0.125
Moderate	0.025 - 0.125	0.125 - 0.200
Severe	0.125 - 0.250	0.200 - 0.375
Very Severe	> 0.250	> 0.375

3.1.2 Measurement of corrosion

To find the extent of corrosion and the thickness of the remaining steel, ultrasonic thickness measurement – UMT are used. See picture 6.

A part of the CAP- and classification inspections are thickness measurement of the steel. Using an ultrasonic thickness gauge points in the steel structure are measured and controlled to be within the limits. Normally a UTM report consists of thousands of measurements. On the CAP survey of Clipper Skagen there was 8300 readings (Clipper Skagen), and on Clipper Viking there were 14800 readings (Clipper Viking 2013).

Picture 6 Technician performing thickness measurement (Cygnus 2014)

How it works

Based on Cygnus (2014)

The ultrasonic thickness gauge is used as a non destructive test – NDT to measure the thickness of steel. When measuring the thickness of the steel structure of a ship, this is the instrument to be used. The material is measured from one side only.

Multiple echoes are sent through the steel. See figure 14. Time T1 is ignored because it measures the steel thickness plus the coating thickness. Time T2 and T3 are equal and measures the time the echo takes through the steel. With these three echoes the instrument calculates the steel thickness. The accuracy if properly calibrated is 0.1mm

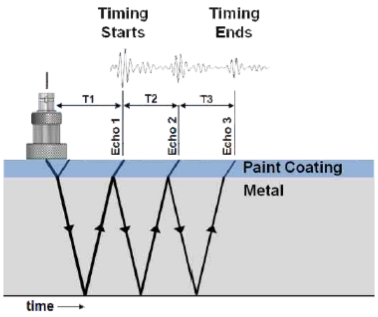


Figure 14 Ultrasonic thickness measurement (Cygnus 2014)

3.2 Fatigue

Based on Ersdal (2014)

Areas which are subjected to cyclic stresses may fail due to fatigue. Fatigue cracking usually appears on places with high stress concentration such as welds, notches and sharp geometric transitions. See picture 7 and 8. A fatigue crack starts at a localized spot and will with cyclic stress gradually increase over the cross section of the member or component.

Picture 7 Crack on a high stress concentration area (Clipper Skagen 2012)

Picture 8 Crack on a weld seam (Clipper Skagen 2012)

On both MV Erika and MV Prestige it was reported cracks before they sank. Erika had a crack in the deck plating that increased fast in the rough weather, resulting in that the ship broke in two.

The fatigue life of an element is highly dependent on the surrounding environment. See chapter 6.2 Fatigue life.

3.2.1 Simplified fatigue life evaluation

Based on DNV (2014c) and DNVGL (2014c)

The fatigue life is calculated with two different approaches. The fatigue life calculations for ships (DNV CN 30.7) and for offshore steel structures (DNVGL RP-C203) are different. It is interesting to see the difference in calculated fatigue life with the two different calculation methods.

To calculate the fatigue life the expected life, normally 20 years are divided by the miner sum, D.

Fatigue life:

$$T = \frac{C}{D} \qquad 1-1$$

Where:

T = Fatigue life

C = Service life (20 years)

D = Miner sum

First the fatigue life is calculated for the area/spot in air or cathodic protected condition by using a two slope S-N curve. This is the same as the coating is intact.

Two slope S-N curve:

$$D = v_0 \cdot T_d \left[\frac{q^{m_1}}{\bar{a}_1} \Gamma\left(1 + \frac{m_1}{h}; \left(\frac{s_1}{q}\right)^h\right) + \frac{q^{m_2}}{\bar{a}_2} \gamma\left(1 + \frac{m_2}{h}; \left(\frac{s_1}{q}\right)^h\right)\right] \leq \eta \qquad 1-2$$

Where:

T_d = design life of ship in seconds

v_0 = long-term average response zero-crossing frequency

s_1 = Stress range for which change of slope of S-N curve occur

$\bar{a}_1, m_1$ = S-N fatigue parameters for $N \leq 10^7$ cycles

$\bar{a}_2, m_2$ = S-N fatigue parameters for $N > 10^7$ cycles

q = Weibull stress range scale distribution parameter for load condition

h = Weibull stress range shape distribution parameter for load condition

$\Gamma(\,)$ = Complementary incomplete gamma function, to be found in standard tables

$\gamma(\,)$ = Incomplete gamma function, to be found in standard tables

The parameters ā and m from the S-N curve are found in figure 15.

$$\bar{a} = 10^{\log \bar{a}}$$

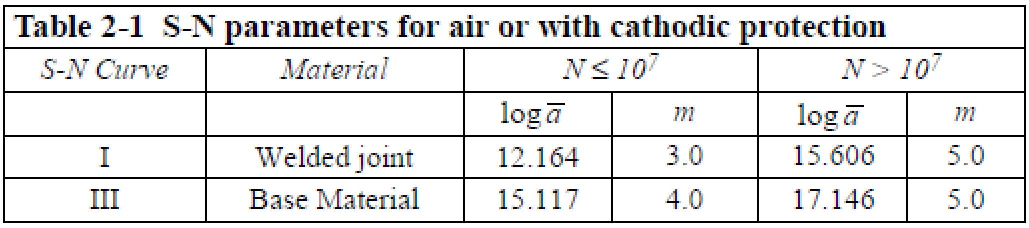


Table 2-1 S-N parameters for air or with cathodic protection

S-N Curve	*Material*	*$N \leq 10^7$*		*$N > 10^7$*	
		$\log \bar{a}$	m	$\log \bar{a}$	m
I	Welded joint	12.164	3.0	15.606	5.0
III	Base Material	15.117	4.0	17.146	5.0

Figure 15 S-N parameters for air or with cathodic protection (DNV 2014c)

For deck longitudinal h = h_0, where:

$$h = h_0 = 2.21 - 0.54 \cdot \log_{10}(L) \qquad 1-3$$

The long-term average response zero-crossing frequency v_0, are calculated by:

$$v_0 = \frac{1}{4 \cdot \log_{10}(L)} \qquad 1-4$$

Where:

L = the ships length between perpendiculars

The combined local and global stress range are as follows:

$$\Delta\sigma_0 = f_m \cdot f_{HT} \cdot f_e \cdot \Delta\sigma \qquad 1-5$$

f_m = Reduction factor
= 1.0 in this calculation

f_{HT} = Reduction factor
= 1.0 for welded joints

f_e = Reduction factor
= 0.8 for world wide operation.

$\Delta\sigma$ = Stress range (The stresses are not adjusted for corrosion reduction of plate thickness)

Stress range:

$$\Delta\sigma = \sigma_{Wave,sagg} + \sigma_{Wave,hogg} \qquad 1-6$$

Where:

$$\sigma_{Wave,sagg} = \frac{M_{Wave,sagg}}{W_{Deck}} \qquad 1-7$$

$$\sigma_{Wave,hogg} = \frac{M_{Wave,hogg}}{W_{Deck}} \qquad 1-8$$

Where:

$\sigma_{Wave,sagg}$	=Wave induced stress, sagging
$\sigma_{Wave,hogg}$	=Wave induced stress, hogging
$M_{Wave,sagg}$	=Design wave bending moments, sagging
$M_{Wave,hogg}$	=Design wave bending moments, hogging
W_{Deck}	=Midship section modulus, deck

Weibull stress range scale distribution parameter for load condition:

$$q = \frac{\Delta\sigma_0 \cdot SCF}{(\ln n_0)^{\frac{1}{h}}} \qquad 1-9$$

Where:

SCF = Hot Spot Factor/K-factor, found in DNV Class Note 30.7 Table A-1 – A-9

Due to not 100% sailing time, D is redused with an factor of 0.85, to 85% sailing time. See figure 16.

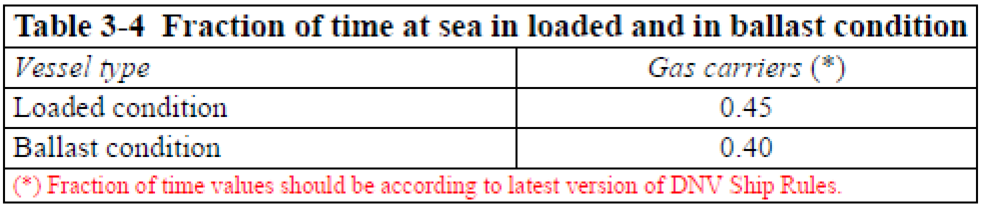


Table 3-4 Fraction of time at sea in loaded and in ballast condition	
Vessel type	*Gas carriers (*)*
Loaded condition	0.45
Ballast condition	0.40
(*) Fraction of time values should be according to latest version of DNV Ship Rules.	

Figure 16 Liquefied gas tanker, operation time. (DNV-GL ship rules)

$$D = D \cdot 0.85 \qquad\qquad 1-11$$

Total fatigue life in air or with cathodic protection (Intact coating) :

$$Life\ time(year): T_{air} = \frac{20}{D} \qquad\qquad 1-12$$

$$D_{year,air} = \frac{D}{20} \qquad\qquad 1-13$$

The fatigue life is calculated with two different approaches. The fatigue life calculations for ships (DNV CN 30.7) and for offshore steel structures (DNVGL RP-C203) are different. It is interesting to see the difference in calculated fatigue life with the two different calculation methods.

Corrosive environment (Coating failure):

In corrosive environment the fatigue life are calculated differently in DNV CN 30.7 for ships and DNVGL RP-C203 for offshore steel structures.

With corrosion the stresses applied to the structure will increase:

$$\sigma = \frac{F}{A}$$

Smaller cross-sectional area (A) gives larger stress (σ). Larger stress leads to shorter fatigue life. This is not taken into account during the fatigue life evaluation.

Ships (DNV CN 30.7)

For unprotected joints in corrosive environment the the S-N curve in the table XX shall be reduced by a factor of 2:

- In Air; Miner sum $D_{Air} = D$
- In corrosive environment; Miner sum $D_{Corr} = D*2$ 1 – 14

Offshore steel structures (DNVGL RP-C203)

In corrosive environment a one slope S-N curve are used:

$$D_{Corr} = \frac{v_0 \cdot T_d}{\bar{a}} \cdot q^m \cdot \Gamma\left(1 + \frac{m}{h}\right) \leq \eta \qquad 1-15$$

Where:

T_d = design life of ship in seconds

v_0 = long-term average response zero-crossing frequency

$\bar{a}$ = parameter from S-N curve, see figure 15

m = parameter from S-N curve, see figure 15

q = Weibull stress range scale distribution parameter for load condition

h = Weibull stress range shape distribution parameter for load condition

$\Gamma\left(1 + \frac{m}{h}\right)$ = gamma function, from figure 17.

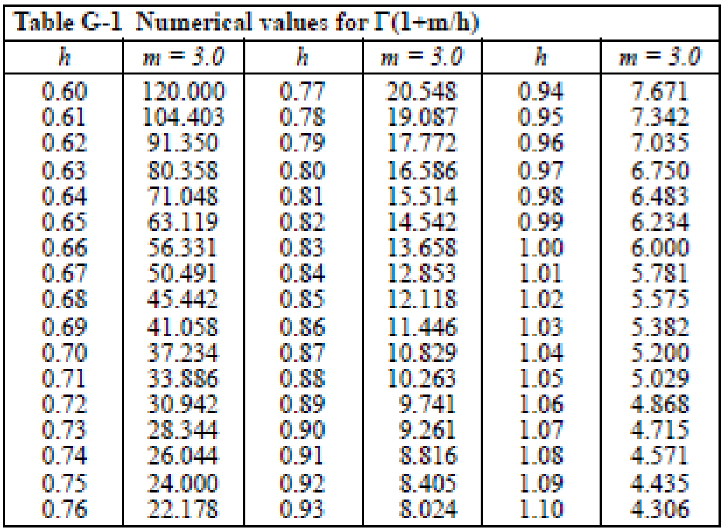


Table G-1 Numerical values for $\Gamma(1+m/h)$

h	$m = 3.0$	h	$m = 3.0$	h	$m = 3.0$
0.60	120.000	0.77	20.548	0.94	7.671
0.61	104.403	0.78	19.087	0.95	7.342
0.62	91.350	0.79	17.772	0.96	7.035
0.63	80.358	0.80	16.586	0.97	6.750
0.64	71.048	0.81	15.514	0.98	6.483
0.65	63.119	0.82	14.542	0.99	6.234
0.66	56.331	0.83	13.658	1.00	6.000
0.67	50.491	0.84	12.853	1.01	5.781
0.68	45.442	0.85	12.118	1.02	5.575
0.69	41.058	0.86	11.446	1.03	5.382
0.70	37.234	0.87	10.829	1.04	5.200
0.71	33.886	0.88	10.263	1.05	5.029
0.72	30.942	0.89	9.741	1.06	4.868
0.73	28.344	0.90	9.261	1.07	4.715
0.74	26.044	0.91	8.816	1.08	4.571
0.75	24.000	0.92	8.405	1.09	4.435
0.76	22.178	0.93	8.024	1.10	4.306

Figure 17 Gamma function values (DNV 2014c)

Total fatigue life with ex. 10 years effective coating:

10 years with protective coating:

$$D_{air,10\ year} = D_{year,air} \cdot 10 \qquad 1-16$$

$$D_{year,corr} = \frac{2 \cdot D_{year,air}}{20} \qquad 1-17$$

Ex 10 years effective protective coating

$$T_{Total} = 10\ years + \left(\frac{1 - D_{air,10\ year}}{D_{year,corr}}\right) \qquad 1 - 18$$

3.3 Buckling

Based on DNV (2014b)

Buckling causes failure in the structure and is caused by a load exceeding the resistance in the structure. Due to corrosion and therefor smaller cross-section area in the steel, the resistance to withstand the stress will reduce:

$$\sigma_{el} = 0.9kE\left(\frac{t}{1000s}\right)$$

When the thickness (t) reduces, the buckling capacity (σ_{el}) reduces.

At the same time the stresses applied to the structure will increase:

$$\sigma = \frac{F}{A}$$

Smaller cross-sectional area (A) gives larger stress (σ).

Figure 18 Buckling example of a plate with one stiffener/longitudinal (UMBC 2014)

3.3.1 Simplified buckling evaluation

Due to lack of computerized software to calculate the buckling capacity, e.g. PULS, the rules for new builds - Rules for classification of ships, part 3 chapter 1, Hull Structural Design, Ships with length 100 metres and above, are used.

3.3.1.1 Buckling capacity in plating

Based on DNV (2014b)

To simplify the calculation it is in the calculation only taken consideration to the uni-axial compressive stresses, and not the bi-axial compressive stresses or shear stresses, as they are considered to be relatively small.

The ideal elastic buckling stress is calculated by:

$$\sigma_{el} = 0.9kE\left(\frac{t - t_k}{1000s}\right)^2 \qquad (N/mm^2) \qquad 2-1$$

The critical buckling stress is calculated by:

$$\sigma_c = \sigma_{el} \qquad when \quad \sigma_{el} < \frac{\sigma_f}{2} \qquad 2-2$$

$$\sigma_c = \sigma_f\left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) \qquad when \quad \sigma_{el} > \frac{\sigma_f}{2} \qquad 2-3$$

For plating with longitudinal stiffeners, as in the ballast tanks the k-factor is calculated by:

$$k = \frac{8.4}{\psi + 1.1} \qquad for\ (0 \leq \psi \leq 1) \qquad 2-4$$

ψ is the ratio between the smaller and the larger compressive stress assuming linear variation. See figure 19. ψ is often assumed to be 1.0 in deck plating between longitudinals.

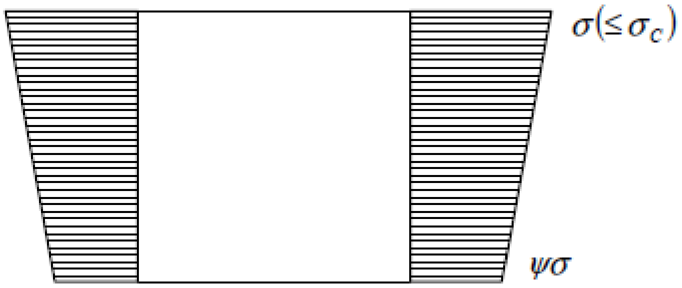


Figure 19 The ratio between the smaller and the larger compressive stress, (DNV 2014a))

Where:

t = thickness if plating in mm

t_k = corrosion addition in mm

s = shortest side of plate panel in m

E = modulus of elasticity of the material

σ_{el} = the ideal elastic compressive buckling stress in $\mathrm{N/mm^2}$

σ_f = minimum upper yield stress of material in $\mathrm{N/mm^2}$

σ_c = the critical compressive buckling stress in $\mathrm{N/mm^2}$

k = factor

ψ = factor

The actual compressive stress is calculated as below:

$$\Delta\sigma_0 = \sigma_w + \sigma_{stw} \qquad 2-5$$

Where

σ_w = wave induced stresses

σ_{stw} = Stillwater induced stresses

The utilization factor, η are calculated as follows:

$$\eta = \frac{\Delta\sigma_0}{\sigma_c} \qquad 2-6$$

When the utilization factor exceeds 1.0, it is reason for concern.

3.3.1.2 Buckling capacity in stiffeners and pillars

Based on DNV (2014b)

Stiffeners and pillars may be exposed to ideal elastic lateral buckling stress and torsional buckling. To simplify the calculation the torsional buckling are disregarded. The ideal elastic lateral buckling stress is the main factor for buckling in longitudinals.

The ideal elastic buckling stress is calculated by:

$$\sigma_{el} = 0.001E\,\frac{I_A}{Al^2} \qquad (N/mm^2) \qquad 2-7$$

The critical buckling stress is calculated by:

$$\sigma_c = \sigma_{el} \qquad when \qquad \sigma_{el} < \frac{\sigma_f}{2} \qquad 2-2$$

$$\sigma_c = \sigma_f\left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) \qquad when \qquad \sigma_{el} > \frac{\sigma_f}{2} \qquad 2-3$$

Where:

E = modulus of elasticity of the material

I_A = moment of inertia in cm^4 about the axis perpendicular to the expected direction of buckling

A = cross-section area in cm^2

l = Length of member in m

σ_{el} = the ideal elastic compressive buckling stress in $\mathrm{N/mm^2}$

σ_f = minimum upper yield stress of material in $\mathrm{N/mm^2}$

σ_c = the critical compressive buckling stress in $\mathrm{N/mm^2}$

The actual compressive stress is calculated as below:

$$\Delta\sigma_0 = \sigma_w + \sigma_{stw} \qquad 2-5$$

Where

σ_w = wave induced stresses

σ_{stw} = Stillwater induced stresses

The utilization factor, η are calculated as follows:

$$\eta = \frac{\Delta\sigma_0}{\sigma_c} \qquad 2-6$$

When the utilization factor exceeds 1.0, it is reason for concern.

3.4 Coating

Coating is the main protection against corrosion in ballast tanks. It is very important to do the coating work at new build state and at maintenance according to the rules and regulations.

3.4.1 The history of coating rules for sea water ballast tanks

Coating in ballast tanks is very important to reduce corrosion and secure safe shipping. The rules and regulations concerning coating in ballast tanks are relatively modern. The historical development of coating rules are presented below

The first regulations concerning coating and protection of ballast tanks came in 1990, the IACS Z8 Corrosion Protection Coating for Salt Water Ballast Spaces, 1990, (Rev 1 1995). And said –
"At the time of new construction, all salt water ballast spaces having boundaries formed by the hull envelope shall have an efficient protective coating, epoxy or equivalent, applied in accordance with the manufacturer's recommendations" (IACS 2014b)

Before this rule there was no requirement for coating in ballast tanks, it was only up to the ship-owner to decide whether to use coating or not. The new requirement was a pretty loose rule, and it just said that ballast tanks should have some kind of coating, epoxy or equivalent when the vessel was built. And that it should be applied in accordance with the manufacturer's recommendations.

The IMO Resolution A.798(19) came on 23 November 1995 and was a guideline for the selection, application and maintenance of corrosion prevention systems of dedicated seawater ballast tanks. This states that among other things that the ship owner should select and maintain a system which will ensure an adequate level of corrosion prevention of the seawater ballast tanks. (IMO 1995)

In 2000 DNV gave out a recommended practice for corrosion protection of ships where they had three systems for protecting ballast tanks. System 1 with a life span range of 5 ± 3 years, system 2 with a life span range of 10 ± 3 years, and system 3 with a life span range of 15 ± 3 years. With the greater life span range, it requires better preparations before coating, and more layers and thicker coating. (DNV 2000)

The first requirement from IMO regulating the corrosion protection of ballast tanks came in 2002 when the SOLAS regulation II-1/3-2 made it mandatory to use coating in ballast tanks. The IMO Resolution A.798(19) mentioned above, was used a reference to the new requirement. (Hoppe 2007)

The development of the performance standard for protective coating started in 2003 with the DE 46, and DE 47 in 2004. The MSC 79 in 2004. The DE 48 started in 2005, where a group of the industries organizations, Bimco, IACS, ICS, Intercargo and Intertanko, met to do the first draft of the performance standard for protective coating of ballast tanks. (Hoppe 2007)

In 2006 the new IMO Performance Standard for Protective Coating – PSPC was adopted and entered into force for ships, which:

- Building contract on or after 1 July 2008
- Keels laid on or after January 2009
- Delivery on or after 1 July 2012

This new requirement PSPC is very comprehensive compared to earlier requirements for ballast tanks, taking care of every small detail concerning to get a satisfactory result on the protection of the ballast tanks. (IMO 2006)

DNV Rules for classification of ships Part 6 chapter 31 – Coating. It requires new buildings to follow the IMO PSPC standard, concerning coating in ballast tanks. (DNV 2013b)

3.4.2 PSPC – Performance Standard for Protective Coating Requirement

After the condition of ballast tanks were considered as a safety issue by IMO, they adopted the PSPC in 2006 to have a stricter requirement concerning the coating in ballast tanks. Some of the elements included in the PSPC are mentioned in chapter 3.4.2.1 and 3.4.2.2.

3.4.2.1 Basic coating system requirement

Based on IMO (2006)

The basic coating requirement from PSPC consists of four parts.

The first part is the design of coating system which describes the selection of coating system, coating type, coating pre-qualification test, job specification and the nominal dry film thickness (NDFT)

The second part is the primary surface preparation (PSP) which describes the blasting and profile, the water soluble salt limit and which type of shop primer to use.

The third part is the secondary surface preparation which describes the steel condition, the surface treatment, profile requirements, dust and salt appearance, and oil contamination.

The fourth part consists of miscellaneous which describes the ventilation and environmental conditions, which type of testing to use on the coating, and how to repair any damaged areas.

3.4.2.2 Coating inspection requirement at construction stage

Based on IMO (2006)

The coating inspection requirement at construction stage for PSPC consists of four parts

The first part is the primary surface preparation which describes the condition of the steel surface with regard to temperature, humidity, contamination etc. Everything shall be recorded.

The second part describes the coating thickness. It is important to take spot checks on the coating thickness.

The third part describes the inspection during block assembly which is much the same as the primary surface preparation mentioned in the first part.

The fourth part describes the inspection during erection.

3.4.3 Coating failures

Based on ABS (2007)

There are many types of coating failures, and they can be divided into two categories. Coating defects during application and in-service coating failures. Here are some examples of some of them.

Coating defects during application:

- Sags
- Runs
- Cissing
- Orange peel
- Cracking or mud cracking
- Holidays
- Over thickness
- Under thickness
- Overspray
- Grit inclusions
- Human error
    - Poor penetration
    - Footprints
    - Winter and summer grades
    - Poor mixing
    - Pot life exceeded
    - Induction period not allowed
    - Shelf life exceeded
    - Storage temperature to low or to high

In service coating failures:

- Shop primer failure
- Through film breakdown
- Blistering
- Edge breakdown
- Weld corrosion
- Calcareous deposits induced coating failures
- Poor surface preparation
- Reverse impact damage
- Mud cracking
- Stress related coating failures

3.4.4 Coating failures found in ballast tanks on Solvang ships

Of the above mentioned coating failures these were present in ballast tanks on Solvang ships inspected by undersigned:

- Blistering
- Edge breakdown
- Weld corrosion

3.4.4.1 Blisters

Based on ABS (2007)

There are two types of blisters, blistering via osmosis and blistering via electro osmosis. Osmotic blisters are normally small and closely spaced, then when the blister get a pore in the coating, electro osmosis can happen

Blistering via osmosis

Osmotic blisters are often caused because of "poor" surface preparation before coating application on new buildings. If any water soluble species or ionic contamination is trapped between the coating and the steel surface, there is a risk for osmotic blistering. Osmosis draws water from the environment through the coating. See figure 20, to see the coating blister due to the pressure difference.

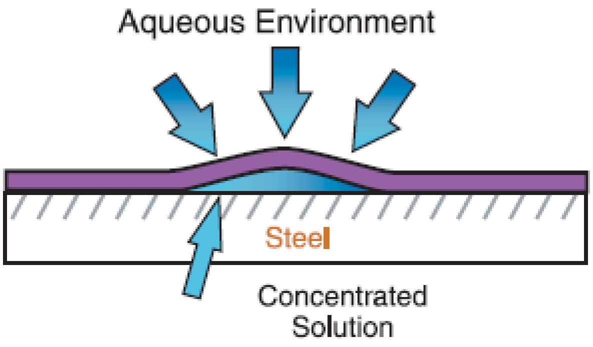
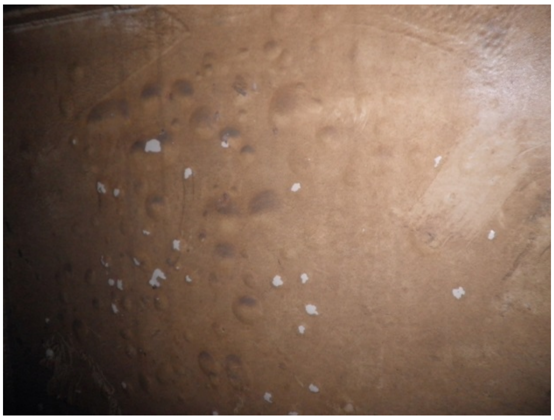


Figure 20 Blistering via osmosis (ABS 2007)

See picture 9 for small closely spaced osmotic blisters for real life example.



Picture 9 Small blisters in a double bottom ballast tank (Ask 2014a)

Blistering via electro osmosis

When osmotic blisters have grown as large to get a pore in the coating, electro osmosis can happen. The blisters continue to grow and electro osmosis causes large blisters. The blister grows as a result of ions driven into the blister due to the difference in potential between the anodic and cathodic site. See figure 21 for mechanism for blistering via electro osmosis

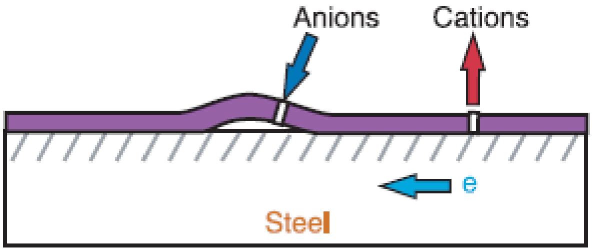


Figure 21 Blistering via electro osmosis (ABS 2007)

See picture 10 for large blisters caused by electro osmosis. The picture is from a double bottom ballast tank.

Picture 10 Large blisters in a double bottom ballast tank (Ask 2014a)

3.4.4.2 Edge breakdown

Based on ABS

Edge breakdown are a common problem in ballast tanks. In all ballast tanks inspected by undersigned, edge corrosion was found. On Clipper Skagen (1989), Clipper Harald (1999) and Clipper Posh (2013).

Edge breakdown is the result of sharp edges with to thin coating thickness. All edges shall be ground smooth and stipe coat shall be applied by hand. (ABS 2007) Picture 11 shows coating edge breakdown on a stiffener support

Picture 11 Edge breakdown on Clipper Posh (Ask 2014c)

Picture 12 shows coating edge breakdown on a longitudinal.

Picture 12 Edge breakdown in drain hole (Ask 2014a)

3.4.4.3 Weld corrosion

Based on ABS (2007)

Local corrosion around and on welds are common in ballast tanks. Weld corrosion are a result of poor surface preparation prior to coating. There are two types of weld corrosion, where the one with corrosion around the weld are in the heat affected zone – HAZ and caused by oxide build up after welding. See picture 13.

Picture 13 Type 1 weld corrosion (ABS 2007)

The second type of weld corrosion is shown in picture 14. It is caused by poor surface cleanliness and the corrosion appears closer to the weld seam than the first type weld corrosion.

Picture 14 Type 2 weld corrosion (ABS 2007)

3.4.4.4 Rust jacking

Based on ABS (2007)

The coating failure called rust jacking occurs when iron becomes rust underneath the coating. Rust typically leads to an increase in volume between 8 to 12 times. When this volume increase happens between the steel surface and the coating, the coating is pushed away from the steel surface. It often happens on areas with damaged coating, especially on cut edges and welds. See figure 22.

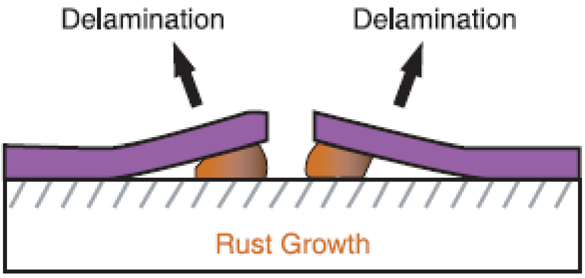


Figure 22 Rust jacking (ABS 2007)

See pictures 15 and 16 for examples of rust jacking on cut edges.

Picture 15 Rust jacking (Ask 2014a)

Picture 16 Rust jacking (Ask 2014a)

3.4.5 Stripe coat

Stripe coating is done to secure additional coating thickness on welds and sharp edges. This is of high importance because it is usually these places that will corrode first due to thin coating and/or wear and tear. Stripe coat in ballast tanks are applied by brush on welds and edges after the first- and the second coat (ABS 2007). The Performance standard for protective coating requires stripe coat to be applied both on new build stadium and on maintenance work carried out during the ship's service life (IMO 2006). On vessels delivered before PSPC was implemented, and not stripe coated from yard, applying stripe coating when maintenance in ballast tanks would secure a longer coating life.

Before stripe coat are applied, the sharp edges have to be rounded of to a radius of minimum 2 mm or be subjected to three pass grinding, for the paint to stick properly. In ballast tanks with two coats of paint, there is added a stripe coat after the first coat of paint and after the second coat of paint (IMO 2006). See figure 23.

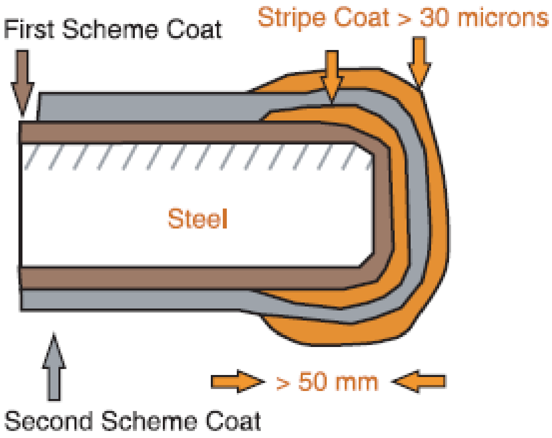


Figure 23 Stripe coat on sharp edge (ABS 2007)

Concerning the stripe coat on welded seams, the second stripe coat can be skipped to avoid unnecessary thickness of coating, if it can be proven that the nominal dry film thickness – NDFT is met. (IMO 2006). See figure 24 for a two layer stripe coat on a weld seem.

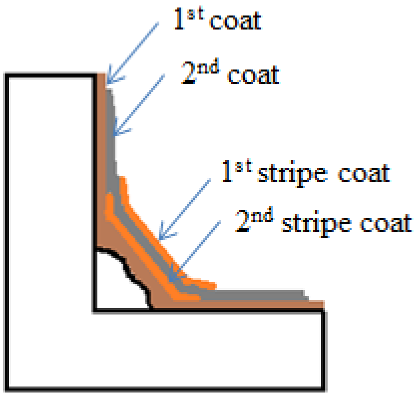


Figure 24 Stripe coat on weld

Example of stripe coat in an upper wing ballast tank, where all edges and weld seams has been stripe coated once after the first coat of paint. See picture 17.

Picture 17 Stripe coated ballast tank (GS 2014)

How a drain hole can be after a relatively short period of time (~5 years) if the stripe coating are not properly carried out. See picture 18.

Picture 18 Drain hole in a wing ballast tank (Clipper Mars 2014)

3.5 Cathodic protection

Based on ABS (2007)

Cathodic protection is an effective method to reduce the extent of corrosion in ballast tanks. If the coating is in “POOR” condition and damaged, the sacrificial anodes will be offered instead of the steel. This works well in the *bottom* ballast tanks and the lower part of the upper wing ballast tanks, but in the top of the wing ballast tanks, the sacrificial anodes will not do their purpose. Sacrificial anodes are only effective when anodes and the steel which it will protect are under water. See picture 19 and 20 for breakdown of anodes in ballast tanks.

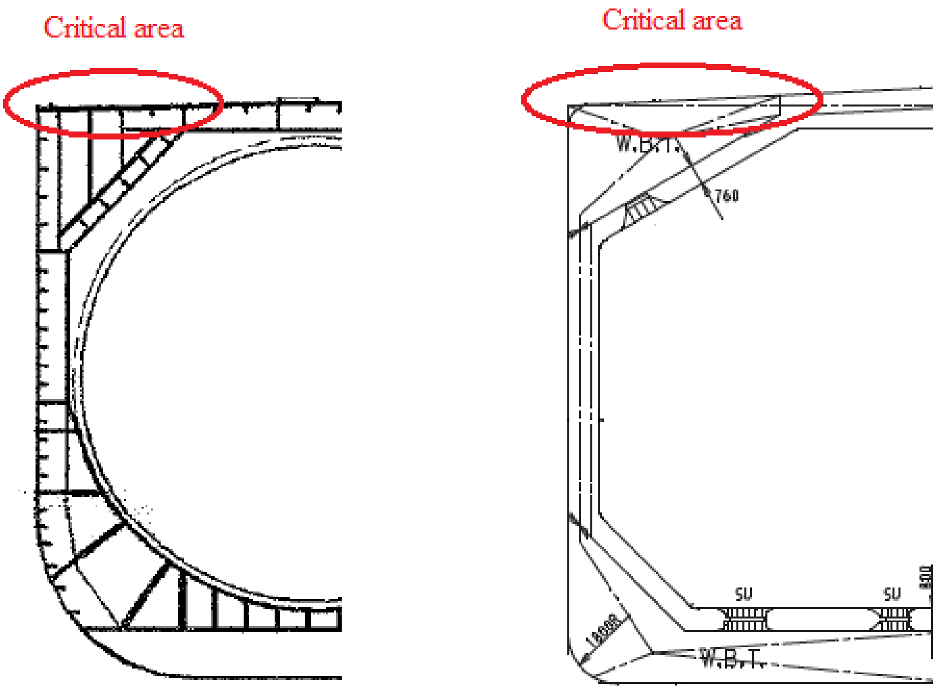
Double bottom ballast tanks are full when vessel in ballast, and has good cathodic protection when sacrificial anodes are installed. Wing ballast tanks will not be completely full when vessel in ballast, and the upper part of the tank where it moist air, has not cathodic protection.

Picture 19 100% and 80% anode (Ask 2014a)

Picture 20 0% anode (Ask 2014a)

When the vessel has cargo loaded, most of the ballast tanks are empty. Then ballast tanks are only used for trimming the vessel. All the empty ballast tanks will then contain moist air, and then the anodes will therefore not be useful. Now only good coating will protect the ballast tanks from corrosion.

The critical area concerning areas not protected properly by the anodes is the upper part of the wing ballast tanks, underneath the deck plating. See figure 25.



Semi ref.LPG/Ethylene

Fully ref.LPG/Ammonia

Figure 25 Critical area where anodes have no/reduced function

See picture 21 below for an example of corrosion in the top of a wing ballast tank. See picture 22 for the general condition of the lower part of the same wing ballast tank. The lower part of the tank is in generally good condition, but the top part is in FAIR/POOR condition.

Picture 21 Top of a wing ballast tank (Ask 2014a)

Picture 22 Bottom and sides of a wing ballast tank (Ask 2014a)

Anodes with salt deposits.

Based on Havn (2014)

Deposits on the anode surface can occur when the anode not are in use, and should not happen if the anode is in use. Salt deposit covering them may result in reduced function in the anode. See picture 23. If not the salt are dissolved when water is in the tank, the anode function is reduced. It may be clever to brush the anodes when inspecting the tank, to be sure the anode will work properly.

Picture 23 Zinc anode with salt deposits (Ask 2014a)

3.6 Maintenance

In addition to all the class inspections mentioned in chapter 4.2.1, shipping companies are required to have proper maintenance procedures according to the International Safety Managemet – ISM code. (DNVGL 2014b). The main part of the Solvang maintenance coating procedure are presented below.

3.6.1 Ballast tank maintenance – Solvang Procedure

Based on Solvang (2012)

The Solvang procedure for correct painting maintenance onboard is divided into seven stages, as seen below:

1. Inspection and work planning
2. Proper ventilation
3. Washing
4. Choosing power tools and removal of corrosion spots and smoothening the outer areas of damaged paint
5. Wash with freshwater. Wash the areas which has been processed and are ready for paint
6. Check the painting maintenance chart for correct paint and thickness, and rea the health data safety sheet.
7. Measure the paint thickness on some spots to get an overview if the thickness is correct. Measure after first and last layer. Report in Star IPS.

Every one of the stages in the procedure are of equal importance to follow to get a good result. If one of the stages is neglected the result will be thereafter and the coating will not last for a very long time, and the same maintenance are to be carried out at the same spot not muck later.

1. Inspection and planning. (See picture 24)

All findings of corrosion should be marked with a permanent marker with a ring around the corrosion spot and with month and year. See picture 25. Easy accessible corrosion spots should be taken care of as soon as possible. Other corrosion spots which there are no time to fix at the moment can be held under control with date of inspection and size of corrosion spot. Then it will be possible to see the development of the corrosion on the next inspection. All corrosion should be taken care of in a prioritized order, and as soon as possible to prevent the corrosion to develop into unmanageable dimensions.

Picture 24 Ballast tank inspection by chief officer (Solvang 2012)

Picture 25 Mark the spots to "keep them under control" (Solvang 2012)

2. Ventilation

It is important to have the correct ventilation to get a good result of the painting maintenance work. Correct ventilation in sea water ballast tanks is dry air from the inert gas plant. On the 60,000+ cbm ships, air inlet should be through the manholes in the double bottom ballast tank and outlet on the top of the wing ballast tanks. All the ballast tank manholes have to be opened to get air circulation. The lower humidity, the better final result on the paint job.

3. Washing

Clean environment is important to get a good result. It is important to always wash the areas to be maintained properly. It is to be used washing brushes or similar with ordinary soap to wash the corroded areas free from contamination, such as oil ,grease, stains, etc. Pressure washer or similar is to be used afterwards, to remove the salt laying inside the steel pours, and to remove oil and grease so it will not be hammered into the steel when using power tools to remove the corrosion. If it is only a small corrosion spot and the pressure washer is not available, a wash with soap water can be sufficient.

If there are grease or oil left on the surface the paint will not stick to the surface, with poor quality as result. If there are any salt left under the paint, it will be blisters in the paint. See picture 26.

Picture 26 Blisters in the ballast tank in Clipper Skagen (Solvang 2012)

See figure 26 to understand how the surface of steel is, and how important it is to clean all the pores to get the coating to stick properly.

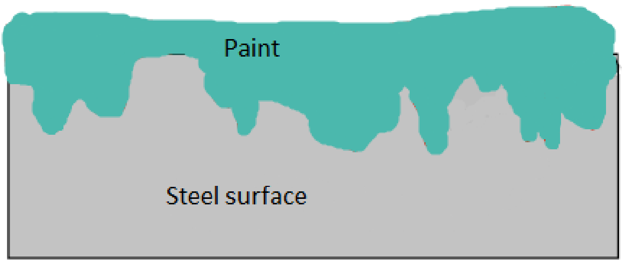


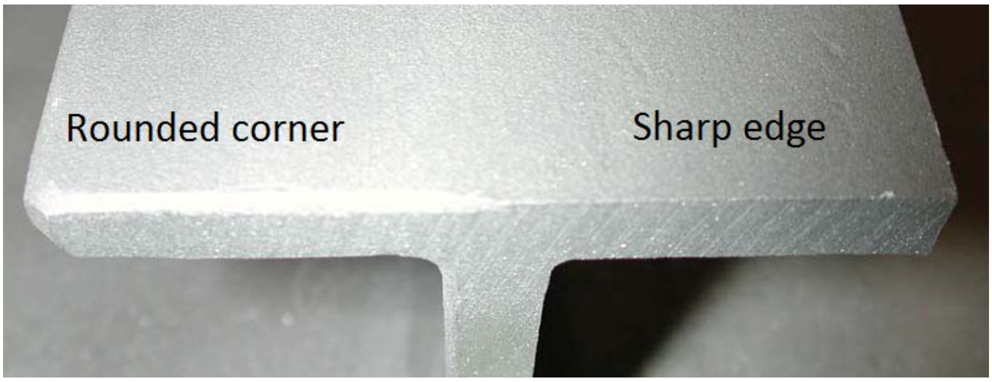
Figure 26 Cross-section of a steel plate with paint (Solvang 2012)

4. Corrosion spots

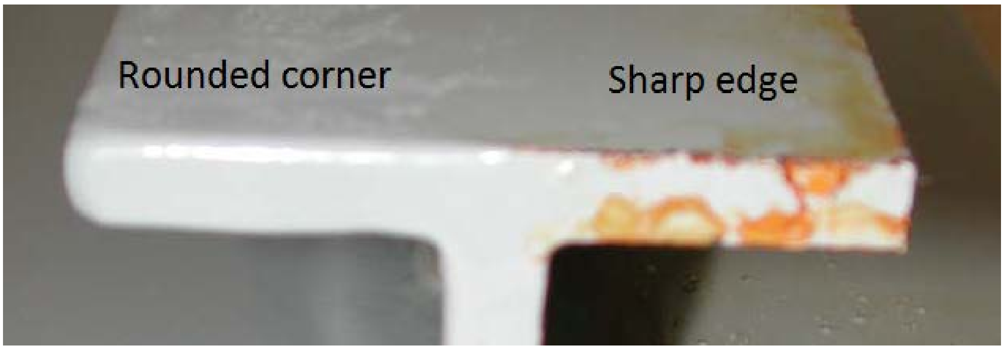
To remove the corrosion it is convenient to use the right tool for the job. Two things to consider when choosing a tool. Chose the tool which removes the corrosion in the quickest way and leaves the roughest surface for the paint to stick to. Sand blaster or bristle blaster is considered to be the best tools for removing corrosion in ballast tanks. See picture 27. Sand blaster is definitively the tool that removes the corrosion quickest, but if it is more convenient to use the bristle blaster, this is also a good tool that makes a rough surface, but it is slow to use. Steel brush is not to be used because it polishes the steel, makes the surface with a very smooth finish, and hard for the paint to stick.

Picture 27 A bristle blaster used in the ballast tank (Solvang 2012)

All sharp corners have to be rounded with an angle grinder or similar, for the paint to stick. And the edges where old and new paint meet has to be smothered. This to avoid sea water penetrating between the layers and to avoid the paint to crack. The difference on coating breakdown on a rounded edge and a sharp edge after 6 months are shown in picture 28 and 29.



Picture 28 Rounded corner - sharp edge, painted (Solvang 2012)



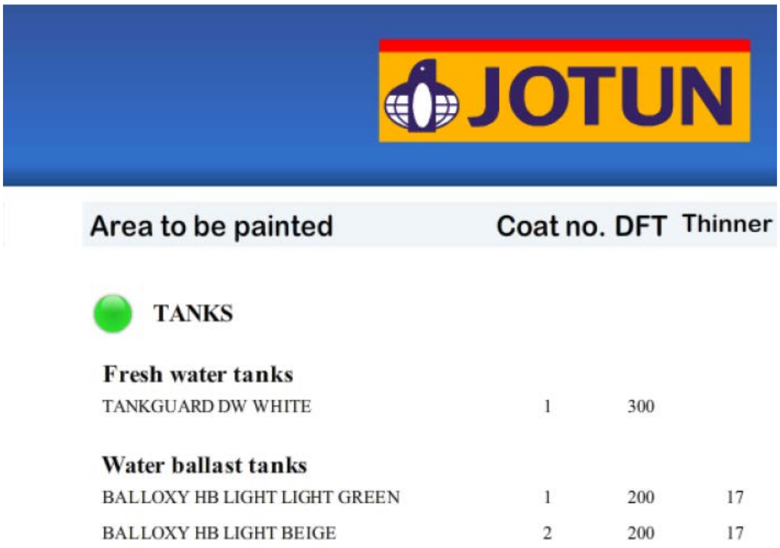
Picture 29 Rounded corner - sharp edge, 6 months later (Solvang 2012)

5. Washing with freshwater

After the corrosion removal of the areas to be painted, it has to be flushed with freshwater to remove any corrosion particles, old paint particles or dust. This to get the paint to stick properly to the surface. If any corrosion particles are left beneath the new paint, corrosion will occur shortly afterwards. It is not recommended to use air hose to dry the surface due possible oil mist in the air, and then problems to get the paint to stick.

6. Painting maintenance chart

To check which paint to apply, the onboard maintenance chart has to be checked. The coating manufacturer has specified which type of paint, number of layers and DFT dry film thickness. See figure 27. It is important to read the health and safety data sheet prior to painting.



Area to be painted	Coat no.	DFT	Thinner
TANKS			
Fresh water tanks			
TANKGUARD DW WHITE	1	300	
Water ballast tanks			
BALLOXY HB LIGHT LIGHT GREEN	1	200	17
BALLOXY HB LIGHT BEIGE	2	200	17

Figure 27 Section of a painting maintenance chart (Solvang 2012)

7. Painting, measuring and reporting.

The last step before painting is to mix the paint properly, using a rotating paint mixer or similar, not just stir it with a stick. To get the best painting result the best is to use a paint gun, there the paint thickness will be satisfying. A brush will also give a good result on smaller areas, with satisfying paint thickness. After painting, the thickness should be measured using a DFT measuring instrument, and reported in. See picture 30. A permanent marker is to be used on some spots to write down the date of the repair, so it in the future is easy to know when the repair was done. This is to monitor the development of the repair. See picture 31.

Picture 30 Thickness measurement of coating (Solvang 2012)

Picture 31 Corrosion repair with date (Solvang 2012)

4 Rules regulation the shipping industry

This chapter consists of the different organizations regulating the shipping industry, the different types of inspections, inspection requirements and corrosion additions to new builds

4.1 Organizations

Based on Wang et al. (2009)

There are both governmental and non-governmental organizations regulating the shipping industry. In most cases the government in each country sets the rules and requirements, and the non-governmental organizations inspect the ships and make sure they are in accordance with current rules and regulations.

The different organizations are shown in table 6.

Table 6 Different organizations and what they do (Wang et al 2009)

Organization	Regulation, rule, guidance	Survey	Inspection area & item	Applicable ship types
IMO	International conventions and class rules (mandatory)	Initial, Annual, Intermediate, Periodical/Renewal	Safety, pollution and load line ISM, ISPS	All type of ships
Classification societies			Hull and machinery	
Port state	Memorandum of Understanding	On purpose (targeting of ships)	Hull and machinery Safety, pollution, load line	
Flag state	National regulations	Initial, occasional, periodical	Hull and machinery Safety, pollution, load line	All type of ships
Insurance company (including P&I Clubs)	Insurance / P&I requirements	Insurance inspections	CAS / ESP (mandatory)	Tanker, bulk carriers (mainly)
Terminal operators	Local regulations and procedures	Safety & pollution prevention survey	Cargo handling and equipment, procedures, loading master	Oil & chemical tanker, bulk carriers, gas carriers
Cargo owners	Commercial requirements	Charterer/vetting (oil majors, CDI, OCIMF/SIRE, etc.)	CAP, cargo operation and management, survey on purpose, risk-based analyses	
Ship owners / managers				

4.1.1 IMO

Based on IMO (2014c)

The International Maritime Organization is an international organization of United Nations, which are responsible for the safety and security of shipping and the prevention of marine pollution of ships. IMOs slogan: “Safe, secure and efficient shipping on clean oceans”

The purpose of IMO is:

"to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships"(IMO 2014c)

IMO do not implement legislation, just adopt them. It’s the government of each flag states responsibility to implement the legislation adopted by IMO. This way the legislation becomes a national law and enforced by the flag state.

Since shipping transports about 90% of all trade world wide, it is important to have an international organization setting the standards and requirements applicable to the shipping industry. Currently IMO has 170 member states and a representative from each normally meets once every two years.

IMO does not directly impact on the ageing of ships, but indirectly by adopting the rules and requirements to secure safe and secure shipping. It is up to the classification societies to enforce the rules and requirements, to secure safe and secure shipping.

IMO regulation concerning sea water ballast tanks

PSPC – Performance Standard Protective Coating was adopted by IMO in 2006. This was the first time IMO adopted a regulation for protective coating. Now corrosion of sea water ballast tanks was considered as a safety issue and PSPC was implemented to secure better protection against corrosion.

4.1.2 IACS

IACS is a non-governmental organization developing unified interpretations of IMO – International Maritime Organization regulations. Unified Requirements – URs and Common Structural Rules – CSR for oil tankers are also developed by IACS. (DNVGL 2014d)

IACS consists of twelve of the marine classification societies covering over 90% of the tonnage carried by ships. IACS was founded in Hamburg, Germany in 1968 by the seven leading classification societies, to help them aligning the classification standards. (IACS 2014a)

By cooperation between the different classification societies, and developing URs, CSRs and unified interpretations of IMOs regulations IACS helps the classification societies to best take care of ageing ships.

4.1.3 Flag State

The flag state is the authority in the country the ship is registered or licensed. The flag state is responsible to enforce the states regulations for the ships. (Flag state 2014)

Open registry of ships makes it possible for ship owners to register their vessel in a foreign country/flag state. This may be done to reduce operating costs or avoid the regulations that are current in the owner’s country. This is called “flag of convenience”, and with almost 25% of the tonnage going with a ship registered in Panama, this is the largest flag state with a lot of foreign ship owners. (Flag state 2014)

In Norway there are two ship registers, NIS – Norwegian International Ships register and NOR – Norwegian Ordinary Ships register. NIS was established in 1987 to compete with flag of convenience and secure Norwegian owned ships to be registered in Norway and flying the Norwegian flag. NIS opened for foreign personnel on their home county wages, securing better competitiveness for Norwegian ships trading international. (NMA 2014)

4.1.4 Classification society

A classification society is a non-governmental organization adopting the IACS regulations. The classification society carries out surveys on ships, which are annual-, intermediate- and renewal surveys. They issues certificates on behalf of the flag state. (Oma 2013)

With the surveys performed by the classification societies, the ships will be kept in a good/acceptable condition. The condition of the ship is inspected and if some of the ageing mechanisms cause the ship to not be corresponding with the current rules and regulations, it has to be repaired or replaced. As older a ships gets, the scope of the inspections increases. The two first renewal surveys may just consist of partly inspection of the hull, when on the third renewal survey and after, the whole hull will be inspected mainly in terms of the ageing mechanisms corrosion and cracks due to corrosion and/or fatigue. (DNV 2014a)

Some of the largest classification societies today are, DNVGL, LR, BV, RINA, ABS, and ClassNK. (CS 2014)

4.1.5 Port state control

Based on PSC (2014)

Inspection of foreign ships done by the port state control (PSC) inspector to check if the ships condition comply with the international requirements. Port state can put a ship in detention if something is as it should not be.

As older the ship is, the more likely it will be inspected by port state at arrival at a foreign port.

4.1.6 Third party/ oil companies

Based on Snaith (2011)

The oil- and gas companies and terminal operator have their own inspections of ships. Due to large ship disasters in the 80- and 90s with oil tankers grounding and a lot of oil spill as the result, the charterers and terminal operators would be safe that their cargo is not transported by a deficient ship. This because when accidents happened it was not only the ship owners getting the focus, but also the cargo owners got in the focus in a greater way during the 80s and 90s.

The inspectors, whom can be the charterers or terminals own inspectors, or an inspector accredited by SIRE – Ships Inspection Reporting Program or by CDI – Chemical Distribution Institute in most cases do a survey on the safety equipment and pollution prevention systems. This is done to assess if the vessel is suitable to ship their cargo

4.2 Types of inspections

There are a few different types of inspection of ships. The main one, and imposed by rules and regulations are the surveys carried out by a classification society. For a ship to have the necessary certificates it has to pass the surveys.

Other types of inspections imposed by rules and regulations are the inspections done by flag state and port state. The inspection carried out by the ship's personnel according to the ISM – International Safety Management code is also imposed by rules and regulations.

The other type of inspections are those which not are regulated by law, but demanded by the market, such as third party- and CAP inspections.

4.2.1 Inspection imposed by rules and regulations

Inspections imposed by law are classification survey to classify the ship, inspections done by flag state, inspection done by port state, and the maintenance inspections the ship's crew are required to do according to the ISM – International Safety Management code.

4.2.1.1 Survey, liquefied gas tankers

Based on DNV (2014a)

Many of the survey requirements are the same on the different types of ships, but there are survey requirements applicable especially for each ship type. The different ship types are:

- General dry cargo ship
- Bulk carrier
- Oil tanker
- Chemical tanker
- Gas tanker

The survey requirements mentioned below are for liquefied gas tankers.

Too keep the ageing mechanisms under control ships are surveyed by representative from the classification society which the ship is registered under. For the different surveys there are different survey interval, and the time windows for the surveys are as follows:

- Annual survey, with survey interval 12 months and time windows of 3 months on either side of due date.
- Intermediate survey, with a survey interval of 30 months and time window of 9 months on either side of the due date
- Renewal survey, with survey interval of 60 months and time window of 15 months before the due date.

Figure 28 shows the principle with survey interval and time window.

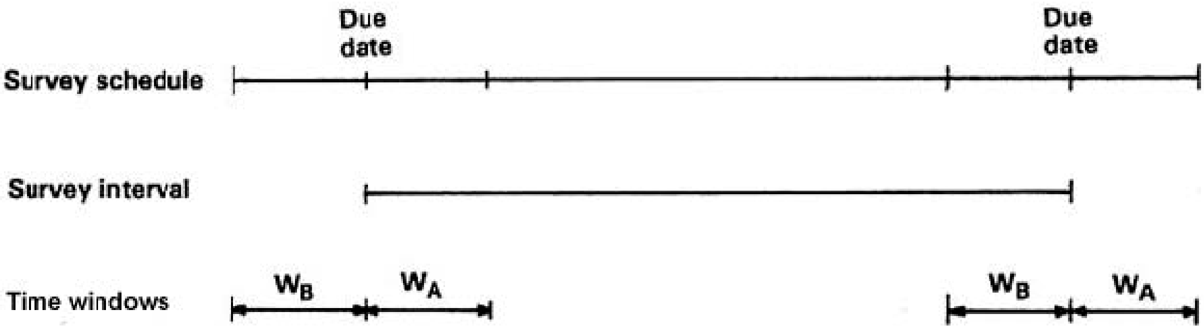


Figure 28 (DNV 2014a)

- Annual survey: W_B = 3 months, W_A = 3 months
- Intermediate survey: W_B = 9 months, W_A = 9 months
- Renewal survey: W_B = 15 months, W_A = 0 months

W_B =Time before due date

W_A =Time after due date

Figure 29 shows the whole 5 years class survey cycle with annual-, intermediate-, and renewal survey

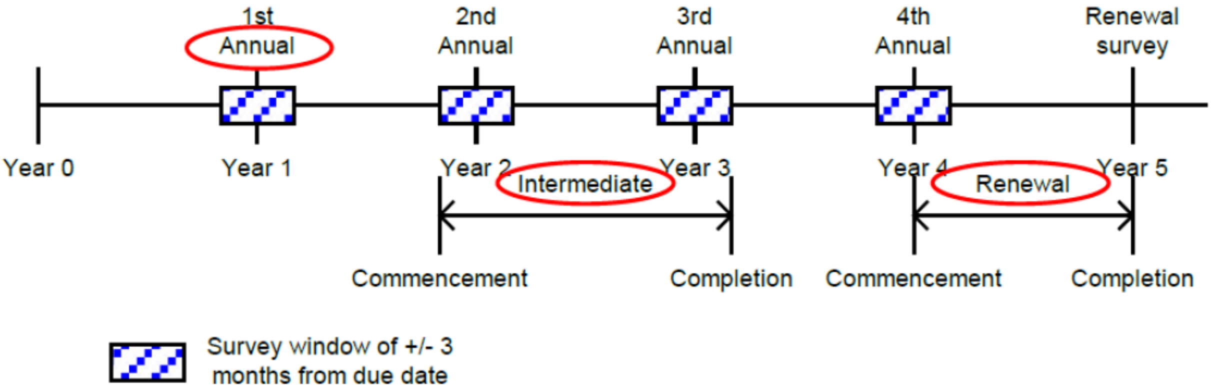


Figure 29 Five years inspection cycle with annual-, intermediate- and renewal survey (Oma 2013)

4.2.1.1.1 Annual survey

Based on DNV (2014a)

Annual survey are carried out by a classification society every 12 months/ 1 year.

“Annual survey is a general survey of the hull and equipment, machinery and systems to confirm that the ship complies with the relevant rule requirements and is in satisfactorily maintained condition.”(DNV 2014a)

Regarding to ageing of hull and equipment the annual survey consists of inspection of weather decks and ships side plating above water line, anchoring equipment, openings and closing appliances for cargo holds or tanks, other openings and closing appliances, scuppers, discharges and valves with hull attachments, freeing ports and shutters, fitting and hull supporting structures, piping arrangements on deck, means of protection of crew, towing and mooring equipment, emergency towing arrangements, and spaces such as ballast tanks, suspect areas, spaces with substantial corrosion, and special installation such as plants for refrigerated cargoes and inert gas plant.

Areas recorded for annual inspection at previous survey shall be inspected. It may be ballast tanks, suspect areas, areas with coating breakdown or areas with substantial corrosion.

The scope of the annual survey increases as the ship gets older.

4.2.1.1.2 Intermediate survey

Based on DNV (2014a)

Intermediate survey are carried out by a classification society every 30months/ 2.5 years.

“Intermediate survey is a survey including visual examinations, measurements and testing as applicable, of the hull and equipment, machinery and systems, in order to confirm that the ship complies with the relevant rule requirements and is in satisfactorily maintained condition.” (DNV 2014a)

The scope of intermediate surveys on 10+ years old ships are much the same as the scope of renewal survey.

Concerning the ballast tanks on 5 – 10 year vessels, some representative tanks shall be inspected, and if some of them are found to have no coating, semi hard coating or coating in “POOR” condition, other tanks of the same type also has to be inspected.

Concerning the ballast tanks on 10+ year vessels, all the ballast tanks has to be inspected.

If any of the tanks are found to have no protective coating, no hard coating applied from the time of construction, soft or semi hard coating, or coating in POOR condition, the tanks shall be recorded and inspected on next annual survey.

For ships with age 10+ years, the intermediate survey will include close-up examination of all web frames and both transverse bulkheads in a representative ballast tank, the upper part of one web frame in another representative ballast tank and one transverse bulkhead in another representative ballast tank

For ships with age 15+ years, the intermediate survey will also include close-up examination of all web frames and both transverse bulkheads in two representative ballast tanks

Regarding the scope of intermediate surveys, it increases as the ship gets older.

4.2.1.1.3 Renewal/special survey

Based on DNV (2014a)

Special survey are carried out by a classification society every 60months/ 5 years.

"Renewal survey is a major survey including visual examinations, measurements and testing of the hull and equipment, machinery and systems, in order to confirm that the ship complies with the relevant rule requirements and is in satisfactorily maintained condition." (DNV 2014a)

Regarding to ageing of hull and equipment the renewal survey consists of inspection of anchoring equipment, hatch covers and coamings, doors in ships bow, sides and stern, air pipes and ventilators on deck, mooring and towing equipment, pushing arrangement.

Inspection of all internal spaces, watertight integrity of internal bulkheads and decks, tightness of tank boundaries, ballast tanks, engine room structure, piping on deck and in spaces outside the machinery area, sea connections in machinery area, coating in tanks for potable water and tanks for low flashpoint liquids.

Thickness measurement of hull structure shall be carried out on predefined areas and extended measurement when substantial corrosion is present. The scope of thickness measurement will get larger as the ship gets older. The scope of close-up inspections will also increase as the ship gets older.

Example of how the scope of close-up inspection of ballast tanks increases with the age of the ship. Close-up inspection of ballast tanks transverse bulkheads, including girder system and adjacent structural members:

Renewal survey no. 1: One, lower part – in a tank

Renewal survey no. 2: One in each tank

Renewal survey no. 3: All – in all ballast tanks

The scope of thickness measurement increases with the ships age as shown below.

Thickness measurement renewal survey

From DNV (2014a)

Renewal survey no. 1: (5 years)

- One section of deck plating only, for the full beam of the ship within 0.5 L amidship
- Measurements, for general assessment and recording of corrosion pattern

Renewal survey no. 2: (10 years)

- One complete section, within 0.5 L amidship
- Measurements, for general assessment and recording of corrosion pattern
- Main deck plating
- Wind - and water strakes.

Renewal survey no. 3: (15 years)

- Two complete sections, at least one within 0.5 L amidship
- Measurements, for general assessment and recording of corrosion pattern
- Main deck plating
- Wind - and water strakes.
- Internals in peak tanks.
- Air pipes and ventilators

Renewal survey no. 4: (20 years)

- Three complete sections, at least one within 0.5 L amidship
- Measurements, for general assessment and recording of corrosion pattern
- Main deck plating
- Wind - and water strakes.
- Keel plates and bottom plates.
- Sea chests and shell plating in way of overboard discharges.
- Duct keel or pipe tunnel.
- Superstructure deck plating (poop, bridge and forecastle deck).
- Internals in peak tanks.
- Air pipes and ventilators

4.2.1.2 Port state inspections

Based on Lloyd’s Register (2011)

The port state inspection consists mainly of inspection of documents, navigation equipment, life-saving equipment, accommodation, engine room and deck area. If something is out of order the port state can detain the ship. E.g. if there are found much corrosion on the hull or other areas, the port state can detain the ship until the ships classification society has documented that ship is above class limit.

The port state has more often inspections on older ships.

4.2.1.3 Flag state inspections

The flag state inspections done by the Norwegian Maritime Authority (NMA) in Norway are mainly the same as port state control inspections. See chapter 4.2.1.2.

4.2.1.4 Chief officer/6th month’s inspection in ballast tanks

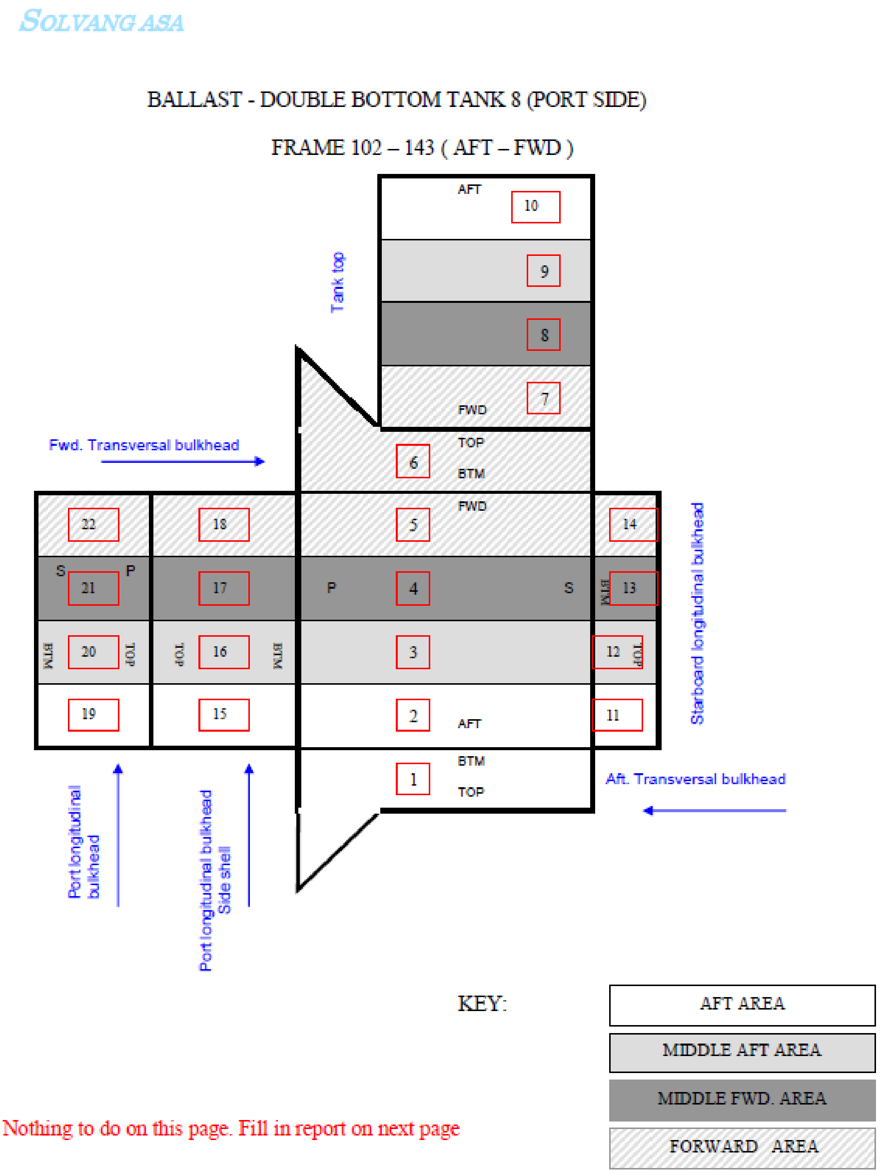
The inspection is carried out by the chief officer on the ship every sixth month. It is a class/ISM – International safety management requirement that the ships ballast tank shall be inspected by the company in accordance with the required maintenance rules. The inspection intervals are set by the company at appropriate length. (DNVGL 2014b)

All the sea water ballast tanks are inspected, using the “IACS Recommendation 87 GUIDELINES FOR COATING MAINTENANCE & REPAIRS FOR BALLAST TANKS AND COMBINED CARGO/BALLAST TANKS ON OIL TANKES”.

Internal work orders are created if coating maintenance is necessary. The coating maintenance will be done in a prioritized order, following the internal “Solvang procedure for correct painting maintenance onboard”.

After every inspection, the condition of the tank is documented in a tank inspection report. The condition of coating, anodes, ladders, internal piping, valves and handrails are inspected and are found to be in either “GOOD”,” FAIR” or “POOR” condition. (Solvang 2012)

See figure 30 and 31 for an example of a tank inspection report.



SOLVANG ASA

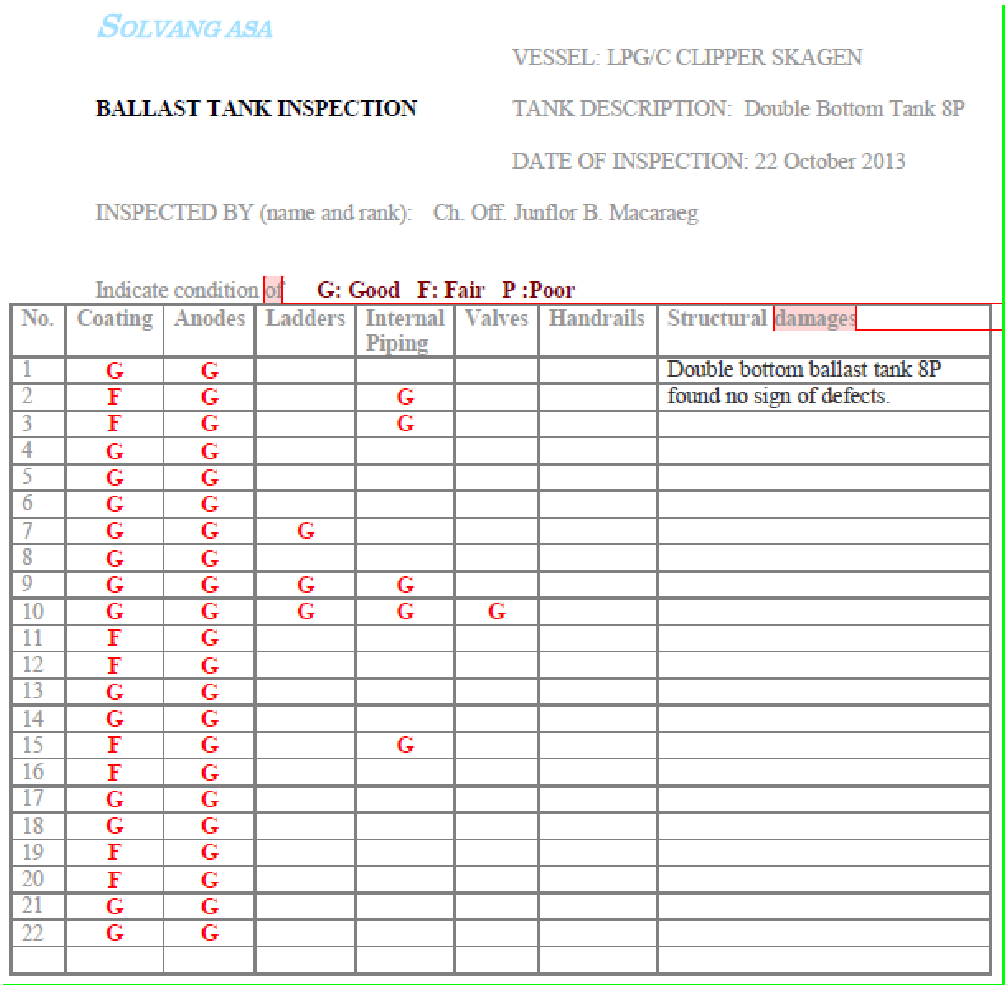
BALLAST - DOUBLE BOTTOM TANK 8 (PORT SIDE)

FRAME 102 – 143 (AFT – FWD)

Note: Nothing to do on this page. Fill in report on next page

Figure 30 Split open drawing of double bottom ballast tank on Clipper Skagen (Clipper Skagen 2013b)

First it is a drawing of the tank split up (figure 30), with the different frame numbers. This makes is easy to fill in the table (figure 31) with the relevant grade of condition (“GOOD”, “FAIR” or “POOR”, and find back to the area needing repair if not time for maintenance at the time of inspection. Additional remarks are added if necessary.



SOLVANG ASA

VESSEL: LPG/C CLIPPER SKAGEN

BALLAST TANK INSPECTION

TANK DESCRIPTION: Double Bottom Tank 8P

DATE OF INSPECTION: 22 October 2013

INSPECTED BY (name and rank): Ch. Off. Junflor B. Macaraeg

Indicate condition of **G: Good F: Fair P :Poor**

No.	Coating	Anodes	Ladders	Internal Piping	Valves	Handrails	Structural damages
1	G	G					Double bottom ballast tank 8P
2	F	G		G			found no sign of defects.
3	F	G		G			
4	G	G					
5	G	G					
6	G	G					
7	G	G	G				
8	G	G					
9	G	G	G	G			
10	G	G	G	G	G		
11	F	G					
12	F	G					
13	G	G					
14	G	G					
15	F	G		G			
16	F	G					
17	G	G					
18	G	G					
19	F	G					
20	F	G					
21	G	G					
22	G	G					

Figure 31 Ballast tank condition report (Clipper Skagen 2013b)

4.2.2 Voluntary inspections

Voluntary inspections are inspections not imposed by law, but inspections done or demanded by terminal operators or cargo owners. They have their own inspections and the majority of the cargo owners demand CAP surveys on ships older than 15 years.

4.2.2.1 Third party inspections

Third party inspections are normally demanded by the oil and gas companies or terminal owners. The inspectors can be their own or an inspector accredited by SIRE – Ships Inspection Reporting Program or by CDI – Chemical Distribution Institute. (Snaith 2011)

The oil and gas companies want to assess if the ship is suitable to ship their cargo. They inspects the cargo operation and management. The terminal owners are inspecting the ship in accordance to safety and pollution prevention. (Wang 2009)

Because of the third party inspection mainly consist of survey of operation, safety and pollution prevention, this is not very relevant for ageing issues in ballast tank.

4.2.2.2 CAP – Condition Assessment Programme

A DNV developed Inspection program to evaluate the vessels actual condition on a scale from 1 to 4. This allows the vessel to be judged on its actual condition rather than its age. CAP was introduced in 1989 (DNV 2005). After MV Erika and MV Prestige sank in 1999 and 2002, there was an increased focus on the safety and quality of older ships. Now, most of the oil and gas companies require CAP testing of all vessels older than 15 years shipping their cargo. They require the vessel to be in CAP class 1 or 2, which is much better than the classification requirement that is the same as CAP class 3. (Ref Ch. 2.1.5.)

DNVs CAP service is divided into two areas, CAP Hull and CAP Machinery and Cargo Handling Systems.

4.2.2.2.1 CAP Hull

Based on Clipper Harald (2014)

The CAP hull inspection is an inspection of the hull of the ship, with both visual inspection and thickness measurement.

The rating for CAP hull are shown below:

From Clipper Harald (2014)

1 Very good condition

Items examined and measured found with only superficial reductions from “as new” or current rule scantlings. No maintenance or repair required.

2 Good condition

Items examined and measured found to have deficiencies of a minor nature not requiring correction or repairs and or found to have thicknesses significantly above class limits.

3 Satisfactory condition

Items examined and measured either found to have deficiencies which do not require immediate corrective actions, or found to have thicknesses, although generally above class renewal levels, with substantial corrosion.

Below Class Standard:

4 Poor condition

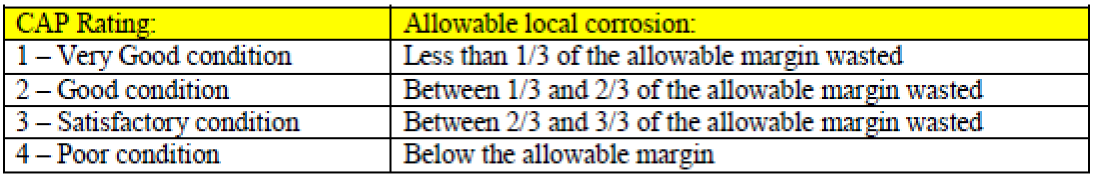
Items examined and measured either found to have deficiencies which may affect the ship’s potential to remain in class, or found to have, in some areas, thicknesses that are at or below the class renewal levels.

The CAP Hull inspection consists of:

1. A visual inspection of

- deck
- side
- bottom
- inner bottom
- longitudinal bulkheads
- internal structure

The visual inspection is to reveal deficiencies and local corrosion, such as edge corrosion, grooving corrosion, pitting corrosion, indents and other local defects. The rating scale for allowable local corrosion is shown in figure 32.

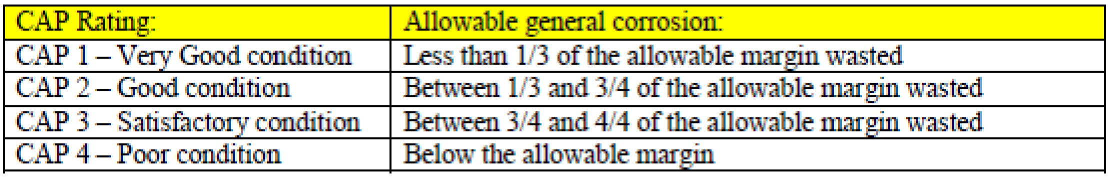


CAP Rating:	Allowable local corrosion:
1 – Very Good condition	Less than 1/3 of the allowable margin wasted
2 – Good condition	Between 1/3 and 2/3 of the allowable margin wasted
3 – Satisfactory condition	Between 2/3 and 3/3 of the allowable margin wasted
4 – Poor condition	Below the allowable margin

Figure 32 Allowable local corrosion at visual inspection (Clipper Harald 2014)

2. Ultrasonic Thickness Measurement – UTM

To establish the extent of general corrosion on the ship, thickness measurements are carried out over a large part of the ship, giving representative data for all main structural elements of all tanks. The rating scale for allowable general corrosion is shown in figure 33.

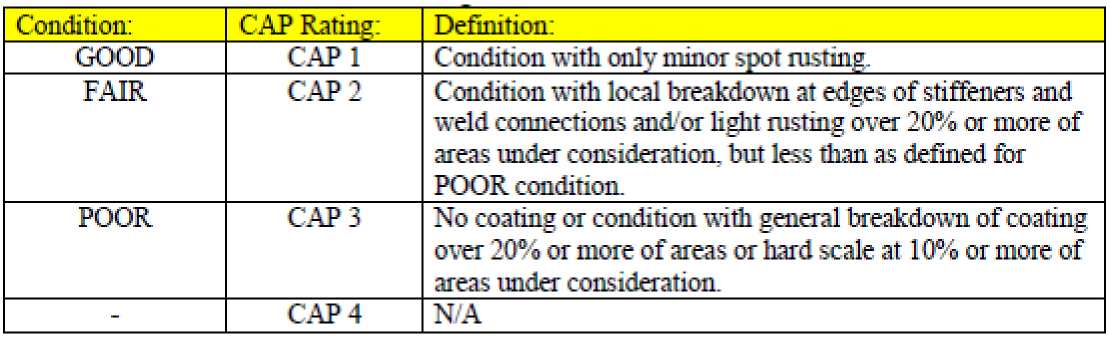


CAP Rating:	Allowable general corrosion:
CAP 1 – Very Good condition	Less than 1/3 of the allowable margin wasted
CAP 2 – Good condition	Between 1/3 and 3/4 of the allowable margin wasted
CAP 3 – Satisfactory condition	Between 3/4 and 4/4 of the allowable margin wasted
CAP 4 – Poor condition	Below the allowable margin

Figure 33 Allowable general corrosion at ultrasonic thickness measurement (Clipper Harald 2014)

3. Coating in ballast tanks

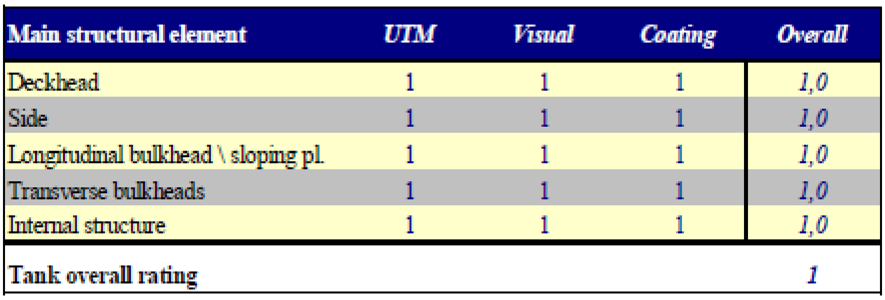
The visual inspection of coating in all the ballast tanks are independent of the visual inspection in item number 1 (visual inspection to reveal deficiencies and local corrosion). Coating on all the main structural elements in ballast tanks are rated independently to be in either “GOOD”, “FAIR” or “POOR” condition. The rating scale for coating breakdown is shown in figure 34.



Condition:	CAP Rating:	Definition:
GOOD	CAP 1	Condition with only minor spot rusting.
FAIR	CAP 2	Condition with local breakdown at edges of stiffeners and weld connections and/or light rusting over 20% or more of areas under consideration, but less than as defined for POOR condition.
POOR	CAP 3	No coating or condition with general breakdown of coating over 20% or more of areas or hard scale at 10% or more of areas under consideration.
-	CAP 4	N/A

Figure 34 Allowable coating breakdown (Clipper Harald 2014)

The rating from the thickness measurement, the visual inspection of local corrosion and deficiencies and the visual inspection of coating are added up and gives the overall tank rating. See figure 35.



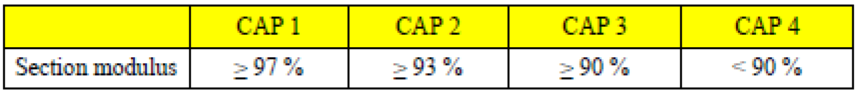
Main structural element	UTM	Visual	Coating	Overall
Deckhead	1	1	1	1,0
Side	1	1	1	1,0
Longitudinal bulkhead \ sloping pl.	1	1	1	1,0
Transverse bulkheads	1	1	1	1,0
Internal structure	1	1	1	1,0
Tank overall rating				1

Figure 35 Example of CAP rating of a ballast tank with UTM-, Visual- and Coating rating. (Clipper Harald 2014)

4. Structural strength rating

The hull structural strength is calculated using data software. E.g. PULS. Data from the thickness measurements are used to find the section modulus and buckling capacity.

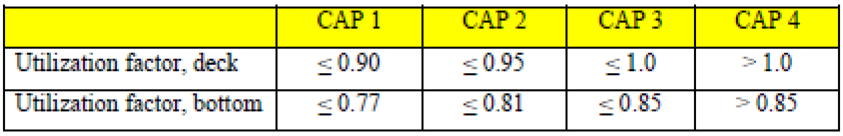
The calculated section modulus are compared to the newbuiling requirements and needs to be within the ratio given in figure 36.



	CAP 1	CAP 2	CAP 3	CAP 4
Section modulus	≥ 97 %	≥ 93 %	≥ 90 %	< 90 %

Figure 36 Rating of section modulus compared to as built (Clipper Harald 2014)

From the thickness measurements the utilization factor in deck and bottom are calculated. The calculated values need to be within the ratio given in figure 37.



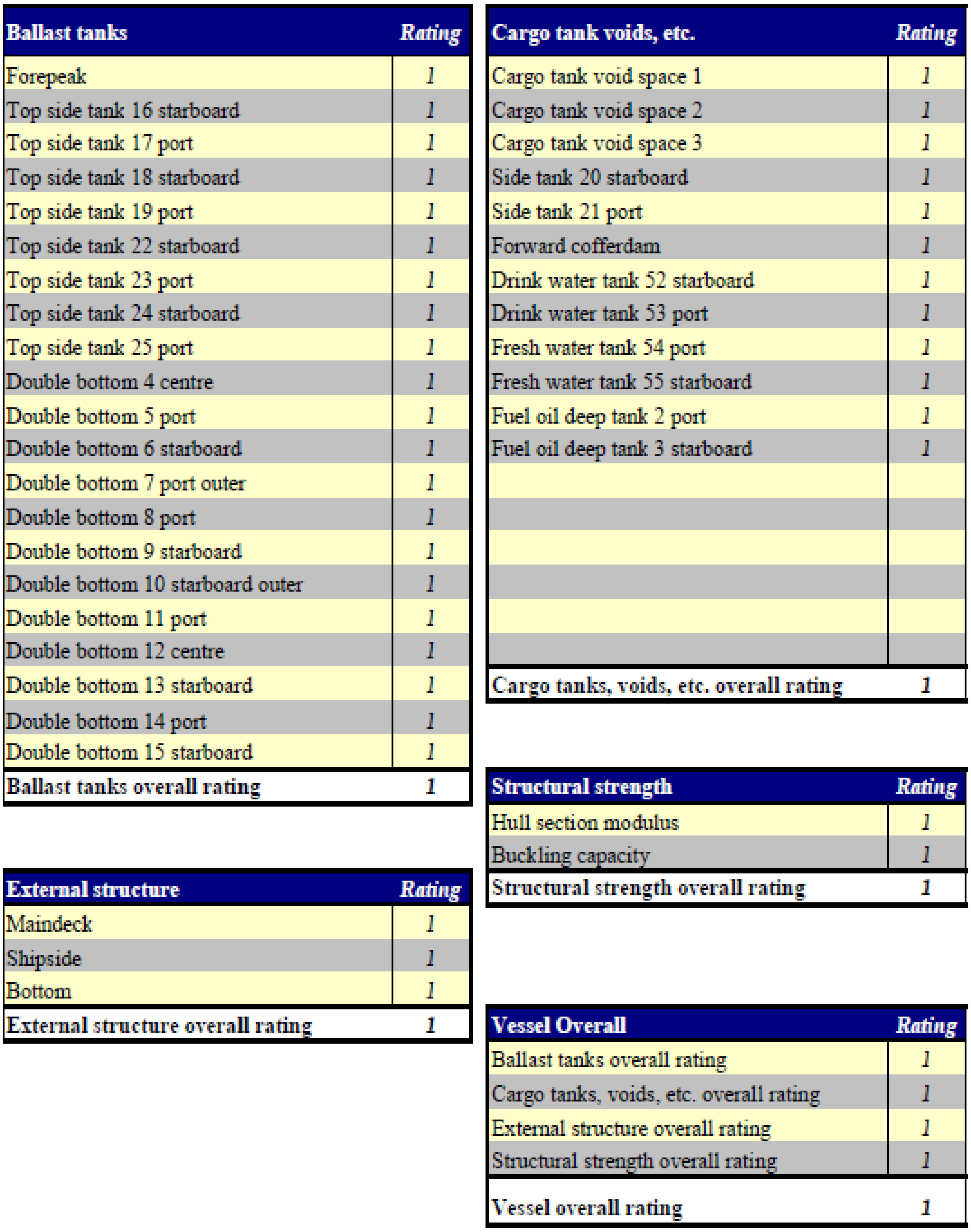
	CAP 1	CAP 2	CAP 3	CAP 4
Utilization factor, deck	≤ 0.90	≤ 0.95	≤ 1.0	> 1.0
Utilization factor, bottom	≤ 0.77	≤ 0.81	≤ 0.85	> 0.85

Figure 37 Rating for utilization factor in deck and bottom (Clipper Harald 2014)

5. The overall CAP Hull Rating

The overall rating are calculated by combining the rating results from ballast tanks, void spaces etc., rating results from the external structure and the rating from the structural strength evaluation. See figure 38.

The end overall result are decided by a CAP committee.



Ballast tanks	***Rating***
Forepeak	1
Top side tank 16 starboard	1
Top side tank 17 port	1
Top side tank 18 starboard	1
Top side tank 19 port	1
Top side tank 22 starboard	1
Top side tank 23 port	1
Top side tank 24 starboard	1
Top side tank 25 port	1
Double bottom 4 centre	1
Double bottom 5 port	1
Double bottom 6 starboard	1
Double bottom 7 port outer	1
Double bottom 8 port	1
Double bottom 9 starboard	1
Double bottom 10 starboard outer	1
Double bottom 11 port	1
Double bottom 12 centre	1
Double bottom 13 starboard	1
Double bottom 14 port	1
Double bottom 15 starboard	1
Ballast tanks overall rating	1

Cargo tank voids, etc.	***Rating***
Cargo tank void space 1	1
Cargo tank void space 2	1
Cargo tank void space 3	1
Side tank 20 starboard	1
Side tank 21 port	1
Forward cofferdam	1
Drink water tank 52 starboard	1
Drink water tank 53 port	1
Fresh water tank 54 port	1
Fresh water tank 55 starboard	1
Fuel oil deep tank 2 port	1
Fuel oil deep tank 3 starboard	1
Cargo tanks, voids, etc. overall rating	1

Structural strength	***Rating***
Hull section modulus	1
Buckling capacity	1
Structural strength overall rating	1

External structure	***Rating***
Maindeck	1
Shipside	1
Bottom	1
External structure overall rating	1

Vessel Overall	***Rating***
Ballast tanks overall rating	1
Cargo tanks, voids, etc. overall rating	1
External structure overall rating	1
Structural strength overall rating	1
Vessel overall rating	1

Figure 38 CAP rating example (Clipper Skagen 2012)

4.2.2.2.2 CAP Machinery and Cargo Systems

Based on Clipper Skagen (2013a)

In a CAP Machinery and Cargo System inspection, the technical condition of propulsion, steering, electric power generation and transfer, auxiliary functions, cargo handling, general ship support functions and fire safety functions are assessed and rated.

The rating scale for CAP Machinery and Cargo System is shown below:

From Clipper Skagen (2013a)

1 Very good condition

Items and systems examined and function tested, found with no deficiencies affecting safe operation and/or performance. Documentation and maintenance practices considered good. No maintenance or repair required.

2 Good condition

Items and systems examined and function tested, found with some minor deficiencies, which do not affect safe operation and/or normal performance. Documentation and maintenance practices considered adequate. No immediate maintenance or repair considered necessary.

3 Satisfactory condition

Items and systems examined and function tested, found with deficiencies not affecting safe operation and/or performance. Documentation and maintenance practices considered to be of a minimum standard. Some maintenance and repair may be considered necessary.

Below Class Standard

4 Poor condition

Items and systems examined and function tested, found with deficiencies significantly affecting safe operation and/or performance. Documentation and maintenance practices considered inadequate. Maintenance and repair required re-instating serviceability.

The technical condition, and maintenance standard and spare parts are rated, with a weight factor 0.7 and 0.3 respectively. See example in figure 39 and 40.

Example:

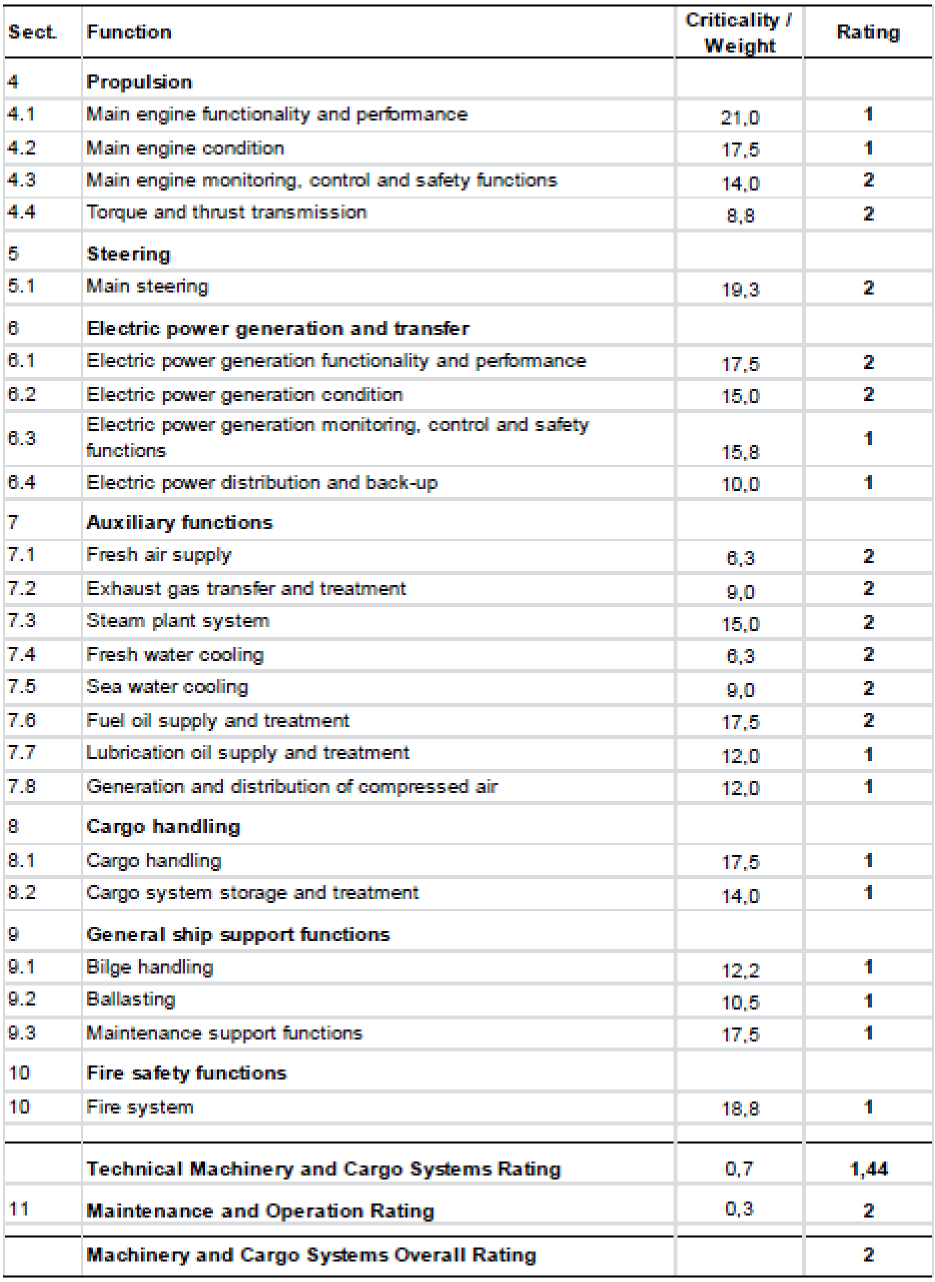
The technical factor is found by dividing the sum of the product with the sum of the criticality

Figure 39 Example of how to calculate the technical rating factor

The Maintenance standard and spare parts factor is set by the surveyor's general opinion. The overall rating is calculated shown in figure 40.

Figure 40 Example of how to calculate the overall rating

See figure 41 for an example CAP Machinery and Cargo System rating. Here all the all the technical machinery and cargo system are tested and rated. The surveyors impression of the maintenance standard and spare parts availability are also rated. Then the technical rating and the maintenance standard and spare parts rating are combined to the overall rating.



Sect.	Function	Criticality / Weight	Rating
4	**Propulsion**		
4.1	Main engine functionality and performance	21,0	**1**
4.2	Main engine condition	17,5	**1**
4.3	Main engine monitoring, control and safety functions	14,0	**2**
4.4	Torque and thrust transmission	8,8	**2**
5	**Steering**		
5.1	Main steering	19,3	**2**
6	**Electric power generation and transfer**		
6.1	Electric power generation functionality and performance	17,5	**2**
6.2	Electric power generation condition	15,0	**2**
6.3	Electric power generation monitoring, control and safety functions	15,8	**1**
6.4	Electric power distribution and back-up	10,0	**1**
7	**Auxiliary functions**		
7.1	Fresh air supply	6,3	**2**
7.2	Exhaust gas transfer and treatment	9,0	**2**
7.3	Steam plant system	15,0	**2**
7.4	Fresh water cooling	6,3	**2**
7.5	Sea water cooling	9,0	**2**
7.6	Fuel oil supply and treatment	17,5	**2**
7.7	Lubrication oil supply and treatment	12,0	**1**
7.8	Generation and distribution of compressed air	12,0	**1**
8	**Cargo handling**		
8.1	Cargo handling	17,5	**1**
8.2	Cargo system storage and treatment	14,0	**1**
9	**General ship support functions**		
9.1	Bilge handling	12,2	**1**
9.2	Ballasting	10,5	**1**
9.3	Maintenance support functions	17,5	**1**
10	**Fire safety functions**		
10	Fire system	18,8	**1**
	Technical Machinery and Cargo Systems Rating	0,7	**1,44**
11	**Maintenance and Operation Rating**	0,3	**2**
	Machinery and Cargo Systems Overall Rating		**2**

Figure 41 CAP M&C example with every function rated with criticality/weight (Clipper Skagen 2013)

4.3 Inspection requirements

The requirement to determine the condition of ballast tanks are reviewed below, with the allowable extent of coating breakdown and the allowable thickness diminution.

4.3.1 Extent of coating breakdown

When inspecting ballast tanks, the coating condition is evaluated to be in “GOOD”, “FAIR” or “POOR” condition.

The definition of the conditions are given in IMO Resolution A.744(18) as follows: (IMO 1993)

GOOD	“condition with only minor spot rusting.”
FAIR	“condition with local breakdown of coating at edges of stiffeners and weld connections and/or light rusting over 20% or more of areas under consideration, but less than as defined for POOR condition.”
POOR	“condition with general breakdown of coating over 20% or more of areas or hard scale at 10% or more of areas under consideration.”

From IACS Rec 87 a more specified clarification of the definition of conditions are defined as follows: (IACS 2006)

GOOD	“Condition with spot rusting on less than 3% of the area under consideration without visible failure of the coating. Rusting at edges or welds, must be on less than 20 % of edges or weld lines in the area under consideration.”
FAIR	“Condition with breakdown of coating or rust penetration on less than 20 % of the area under consideration. Hard rust scale must be less than 10 % of the area under consideration. Rusting at edges or welds must be on less than 50 % of edges or weld lines in the area under consideration.”
POOR	“Condition with breakdown of coating or rust penetration on more than 20% or hard rust scale on more than 10% of the area under consideration or local breakdown concentrated at edges or welds on more than 50 % of edges or weld lines in the area under consideration.”

The extent of allowable coating breakdown in accordance to IACS Rec 87 is shown in table 7.

Table 7 Extent of coating breakdown according to IACS Rec 87 (IACS 2006)

	GOOD	FAIR	POOR
Breakdown of coating or area rusted	< 3%	3 – 20 %	> 20 %
Area of hard rust scale	-	< 10 %	≥ 10 %
Local breakdown of coating or rust on edges or weld lines	< 20 %	20 – 50 %	> 50 %

Examples of coating breakdown are shown in figure 42

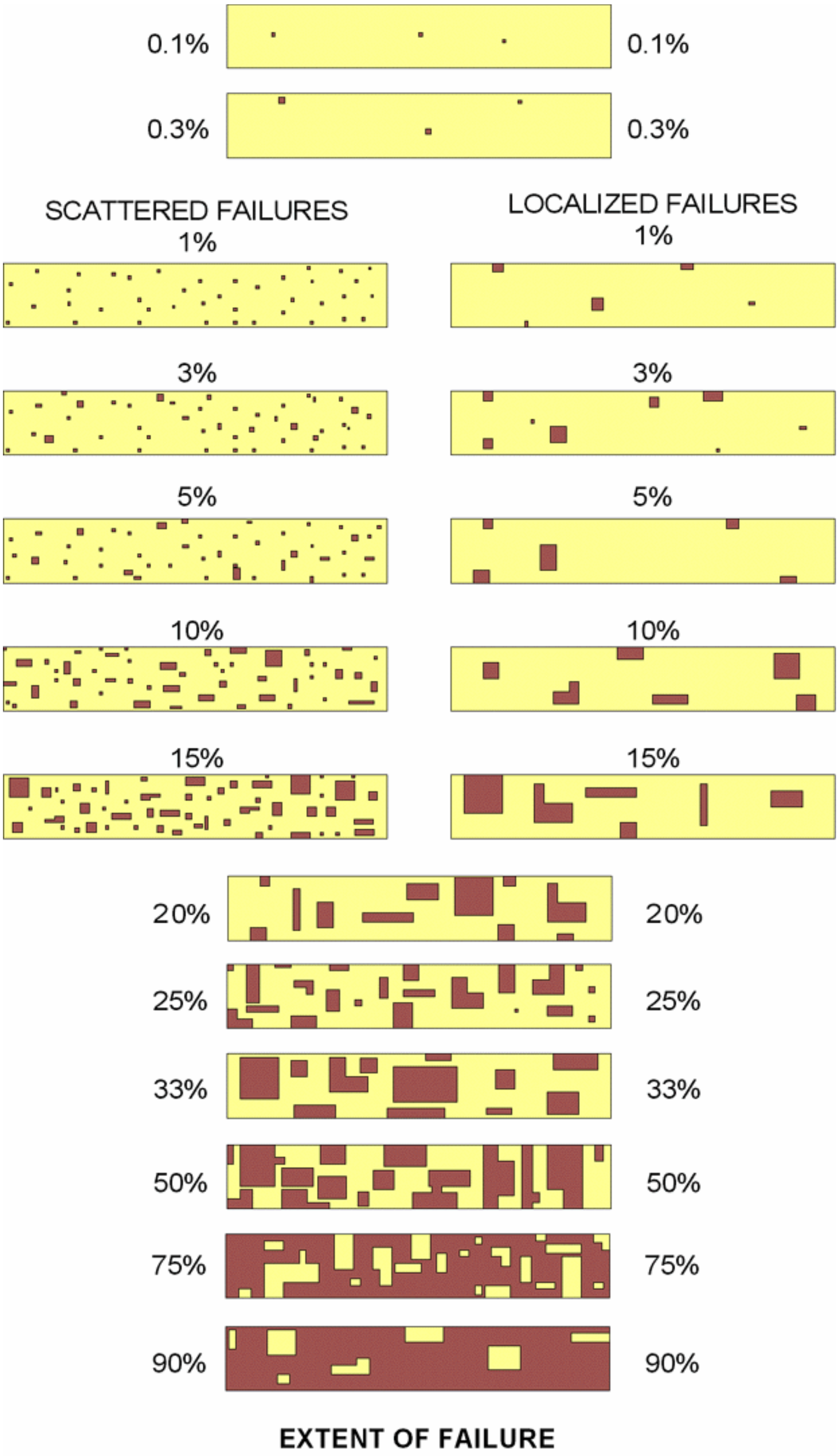


Figure 42 How to rate the extent of coating failure (ABS 2007)

Examples of different grade of coating failure on a flat area are shown below:

“GOOD” Condition. See figure 43 and picture 32.

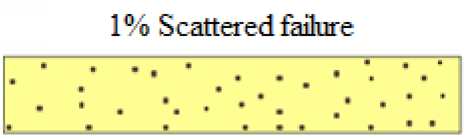
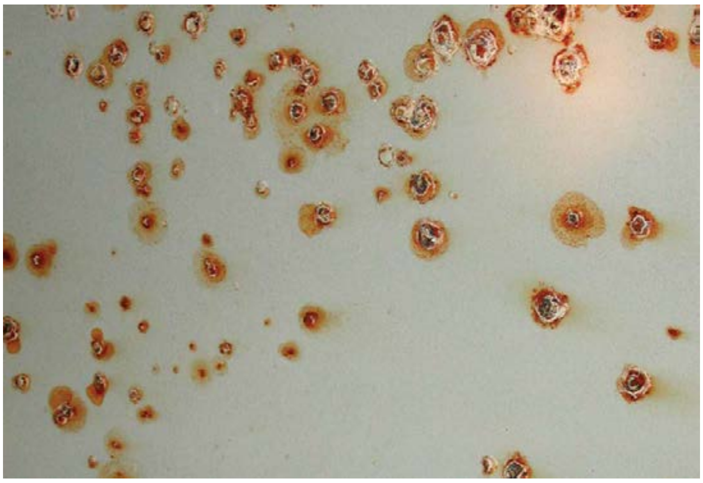


Figure 43 Extent of coating failure (ABS 2007)

Picture 32 1% Scattered coating failure (ABS 2007)

“FAIR” Condition. See figure 44, 45 and picture 33, 34.

Figure 44 Extent of coating failure (ABS 2007)



Picture 33 5% scattered failure (ABS 2007)

Figure 45 Extent of coating failure (ABS 2007)

Picture 34 10% Localized failure (ABS 2007)

“POOR” Condition. See figure 46, 47 and picture 35, 36.

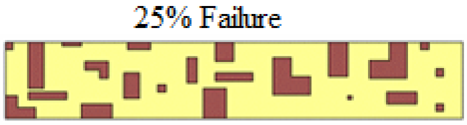


Figure 46 Extent of coating failure (ABS 2007)

Picture 35 25% coating failure (ABS 2007)

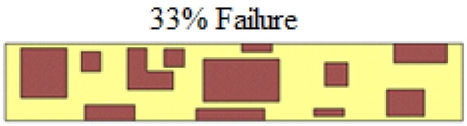


Figure 47 Extent of coating failure (ABS 2007)

Picture 36 33% coating failure (ABS 2007)

Examples of different grade of local coating failure on edges or weld lines are shown below:

“GOOD” Condition. See picture 37.

Picture 37 Coating in good condition (IACS 2006)

Local breakdown of coating less than 20% of edges considered to be the critical structural area

“FAIR” Condition. See picture 38.

Picture 38 Coating in fair condition (IACS 2006)

Local breakdown of coating between 20 – 50% of edges considered to be the critical structural area

“POOR” Condition. See picture 39.

Picture 39 Coating in poor condition (IACS 2006)

Local breakdown of coating more than 50% of edges considered to be the critical structural area

As it is seen above, it can be relatively much corrosion and the coating can still be considered to be in “GOOD” or “FAIR” condition. But it will not take much time before it is considered to be in “POOR” condition and are required to be repaired.

4.3.2 Allowable Thickness Diminution

Based on DNV (2013a)

Although the corrosion additions are fixed, the allowable thickness diminution will vary on which type of corrosion it is and where it appears. See below for allowable thickness diminution for typical corrosion types as general corrosion, pitting corrosion, grooving corrosion and edge corrosion.

4.3.2.1 General corrosion

Based on DNV (2013a)

General corrosion or uniform corrosion is as the name tells, corrosion that is uniform and the extent of the reduction of steel is the more or less the same over a large area.

The allowable minimum thickness t_{min} can be found by the general corrosion criteria. The companies carrying out the thickness measurements work out a scheme with the allowable thickness reduction, in accordance to the general corrosion criteria.

General corrosion criteria: $t_{min} = k\ t_{orig}$

Where:

t_{min} = minimum allowable steel thickness

t_{orig} = original 'as built' thickness

k = diminution coefficient from table 8 or 9

Table 8 Longitudinal strength members (DNV 2013a)

Structural component	*Diminution coefficients "k"*
Strength members within 0.15 D from deck and bottom	
Plating	0.80
Stiffeners	0.75
Girders and stringers	0.80
Side and longitudinal bulkhead between 0.15 D and 0.85 D from bottom	
Plating	0.80
Stiffeners	0.75
Other longitudinal structure between 0.15 D and 0.85 D from bottom	
Plating	0.80
Stiffeners	0.75
Girders and stringers	0.80

The difference between “within 0.15 D from deck and bottom” and “between 0.15 D and 0.85 D from bottom” is shown in figure 49.

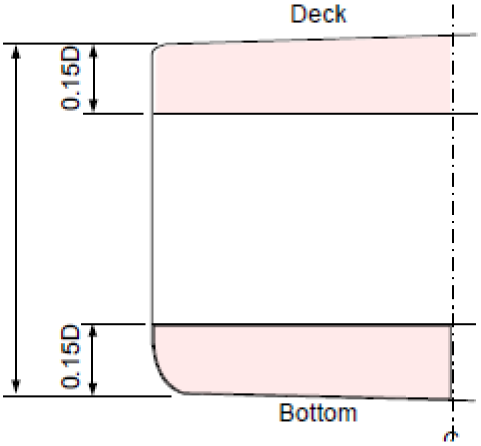


Figure 48 (DNV 2013a)

Table 9 Transverse strength members (DNV 2013a)

Structural component			*Diminution coefficients "k"*
Deck plating between hatches	Plate		0.80
	Stiffener		0.75
Transverse bulkhead	Plain bulkhead		0.75
	Corrugated bulkhead	Flange	0.80
		Web	0.80
Frames/Stiffeners	Web		0.75
	Flange		0.75
Web frames/ Floors/ Girders and stringers	Web		0.80
	Flange		0.75

From table 8 and 9 it can be seen that all the plating, stiffeners, girders and stringers in the ballast tanks have a diminution coefficient k, either 0.75 or 0.80 both on longitudinal- and transverse strength members.

4.3.2.2 Pitting corrosion

Based on DNV (2013a)

Pitting corrosion with less than 20% scattered pitting, the minimum remaining thickness in pitting has to be at least, $t_{min} = 0.6\ t_{orig}$, but not less than 6 mm.,

100% pitting is the same as general corrosion and t_{min} has to be the same as general corrosion criteria: $t_{min} = k\ t_{orig}$

See figure 50 for a pitting intensity diagram.

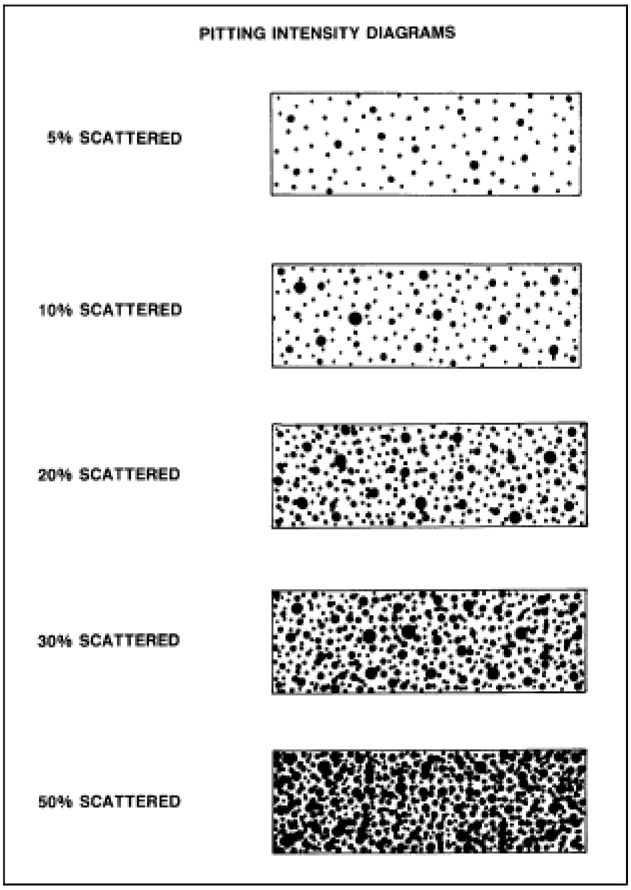


Figure 49 Pitting intensity diagram. (DNV 2013a)

4.3.2.3 Groove corrosion

Based on DNV (2013a)

Grooving corrosion typically occurs on or near weld seams. The allowable thickness diminution criteria for grooving corrosion are limited due to the effects and complexity of the corrosion type.

In connection with ballast tanks, the weld seams on the longitudinal under deck plating are commonly affected by grooving corrosion. See figure 51.

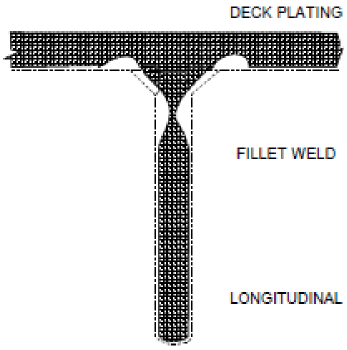


Figure 50 Typical grooving area, deck/longitudinal. (DNV 2013a)

The minimum allowable thickness where it is groove corrosion, if the groove breadth is maximum 15% of the web height (see figure 52), but not more than 100 mm are:

Minimum thickness: $t_{min} = 0.7\ t_{orig}$ but not less than 6 mm.

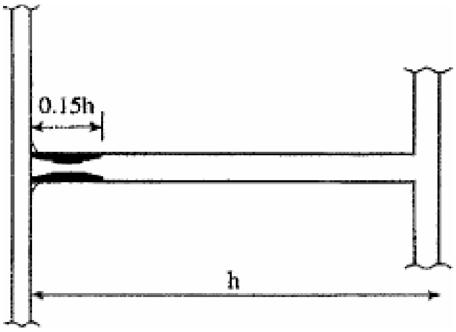


Figure 51 Grooving breath max 15% of the web height (DNV 2013a)

4.3.2.4 Edge corrosion

Based on DNV (2013a)

Corrosion on edges is common where the coating is thin due to sharp edges, or because of abrasion.

There is different allowable thickness diminution for edge corrosion on flat bars and manholes, drain holes etc.

For flat bars the allowable extent of edge corrosion is, that the edge thickness is not less than 33% of the original thickness and well rounded, if the corroded area are less than 25% of the height of the bar. The thickness of the rest of the flat bar has to be not less than the limit for general corrosion. See figure 53

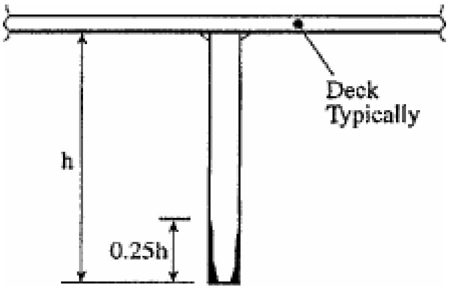


Figure 52 Allowed edge corrosion (DNV 2013a)

For manholes, drain holes etc. the edge corrosion can give reduced thickness below allowable limit if the criteria for shear stress are checked and if the reduced area are less than 20 % of the smallest diameter in the opening and not larger than 100 mm. See figure 54.

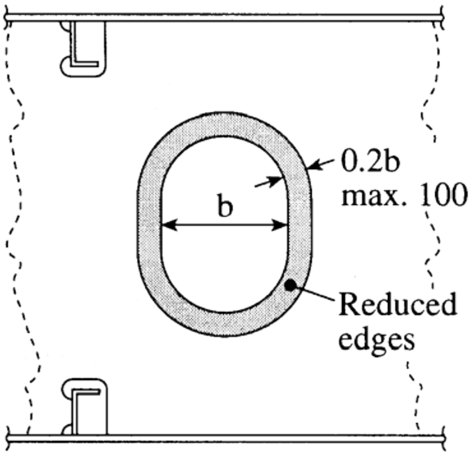


Figure 53 Allowed edge corrosion (DNV 2013a)

If the edges are uneven they may be grinded smooth, if the maximum opening of the hole is not increased with more than 10%.

4.4 Corrosion additions on new builds

To secure the structural integrity of the vessel when corrosion occurs, there are corrosion additions on new builds. The corrosion additions t_k are typically 0.5 – 3.0 mm as to where it is on the ship, and which type of member or plate. See table 10. (DNV 2014a)

The corrosion additions are based on a coating life of 15 years, which PSPC aims for, and for total life time of ship, 20 years for Nauticus Newbuilding and 25 years for Common Structural Rules – CSR. Corrosion rates are assumed to be 0,2 – 0,4 mm/year in general and <0,5 mm/year within 1,5 m below weather deck tank or hold top. (Skaret 2014)

For an additional corrosion addition t_c the class notation ICM – Increased Corrosion Margin is used. Here the corrosion additions are 0.5 – 3.0 mm in addition to t_k. See table 11. This is if the ship-owner wants an extra corrosion margin. (DNV 2014a)

Table 10 Corrosion addition t_k in mm (DNV 2014a)

Internal members and plate boundary between spaces of the given category	*Tank/hold region*	
	Within 1.5 m below weather deck tank or hold top	*Elsewhere*
Ballast tank 1)	3.0	1.5
Cargo oil tank only	2.0	1.0 (0) 1)
Plate boundary between given space categories	*Tank/hold region*	
	Within 1.5 m below weather deck tank or hold top	*Elsewhere*
Ballast tank /Cargo oil tank only	2.5	1.5 (1.0) 1)
Ballast tank /Other category space 2)	2.0	1.0
Cargo oil tank only/ Other category space 2)	1.0	0.5 (0) 1)
1) The figure in brackets refers to non-horizontal surfaces. 2) Other category space denotes the hull exterior and all spaces other than water ballast and cargo oil tanks and holds of dry bulk cargo carriers.		

Table 11 Additional corrosion addition t_c in mm. (DNV 2014a)

Internal members and plate boundary between spaces of the given category	*Tank/hold region*	
	Within 1.5 m below weather deck tank or hold top	*Elsewhere*
Ballast tank	3.0	1.5
Cargo oil tank only	2.0	1.0 (0) 1)
Plate boundary between given space categories	*Tank/hold region*	
	Within 1.5 m below weather deck tank or hold top	*Elsewhere*
Ballast tank 1)/Cargo oil tank only	2.5	1.5
Ballast tank 1)/Other category space 1)	2.0	1.0
Cargo oil tank only/ Other category space 1)	1.0	0.5
1) Other category space denotes the hull exterior and all spaces other than water ballast and cargo oil tanks and holds of dry bulk cargo carriers.		

As it can be seen in table 10 and 10, the corrosion addition (t_k) and the additional corrosion addition (t_c) have the same values. The additional corrosion addition is therefore a doubling of the corrosion addition.

5 Inspection of ballast tanks in Solvang ships

To get an overview of the condition of the ballast tanks on the ships in the Solvang fleet, internal ballast tank inspection reports done by chief officer every 6th month and CAP reports were used.

Some of the ballast tanks on Clipper Skagen were inspected by undersigned during stay in Gibraltar from 05.10.2014 to 08.10.2014.

Some of the ballast tanks on Clipper Harald and Clipper Posh were inspected by undersigned during stay on Kårstø, Norway, respectively 01.12.2014 and 26.11.2014

Solvang Shipping has 17 ships with age from 1 to 25 years old. Five of the ships with various ages were selected for further assessment. As listed below:

- Clipper Skagen (1989) – Inspected by undersigned, inspection reports, CAP reports
- Clipper Harald (1999) – Inspected by undersigned, inspection reports, CAP reports
- Clipper Star (2003) – Inspection reports only
- Clipper Mars (2008) – Inspection reports only
- Clipper Posh (2013) – Inspected by undersigned, inspection reports

The ships are presented below with some of the main findings, with explanation of the findings and possible solutions. The findings are based on examples of a lot of reviewed inspection reports, some CAP reports and the physical inspections done by undersigned.

5.1 Clipper Skagen (1989)

Clipper Skagen is a Semi ref. LPG/Ethylene carrier delivered in 1989. See picture 1. Built by Meyer shipyard in Germany. Vessels LOA is 158 m and breadth is 21.3 m, with a cargo capacity of 15.098 cbm. See picture 40.

Picture 40 Clipper Skagen moored outside Gibraltar (Ask 2014a)

The oldest vessel in the Solvang fleet has had a number of repairs in the ballast tanks due to corrosion and poor quality on the coating and/or coating preparation and/or coating application. This is costly and this cost is wanted to be reduced to a minimum.

Some of the ballast tanks on Clipper Skagen were inspected by undersigned during anchorage in Gibraltar. Wing ballast tank number 16, 17, 18, 19, 24 and 25, and double bottom tank number 4, 7 and 9 were inspected. See figure 55.

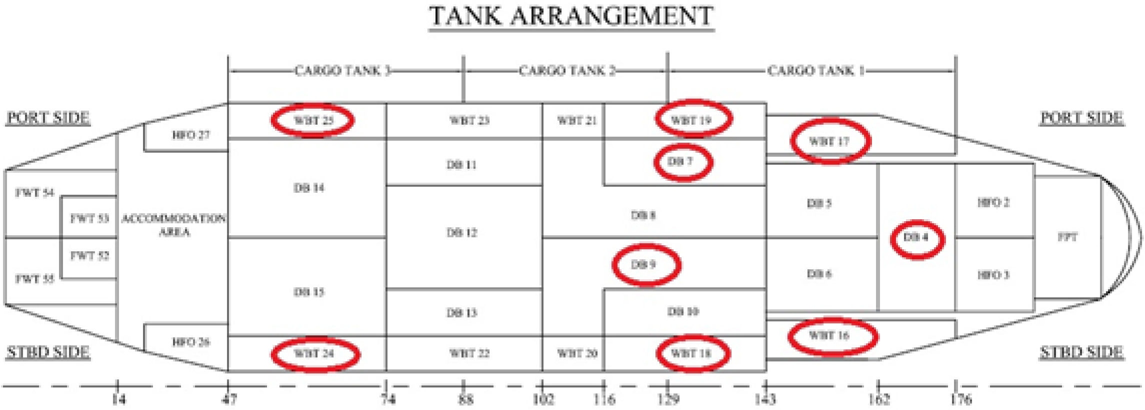


Figure 54 Tank arrangement Clipper Skagen with tanks inspected by undersigned

Wing ballast tanks 22, 24 and 25

Remontowa Shipyard, Gdansk, Poland 2009

In the wing ballast tanks number 22, 24 and 25 a lot of the drain holes in deck longitudinal were found with edge corrosion. See picture 41.

Picture 41 Edge corrosion on drain hole (Clipper Skagen 2009)

Some of the drain holes were maintained before CAP inspection, but the edge corrosion wastage was too much to pass the inspection. See picture 42.

Picture 42 Maintained drain hole (Clipper Skagen 2009)

All drain holes with corrosion over allowable limit were renewed with inserts. See picture 43.

Picture 43 Renewed drain hole (Clipper Skagen 2009)

After insert was fitted, coating was applied. See picture 44. From the picture it looks like the coating are applied in a too tin coat.

Picture 44 Renewed drain hole after coating (Clipper Skagen 2009)

Web frames cut outs for deck longitudinals and side longitudinals were found with edge corrosion. See picture 45.

Picture 45 Marked area needs reneval. (Clipper Skagen 2009)

The corroded parts were cut out. See picture 46.

Picture 46 Corroded part cut out (Clipper Skagen 2009)

Renewed with inserts and coated. See picture 47. Coating application here also looks to be too thin.

Picture 47 New insert welded in place and coated (Clipper Skagen 2009)

The examples shown above are only some of the steel replacement carried out during dry docking in 2009. But it emerges from the reports that all the steel replacement necessary due to corrosion, was in the top of the wing ballast tanks. Steel replacement was also done in the lower part of the wing ballast tanks and the double bottom tanks, but this was not because of corrosion. This steel replacement was due to damage. E.g. impact by tugboat.

Inspection 30.08.2010

One year after steel renewal, corrosion starts to appear in the renewed areas. Especially on and around welds, and also on the sharp edges in the drain hole itself. See picture 48.

Picture 48 Drain hole one year after renewal (Clipper Skagen 2010)

Inspection in Gibraltar 06.10.2014

When inspected in Gibraltar, it was five years since most of the steel replacement carried out in 2009. During the inspection it was found substantial corrosion on and around the repaired areas. Corrosion on welds and around the drain hole. See picture 49 and 50.

Picture 49 Corrosion on renewed steel (Ask 2014a)

The corrosion on the weld seams and near them normally occurs when it is poor surface preparation before coating. The corrosion near a weld seam can also appear due to coating breakdown when welding. After welding all the coating nearby, which has been affected by the heat of the welding should be grit blasted and recoated.

Picture 50 Corrosion on renewed steel (Ask 2014a)

Corrosion near welding after steel replacement. See picture 51. This is probably caused because of the original coating near the new welded insert has been damaged be the heat of the welding process.

Picture 51 Corrosion near a welded insert (Ask 2014a)

Only five years after steel replacement substantial corrosion are found in replaced drain holes and near welds done in connection with steel replacement.

Wing Ballast Tank 16 & 17

Victor Lenac Shipyard, dry dock 5 Rijeka, Croatia 2012

Due to fair/poor coating condition in wing ballast tanks number 16 and 17, (See picture 52) they were grit blasted and recoated during dry docking in 2012. The coating used was Hempadur Quattro by Hempel.

Picture 52 Before grit blasting and recoating (Clipper Skagen 2012)

After recoating, the coating condition in both tanks were very good. See picture 53.

Picture 53 After grit blasting and recoating (Clipper Skagen 2012)

Inspection 26/09-2013

Coating in good condition one year after recoating. See picture 54.

Picture 54 One year after recoating (Clipper Skagen 2013c)

Inspection in Gibraltar 6/10-2014

During the inspection in Gibraltar, some corrosion was found in these tanks which were recoated two years ago. Some of the corrosion spots are presented below.

Crevice corrosion was found around bolts/nuts on flange and pipe clamp. See picture 55.

Picture 55 Two years after recoating (Ask 2014a)

The backside of a water pipe inside the tank was found with much corrosion. See picture 56. This is probably caused because of problem with access for the grit blaster and/or carelessness by the grit blaster operator.

Picture 56 Two years after recoating (Ask 2014a)

In the top of the ballast tank edge corrosion was present on a cross bracing. Probably caused by poor access and/or carelessness when grit blasting. See picture 57.

Picture 57 Two years after recoating (Ask 2014a)

Edge corrosion on beam, and grooving/pitting corrosion was found in the in tank top. See picture 58.

Picture 58 Two years after recoating (Ask 2014a)

If the ballast tanks not are properly maintained, total renewal of coating will be necessary. From the pictures above it can be seen that grit blasting may not reach all the spots in the tank, e.g. behind pipes, around bolts etc. But the overall condition of the tanks are good (Something they clearly should, since they have been recoated), but it is a problem with this much corrosion after just two years in operation.

5.1.1 Summary:

During dry docking in 2009 much steel renewal in top of the wing tanks were necessary due to corrosion. When inspected in Gibraltar 2014, much corrosion was found on and nearby the renewed steel from 2009. The corrosion on the renewed steel sections is mainly caused by poor coating application. The coating thickness also seems to be too thin. Substantial corrosion was found nearby new steel inserts. This corrosion is probably caused due to coating breakdown due to the heat from welding nearby. A larger area around the welds should be grit blasted and recoated.

Two of the wing ballast tanks were totally recoated in 2012. Some corrosion was found during the inspection in Gibraltar. Especially on piping, flanges and some sharp edges. This shows that even with coating maintenance done at yard, the result are not as good as it should.

5.2 Clipper Harald (1999)

Clipper Harald is a Semi ref. LPG/Ethylene Carrier delivered in 1999 (See picture 20). Built by Meyer shipyard in Germany. The ship's LOA is 146.4 m and breadth is 20.5 m, with a cargo capacity of 12.600 cbm. See picture 59.

Picture 59 Clipper Harald (Solvang)

Original coating: unknown

Coating maintenance done with

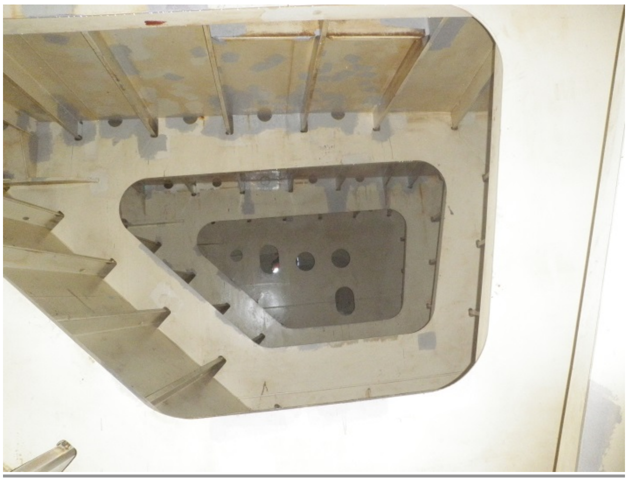
- X – 2011 : Jotun Balloxy HB light
- 2012 – 2014: Hempadur 35740

Ballast tank inspections

Water ballast tank 1. port top side

Inspection 03 January 2012 by the chief officer.

A lot of minor coating maintenance done in the tank earlier, especially in the top deck plating. See picture 60 and 61.



Picture 60 General condition wing ballast tank (Clipper Harald 2012a)

Picture 61 Deckhead (Clipper Harald 2012a)

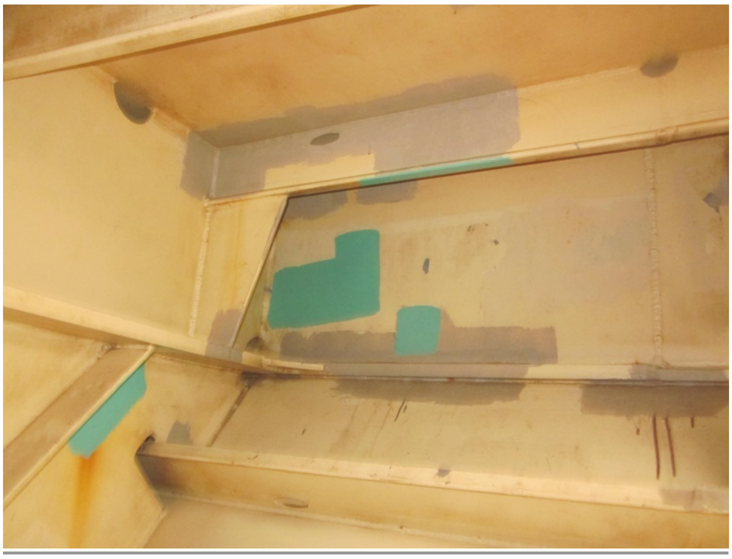
Some coating maintenance is also done in the bottom of the ballast tank. See picture 62.

Picture 62 Bottom (Clipper Harald 2012a)

The tanks are in generally very good condition.

Inspection 31.05.2012

Corrosion spots found and painted. See pictures 63 and 64.



Picture 63 Sloping plate (Clipper Harald 2012b)

Picture 64 Bottom (Clipper Harald 2012b)

The tanks are in generally very good condition.

Inspection at Kårstø 01.12.14

Three of the wing ballast tanks were inspected at anchorage outside Kårstø. Since the ship was in ballast condition, only three of the tanks were possible to inspect. Wing tank number 4 port and starboard, and number 3 starboard. See figure 56.

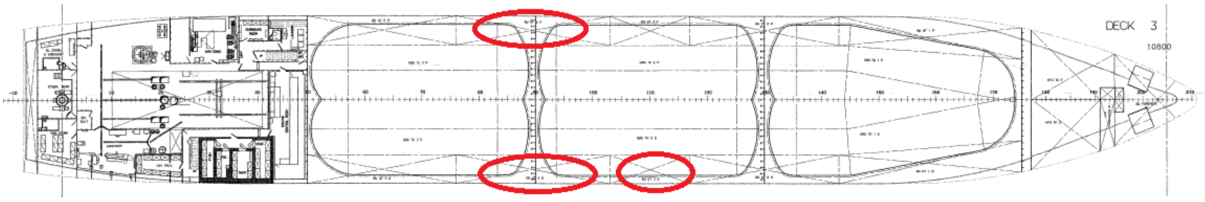
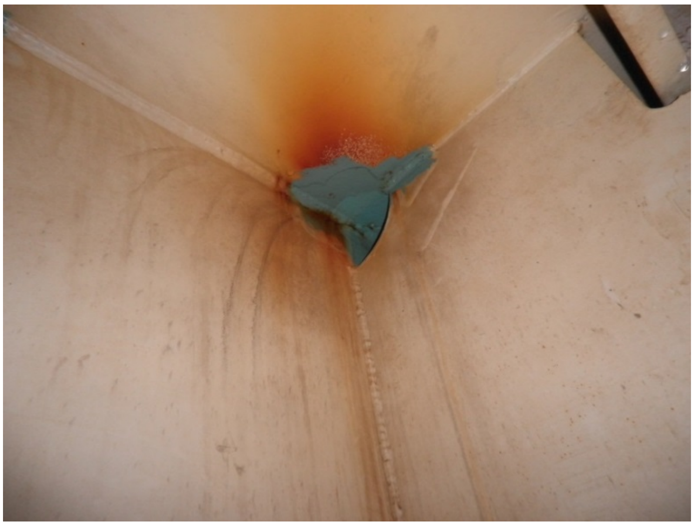


Figure 55 Wing tanks inspected by undersigned

All the tanks were in general good condition with minor rust spots. Corrosion on earlier maintained areas was found. See picture 65, 66 and 67.



Picture 65 Deckhead (Ask 2014b)

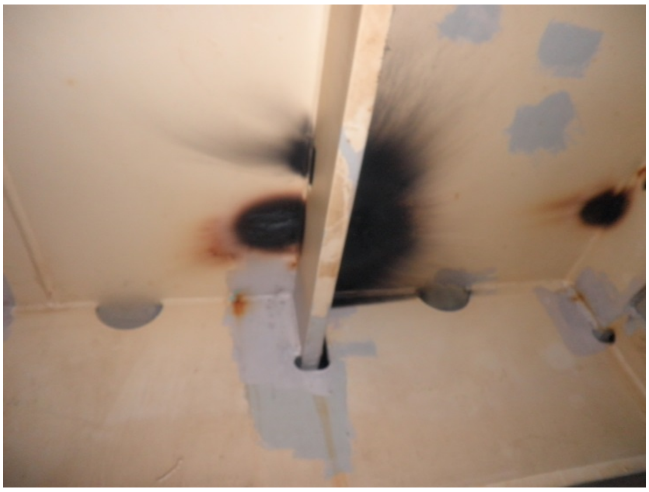
Picture 66 Deckhead (Ask 2014b)

Picture 67 Deckhead (Ask 2014b)

Small corrosion spots were found on earlier maintained areas.

Welding on deck has been carried out, and caused coating breakdown in the ballast tank. See picture 68 and 69. All the heat damaged coating need to be grit blasted and recoated.

Picture 68 Deckhead after welding on deck (Ask 2014b)



Picture 69 Deckhead after welding on deck (Ask 2014b)

The coating in the tanks were in overall good condition with small spots of corrosion, most of them in the top of the tank.

5.2.1 Summary:

Clipper Harald is on long time charter with Statoil, only sailing between Kårstø and Rafnes in Norway. This is clearly an advantage concerning corrosion. Ships sailing in cold climate has much less corrosion problems than ships sailing in hot climate.

Clipper Harald is the only ship in the Solvang fleet without cathodic protection in the ballast tanks, and according to the captain onboard it was not necessary due to the cold climate.

Most of the corrosion spots were found on previously maintained areas. There can be many reasons for this, ex. poor preparation, high humidity, salt inclusions, too thin coating, etc.

For the corrosion in the deckhead it is only proper coating maintenance that will keep it under control. As discussed earlier the cathodic protection with sacrificial zinc would not make any difference in the top of the wing ballast tank.

After welding has been done on deck it is important to remove all the coating damaged by the heat before new coating is applied.

5.3 Clipper Star (2003)

Clipper Star is a Large Gas Carrier – LGC delivered in March 2003. See picture 31. Built by Kawasaki Heavy Industries. The vessels LOA is 204.85 m and breadth is 32.2 m, with a cargo capacity of 59.300 cbm. See picture 70.

Picture 70 Clipper Star (Solvang)

Ballast tanks

The ballast tanks in the three Kawasaki built ships (Clipper Star, Clipper Moon and Clipper Sky) are coated with a dark color. This makes corrosion more difficult to detect than if the coating was with a light color.

Inspection 22.10.14

Corrosion spots found on previously maintained areas around drain holes and weld seams in the deckhead. See picture 71 and 72.

Picture 71 Corrosion on weld seams in deckhead (Clipper Star 2014)

Picture 72 Corrosion in drainholes in deckhead (Clipper Star 2014)

5.3.1 Summary:

The tanks are in generally very good condition.

From the inspection reports it emerges that is it usually in the top of the wing ballast tanks the corrosion problem are most present.

Due to the dark coating, inspections are more demanding and time consuming. It is much harder to discover corrosion on a dark surface than on light colored surface.

5.4 Clipper Mars (2008)

Clipper Mars is Large Gas Carrier – LGC delivered in November 2008. See picture 34. Built by Hyundai Heavy Industries – HHI in South Korea. The vessels LOA is 204.98 m and breadth is 32.2 m, with a cargo capacity of 60.200 cbm. See picture 73.

Picture 73 Clipper Mars (Solvang)

This vessel is built before PSPC was a requirement for ballast tank, but the coating specification is similar. But there is not mentioned something about sharp edges and corners need to be rounded in the coating specification.

Maintenance coating: Jotun Balloxy HB light

Inspection reports from ballast tank 1 starboard top side

Inspection 09.06.2009

Small corrosion spots were found in these areas:

- Drain pipe angular support
- Underneath the longitudinal frame adjacent to drain pipe
- Aft bulkhead underneath the shipside longitudinal frame
- Trunk space from top to bottom
- Bottom part of the ladder

All spots were marked with the date of the inspection, but not recoated. In total the overall condition of the tank was very good.

Inspection 20.12.2012

Corrosion in the top of the tank was found in drain holes in longitudinals. See picture 74. Maintenance scheduled to be done in the best time opportunity

Picture 74 Drainhole in longitudinal (Clipper Mars 2012)

Overall condition of the tank was good, with some corrosion in the drain holes in the top of the tank. See picture 75.

Picture 75 Sloping plate and deckhead (Clipper Mars 2012)

Inspection 27.11.2013

Corrosion found among other things on a longitudinal (see picture 73) and in drain holes (see picture 77). No coating maintenance carried out at inspection.

Picture 76 Corrosion on longitudinal near manhole (Clipper Mars 2013)

Picture 77 Corrosion in drain holes under deckhead (Clipper Mars 2013)

Inspection 03.06.2014

The tank are in generally good condition , but with corrosion around drain holes in longitudinal. See picture 78 and 79.

Picture 78 Drain holes in the deckhead (Clipper Mars 2014)

Picture 79 Drain holes in the deckhead (Clipper Mars 2014)

5.4.1 Summary:

Corrosion spots discovered at the first 6 months inspection on 9th June 2009. The ship was then only 6 months old.

From the inspection reports its look like “poor” or none coating maintenance are carried out. The corrosion in longitudinal (see picture 39 and 40), may result in steel replacement in short time if not maintained properly in the near future.

5.5 Clipper Posh (2013)

Clipper Posh is a Very Large Gas Carrier – VLGC delivered in December 2013. See picture 46. The sister ship to Clipper Quito, built by Hyundai Heavy Industries in South Korea. Vessels LOA is 225 m and is breadth 36.6 m with a cargo capacity of 84.000 cbm. See picture 80.

Picture 80 Clipper Posh (Solvang)

Some of the ballast tanks on Clipper Posh were inspected by writer. Wing ballast tank number 2 port and starboard, and number 1 port. The aft peak ballast tank was also inspected. See figure 57.

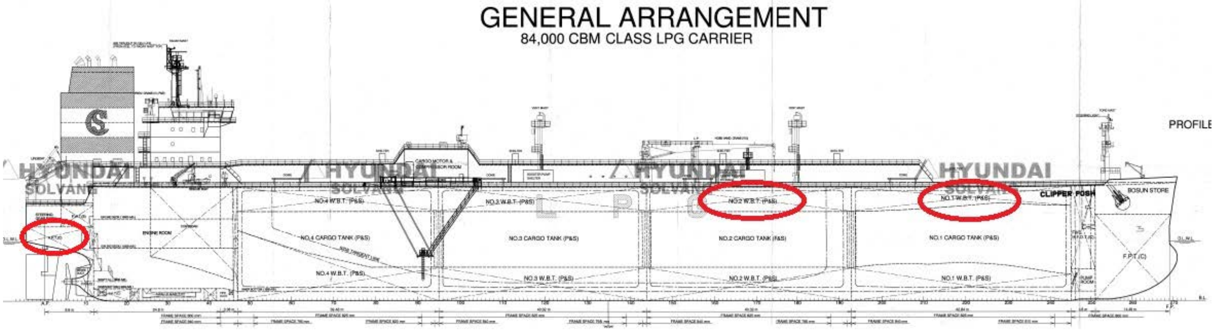


Figure 56 General arrangement Clipper Posh

Ballast tanks

The protection of ballast tanks on this vessel is required to be by the Performance Standard for Protective Coating – PSPC. Coating used in ballast tanks is KCC Korepox EH2350, a two component, polyamide cured pure epoxy resin based self-priming, anti-abrasion coating. It is also cathodic protection in all ballast tanks.

The first 6 months ballast tank inspections were carried out 14 – 16 April 2014 by chief officer.

Water ballast tank 1. Port top side

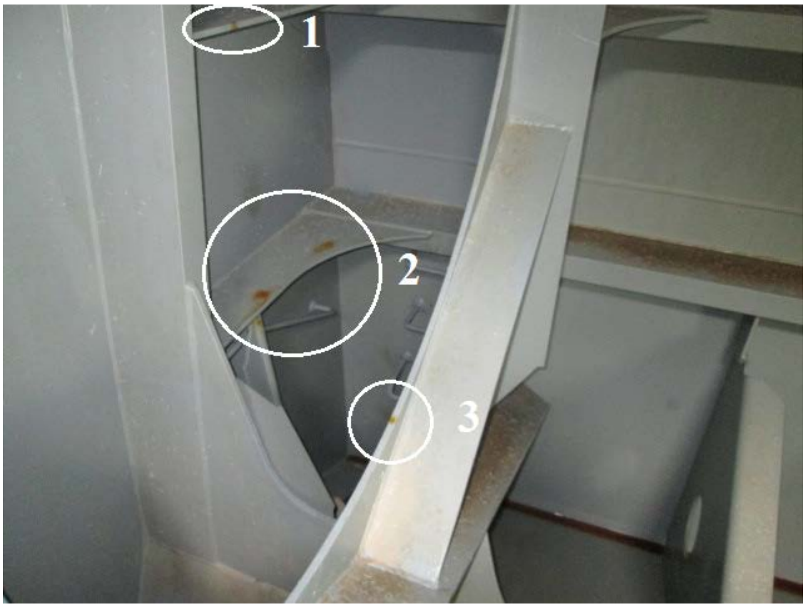
Spot rust found in tank top deck head. It was treated and painted at same day. Spot rust probably caused by welding on the outside of deck plating. See picture 81.

Picture 81 Deckhead after welding (Clipper Posh 2014)

Water ballast tank 2 Starboard top side

Spot rust found in forward entrance access to double bottom. Treated and painted the same day. See picture 82 and 83 for spot rust

1. Edge corrosion
2. Localized corrosion – grooving or pitting corrosion
3. Edge corrosion



Picture 82 Tranverse bulkhead (Clipper Posh 2014)

1. Edge corrosion
2. Edge corrosion

Picture 83 Side shell (Clipper Posh 2014)

Water ballast tank 2 Port top side

Spot rust found in entrance access to double bottom. See picture 84.

1. Edge corrosion

Picture 84 Trunk to double bottom tank (Clipper Posh 2014)

The second 6 months ballast tank inspections were carried out 2 – 3 October 2014.

Water ballast tank 4 Port double bottom

Crevice corrosion found on the access platform for ladder to double bottom. See picture 85.

Picture 85 Double bottom tank (Clipper Posh 2014)

Fore peak tank

Spots of rust found on the ladder. See picture 86.

1. Edge corrosion
2. Edge corrosion

Picture 86 Ladder in fore peak tank (Clipper Posh 2014)

Inspection on Kårstø 26/11-14 done by undersigned.

The upper ballast tank number 1 port, number 2 port and starboard, and the aft. peak tank were inspected. The aft. peak tank was nearly not used and was in perfect condition. In the other tanks there were some small spots of corrosion and some pitting corrosion under the deck plating.

The overall condition of the tanks inspected was good (As they should be on a one year old ship). See picture 87.

Picture 87 General condition of wing ballast tanks (Ask 2014c)

Edge corrosion was found on a sharp edge on the transverse bulkhead. See picture 88. Probably caused by too sharp edge and/or too thin coating.

Picture 88 Edge corrosion on transverse bulkhead (Ask 2014c)

Edge corrosion was found on a sharp edge on a longitudinal on the side shell. See picture 89. Probably caused by too sharp edge and/or too thin coating.

Picture 89 Longitudinal on side shell (Ask 2014c)

Pitting corrosion or abrasive dust from grinding was found in the deck-head. See picture 90 and 91. Some of the areas with what looks to be pitting corrosion may just be abrasive dust after grinding during new build.

Picture 90 Pitting/abrasive dust in the deckhead (Ask 2014c)

Picture 91 Pitting in the deckhead (Ask 2014c)

It was also found blisters on a ballast water pipe going through the wing ballast tank. See picture 92.

Picture 92 Blisters on a ballast water pipe (Ask 2014c)

5.5.1 Summary:

The ballast tanks were in generally very good condition, as they should considering the ships age. Nevertheless it was found a lot of small corrosion spots, mainly edge corrosion on sharp edges. It is important that coating maintenance are carried out as soon as possible to restrict the extent of corrosion.

5.6 Result / discussion of ballast tank inspections

From the inspections done by undersigned, the inspection reports from chief officer onboard and CAP reports (Only CAP reports for 15+ years old Clipper Skagen and Clipper Harald) there are many findings.

There is corrosion in a varying degree in all ballast tanks inspected regardless of the age of the ship. Most of the corrosion is found under the deck plating in the top of the wing ballast tanks. Especially on sharp edges on longitudinals, in drain holes under deck-plating and on weld seams.

It was only Clipper Skagen that had renewed steel in the ballast tanks due to corrosion, but Clipper Mars may also need steel renewal of drain holes in longitudinal if not coating maintenance are carried out in the near future.

All ships except Clipper Posh had coating maintenance in ballast tanks carried out. From the inspection reports it is experienced that the coating maintenance does not last for a very long time. In most cases it is only a few years before corrosion is present again (~ 1 – 3 years). In most of the cases the maintenance work carried out in the ballast tanks are not good enough. It seems like it is extremely difficult to get the maintenance work to be properly done, due to many different reasons. E.g. poor surface preparation, humidity, temperature, curing time, etc. It is maybe an idea to do all the coating maintenance during dry docking, if it cannot be properly done when the ship is in service. But as seen on Clipper Skagen it is not sure the result from dry docking are perfect either

Clipper Harald was the only ship without cathodic protection in ballast tanks, but because of the trading routes (Kårstø, Norway to Rafnes, Norway) in cold climate the corrosion problem on this ship are much less severe than on ships sailing in warmer climate, as the rest of the Solvang fleet are.

The oldest ships (Semi ref.LPG/Ethylene) are the smallest and with only ~3000 m^3 ballast capacity, and the newer large gas carriers – LGC with ~15500 m^3 ballast capacity and the newest Very large gas carriers – VLGC have ~20000 m^3 ballast water capacity. This means a much larger surface to maintain inside the ballast tanks on the larger ships. Due to the complexity of maintenance in ballast tanks and due to the large areas inside the tanks it will be very important to repair the corrosion spots as soon as possible to minimize the corrosion development. It will also be very important to do the maintenance properly in accordance with the company’s procedure.

6 Strength evaluation of critical area for corrosion

- Buckling capacity
- Fatigue life

To show the importance with good protective coating in ballast tanks and proper maintenance, some simplified buckling capacity evaluations and fatigue life evaluations calculations are carried out. This evaluation is done for Clipper Skagen, and therefor only applicable to this ship.

All the elements evaluated are in the top of a wing ballast tank. From the inspections done in ballast tanks on Solvang ships, and from the corrosion rates presented in table 4 it has been learned that this is the most critical area concerning corrosion.

Clipper Skagen data:

Length between perpendiculars (L_{pp})	148.8 m
Length overall (L)	158.0 m
Draught	9.762 m
Breadth extreme	21.33 m
Depth moulded	13.9 m
Deadweight	16137 ton

Clipper Skagen was originally coated in the ballast tanks, and the coating is assumed to have an effective coating life of 10 years.

6.1 Buckling capacity

In this evaluation the buckling capacity in the deck plating and longitudinal in a wing ballast tank in the midship section is calculated with corrosion wastage. See figure 58 and 59.

The upper wing water ballast tank are shown in figure 58 and 59.

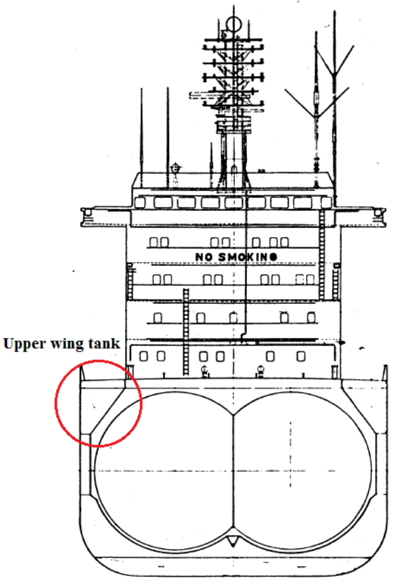


Figure 57 Clipper Skagen upper wing ballast tank - Cross section

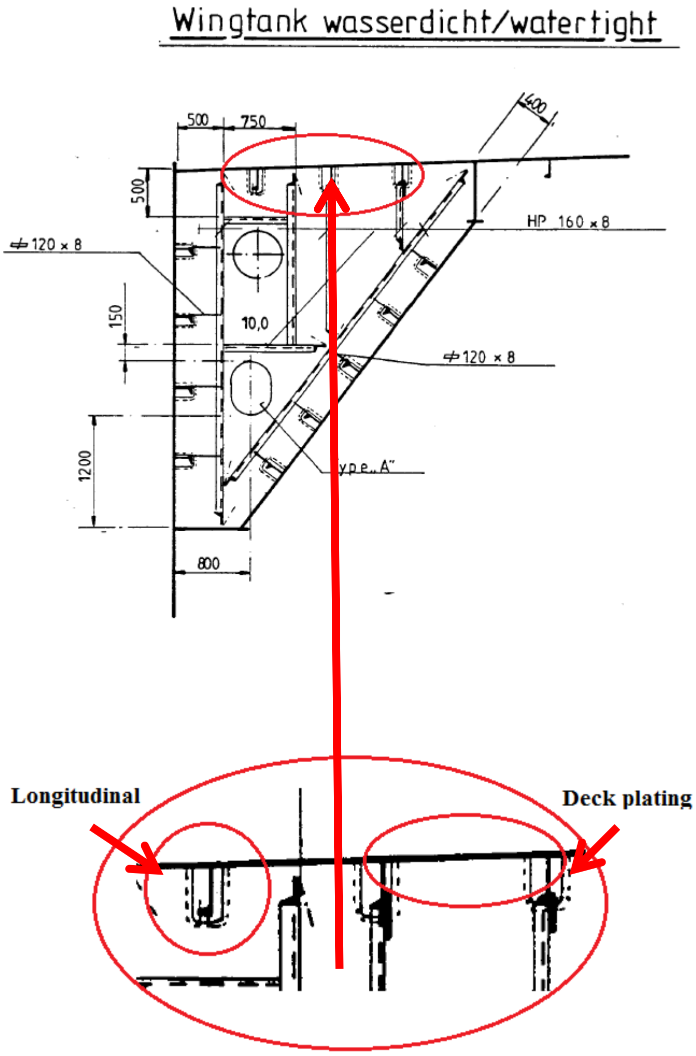


Figure 58 Wing tank with longitudinal and deck plating

To simplify the calculation it is assumed that the ship only gets wave loads from bow or stern, making the plate field and longitudinals only getting tension from global vertically bending moment. The thickness limits are based on general corrosion, so the steel thickness may be reduced if the corrosion is very local. (Grooving- or pitting corrosion)

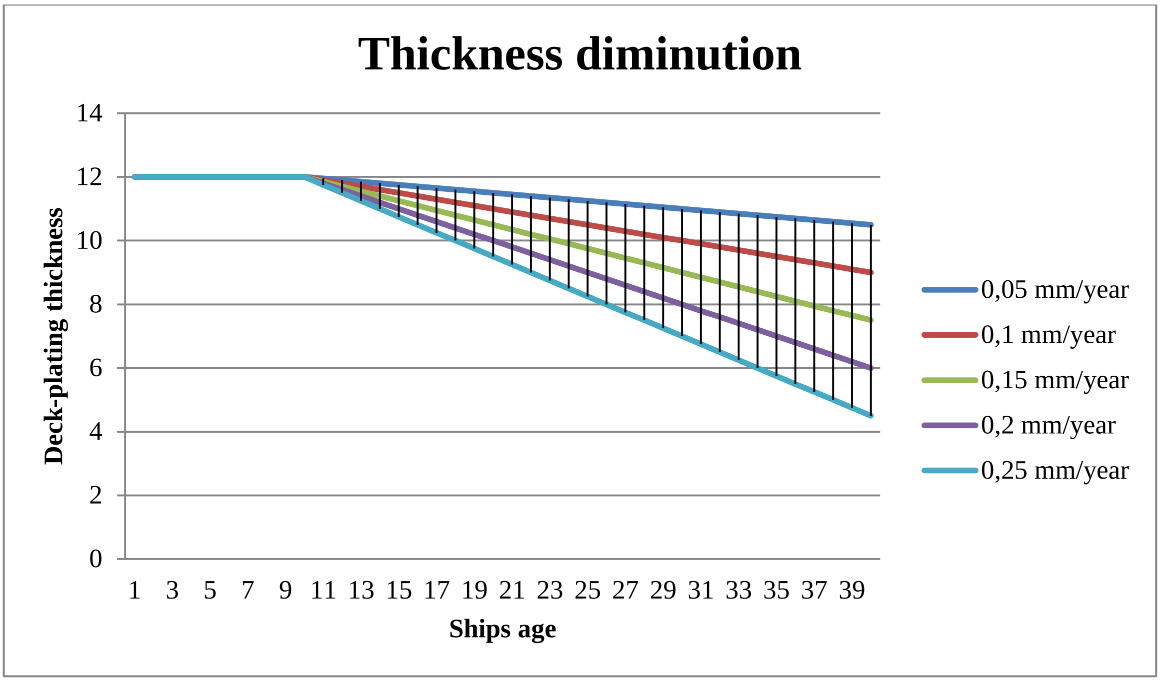
6.1.1 Buckling capacity in deck plating

In graph 1 below it is shown how the thickness of the deck-plating is reduced with different corrosion rates. The initial thickness was 12 mm, and is assumed to be the same through the 10 year coating life. It is shown when it is within the different CAP classes, where CAP 3 is the same as class limit.

Thickness diminution

CAP limits for thickness in deck plating (general corrosion):

CAP 1 – 11.4 mm CAP 2 – 10.8 mm CAP 3 – 10.2 mm



Graph 1 Thickness diminution in deck plating

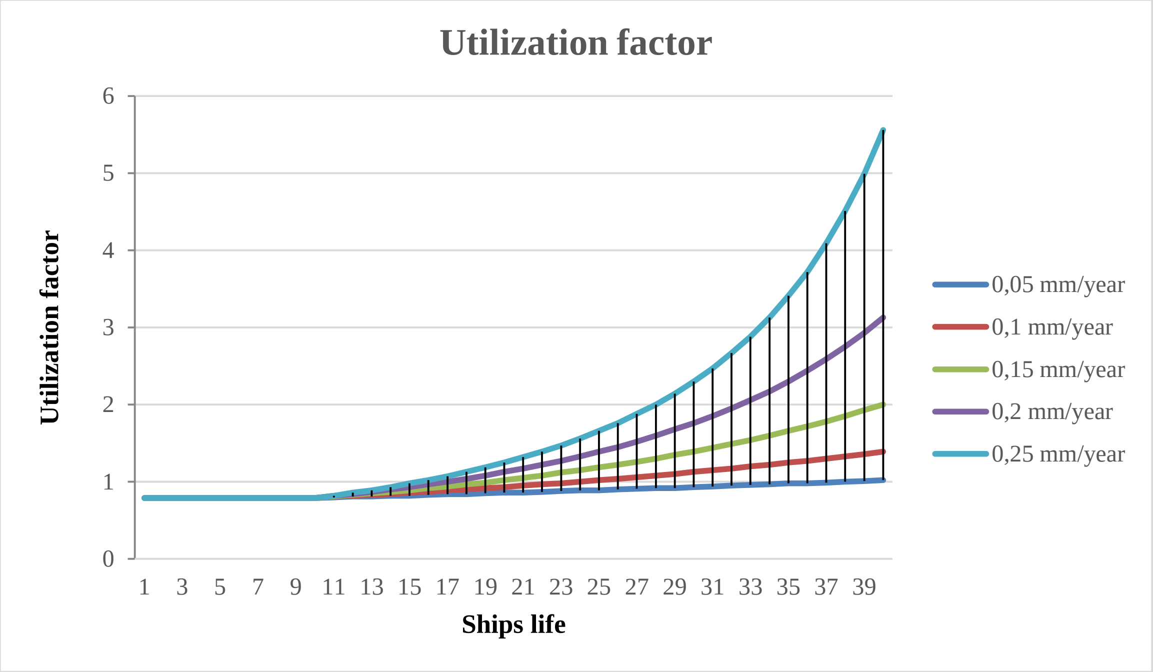
The steel thickness will reduce to under CAP 2 limit rapidly if the corrosion rate are 0.15 mm/year or above. (See graph 1)

Utilization Factor

As the total global axial stresses $\Delta\sigma_0$ will increase, and the elastic σ_{el} and critical σ_c buckling stress will decrease, the utilization factor increases as shown in graph 2 below.

CAP limits utilization factor in deck plating:

CAP 1 =< 0.90 CAP 2 =<0.95 CAP 3 =< 1.0



Graph 2 Utilization factor in deck plating

Graph 2 shows that the utilization factor relatively rapidly exceeds the CAP limits after corrosion appears.

How many years the ship will be able to be in accordance with regulations with the different corrosion rates in deck-plating inside wing ballast tank, with coating lasting 10 years. See table 12 and 13.

Table 12 Assumed service life in accordance to thickness of deck plating

	0,05	0,1	0,15	0,2	0,25
CAP1	22	16	14	13	12
CAP2	34	22	18	16	14
CAP3	46	28	22	19	17

The results from table 12 shows that after coating breakdown the ship will have a relatively short life time before steel renewal is necessary. E.g. With 0.2 mm/year corrosion rate, the ship will at 16 years, 6 years after coating breakdown need steel renewal to be within the CAP 2 rating. Since the steel thickness for the CAP grading are based on general corrosion, which is stricter than for localized corrosion, it may have longer service life if it is local corrosion.

Table 13 Assumed service life in accordance to utilization factor in deck plating

	0,05	0,1	0,15	0,2	0,25
CAP1	26	18	15	14	13
CAP2	32	21	17	15	14
CAP3	38	24	19	17	15

The results in table 13 for utilization factor are much the same as the result in table 11 for allowable thickness diminution.

6.1.2 Buckling capacity in longitudinal, stiffener under deck plating

In graph 3 it is shown how the thickness of the longitudinal is reduced with different corrosion rates. The initial thickness was 9 mm, and is assumed to be the same through the 10 year coating life. It is shown when it is within the different CAP classes, where CAP 3 is the same as class limit.

On the longitudinal corrosion can occur on both sides within the ballast tank, and therefor thickness diminution can be two times as fast as ex. deck-plating which only corrodes on one side within the ballast tank

Thickness diminution

CAP limits for thickness in longitudinal (general corrosion):

CAP 1 – 8.4 mm CAP 2 – 7.9 mm CAP 3 – 7.3 mm

Graph 3 Thickness diminution in longitudinal

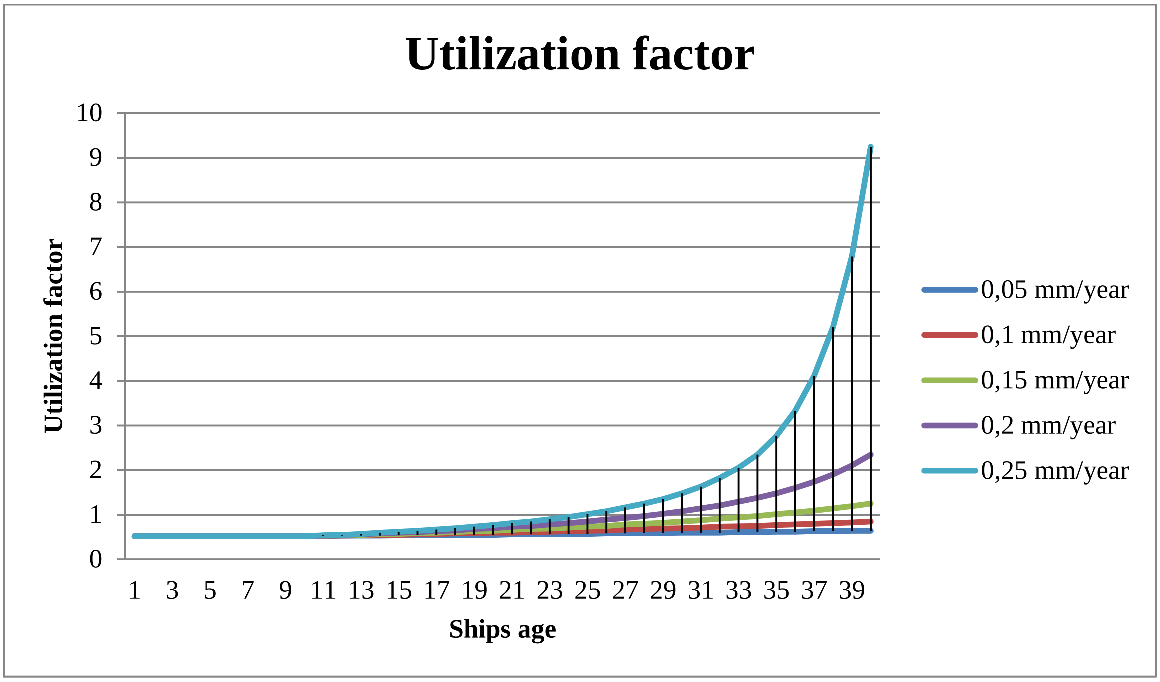
The steel thickness will reduce to under CAP 2 limit rapidly if the corrosion rate are 0.15 mm/year or above. (See graph 2)

Utilization factor

As the total global axial stresses $\Delta\sigma_0$ will increase, and the elastic σ_{el} and critical σ_c buckling stress will decrease, the utilization factor increases as shown in table 3 below.

CAP limits utilization factor in longitudinal:

CAP 1 =< 0.90 CAP 2 =<0.95 CAP 3 =< 1.0



Graph 4 Utilization factor in longitudinal

Graph 4 shows that the utilization factor for the stiffener is less steep than the utilization factor for the deck plating in graph 2.

How many years the ship will be able to be in accordance with regulations with the different corrosion rates on longitudinal inside wing ballast tank, with coating lasting 10 years. See table 14 and 15.

Table 14 Assumed service life in accordance to thickness of longitudinal

	0,05	0,1	0,15	0,2	0,25
CAP1	22	16	14	13	12
CAP2	32	21	17	15	14
CAP3	44	27	21	18	16

In the table it is only assumed corrosion from one side of the longitudinal, but the longitudinal can corrode from both sides. If the longitudinal corrodes 0.1 mm/year from both sides, the total will be 0.2 mm/year.

The results from table 14 shows that after coating breakdown the ship will have a relatively short life time before steel renewal is necessary. E.g. With 0.2 mm/year corrosion rate, the ship will at 15 years old, 5 years after coating breakdown need steel renewal to be within the CAP 2 rating. Since the steel thickness for the CAP grading are based on general corrosion, which is stricter than for localized corrosion, it may have longer service life if it is local corrosion. (Grooving- or pitting corrosion)

Table 15 Assumed service life in accordance to utilization factor in longitudinal

	0,05	**0,1**	**0,15**	**0,2**	**0,25**
CAP1	-	-	31	26	23
CAP2	-	-	33	27	24
CAP3	-	-	34	28	25

The results from table 15 shows longer service life than the results in table 14. But if the steel thickness are below allowable limit steel renewal will be necessary anyway.

For complete calculations see APPENDIX A

6.1.3 Discussion / conclusion buckling capacity

It is assumed that the ship only has wave loads from the bow or stern, so it is only uni-axial compressive stresses on the deck plating and lateral buckling on the longitudinal. The bi-axial stresses and shear stresses are believed to have a small effect on the buckling capacity. The corrosion rates are assumed to be uniformly distributed.

From the evaluation of the buckling capacity it can be seen that with a large corrosion rate (0.15 – 0.25 mm/year) it does not take many years before the limit for allowable thickness diminution are reached. The allowable thickness reductions used in the tables are for general corrosion, so if the corrosion are very localized (grooving- or pitting corrosion) the ship will keep its structural strength with deeper corrosion penetration.

6.2 Fatigue life

Due to corrosion problems in the upper part of the wing water ballast tanks, fatigue life will be calculated in this section of the ship. Two sections will be calculated, a stiffener support and a butt-weld in the deck-plating.

6.2.1 Fatigue life of a stiffener support

In this first fatigue calculation, a spot known to have problems with corrosion and cracks are selected. A stiffener support. See picture 93.

Picture 93 Stiffener support in top of wing ballast tank (Skagen 2014)

A selection of different stiffener support types are found in DNV CN30.7 among the selected one, shown in figure 60 below.

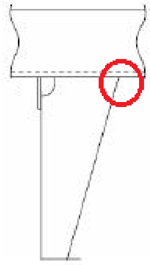


Figure 59 Stiffener support with calculated point (DNV 2014c)

In the calculation it is assumed 85% operation time, which is normal to assume, due to drydocking, loading/unloading, waiting at anchor etc. the operation time on ships usually is 45% in loaded condition and 40% in ballast condition.

The fatigue life calculations for ships (DNV CN 30.7) and for offshore steel structures (DNVGL RP-C203) are different. It is interesting to see the difference in calculated fatigue life with the two different calculation methods.

For ships (DNV CN 30.7) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment the miner sum is 2* D_{air}. See table 16.

For offshore steel structures (DNVGL RP-C203) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment, the miner sum is calculated by using a one-slope S-N curve. See table 17.

The fatigue life in table 16 and 17 may be shorter because corrosion will increase the stresses applied to the structure:

$$\sigma = \frac{F}{A}$$

Smaller cross-sectional area (A) gives larger stress (σ). Larger stress leads to shorter fatigue life. This is not taken into account during the fatigue life evaluation.

Table 16 Fatigue life – stiffener support (DNV CN30.7)

Years with effective protective coating	Total fatigue life in years
5	22,7
10	25,2
15	27,7
20	30,2
25	32,7
30	35,2
35	37,7
40	40,2

Table 16 shows that the fatigue life is 40 years if the coating are intact. If coating failure appears after 5 years, the total fatigue life is reduced to 22.7 years.

Table 17 Fatigue life - stiffener support (DNVGL RP-C203)

Years with effective protective coating	Total fatigue life in years
5	13,6
10	17,4
15	21,2
20	24,9
25	28,7
30	32,5
35	36,3
40	40,1

Table 17 shows that the fatigue life is 40 years if the coating are intact. If coating failure appears after 5 years, the total fatigue life is reduced to 13.6 years.

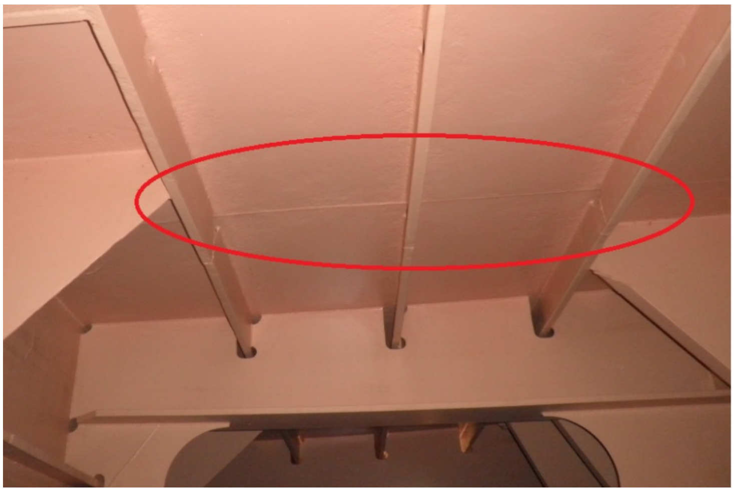
It is aslo interesting to notify that the fatigue life is a lot shorter using the method in DNVGL RP-C203 (table 17) than DNV CN 30.7 (table 16).

This states the importance with a good protective coating and the importance with proper maintenance.

For full calculation see APPENDIX A

6.2.2 Fatigue life of a butt-weld in the deck-plating

To have something to compare the fatigue life of the stiffener support with, the fatigue life of a butt-weld in the deck plating were calculated. See picture 94.



Picture 94 Butt-weld in deck-plating (Skagen 2014)

The only difference in the calculation of the stiffener support and the butt-weld is the K-factor found in DNV CN30.7. Butt-weld in deck plating are shown in figure 61.

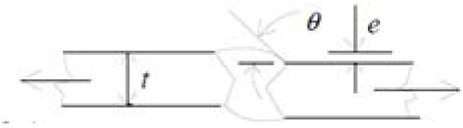


Figure 60 Butt-weld in deck-plating (DNV 2014c)

In the evaluation it is assumed 85% operation time, which is normal to assume, due to drydocking, loading/unloading, waiting at anchor etc. the operation time on ships usually is 45% in loaded condition and 40% in ballast condition.

The fatigue life calculations for ships (DNV CN 30.7) and for offshore steel structures (DNVGL RP-C203) are different. It is interesting to see the difference in calculated fatigue life with the two different calculation methods.

For ships (DNV CN 30.7) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment the miner sum is 2* D_{air}. See table 18.

For offshore steel structures (DNVGL RP-C203) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment, the miner sum is calculated by using a one-slope S-N curve. See table 19.

The fatigue life in table 16 and 17 may be shorter because corrosion will increase the stresses applied to the structure:

$$\sigma = \frac{F}{A}$$

Smaller cross-sectional area (A) gives larger stress (σ). Larger stress leads to shorter fatigue life. This is not taken into account during the fatigue life evaluation.

Table 18 Total fatigue life of a butt-weld in deck plating (DNV CN30.7)

Years with effective protective coating	Total fatigue life in years
5	76,0
10	78,5
15	81,0
20	83,5
25	86,0
30	88,5
35	91,0
40	93,5

Table 18 shows that the fatigue life is 93.5 years if the coating are intact. If coating failure appears after 5 years, the total fatigue life is reduced to 76 years.

Table 19 Total fatigue life of a butt-weld in deck plating (DNVGL RP-C203)

Years with effective protective coating	Total fatigue life in years
5	30,3
10	34,4
15	38,5
20	42,6
25	46,7
30	50,8
35	54,9
40	59,0

Table 19 shows that the fatigue life is 59 years if the coating are intact. If coating failure appears after 5 years, the total fatigue life is reduced to 30.3 years.

It is aslo interesting to notify that the fatigue life is a lot shorter using the method in DNVGL RP-C203 (table 17) than DNV CN 30.7 (table 16).

The fatigue life of a butt-weld in the deck plating is 2 – 3 times longer than the fatigue life of the stiffener support in the evaluation. Therefore it seems that a butt-weld is not as critical as the stiffener support. It is assumed that the deck plating’s are perfectly aligned to each other. Offset between the plates will lead to a shorter fatigue life.

For complete calculations see APPENDIX A

6.2.3 Discussion / conclusion fatigue life

The thickness reduction in the steel that is leading to larger stresses applied to structure is not taken into account. Therefore the fatigue life may be shorter than found in this fatigue life evaluation..

The fatigue life of a stiffener support is reduced severely in corrosive environment compared to in air or with cathodic protection. The fatigue life is calculated to be approximately 40 years if the coating is intact. If coating breakdown occurs after 5 years the fatigue life is reduced to 13.6 years if using the rules for offshore structures and 22.7 years if using the rules for ships.

The fatigue life for the butt-weld in the deck plating are calculated to be much higher than for the stiffener support. It is assumed that the deck plating’s are perfectly aligned to each other. Offset between the plates will lead to a shorter fatigue life.

This evaluation of fatigue life states the importance with good coating and good routines for coating maintenance. If the coating fails on places with high stress concentration such as welds, notches and sharp geometric transitions, fatigue cracking is likely to occur.

7 Discussion / conclusion

The few accidents caused by ageing on ships (tankers) indicate that the rules and regulations today are effective and secure that the sailing ships have sufficient structural strength. I.e. IMO adopting the rules and regulations and classification societies makes the shipping companies enforce them. With port state control, vetting and strict requirements from cargo owners etc. makes it difficult to operate a substandard LPG-tanker. Anyhow there will always be room for improvements, and new rule and regulations will continuously be developed.

One of the most important matters concerning the service life of a ship is the condition of sea water ballast tanks, which is a functional ageing issue. The findings in this thesis support the statement below, given by Germanischer Lloyd's Principal surveyor (GL 2014):

“Effective corrosion control in segregated water ballast spaces is probably the single most important feature, next to the integrity of the initial design, in determining the ship’s effective life span and structural reliability”

Ships in the Solvang fleet have/have had corrosion problems in the ballast tanks, especially in the oldest ships, where a lot of steel replacements were necessary in the top of the wing ballast tanks due to corrosion. In the newer ships corrosion spots seems to appear in ballast tanks short time after delivery, meaning that Solvang needs to increase the focus on the quality of coating at the new building stage. The better quality from start will cause less problems later. This is especially important if the company have a long term perspective on operating the ships.

The oldest ships (Semi ref.LPG/Ethylene) are the smallest and with only ~3000 m^3 ballast capacity, and the newer large gas carriers – LGC with ~15500 m^3 ballast capacity and the newest Very large gas carriers – VLGC have ~20000 m^3 ballast water capacity. This means a much larger surface to maintain inside the ballast tanks. Due to the complexity of maintenance and due to the large areas inside the tanks, it is very important to repair the corrosion spots properly as soon as possible to minimize the corrosion development.

The result from the review shows that in many cases the maintenance work carried out is not good enough. Due to many different reasons it seems very difficult to get long lasting coating repair. E.g. poor surface preparation, humidity, temperature, curing time, coating thickness etc.

One solution may be to do the coating maintenance during dry docking, but result from Clipper Skagen shows coating breakdown two years after total recoating at yard.

From the simplified evaluation of buckling capacity and fatigue life of some of the elements in the top of a wing ballast tank it can be seen that the service life of the ship will be severely reduced if not the ballast tanks are not properly maintained. From the results from the buckling- and fatigue evaluation it is likely to believe that the thickness reduction due to local coating breakdown will be the main cause for steel renewal.

8 Suggestion to improvements

As the corrosion rate in ballast tanks depends on the humidity, temperature, salt content etc. in the tank, things that would help keep the corrosion rate to a minimum would be to reduce these factors. The suggestions listed below are related to empty ballast tanks, when the corrosion rate is highest

- Humidity: The humidity when ballast tanks are empty can be reduced by supplying dry air from the inert gas plant.
- Temperature: The temperature in the double bottom tanks are more or less the same as the sea water outside, but the temperature of the air inside the wing ballast tanks are greatly affected by the heat from the sun absorbed by the deck and the side plating. Since all Solvang ships are painted with a relatively dark “brown red” color, the temperature in the wing ballast tanks are assumed to get relatively high. If the ships were painted with a lighter color, it would help reducing the corrosion rate in the wing ballast tanks. (It is reported much less corrosion problems on Clipper Harald which only sails in cold climate, than on the ships sailing world wide and much in hot climate.)
- Salt content: the salt content can be reduced by flushing/washing the tank with fresh water after every ballast voyage.

Of the suggestions above, changing color on deck will probably be the cheapest and easiest to implement

To reduce the corrosion in ballast tanks there are in addition to cathodic protection ballast water treatment systems – BWTS that reduces the oxygen content in the ballast water to a minimum before entering the ballast tank. The reaction to produce corrosion needs oxygen, and with reducing the oxygen content, the corrosion rate will be reduced. When the ballast tanks are filled with water the anodes will also protect uncoated steel. As experienced in this thesis it is the condition when the ballast tanks are empty that are the most corrosive. The BWTS will not make any difference to the oxygen content in the air supplying the tank when the ballast water is pumped out.

From the inspection reports it has been seen that coating failure in many cases not are repaired immediately, often because too large workload on the crew. One solution may be to increase the maintenance crew onboard to secure coating maintenance every time corrosion is found.

Proper training in coating maintenance of the crew is also very important. Coating maintenance is a very comprehensive job with many different parts that needs to be done correctly to get a satisfying result.

9 References

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APPENDIX A

Calculation example of Clipper Skagen (1989)

- Buckling capacity
- Fatigue

To show the importance with good protective coating in ballast tanks and proper maintenance, some simplified buckling and fatigue calculations are carried out. This calculation are done for Clipper Skagen, and therefor only applicable to this ship.

Clipper Skagen is a Semi ref. LPG/Ethylene Carrier delivered in 1989. Built by Meyer shipyard in Germany. The ship's LOA is 158 m and breadth is 21.3 m, with a cargo capacity of 15.098 cbm.

Picture 1 Clipper Skagen moored outside Gibraltar

Clipper Skagen data:

Length between perpendiculars (L_{pp})	148.8 m
Length overall (L)	158.0 m
Draught	9.762 m
Breadth extreme	21.33 m
Depth moulded	13.9 m
Deadweight	16137 ton

Clipper Skagen was originally coated in the ballast tanks, and the coating is assumed to have an effective coating life of 10 years.

Buckling capacity Clipper Skagen

In this calculation the buckling capacity in the deck plating and longitudinal in a wing ballast tank in the midship section is calculated with corrosion wastage.

The wing ballast tank is the same as the upper ballast tank. See figure 1. The cross section of the ballast tank is shown in figure 2, with drawing of the deck plating and longitudinal.

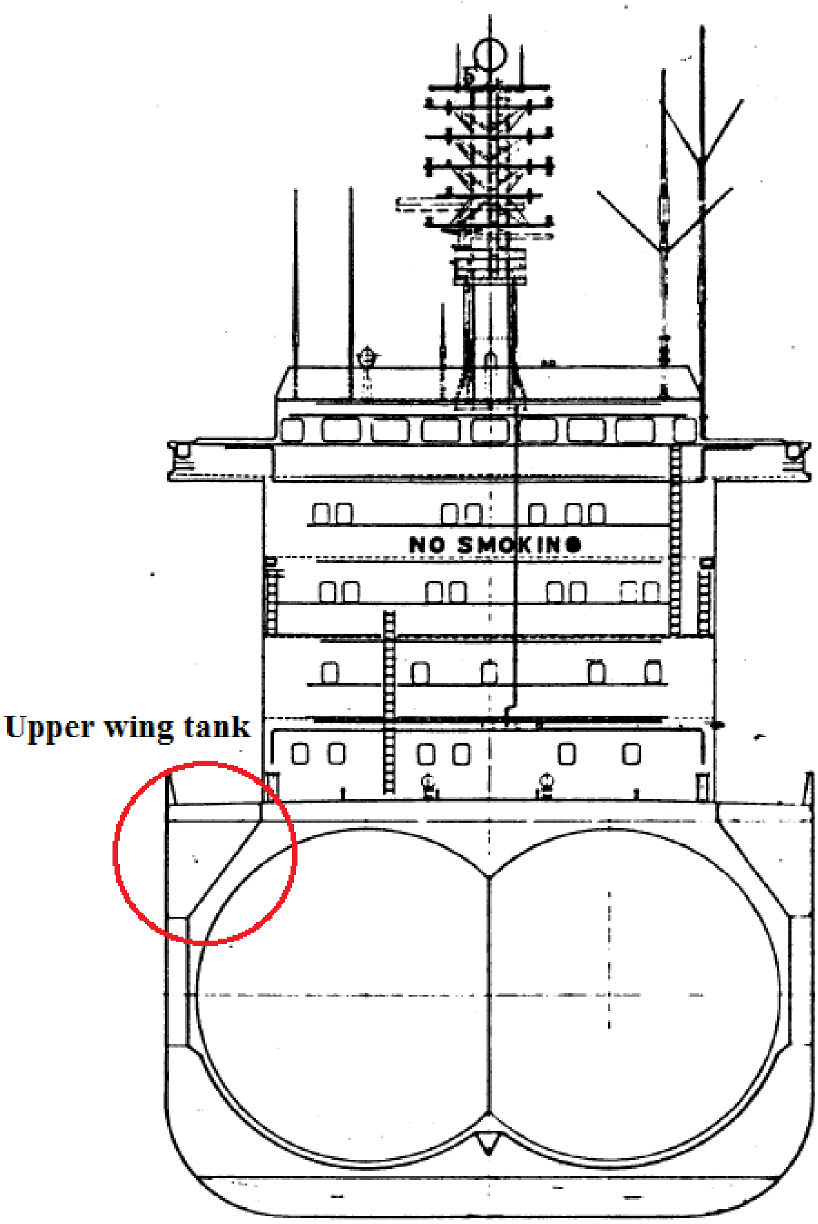


Figure 1 Clipper Skagen - Cross section

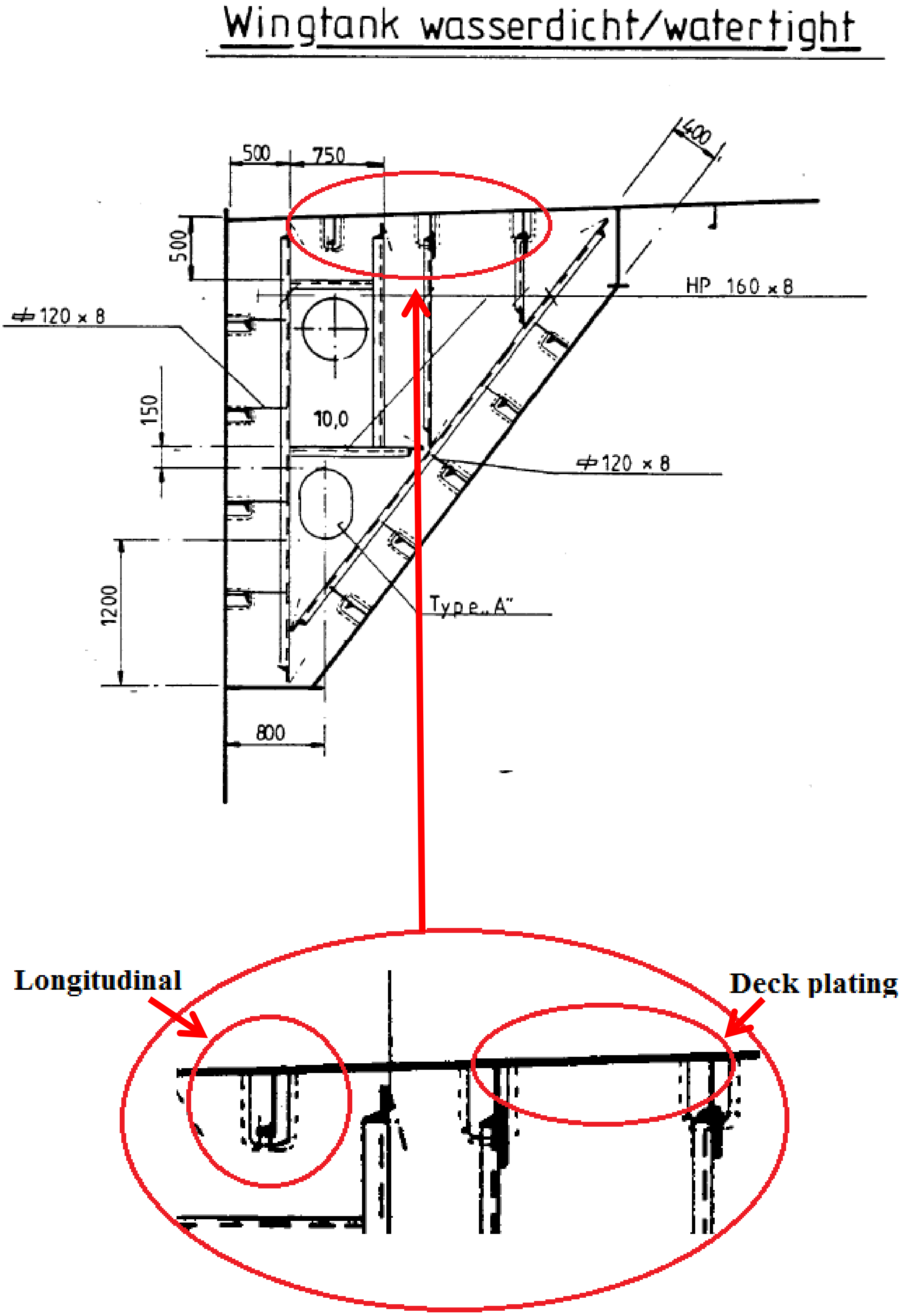


Figure 2 Cross section of a wing ballast tank

The corrosion protection is assumed to last 10 years, and it is useful to know how many years the ship will be able to sail without major repairs.

The first calculation is a section of the deck plating between two longitudinals, with dimensions as shown below

Length (l) = 3750 mm

Breadth (s) = 750 mm

Thickness (t) = 12 mm, including the corrosion addition

To simplify the calculation it is assumed that the ship only gets wave loads from bow or stern, making the plate field and longitudinals only getting tension from global vertically bending moment. The global bending moment is the sum of the stillwater induced stress σ_{stw} and wave induced stress σ_w

Transverse stresses and shear stresses are neglected.

Corrosion rates in ballast tanks are known to vary a lot, but in this calculation the corrosion rates are assumed to be 0.05, 0.1, 0.15, 0.2 and 0.25 mm/year. The yield strength of the steel is σ_f = 335N/mm^2.

Deck Plating

Elastic and critical buckling

The formulas for elastic and critical buckling are found in the DNV-GL "Rules for classification of ships, part 3 chapter 1, Hull Structural Design, Ships with length 100 metres and above, jan 2014". As shown below

The ideal elastic buckling stress is calculated by:

$$\sigma_{el} = 0.9kE\left(\frac{t - t_k}{1000s}\right)^2 \qquad (N/mm^2)$$

The critical buckling stress is calculated by:

$$\sigma_c = \sigma_{el} \qquad when \quad \sigma_{el} < \frac{\sigma_f}{2}$$

$$\sigma_c = \sigma_f\left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) \qquad when \quad \sigma_{el} > \frac{\sigma_f}{2}$$

For plating between longitudinal stiffeners, as in the ballast tanks the k-factor is calculated by:

$$k = \frac{8.4}{\psi + 1.1} \qquad for\ (0 \leq \psi \leq 1)$$

ψ is the ratio between the smaller and the larger compressive stress assuming linear variation, often assumed to be 1.0 in deck plating between longitudinals.

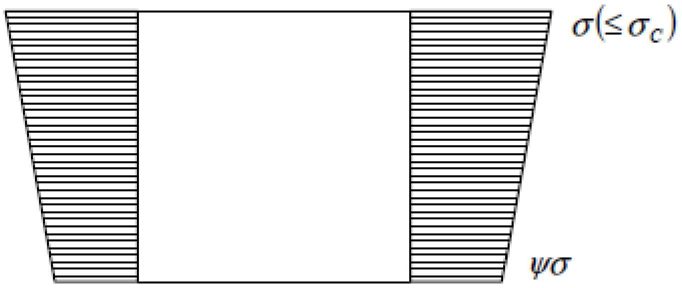


Figure 3 The ratio between the smaller and the larger compressive stress. (DNV Rules for classification of ships, 3.1)

Where:

t = thickness if plating in mm

t_k = corrosion addition in mm

s = shortest side of plate panel in m

E = modulus of elasticity of the material

σ_{el} = the ideal elastic compressive buckling stress in $\mathrm{N/mm^2}$

σ_f = minimum upper yield stress of material in $\mathrm{N/mm^2}$

σ_c = the critical compressive buckling stress in $\mathrm{N/mm^2}$

k = factor

ψ = factor

Data:

t = 12 mm

t_k = 0, will increase with corrosion rates of 0.05, 0.1, 0.15, 0.2 and 0.25 mm/year

s = 0.750 m

E = $2.06 \cdot 10^5\, N/mm^2$

σ_f = $335\, N/mm^2$

ψ = 1

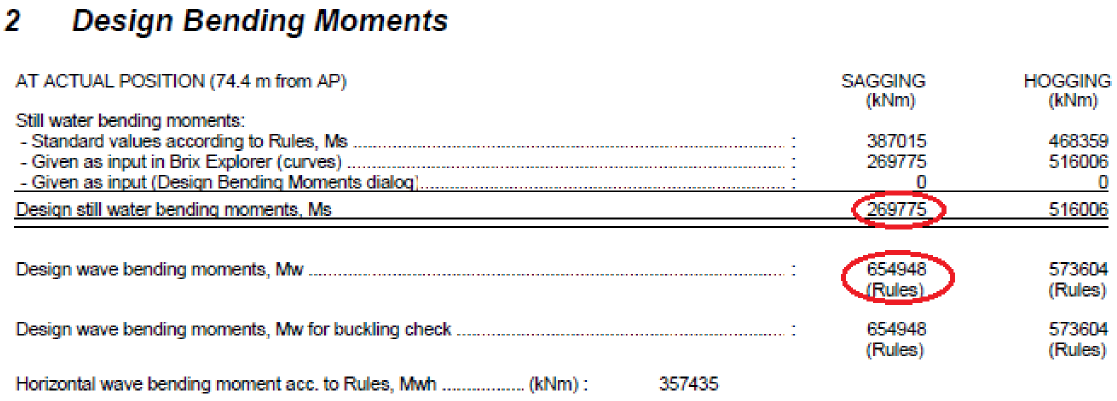
k $= \dfrac{8.4}{1 + 1.1} = 4$

Calculated buckling capacity.

$$\sigma_{el} = 0.9 \cdot 4 \cdot 2.06 \cdot 10^5\, N/mm^2 \cdot \left(\frac{12mm}{1000 \cdot 0.750m}\right)^2 = 189.85\, N/mm^2$$

$$\sigma_c = 335\, N/mm^2 \cdot \left(1 - \frac{335\, N/mm^2}{4 \cdot 189.85\, N/mm^2}\right) = 187.22\, N/mm^2$$

The global bending moment is the sum of the still water induced stress σ_{stw} and wave induced stress σ_w.



2 Design Bending Moments

AT ACTUAL POSITION (74.4 m from AP)	SAGGING (kNm)	HOGGING (kNm)
Still water bending moments:		
- Standard values according to Rules, Ms	387015	468359
- Given as input in Brix Explorer (curves)	269775	516006
- Given as input (Design Bending Moments dialog)	0	0
Design still water bending moments, Ms	269775	516006
Design wave bending moments, Mw	654948 (Rules)	573604 (Rules)
Design wave bending moments, Mw for buckling check	654948 (Rules)	573604 (Rules)

Horizontal wave bending moment acc. to Rules, Mwh .... (kNm) : 357435

Figure 4 Design bending moments

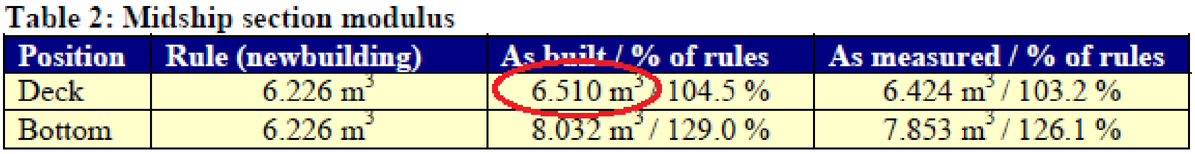


Table 2: Midship section modulus

Position	Rule (newbuilding)	As built / % of rules	As measured / % of rules
Deck	6.226 m^3	6.510 m^3 104.5 %	6.424 m^3 / 103.2 %
Bottom	6.226 m^3	8.032 m^3 / 129.0 %	7.853 m^3 / 126.1 %

Figure 5 Midship section modulus

Stillwater induced stress:

$$\sigma_{stw} = \frac{M_{Stillwater}}{W} = \frac{269775kNm}{6.510m^3} = 41.440\,N/mm^2$$

Wave induced stress:

$$\sigma_w = \frac{M_{Wave}}{W} = \frac{564948kNm}{6.510m^3} = 86.782\,N/mm^2$$

The sum of the Stillwater induced stress σ_{stw} and the wave induced stress σ_w will give the total global axial stresses:

$$\Delta\sigma_0 = \sigma_w + \sigma_{stw} = 86.782\,N/mm^2 + 41.440\,N/mm^2 = 128.222\,N/mm^2$$

The total global axial stress will increase with corrosion, due to less thickness of the steel that gives less cross-sectional area

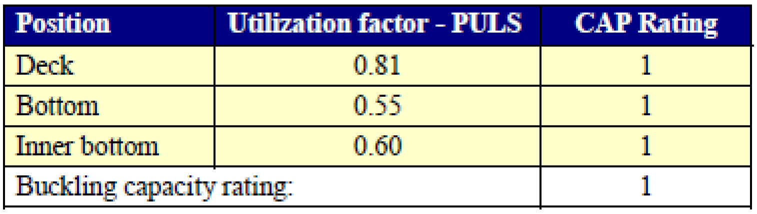
$$\sigma = \frac{F}{A}$$

Smaller cross-sectional area (A) gives larger stress (σ)

Utilization factor, η, for the first 10 years with protective coating intact.

$$\eta = \frac{\Delta\sigma_0}{\sigma_c} = \frac{128.222\,N/mm^2}{187.22\ \ N/mm^2} = 0.68$$

The utilization factor for the first 10 years is 0,68 in the deck plating as long as the coating is intact. The utilization factor of 0,68 is smaller than the utilization factor calculated by PULS by DNV in the CAP report of Clipper Skagen from 2012. See fig XX. This is probably because the utilization factor calculated by PULS are calculated by measured data, and are combined with all elements of the deck. The utilization factor of 0,68 are of a single deck plating between two longitudinals and with "as built" thickness data.



Position	Utilization factor - PULS	CAP Rating
Deck	0.81	1
Bottom	0.55	1
Inner bottom	0.60	1
Buckling capacity rating:		1

Figure 6 Utilization factor from Clipper Skagen CAP report 2012

After 10 years, when corrosion begins, the total global axial stresses $\Delta\sigma_0$ will increase, and the elastic σ_{el} and critical σ_c buckling stress will decrease.

Example:

After 15 years with 5 years with 0,2 mm/year corrosion, the thickness will be reduced from 12 mm to 11 mm, then:

The ideal elastic buckling stress is:

$$\sigma_{el} = 0.9 \cdot 4 \cdot 2.06 \cdot 10^5\,N/mm^2 \cdot \left(\frac{11mm}{1000 \cdot 0.750m}\right)^2 = 159.53\,N/mm^2$$

And the critical buckling stress is

$$\sigma_c = 335\,N/mm^2 \cdot \left(1 - \frac{335\,N/mm^2}{4 \cdot 189.85\,N/mm^2}\right) = 159.13\,N/mm^2$$

The total global axial stresses will increase:

$$\Delta\sigma_{15years} = \Delta\sigma_0 \cdot \frac{12}{11} = 128.222\,N/mm^2 \cdot \frac{12}{11} = 139.879\,N/mm^2$$

Which gives the utilization factor, η, for the 15th year, 5 years after coating failure

$$\eta = \frac{\Delta\sigma_0}{\sigma_c} = \frac{139.879\, N/mm^2}{159.13.\, N/mm^2} = 0.88$$

It will be critical for the ship when the utilization factor meets 1, as is the same as the class limit. CAP limits for utilization factor in deck plating are shown below.

- CAP 1 =< 0.90
- CAP 2 =<0.95
- CAP 3 =< 1.0

In table 1 and 2 it is assumed that the coating life is 10 years. Thereafter the general corrosion rate is assumed to be 0.1, 0.15, 0.2 and 0.25 mm/year.

Table 1 Reduction of thickness of deck plating with different corrosion rates

Year/Corr. rate	0,05	0,1	0,15	0,2	0,25
1	12	12	12	12	12
2	12	12	12	12	12
3	12	12	12	12	12
4	12	12	12	12	12
5	12	12	12	12	12
6	12	12	12	12	12
7	12	12	12	12	12
8	12	12	12	12	12
9	12	12	12	12	12
10	12	12	12	12	12
11	11,95	11,9	11,85	11,8	11,75
12	11,9	11,8	11,7	11,6	11,5
13	11,85	11,7	11,55	11,4	11,25
14	11,8	11,6	11,4	11,2	11
15	11,75	11,5	11,25	11	10,75
16	11,7	11,4	11,1	10,8	10,5
17	11,65	11,3	10,95	10,6	10,25
18	11,6	11,2	10,8	10,4	10
19	11,55	11,1	10,65	10,2	9,75
20	11,5	11	10,5	10	9,5
21	11,45	10,9	10,35	9,8	9,25
22	11,4	10,8	10,2	9,6	9
23	11,35	10,7	10,05	9,4	8,75
24	11,3	10,6	9,9	9,2	8,5
25	11,25	10,5	9,75	9	8,25
26	11,2	10,4	9,6	8,8	8
27	11,15	10,3	9,45	8,6	7,75
28	11,1	10,2	9,3	8,4	7,5
29	11,05	10,1	9,15	8,2	7,25
30	11	10	9	8	7
31	10,95	9,9	8,85	7,8	6,75
32	10,9	9,8	8,7	7,6	6,5
33	10,85	9,7	8,55	7,4	6,25
34	10,8	9,6	8,4	7,2	6
35	10,75	9,5	8,25	7	5,75
36	10,7	9,4	8,1	6,8	5,5
37	10,65	9,3	7,95	6,6	5,25
38	10,6	9,2	7,8	6,4	5
39	10,55	9,1	7,65	6,2	4,75
40	10,5	9	7,5	6	4,5

CAP 1 – 11.4 mm

CAP 2 – 10.8 mm

CAP 3 – 10.2 mm

How many years the ship will be able to be in accordance with regulations regarding thickness of deck plating, with the different corrosion rates.

Table 2 How many years the steel thickness will be within the different CAP ratings

CAP-rating /corr rate	0,05	0,1	0,15	0,2	0,25
CAP1	22	16	14	13	12
CAP2	34	22	18	16	14
CAP3	46	28	22	19	17

Graph 1 Reduction of thickness of deck plating with different corrosion rates

As the total global axial stresses $\Delta\sigma_0$ will increase, and the elastic σ_{el} and critical σ_c buckling stress will decrease, the utilization factor increases as shown in table 3 below.

All the necessary formulas and values are put in a excel sheet to calculate the utilization factor.

Table 3 Utilization factor for deck plating with different corrosion rates

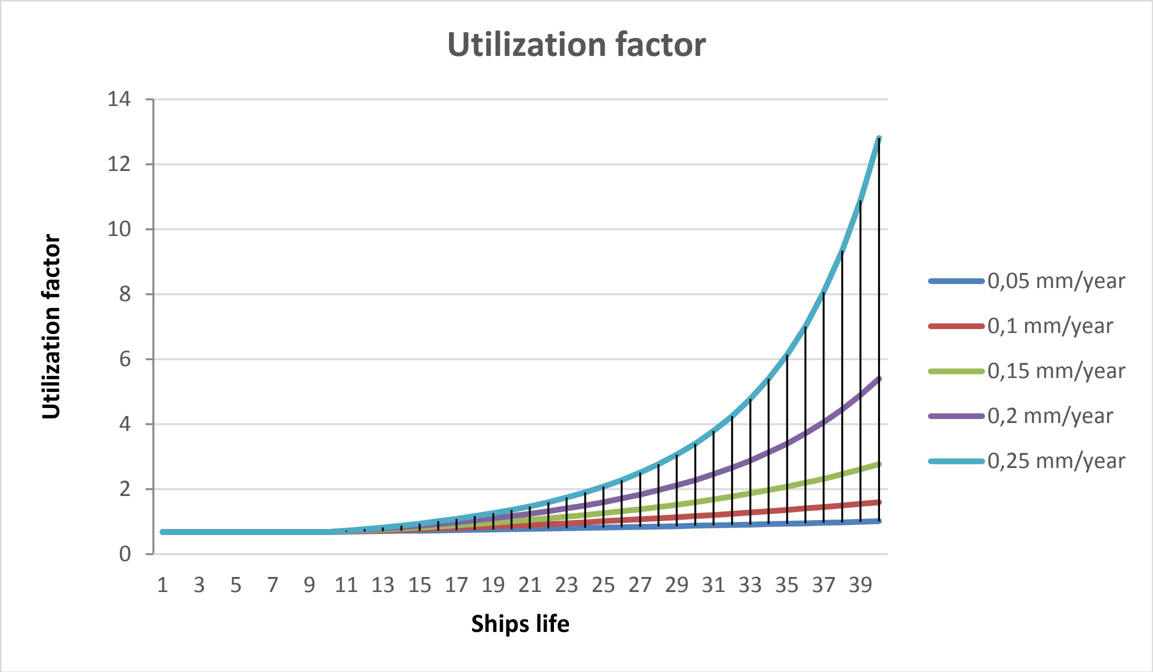
Year/Corr. rate	0,05	0,1	0,15	0,2	0,25
1	0,68	0,68	0,68	0,68	0,68
2	0,68	0,68	0,68	0,68	0,68
3	0,68	0,68	0,68	0,68	0,68
4	0,68	0,68	0,68	0,68	0,68
5	0,68	0,68	0,68	0,68	0,68
6	0,68	0,68	0,68	0,68	0,68
7	0,68	0,68	0,68	0,68	0,68
8	0,68	0,68	0,68	0,68	0,68
9	0,68	0,68	0,68	0,68	0,68
10	0,68	0,68	0,68	0,68	0,68
11	0,69	0,70	0,71	0,72	0,72
12	0,70	0,72	0,73	0,75	0,77
13	0,71	0,73	0,76	0,79	0,82
14	0,72	0,75	0,79	0,83	0,88
15	0,72	0,77	0,82	0,88	0,94
16	0,73	0,79	0,85	0,93	1,01
17	0,74	0,81	0,89	0,98	1,08
18	0,75	0,83	0,93	1,04	1,17
19	0,76	0,85	0,97	1,10	1,26
20	0,77	0,88	1,01	1,17	1,36
21	0,78	0,90	1,05	1,24	1,47
22	0,79	0,93	1,10	1,32	1,60
23	0,80	0,95	1,15	1,41	1,74
24	0,81	0,98	1,20	1,50	1,90
25	0,82	1,01	1,26	1,60	2,08
26	0,83	1,04	1,32	1,71	2,28
27	0,84	1,07	1,38	1,83	2,51
28	0,85	1,10	1,45	1,97	2,77
29	0,86	1,13	1,52	2,12	3,06
30	0,88	1,17	1,60	2,28	3,40
31	0,89	1,20	1,68	2,46	3,79
32	0,90	1,24	1,77	2,66	4,25
33	0,91	1,28	1,87	2,88	4,78
34	0,93	1,32	1,97	3,13	5,40
35	0,94	1,36	2,08	3,40	6,14
36	0,95	1,41	2,20	3,71	7,01
37	0,97	1,45	2,32	4,06	8,07
38	0,98	1,50	2,46	4,45	9,34
39	0,99	1,55	2,61	4,90	10,89
40	1,01	1,60	2,77	5,40	12,81

CAP 1 =< 0.90 CAP 2 =<0.95 CAP 3 =< 1.0

How many years the ship will be able to be in accordance with regulations regarding utilization factor of deck plating, with the different corrosion rates.

Table 4 How many years the utilization factor will be within the different CAP ratings

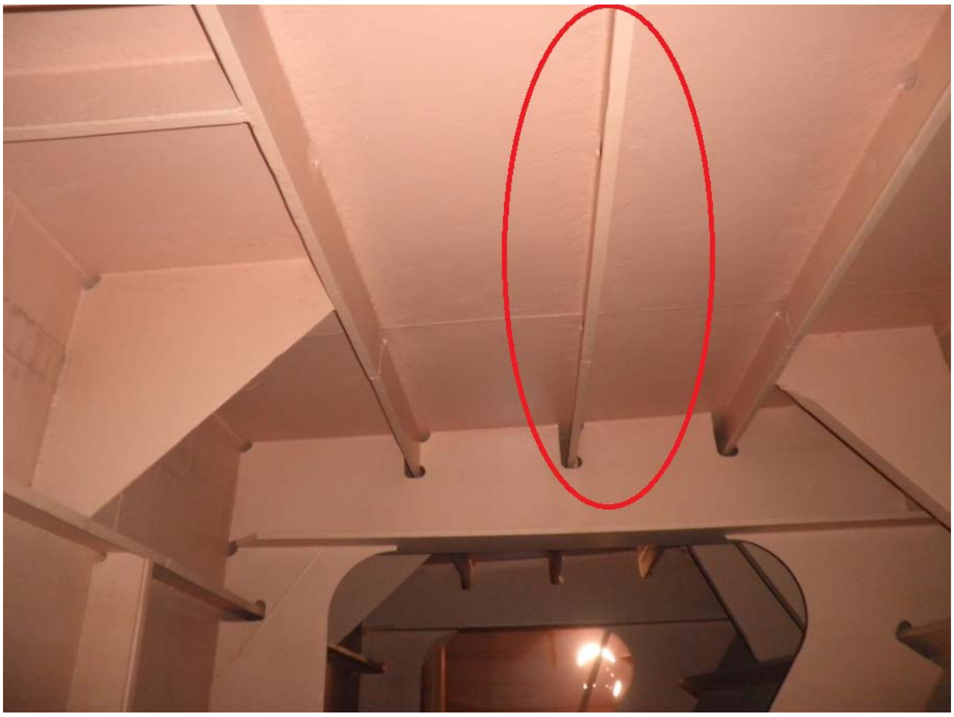
CAP-rating /corr rate	0,05	0,1	0,15	0,2	0,25
CAP1	32	21	17	15	14
CAP2	36	23	18	16	15
CAP3	39	24	19	17	16



Graph 2 Utilization factor in deck plating with different corrosion rates

Buckling capacity Longitudinal

Stiffener under deck plating



Picture 2 Longitudinal under deck plating

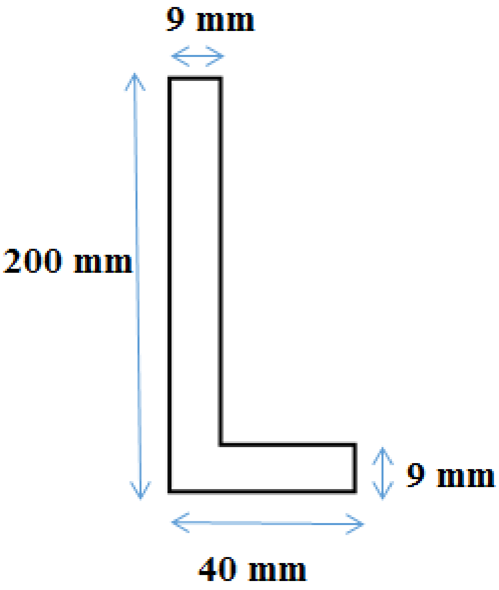


Figure 7 Cross section of longitudinal

The formulas for elastic and critical buckling are found in the DNV-GL "Rules for classification of ships, part 3 chapter 1, Hull Structural Design, Ships with length 100 metres and above, jan 2014". As shown below

The ideal elastic buckling stress is calculated by:

$$\sigma_{el} = 0.001E\frac{I_A}{Al^2} \qquad (N/mm^2)$$

The critical buckling stress is calculated by:

$$\sigma_c = \sigma_{el} \qquad when \qquad \sigma_{el} < \frac{\sigma_f}{2}$$

$$\sigma_c = \sigma_f\left(1 - \frac{\sigma_f}{4\sigma_{el}}\right) \qquad when \qquad \sigma_{el} > \frac{\sigma_f}{2}$$

Where:

E = modulus of elasticity of the material

I_A = moment of inertia in cm^4 about the axis perpendicular to the expected direction of buckling

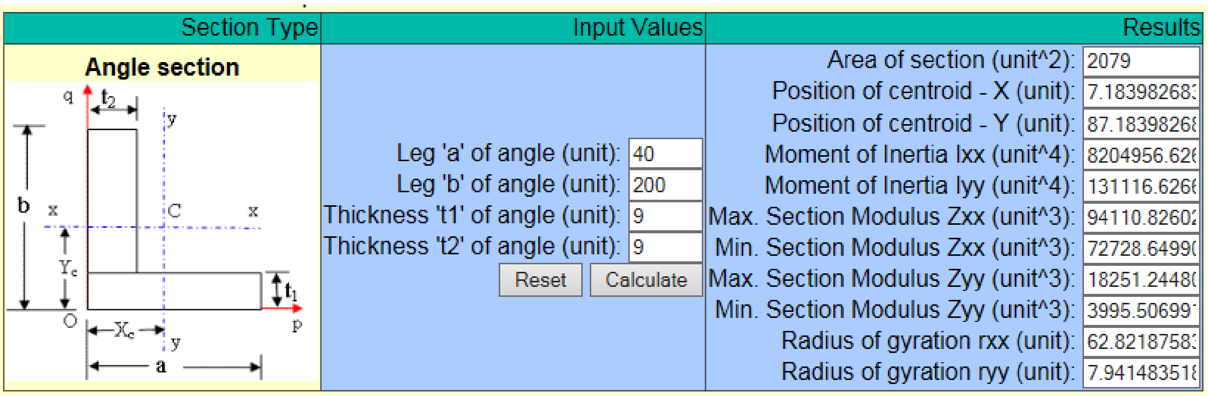
A = cross-section area in cm^2

l = Length of member in m

σ_{el} = the ideal elastic compressive buckling stress in N/mm^2

σ_f = minimum upper yield stress of material in N/mm^2

σ_c = the critical compressive buckling stress in N/mm^2



Leg 'a' of angle (unit): 40
Leg 'b' of angle (unit): 200
Thickness 't1' of angle (unit): 9
Thickness 't2' of angle (unit): 9

Area of section (unit^2): 2079
Position of centroid - X (unit): 7.18398268
Position of centroid - Y (unit): 87.1839826
Moment of Inertia Ixx (unit^4): 8204956.62
Moment of Inertia Iyy (unit^4): 131116.626
Max. Section Modulus Zxx (unit^3): 94110.8260
Min. Section Modulus Zxx (unit^3): 72728.6499
Max. Section Modulus Zyy (unit^3): 18251.2448
Min. Section Modulus Zyy (unit^3): 3995.50699
Radius of gyration rxx (unit): 62.8218758
Radius of gyration ryy (unit): 7.94148351

Figure 8 Calculation of moment of inertia (http://civilengineer.webinfolist.com/str/micalcl.php)

$I_{Axx} \quad = 8204956\,mm^4 = 820.50\,cm^4$

$A \quad = 20.79\,cm^2$

$l \quad = 3.75\,m$

$E \quad = 2.06 \cdot 10^5\,N/mm^2$

$$\sigma_{el} = 0.001E\,\frac{I_A}{Al^2} = 0.001 \cdot 2.06 \cdot 10^5\,N/mm^2 \cdot \frac{820.50cm^4}{20.79\,cm^2 \cdot (3.75\,m)^2} = 578.13\,N/mm^2$$

Examples of how the ideal elastic buckling stress will be reduced with reduced thickness of the longitudinal:

Original 9 mm thickness

$\sigma_{el} = 578.13\,N/mm^2$

CAP 1 min 8.4 mm

$$\sigma_{el} = \frac{8.4}{9}578.13\,N/mm^2 = 539.59\,N/mm^2$$

CAP 2 min 7.9 mm

$$\sigma_{el} = \frac{7.9}{9}578.13\,N/mm^2 = 507.47\,N/mm^2$$

CAP 3 Min 7.3 mm

$$\sigma_{el} = \frac{7.3}{9}578.13\,N/mm^2 = 468.93\,N/mm^2$$

Table 5 Reduction in thickness of longitudinal with different corrosion rates

Year/Corr. rate	0,05	0,1	0,15	0,2	0,25
1	9	9	9	9	9
2	9	9	9	9	9
3	9	9	9	9	9
4	9	9	9	9	9
5	9	9	9	9	9
6	9	9	9	9	9
7	9	9	9	9	9
8	9	9	9	9	9
9	9	9	9	9	9
10	9	9	9	9	9
11	8,95	8,9	8,85	8,8	8,75
12	8,9	8,8	8,7	8,6	8,5
13	8,85	8,7	8,55	8,4	8,25
14	8,8	8,6	8,4	8,2	8
15	8,75	8,5	8,25	8	7,75
16	8,7	8,4	8,1	7,8	7,5
17	8,65	8,3	7,95	7,6	7,25
18	8,6	8,2	7,8	7,4	7
19	8,55	8,1	7,65	7,2	6,75
20	8,5	8	7,5	7	6,5
21	8,45	7,9	7,35	6,8	6,25
22	8,4	7,8	7,2	6,6	6
23	8,35	7,7	7,05	6,4	5,75
24	8,3	7,6	6,9	6,2	5,5
25	8,25	7,5	6,75	6	5,25
26	8,2	7,4	6,6	5,8	5
27	8,15	7,3	6,45	5,6	4,75
28	8,1	7,2	6,3	5,4	4,5
29	8,05	7,1	6,15	5,2	4,25
30	8	7	6	5	4
31	7,95	6,9	5,85	4,8	3,75
32	7,9	6,8	5,7	4,6	3,5
33	7,85	6,7	5,55	4,4	3,25
34	7,8	6,6	5,4	4,2	3
35	7,75	6,5	5,25	4	2,75
36	7,7	6,4	5,1	3,8	2,5
37	7,65	6,3	4,95	3,6	2,25
38	7,6	6,2	4,8	3,4	2
39	7,55	6,1	4,65	3,2	1,75
40	7,5	6	4,5	3	1,5

CAP 1 – 8.4 mm CAP 2 – 7.9 mm CAP 3 – 7.3 mm

Graph 3 Reduction in thickness of longitudinal with different corrosion rates

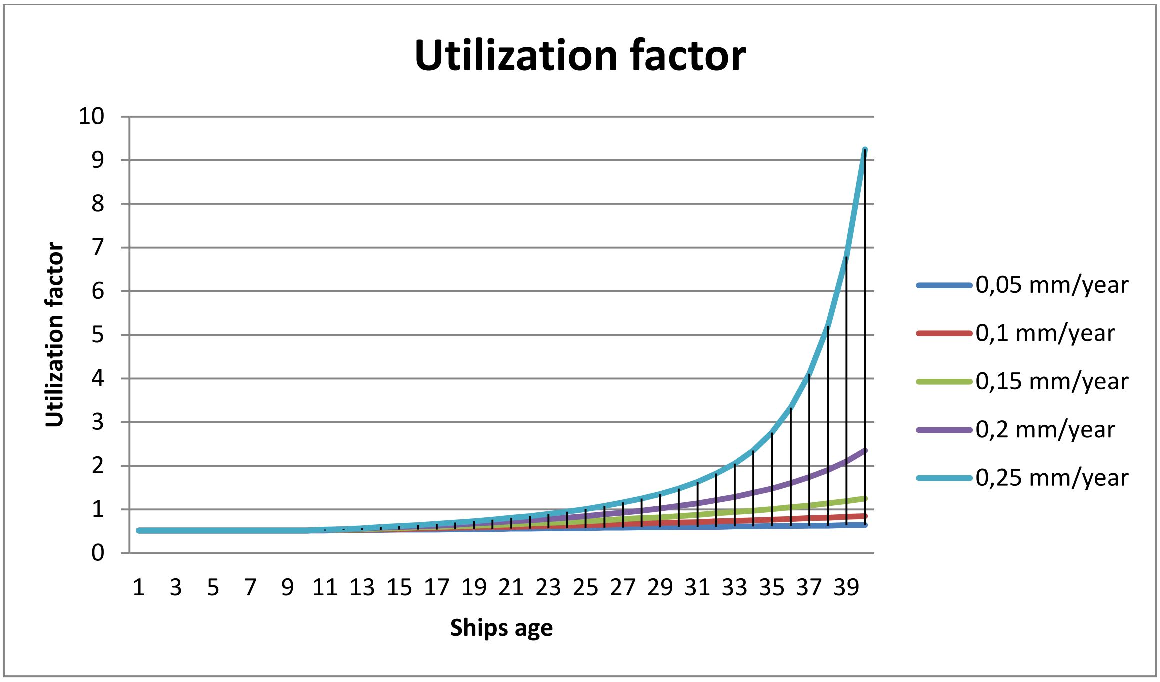
As the total global axial stresses $\Delta\sigma_0$ will increase, and the elastic σ_{el} and critical σ_c buckling stress will decrease, the utilization factor increases as shown in table 6 below.

All the necessary formulas and values are put in a excel sheet to calculate the utilization factor.

Table 6 Utilization factor for longitudinal with different corrosion rates

Year/Corr. rate	0,05	0,1	0,15	0,2	0,25
1	0,52	0,52	0,52	0,52	0,52
2	0,52	0,52	0,52	0,52	0,52
3	0,52	0,52	0,52	0,52	0,52
4	0,52	0,52	0,52	0,52	0,52
5	0,52	0,52	0,52	0,52	0,52
6	0,52	0,52	0,52	0,52	0,52
7	0,52	0,52	0,52	0,52	0,52
8	0,52	0,52	0,52	0,52	0,52
9	0,52	0,52	0,52	0,52	0,52
10	0,52	0,52	0,52	0,52	0,52
11	0,52	0,53	0,53	0,53	0,54
12	0,53	0,53	0,54	0,55	0,55
13	0,53	0,54	0,55	0,56	0,57
14	0,53	0,55	0,56	0,58	0,60
15	0,54	0,55	0,57	0,60	0,62
16	0,54	0,56	0,59	0,61	0,64
17	0,54	0,57	0,60	0,63	0,67
18	0,55	0,58	0,61	0,65	0,70
19	0,55	0,59	0,63	0,68	0,73
20	0,55	0,60	0,64	0,70	0,77
21	0,56	0,60	0,66	0,73	0,81
22	0,56	0,61	0,68	0,75	0,85
23	0,57	0,62	0,69	0,78	0,90
24	0,57	0,63	0,71	0,81	0,95
25	0,57	0,64	0,73	0,85	1,01
26	0,58	0,65	0,75	0,89	1,08
27	0,58	0,67	0,78	0,93	1,16
28	0,59	0,68	0,80	0,97	1,25
29	0,59	0,69	0,82	1,02	1,35
30	0,60	0,70	0,85	1,08	1,48
31	0,60	0,71	0,88	1,14	1,63
32	0,60	0,73	0,91	1,21	1,82
33	0,61	0,74	0,94	1,29	2,05
34	0,61	0,75	0,97	1,38	2,35
35	0,62	0,77	1,01	1,48	2,76
36	0,62	0,78	1,05	1,60	3,33
37	0,63	0,80	1,09	1,74	4,11
38	0,63	0,81	1,14	1,90	5,20
39	0,64	0,83	1,19	2,10	6,79
40	0,64	0,85	1,25	2,35	9,25

CAP 1 =< 0.90 CAP 2 =<0.95 CAP 3 =< 1.0



Graph 4 Utilization factor for longitudinal with different corrosion rates

Fatigue

Due to corrosion problems in the upper part of the wing water ballast tanks, fatigue life will be calculated in this section of the ship. Two sections will be calculated, a stiffener support and a butt-weld in the deck plating.

In this first fatigue calculation, a spot known to have problems with corrosion and cracks are selected. A stiffener support. See picture 3.

Picture 3 Stiffener support in top of a wing ballast tank

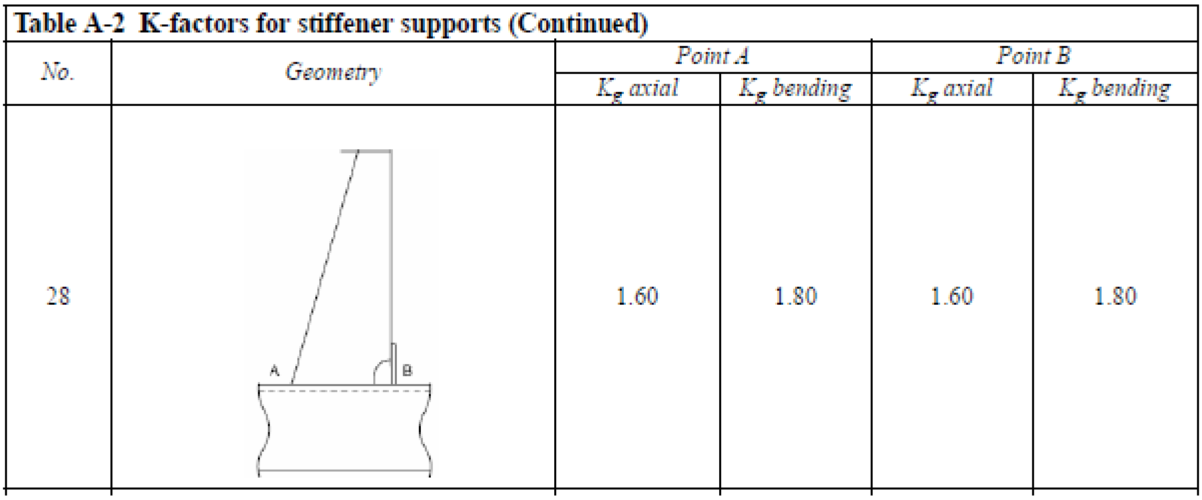


Table A-2 K-factors for stiffener supports (Continued)

No.	Geometry	Point A		Point B	
		K_g axial	K_g bending	K_g axial	K_g bending
28		1.60	1.80	1.60	1.80

Figure 9 K-factor/SCF for stiffener support. DNV-GL CN30.7

To calculate the fatigue life the expected life, normally 20 years are divided by the miner sum, D.

Fatigue life:

$$T = \frac{C}{D}$$

Where:

T = Fatigue life

C = Service life (20 years)

D = Miner sum

The miner sum, D can be calculated using a one slope S-N curve or a two slope S-N curve.

One slope S-N curve:

$$D = \frac{v_0 \cdot T_d}{\bar{a}} \cdot q^m \cdot \Gamma\left(1 + \frac{m}{h}\right) \leq \eta$$

Where:

T_d = design life of ship in seconds

v_0 = long-term average response zero-crossing frequency

$\bar{a}$ = parameter from SN curve, see figure 11

m = parameter from SN curve, see figure 11

q = Weibull stress range scale distribution parameter for load condition

h = Weibull stress range shape distribution parameter for load condition

$\Gamma\left(1 + \frac{m}{h}\right)$ = gamma function, from figure 10.

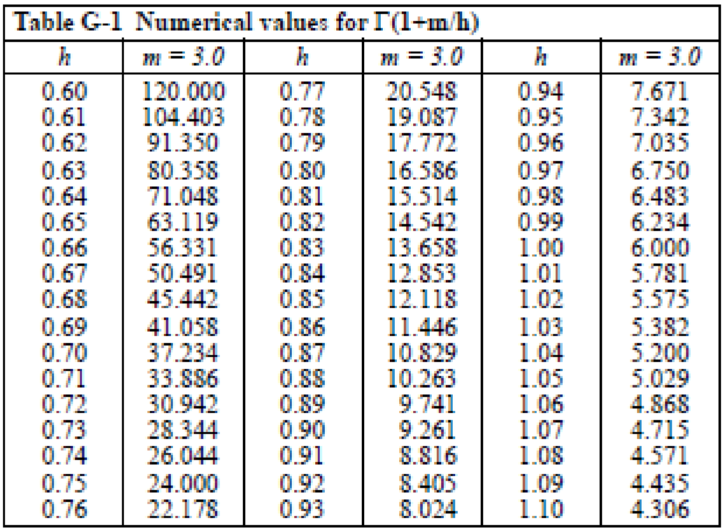


Table G-1 Numerical values for $\Gamma(1+m/h)$

h	$m = 3.0$	h	$m = 3.0$	h	$m = 3.0$
0.60	120.000	0.77	20.548	0.94	7.671
0.61	104.403	0.78	19.087	0.95	7.342
0.62	91.350	0.79	17.772	0.96	7.035
0.63	80.358	0.80	16.586	0.97	6.750
0.64	71.048	0.81	15.514	0.98	6.483
0.65	63.119	0.82	14.542	0.99	6.234
0.66	56.331	0.83	13.658	1.00	6.000
0.67	50.491	0.84	12.853	1.01	5.781
0.68	45.442	0.85	12.118	1.02	5.575
0.69	41.058	0.86	11.446	1.03	5.382
0.70	37.234	0.87	10.829	1.04	5.200
0.71	33.886	0.88	10.263	1.05	5.029
0.72	30.942	0.89	9.741	1.06	4.868
0.73	28.344	0.90	9.261	1.07	4.715
0.74	26.044	0.91	8.816	1.08	4.571
0.75	24.000	0.92	8.405	1.09	4.435
0.76	22.178	0.93	8.024	1.10	4.306

Figure 10 Gamma function values. DNV-GL CN30.7

Two slope S-N curve:

$$D = v_0 \cdot T_d \left[\frac{q^{m_1}}{\bar{a}_1} \Gamma \left(1 + \frac{m_1}{h}; \left(\frac{s_1}{q} \right)^h \right) + \frac{q^{m_2}}{\bar{a}_2} \gamma \left(1 + + \frac{m_2}{h}; \left(\frac{s_1}{q} \right)^h \right) \right] \leq \eta$$

Where:

s_1 = Stress range for which change of slope of S-N curve occur

$\bar{a}_1, m_1$ = S-N fatigue parameters for N < 10^7 cycles

$\bar{a}_2, m_2$ = S-N fatigue parameters for N > 10^7 cycles

$\Gamma(\,)$ = Complementary incomplete gamma function, to be found in standard tables

$\gamma(\,)$ = Incomplete gamma function, to be found in standard tables

Values below are the same for both one- and two slope S-N curves

The parameters $\bar{a}$ and m from the SN curve are found in figure 11 below.

$$\bar{a} = 10^{log\bar{a}}$$

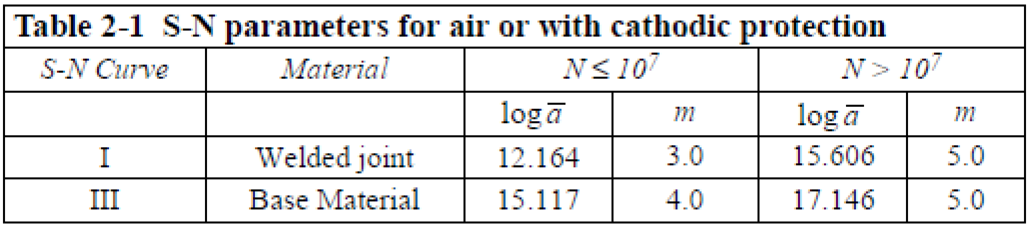


Table 2-1 S-N parameters for air or with cathodic protection

S-N Curve	Material	$N \leq 10^7$		$N > 10^7$	
		$\log \bar{a}$	m	$\log \bar{a}$	m
I	Welded joint	12.164	3.0	15.606	5.0
III	Base Material	15.117	4.0	17.146	5.0

Figure 11 S-N parameters for air or with cathodic protection. DNV-GL CN30.7

For unprotected joints in corrosive environment the the S-N curve in the table XX shall be reduced by a factor of 2:

- In Air; Miner sum D_{Air} = D
- In corrosive environment; Miner sum D_{Corr} = D*2

Air or cathodic protection, data:

log ā	= 12.164	when	m = 3
log ā	= 15.606	when	m = 5
L_{pp}	= 148.8 m (Lpp)		
T_d	= 20 years = $6.31 \cdot 10^8$		
h = h_0	for deck longitudinal		

$$h = h_0 = 2.21 - 0.54 \cdot \log_{10}(L) = 2.21 - 0.54 \cdot \log_{10}(148.8) = 1.037$$

$$v_0 = \frac{1}{4 \cdot \log_{10}(L)} = \frac{1}{4 \cdot \log_{10}(148.8)} = 0.1151$$

The combined local and global stress range are as follows:

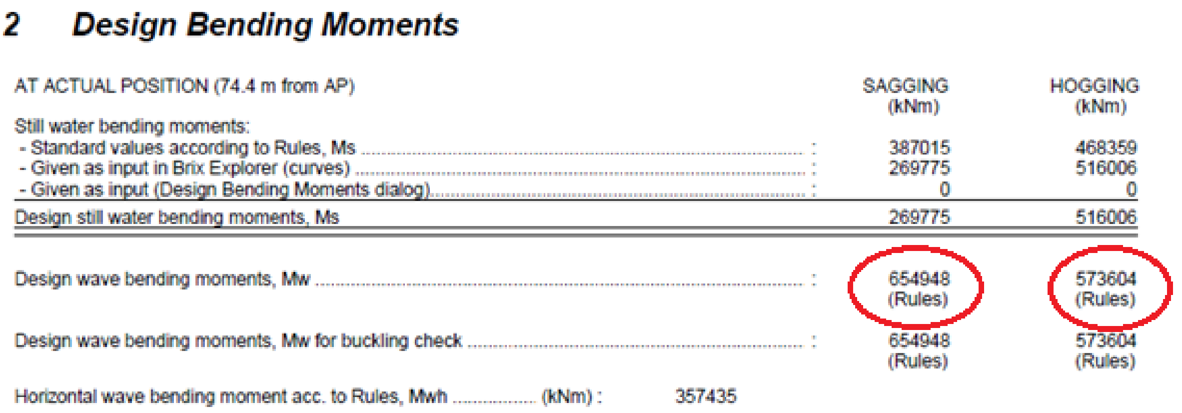
$$\Delta\sigma_0 = f_m \cdot f_{HT} \cdot f_e \cdot \Delta\sigma$$

f_m = Reduction factor
= 1.0 in this calculation

f_{HT} = Reduction factor
= 1.0 for welded joints

f_e = Reduction factor
= 0.8 for world wide operation.

$\Delta\sigma$ = Stress range (The stresses are not adjusted for corrosion reduction of plate thickness)



```
2     Design Bending Moments

AT ACTUAL POSITION (74.4 m from AP)                                      SAGGING      HOGGING
                                                                          (kNm)        (kNm)
Still water bending moments:
 - Standard values according to Rules, Ms ...........................:    387015       468359
 - Given as input in Brix Explorer (curves) .........................:    269775       516006
 - Given as input (Design Bending Moments dialog)....................:         0            0
Design still water bending moments, Ms                                    269775       516006

Design wave bending moments, Mw .....................................:    654948       573604
                                                                          (Rules)      (Rules)

Design wave bending moments, Mw for buckling check ..................:    654948       573604
                                                                          (Rules)      (Rules)

Horizontal wave bending moment acc. to Rules, Mwh ............... (kNm) :    357435
```

Figure 12 Design wave bending moments, sagging and hogging

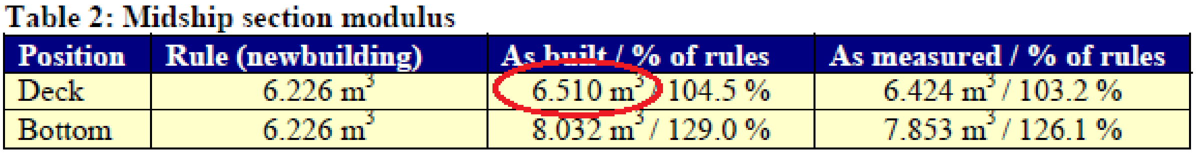


Table 2: Midship section modulus

Position	Rule (newbuilding)	As built / % of rules	As measured / % of rules
Deck	6.226 m^3	6.510 m^3 / 104.5 %	6.424 m^3 / 103.2 %
Bottom	6.226 m^3	8.032 m^3 / 129.0 %	7.853 m^3 / 126.1 %

Figure 13 Midship section modulus, W

$$\Delta\sigma = \sigma_{Wave,sagg} + \sigma_{Wave,hogg}$$

$$\sigma_{Wave,sagg} = \frac{M_{Wave,sagg}}{W_{Deck}} = \frac{654948\ kNm}{6.510\ m^3} = 100606\ \ kN/m^2 = 100.606\ MPa$$

$$\sigma_{Wave,hogg} = \frac{M_{Wave,hogg}}{W_{Deck}} = \frac{573604\ kNm}{6.510\ m^3} = 88111\ \ kN/m^2 = 88.111\ MPa$$

$$\Delta\sigma = \sigma_{Wave,sagg} + \sigma_{Wave,hogg} = 100.606\ MPa + 88.111\ MPa = 188.717\ MPa$$

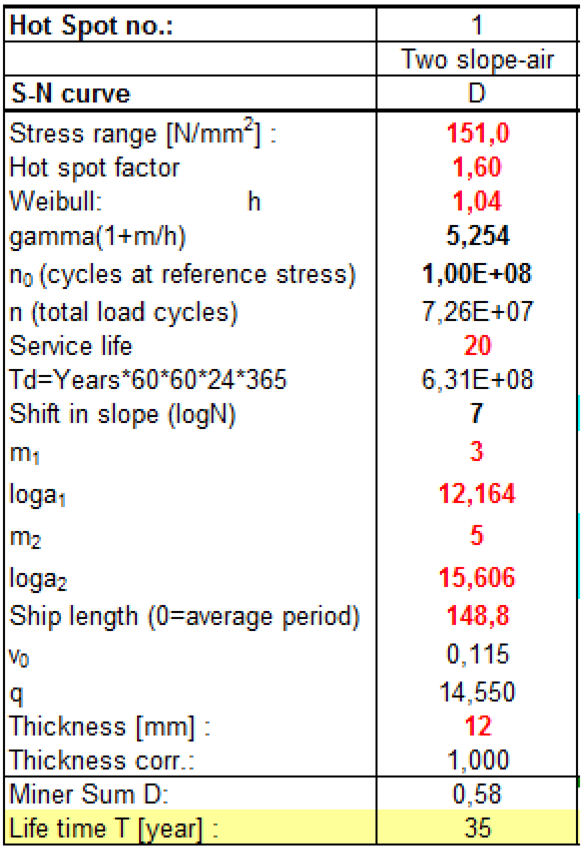
$$\Delta\sigma_0 = f_m \cdot f_{HT} \cdot f_e \cdot \Delta\sigma = 1 \cdot 1 \cdot 0.8 \cdot 188.717\ MPa = 150.974\ MPa$$

$$q = \frac{\Delta\sigma_0 \cdot SCF}{(\ln n_0)^{\frac{1}{h}}} = \frac{150.974\ MPa \cdot 1.60}{(\ln 1 \cdot 10^8)^{\frac{1}{1.037}}} = 14.550$$

Two slope S-N curve:

$$D = v_0 \cdot T_d \left[\frac{q^{m_1}}{\bar{a}_1} \Gamma\left(1 + \frac{m_1}{h}; \left(\frac{S_1}{q}\right)^h\right) + \frac{q^{m_2}}{\bar{a}_2} \gamma\left(1 + \frac{m_2}{h}; \left(\frac{S_1}{q}\right)^h\right) \right] \leq \eta$$

All values are put in an excel sheet, calculating the miner sum D and fatigue life time T. The excel sheet is based on the two slope S-N curve formula above.



Hot Spot no.:	1
	Two slope-air
S-N curve	D
Stress range [N/mm^2] :	**151,0**
Hot spot factor	**1,60**
Weibull: h	**1,04**
gamma(1+m/h)	**5,254**
n_0 (cycles at reference stress)	**1,00E+08**
n (total load cycles)	7,26E+07
Service life	**20**
Td=Years*60*60*24*365	6,31E+08
Shift in slope (logN)	**7**
m_1	**3**
$\log a_1$	**12,164**
m_2	**5**
$\log a_2$	**15,606**
Ship length (0=average period)	**148,8**
v_0	0,115
q	14,550
Thickness [mm] :	**12**
Thickness corr.:	1,000
Miner Sum D:	0,58
Life time T [year] :	35

Figure 14 Excel data sheet, two slope S-N curve (Narve Oma)

Due to not 100% sailing time, D is redused with an factor of 0.85, to 85% sailing time as below:

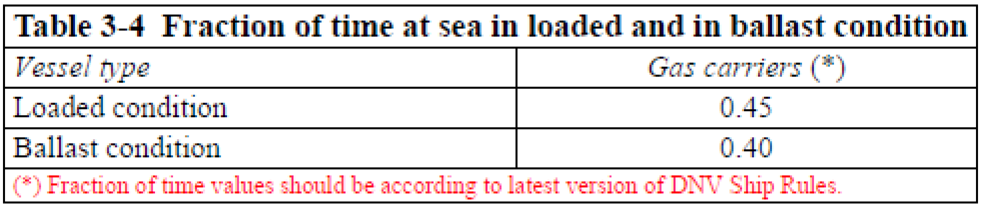


Table 3-4 Fraction of time at sea in loaded and in ballast condition	
Vessel type	*Gas carriers (*)*
Loaded condition	0.45
Ballast condition	0.40
(*) Fraction of time values should be according to latest version of DNV Ship Rules.	

Figure 15 Liquefied gas tanker, operation time. DNV-GL ship rules

$$D = D \cdot 0.85 = 0.58 \cdot 0.85 = 0.493$$

Air:

$$Life\ time(year): T_{air} = \frac{20}{D} = \frac{20}{0.493} = 40.6\ years$$

$$D_{year,air} = \frac{D}{20} = \frac{0.493}{20} = 0.0247$$

10 years with protective coating:

$$D_{air} = D_{year,air} \cdot 10 = 0.0247 \cdot 10 = 0.247$$

Corrosive environment:

$$D_{year,corr} = 2 \cdot D_{year,air} = 2 \cdot 0.247 = 0.494$$

Total fatigue life:

Ex 10 years effective protective coating

$$T_{Total} = 10\ years + \left(\frac{1 - D_{air}}{D_{year,corr}}\right) = 10\ years + \left(\frac{1 - 0.247}{0.0494}\right) years$$
$$= 25.2\ years\ fatigue\ life$$

Table 7 Total fatigue life of a stiffener support, two slope S-N curve

Years with effective protective coating	Total fatigue life in years
5	22,7
10	25,2
15	27,7
20	30,2
25	32,7
30	35,2
35	37,7
40	40,2

This states the importance with a good protective coating and the importance with proper maintenance.

In the calculation it is assumed 85% operation time, which is normal to assume, due to drydocking, loading/unloading, waiting at anchor etc. the operation time on ships usually is 45% in loaded condition and 40% in ballast condition.

One slope S-N curve for corrosion (DNVGL RP-C203 Fatigue design of offshore steel structures)

The fatigue life calculations for ships (DNV CN 30.7) and for offshore steel structures (DNVGL RP-C203) are different. It is interesting to see the difference in calculated fatigue life with the two different calculation methods.

For ships (DNV CN 30.7) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment the miner sum are 2* D_{air}.

For offshore steel structures (DNVGL RP-C203) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment, the miner sum is calculated by using a one-slope S-N curve.

The miner sum for air is the same in both DNV CN 30.7 and DNVGL RP-C203 as shown below:

Air:

$$D = D \cdot 0.85 = 0.58 \cdot 0.85 = 0.493$$

$$Life\ time(year)\colon T_{air} = \frac{20}{D} = \frac{20}{0.493} = 40.6\ years$$

$$D_{year,air} = \frac{D}{20} = \frac{0.493}{20} = 0.0247$$

10 years with protective coating:

$$D_{air} = D_{year,air} \cdot 10 = 0.0247 \cdot 10 = 0.247$$

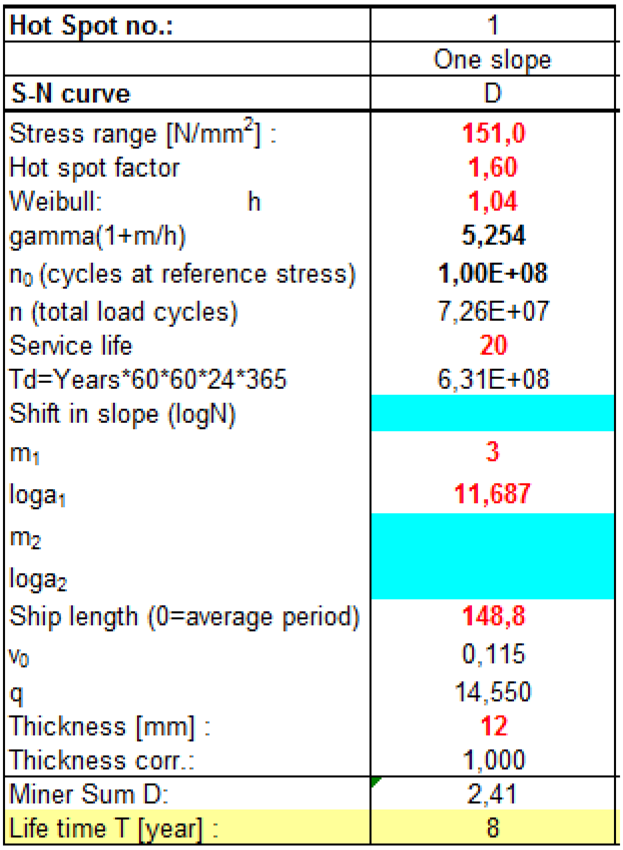
For corrosive environment, the miner sum (D_{corr}) are found by the formula below:

Corrosive environment:

$$D = \frac{v_0 \cdot T_d}{\bar{a}} \cdot q^m \cdot \Gamma\left(1 + \frac{m}{h}\right) \leq \eta$$

$$D = \frac{0.115 \cdot 6.31 \cdot 10^8}{4.864 \cdot 10^{11}} \cdot 14.550^3 \cdot 5.254 = 2.41$$

All values are put in an excel sheet, calculating the miner sum D and fatigue life time T. The excel sheet is based on the one slope S-N curve formula shown above



Hot Spot no.:	1
	One slope
S-N curve	D
Stress range [N/mm^2] :	**151,0**
Hot spot factor	**1,60**
Weibull: h	**1,04**
gamma(1+m/h)	**5,254**
n_0 (cycles at reference stress)	**1,00E+08**
n (total load cycles)	7,26E+07
Service life	20
Td=Years*60*60*24*365	6,31E+08
Shift in slope (logN)	
m_1	3
$loga_1$	**11,687**
m_2	
$loga_2$	
Ship length (0=average period)	**148,8**
v_0	0,115
q	14,550
Thickness [mm] :	12
Thickness corr.:	1,000
Miner Sum D:	2,41
Life time T [year] :	8

Figure 16 Excel data sheet, One slope S-N curve, N. Oma

Due to not 100% sailing time, D is redused with an factor of 0.85, to 85% sailing time as below:

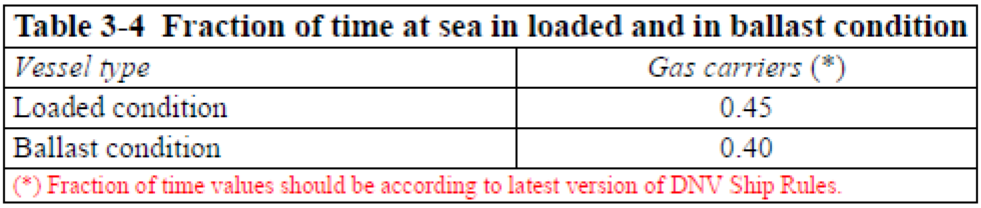


Table 3-4 Fraction of time at sea in loaded and in ballast condition	
Vessel type	*Gas carriers (*)*
Loaded condition	0.45
Ballast condition	0.40
(*) Fraction of time values should be according to latest version of DNV Ship Rules.	

Figure 17 Liquefied gas tanker, operation time. (DNV-GL ship rules)

Corrosive environment:

$$D = D \cdot 0.85 = 2.41 \cdot 0.85 = 2.049$$

$$Life\ time(year): T_{air} = \frac{20}{D} = \frac{20}{2.049} = 9.8\ years$$

$$D_{year,corr} = \frac{D}{20} = \frac{2.049}{20} = 0.1025$$

Total fatigue life:

Ex 10 years effective protective coating

$$T_{Total} = 10\ years + \left(\frac{1 - D_{air}}{D_{year,corr}}\right) = 10\ years + \left(\frac{1 - 0.247}{0.1025}\right) years$$
$$= 17.3\ years\ fatigue\ life$$

Table 8 Total fatigue life of a stiffener support, One slope S-N curve

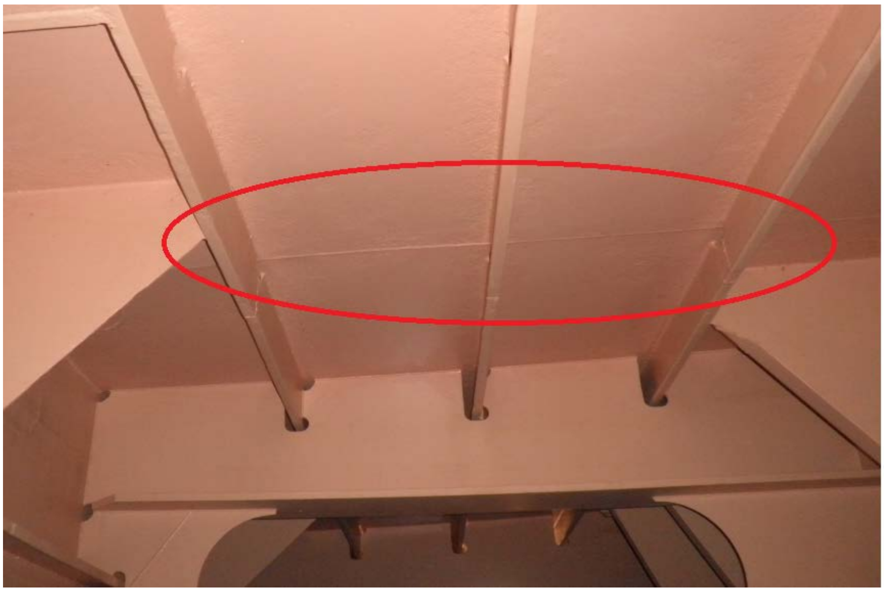
Years with effective protective coating	Total fatigue life in years
5	13,6
10	17,4
15	21,2
20	24,9
25	28,7
30	32,5
35	36,3
40	40,1

This states the importance with a good protective coating and the importance with proper maintenance.

In the calculation it is assumed 85% operation time, which is normal to assume, due to drydocking, loading/unloading, waiting at anchor etc. the operation time on ships usually is 45% in loaded condition and 40% in ballast condition.

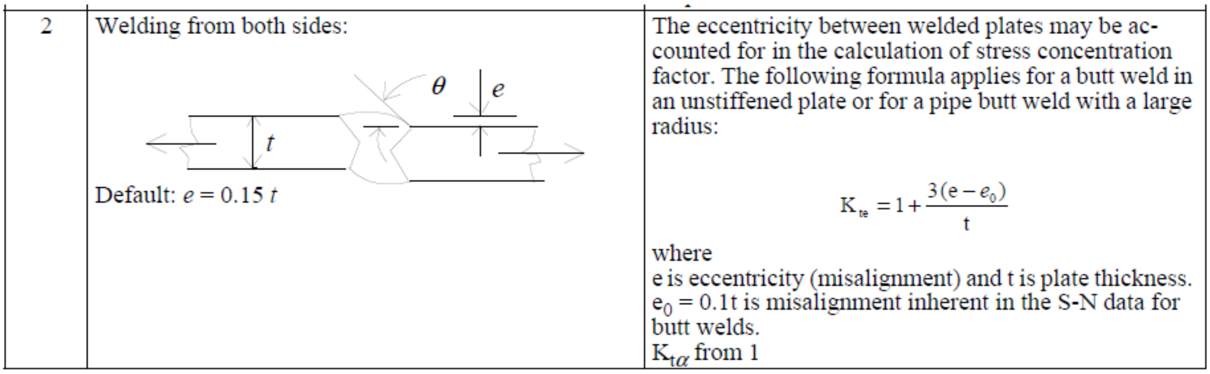
Fatigue in a butt weld in deck plating

To have something to compare the fatigue life of the stiffener support with, the fatigue life of a butt-weld in the deck plating were calculated. See picture 4.



Picture 4 Butt-weld in deck plating

All values for the fatigue life for a butt-weld is the same as for the stiffener support, except for the SCF/K-factor and the Weibull stress range scale distribution parameter for load condition, q. The SCF/K-factor is found from figure 17.



2	Welding from both sides: Default: $e = 0.15\,t$	The eccentricity between welded plates may be accounted for in the calculation of stress concentration factor. The following formula applies for a butt weld in an unstiffened plate or for a pipe butt weld with a large radius: $K_{te} = 1 + \frac{3(e - e_0)}{t}$ where e is eccentricity (misalignment) and t is plate thickness. $e_0 = 0.1t$ is misalignment inherent in the S-N data for butt welds. $K_{t\alpha}$ from 1

Figure 18 SCF/K-factor for a butt-weld. DNV-GL CN30.7

The SCF/K-factor for a butt weld is shown below:

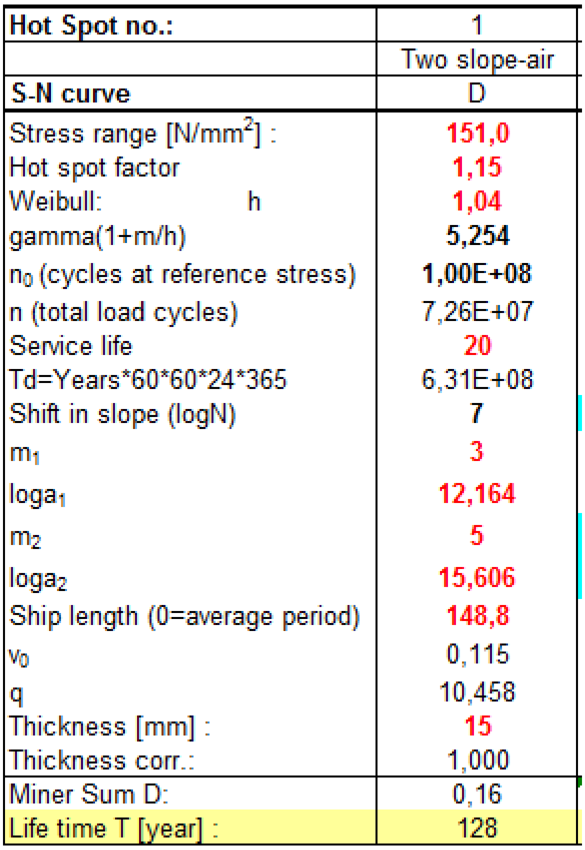
$$Hot\ spot\ factor: K_{te} = 1 + \frac{3(e - e_0)}{t} = 1 + \frac{3(0.15 \cdot 12 - 0.10 \cdot 12)}{12} = 1.15$$

The Weibull stress range scale distribution parameter for load condition for a butt-weld are shown below:

$$q = \frac{\Delta\sigma_0 \cdot SCF}{(\ln n_0)^{\frac{1}{h}}} = \frac{150.974\ MPa \cdot 1.15}{(\ln 1 \cdot 10^8)^{\frac{1}{1.037}}} = 10.458$$

Two slope S-N curve:

All values are put in an excel sheet, calculating the miner sum D and fatigue life time T.



Hot Spot no.:	1
	Two slope-air
S-N curve	D
Stress range [N/mm^2] :	**151,0**
Hot spot factor	**1,15**
Weibull: h	**1,04**
gamma(1+m/h)	**5,254**
n_0 (cycles at reference stress)	**1,00E+08**
n (total load cycles)	7,26E+07
Service life	**20**
Td=Years*60*60*24*365	6,31E+08
Shift in slope (logN)	**7**
m_1	**3**
$\log a_1$	**12,164**
m_2	**5**
$\log a_2$	**15,606**
Ship length (0=average period)	**148,8**
v_0	0,115
q	10,458
Thickness [mm] :	**15**
Thickness corr.:	1,000
Miner Sum D:	0,16
Life time T [year] :	128

Figure 19 Excel data sheet, two slope S-N curve, (Narve Oma)

Due to not 100% sailing time, D is redused with an factor of 0.85, to 85% sailing time as below:

$$D = D \cdot 0.85 = 0.16 \cdot 0.85 = 0.136$$

Air:

$$Life\ time(year): T = \frac{20}{0.136} = 147\ years$$

The fatigue life of the butt-weld in the deck plating is 2 – 3 times longer than the fatigue life of the stiffener support in calculation XX. Therefor the butt-weld is not as critical as the stiffener support.

Table 9 Total fatigue life of a butt-weld in deck plating (DNV CN30.7)

Years with effective protective coating	Total fatigue life in years
5	76,0
10	78,5
15	81,0
20	83,5
25	86,0
30	88,5
35	91,0
40	93,5

One slope S-N curve for corrosion (DNVGL RP-C203 Fatigue design of offshore steel structures)

The fatigue life calculations for ships (DNV CN 30.7) and for offshore steel structures (DNVGL RP-C203) are different. It is interesting to see the difference in calculated fatigue life with the two different calculation methods.

For ships (DNV CN 30.7) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment the miner sum are 2* D_{air}.

For offshore steel structures (DNVGL RP-C203) the miner sum (D_{air}) in air is calculated using a two-slope S-N curve. For corrosive environment, the miner sum is calculated by using a one-slope S-N curve.

The miner sum for air is the same in both DNV CN 30.7 and DNVGL RP-C203 as shown below:

Air:

$$D = D \cdot 0.85 = 0.16 \cdot 0.85 = 0.136$$

$$Life\ time(year): T = \frac{20}{0.136} = 147\ years$$

$$Life\ time(year): T_{air} = \frac{20}{D} = \frac{20}{0.136} = 147.1\ years$$

$$D_{year,air} = \frac{D}{20} = \frac{0.136}{20} = 0.0068$$

10 years with protective coating:

$$D_{air} = D_{year,air} \cdot 10 = 0.0068 \cdot 10 = 0.068$$

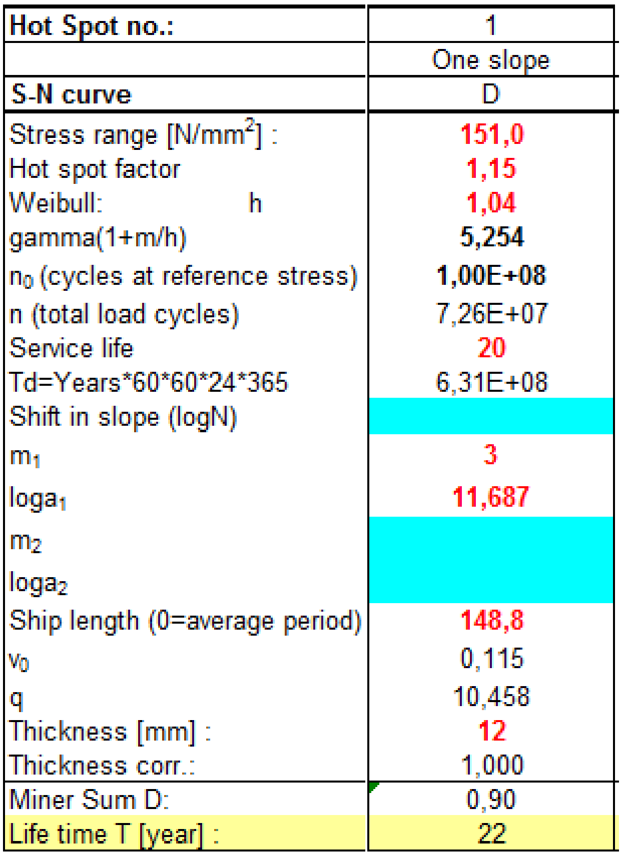
For corrosive environment, the miner sum (D_{corr}) are found by the formula below:

Corrosive environment:

$$D = \frac{v_0 \cdot T_d}{\bar{a}} \cdot q^m \cdot \Gamma\left(1 + \frac{m}{h}\right) \leq \eta$$

$$D = \frac{0.115 \cdot 6.31 \cdot 10^8}{4.864 \cdot 10^{11}} \cdot 10.458^3 \cdot 5.254 = 0.90$$

All values are put in an excel sheet, calculating the miner sum D and fatigue life time T.



Hot Spot no.:	1
	One slope
S-N curve	D
Stress range [N/mm^2] :	151,0
Hot spot factor	1,15
Weibull: h	1,04
gamma(1+m/h)	5,254
n_0 (cycles at reference stress)	1,00E+08
n (total load cycles)	7,26E+07
Service life	20
Td=Years*60*60*24*365	6,31E+08
Shift in slope (logN)	
m_1	3
$loga_1$	11,687
m_2	
$loga_2$	
Ship length (0=average period)	148,8
v_0	0,115
q	10,458
Thickness [mm] :	12
Thickness corr.:	1,000
Miner Sum D:	0,90
Life time T [year] :	22

Figure 20 Excel data sheet, One slope S-N curve, (Narve Oma)

Due to not 100% sailing time, D is redused with an factor of 0.85, to 85% sailing time as below:

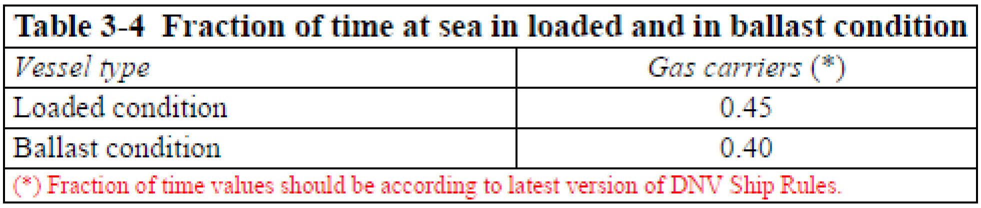


Table 3-4 Fraction of time at sea in loaded and in ballast condition	
Vessel type	*Gas carriers (*)*
Loaded condition	0.45
Ballast condition	0.40
(*) Fraction of time values should be according to latest version of DNV Ship Rules.	

Figure 21 Liquefied gas tanker, operation time. (DNV-GL ship rules)

Corrosive environment:

$$D = D \cdot 0.85 = 0.90 \cdot 0.85 = 0.765$$

$$Life\ time(year)\colon T_{air} = \frac{20}{D} = \frac{20}{0.765} = 26.1\ years$$

$$D_{year,corr} = \frac{D}{20} = \frac{0.765}{20} = 0.03825$$

Total fatigue life:

Ex 10 years effective protective coating

$$T_{Total} = 10\ years + \left(\frac{1 - D_{air}}{D_{year,corr}}\right) = 10\ years + \left(\frac{1 - 0.136}{0.03825}\right) years$$
$$= 32.6\ years\ fatigue\ life$$

Table 10 Total fatigue life of a butt-weld in deck plating (DNVGL RP-C203)

Years with effective protective coating	Total fatigue life in years
5	30,3
10	34,4
15	38,5
20	42,6
25	46,7
30	50,8
35	54,9
40	59,0

This states the importance with a good protective coating and the importance with proper maintenance.

In the calculation it is assumed 85% operation time, which is normal to assume, due to drydocking, loading/unloading, waiting at anchor etc. the operation time on ships usually is 45% in loaded condition and 40% in ballast condition.