# SYSTEM DESIGN FOR RAPID CARGO CHANGE ON LIQUEFIED GAS CARRIERS

by

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### Preface

This report is the result of the Master thesis performed by Øyvind L. Vesterdal, spring 2011 at Dept. of Marine Technology, Norwegian University of Science and Technology (NTNU).

The project work has aimed at developing a function specification for a subsystem of the Rapid Purge Technology, being developed by Environgas AS, which is intended to improve current procedures for cargo change on liquefied gas carriers. This is done by evaluating cargo containment systems on liquefied gas carriers, as well as the implementation of said technology.

The work has been influenced by a rather unsuccessful effort of obtaining information on design and arrangements of existing liquefied gas cargo handling systems due to confidentiality issues. Available information regarding the Rapid Purge Technology has also mostly been of the conceptual type. This has resulted in much of the work in this thesis being based on general information from literature and my own deductions and assumptions, rather than actual systems as preferred and expected. The lack of time caused by the required additional work has therefore been the key element in limiting this thesis.

I have, however, received help from several parties. Acknowledgements are therefore in order to Environgas AS by Ola Ravndal; Det Norske Veritas AS by Pål Einar Spilleth, Magnus Lindgren, John-Inge Marhiniussen, Gunnar Rød; Solvang ASA by Tor Øyvind Ask and Jone Ask; as well as Norner Innovation AS by Espen Ommundsen.

Special thanks are in order to my academic supervisor Prof. Maurice F. White for guidance during the entire process.

Finally, I would like to thank family and friends for all their support during my studies. This applies especially to my wife, and my colleagues at office A1.027 at MTS for making excellent coffee and fostering a high work morale.

Trondheim, 14.06.2011, Øyvind L. Vesterdal

### Executive summary

A major challenge concerning the operation of ships transporting liquefied gases is that they spend much of their time in ballast condition, thus not transporting any cargo. The main reason for this are the large amounts of time, pollution and high cost connected to cargo change on liquefied gas carriers.

There is a new Norwegian technology called Rapid Purge Technology (RPT) being developed by Environgas that may offer an alternative to the current procedures. In short, it works by displacing the dead volume by means of disposable bellows and thus separating the purge and rest gases in the tank. Each of said disposable bellows are to be stored, released into- and retrieved from the cargo tank, in suitable containers, which are designated Gas Locks (GL). This will allow said gases to be reclaimed, and thereby avoiding release of gas to the atmosphere as well as significantly shorten the time usage. The RPT will thus give substantial cost reductions as well as significant reductions in the emissions of carbon dioxide and Volatile Organic Components.

The RPT is still under development, and the goal of this Master thesis is to establish a basis upon which a proper detailed design specification of the GL system can be made. This is to be done by making a function specification of said GL for a case with the liquefied gas cargoes of propane and carbon dioxide.

By describing a typical independent tank Type C and its design criteria, as well as the below system and its operation, the boundary conditions forming the basis for a function specification for a GL is found. As the RPT is under development, potential challenges and in-principle solutions are also explored.

Also, the potential economic and environmental benefits of use of this technology is evaluated. The evaluation gave that use of the RPT will significantly reduce the required time in port, as well as reduce emissions on cargo change procedures, for most liquefied gas cargoes. The reduction of time in port may either increase the annual ship transport capacity, or reduce the required sailing velocity.

A case study for a typical liquefied gas carrier with capacity of approximately 40,000  $(m^3)$ , gives that use of RPT reduces time in port from 6 to 4 (days), or 11.5 to 6.5 (days), with procedures of inerting, and without or with visual inspection respectively. Also, emissions with cargo change procedures are reduced with between 100 and 300 (tonnes) of cargo vapours, and more than 100 tonnes of inert gas. It has therefore been concluded that use of the technology may give both economical and environmental benefits.

A GL is to be able to store, deploy and retrieve a bellow, as well as being able to function in the given environment. For this report, a tank Type C with the following characteristics has been considered:

Item	Value	Unit
Cargo tank capacity	3,500	$(m^3)$
Minimum allowable tank temperature	-55	$(^{\circ}C)$
Maximum allowable tank pressure	6	(bar)
Maximum cargo density	$1,\!150$	$(\mathrm{kgm}^{-3})$

Deployment of bellow requires a GL to have an opening into said cargo tank. This is to be done by way of a gate valve with 300 (mm) inner diameter. When stored, the bellows, with a thickness of 100 ( $\mu$ m), shall be folded in near cylindrical arrangements, with diameters of 240 (mm) to give a safety margin for their openings. As the cargo tank in question has a submerged pump and swash bulkhead, there is a need for at least three bellows (and GLs) as they cannot inflate around these items. The larger bellow volume is 0.0955 (m<sup>3</sup>). Retrieval is thought to be performed by way of a rolling-up mechanism, generating a rough cylinder with a height equal to the diameter of the gate valve. The result is shown in fig 1.

The GL has been analysed with regard to structural integrity according to the DNV Rules for Classification of Ships. From this, recommended material, as well as shell thicknesses and required reinforcements due to forces and moments acting on the GL have been found.



Figure 1: 3D rendering with dimensions

## Contents

Pr	eface			ii
Ex	ecuti	ve sum	nary	iii
Ta	ble of	Conte	nts	vii
Lis	st of f	igures		х
Lis	st of t	ables		xi
Sy	mbols	s and a	cronyms	xii
De	finitio	ons		xv
1	Intro	oduction	1	1
	1.1	Introd	uction	2
	1.2	Task .		2
	1.3	Assum	ptions and definitions	3
		1.3.1	Owner's requirements for Gas Lock	3
		1.3.2	Principal vessel characteristics	3
		1.3.3	Cargo systems	3
		1.3.4 1.3.5	Tank Type C	3 5
		1.5.5		0
2	Liqu	efied ga	ISES	6
	2.1	Liquef	ed gas introduction	6
	2.2	Cargo	properties	$\overline{7}$
		2.2.1	Propane	10
		2.2.2	Carbon dioxide	10
	2.3	Cargo	change procedures	11
		2.3.1	Discharge	15
		2.3.2	Warming-up	15
		2.3.3	Inerting after discharge	16
		2.3.4	Aerating	17
		2.3.5	Visual inspection	17
		2.3.6	Drying	18
		2.3.7	Inerting before loading	19
		2.3.8	Gassing-up	19
		2.3.9	Cool-down	19
		2.3.10	Loading	21
		2.3.11	Summary of current procedures	23
3	Tank	к Туре	С	25

	3.1 3.2	Cargo containment system3.1.1Tank arrangements3.1.2Cargo tank subsystemsDesign criteria3.2.1General requirements3.2.2Loads3.2.3Openings and reinforcements3.2.4Hazards3.2.5Summary of design criteria	· · · ·	· · · · · · · · · · · · · ·	<ul> <li>.</li> <li>.&lt;</li></ul>	· · · · · · · · · · · ·	· · · · · · · · ·	· · · · · · · · · · · · · · · · · · ·		$25 \\ 26 \\ 30 \\ 40 \\ 42 \\ 44 \\ 53 \\ 56 \\ 57$
4	Bello	ow system								58
-	4.1	Rationale for Rapid Purge Technology								58
		4.1.1 Economic and environmental benefits								60
		4.1.2 Environmental benefits								65
	4.2	Systems overview								66
		4.2.1 Bellow system								66
		4.2.2 Inert Gas system								68
	4.3	Bellow system operation								69
		4.3.1 Bellow system principle								69
		4.3.2 New procedures								74
	4.4	Challenges								83
		4.4.1 Bellow arrangement								83
		4.4.2 Bellow deployment								86
		4.4.3 Bellow evacuation								88
	4.5	Hazards								89
		4.5.1 FMECA preliminary steps								89
		4.5.2 FMECA procedure								91
_	-									
5	Func	ction specification								94
	5.1	To Cargo Tank		• •	•••	• •	• •	·	·	95
	5 0	5.1.1 Modus operandi		• •	• •	•••	• •	·	·	96
	5.2	Deck penetration and foundation		• •	• •	•••	• •	·	·	97
	5.3			• •	•••	• •	• •	·	•	98
		$5.3.1$ Modus operandi $\ldots$		• •	•••	•••	• •	·	•	98
		5.3.2 Pipeline characteristics		• •	• •	• •	• •	·	·	99 105
		5.3.3 Moments due to pipeline mass		•••	•••	•••	• •	·	·	105
	F 4	5.3.4 Moments due to now $\ldots \ldots \ldots \ldots \ldots$		• •	•••	• •	• •	·	·	100
	5.4 F F	Deller en entiere		•••	•••	• •	• •	·	·	107
	0.0	5.5.1 Dollars among among at a tan an		• •	• •	• •	• •	·	·	107
		5.5.2 Dealaimed hollow		• •	• •	•••	• •	·	•	107 110
		5.5.2 Reclaimed bellow		•••	• •	•••	• •	·	·	11U
	56	Summery of function specification		• •	• •	•••	• •	·	·	111
	0.0	5.6.1 Design of Cas Lock		• •	• •	•••	• •	•	•	119
		0.0.1 Design of Gas LOCK		• •	• •	• •	• •	•	·	112

	5.6.2	Thickness calculations of Gas Lock	114
	5.6.3	Reinforcements from penetration	120
	5.6.4	Mass and centre of gravity	123
	5.6.5	Moments due to accelerations	124
	5.6.6	Principal characteristics	126
6	Gas Lock ca	ase study	130
7	Conclusion		133
8	Further stuc	dies	137
Re	ferences		139
Aŗ	opendices		Ι
Α	Tank type '	С'	Ι

# List of Figures

1	3D rendering with dimensions	iv
2	Inerting after discharge[24]	17
3	Aerating after inerting $[24]$	18
4	Gassing-up with liquid from shore[24]	20
5	Gassing-up with vapour from shore[24]	20
6	Cargo tank cool-down using liquid from shore[24]	21
7	Loading with vapour return[24]	22
8	Loading without vapour return[24]	22
9	Arrangement, independent tank Type C	27
10	Type C, Cylindrical parallel [30]	27
11	Type C, cylindrical conical [30]	28
12	Type C, bilobe illustration [30]	28
13	Type C, bilobe arrangement	29
14	Arrangement, independent tank Type C	29
15	LPG carrier deck level with pipelines	31
16	Concept of anchors and flexible joints in a pipeline	31
17	Thermal expansion of pipeline	32
18	Expansion joint	32
19	Cargo tank dome	33
20	Cargo tank dome [13]	34
21	Cargo manifolds	35
22	Moody diagram	36
23	Gate valve	38
24	Simply supported beam principle	39
25	LPG tank, supports	39
26	Stiffening rings in a bilobe tank Type C [30]	40
27	Swash bulkhead in bilobe tank [30]	41
28	Vacuum rings on tank Type C (from appendix A)	41
29	Tank Type C, with inner topology	42
30	Tank type 'C', Hamworthy	45
31	Stress components of a cylindrical tank	46
32	Acceleration ellipse used to evaluate pressure differential $1/2$ [3]	48
33	Acceleration ellipse used to evaluate pressure differential $2/2$ citeDNV505	48
34	Resulting acceleration (static+dynamic) $a_{\beta}$ in arbitrary direction $\beta$ [3]	52
35	Liquid heights, $Z_{\beta}$ , for check points I-V in the $\beta$ -direction [3]	53
36	Reinforcement area, $K = 1$	54
37	Reinforcement area, $K = 0.7$	55
38	Minimum distance requirement between cargo tank dome and deck struc-	
	tures	56
39	Q(V, d), T <sub>p</sub> = (4; 6; 6.5; 11.5)	62
40	$Q(T_p)$	63

41	Initial conditions of Bellow system	. 70
42	Step 1: Release of bellows into cargo tank	. 70
43	Step 2: IG is prepared before insertion to bellows	. 71
44	Step 3: Inflating of first bellow	. 72
45	Step 4: Inflating of second bellow	. 72
46	Step 5: Bellows fully inflated	. 73
47	Step 6: Introduction of vapours from cargo "2"	. 73
48	Step 7: First bellow deflated	. 74
49	Step 8: All bellows deflated	. 75
50	Step 9: Bellows retracted	. 75
51	RPT incorporated in existing systems	. 77
52	RPT: Discharge	. 77
53	RPT, artist's expression: Discharge	. 78
54	RPT: Inflation of bellows	. 79
55	RPT, artist's expression: Inflation of bellows	. 79
56	RPT, artist's expression: Bellows fully inflated	. 80
57	RPT: Gassing-up	. 81
58	RPT, artist's expression: Gassing-up and deflating bellows	. 81
59	RPT: Loading	. 82
60	RPT, artist's expression: Loading	. 82
61	Schematic drawing of deployment mechanism [29]	. 86
62	Perforated rolled cylinder	. 87
63	Conceptual sketch of retrieval mechanism [29]	. 88
64	Hierarheical structure of system as presented in the pre-Master	. 90
65	FMECA work sheet 1 of 2	. 92
66	FMECA work sheet 2 of 2	. 93
67	Tank type 'C' with GL	. 94
68	Overview of GL and cargo tank	. 96
69	Pipeline arrangement	. 100
70	Moody diagram, friction factor, $f = 0.018$	. 102
71	Fixed supports	. 106
72	Area for three bellows in a tank Type C	. 108
73	3D rendering of GL storage section with bellow arrangement	. 112
74	3D rendering of GL retrieval (roll-up) unit	. 113
75	Design of GL (2D) in the y-z plane	. 113
76	Design of GL (2D) in the x-z plane	. 114
77	Calculation factor, $k$	. 117
78	Calculation factor, K	. 118
79	Reinforcement area, $K = 1$	. 121
80	Reinforcement thicknesses, $t_{ba}$ and $t_a \ldots \ldots \ldots \ldots \ldots \ldots \ldots$	. 122
81	3D rendering of GL with valves and connection to cargo tank $\ldots$ .	. 123
82	Reinforcement by way of brackets	. 126
83	3D rendering of GL, xz-plane	. 128

84	3D rendering with dimensions
85	Multiple openings, with non-overlapping reinforcements. Top view 131
86	Openings and available space. Side view
87	3D rendering of GL storage section with bellow arrangement
88	Conceptual sketch of retrieval mechanism [29]
89	3D rendering of GL retrieval (roll-up) unit
90	3D rendering of GL, xz-plane
91	3D rendering with dimensions
92	Appendix A

## List of Tables

1	Principal characteristics
2	Cargo systems
3	Properties of <i>carbon dioxide</i> during transport [33] 5
4	Properties of <i>propane</i> during transport [33]
5	Common liquefied gases [24]
6	Inert Gas compositions $[24]$
7	Chemical properties and reactive materials [24]
8	Chemical compatibilities of liquefied gases[24]
9	Properties of propane during transport [33] 10
10	Properties of $CO_2$ during transport [33] $\ldots \ldots \ldots$
11	Tank Cleaning Procedures pt. $1/2$ [24]
12	Tank Cleaning Procedures pt. $2/2$ [24]
13	Explanation to tables 11 and 12 $[24]$
14	Time for cargo change procedures, for cases i), ii) and iii)
15	Emissions for cargo change procedures, Case i)
16	Emissions for cargo change procedures, Case ii)
17	Emissions for cargo change procedures, Case iii)
18	Time with procedures for cargo change
19	Properties of PE
20	Time with new procedures for cargo change

Symbol	Name	$\mathbf{Unit}$
$\overline{\Delta p}$	Dynamic pressure differential	
$\Delta \sigma_A$	Allowable dynamic membrane stress	
$\epsilon$	Surface roughness	(mm)
$\kappa$	Form factor	
$\mu$	absolute viscosity	$(Nsm^{-2})$
ρ	Fluid density	$(kgm^{-3})$
$\sigma$	Stress	$(Nmm^{-2})$
$\sigma_B$	specified minimum tensile strength	$(Nmm^{-2})$
$\sigma_F$	Specified minimum upper yield stress	$(Nmm^{-2})$
$\sigma_t$	Equivalent primary stress	$(Nmm^{-2})$
$\sigma_z$	Longitudinal stress	$(Nmm^{-2})$

## Abbreviations and acronyms

Symbol	Name	$\mathbf{Unit}$
A	Area	$(m^2)$
$\mathbf{a}_x$	Acceleration, longitudinal	$(ms^{-2})$
$\mathbf{a}_y$	Acceleration, transverse	$(ms^{-2})$
$\mathbf{a}_z$	Acceleration, vertical	$(ms^{-2})$
В	Breadth (of vessel)	(m)
b	Width (of tank)	(m)
BC	Boundary conditions	
с	Corrosion margin	(mm)
С	Cost	(USD)
$C_0$	Cost, except fuel (constant)	(USD)
$C_B$	Block coef.	
$C_{fuel}$	Cost of fuel	(USD)
COG	Centre of gravity	· · · · ·
d	Sailing distance	(Nm)
D	Pipe diameter	(m)
DNV	Det norske veritas	
Е	Modulus of elasticity	
е	Joint efficiency	
ET	Empty tank	
f	Friction factor	
$\operatorname{FL}$	Filling limit	
g	Gravitation	$(ms^{-2})$
GL	Gas lock	,
GM	Metacentric height	(m)
$h_L$	Head loss	(m)
$h_P$	Pump head	(m)
$I_Z$	Moment of inertia, z-axis	$(mm^4)$
IGC	International Gas Code	· · · · ·
IMO	International Maritime Organization	
k	Form factor	(m)
$K_L$	Loss coef.	
kW	Installed propulsion power	(kW)
L	Length (of vessel)	(m)
L	Length (of material reinforcement)	(mm)
L	Length (of pipeline)	(m)
Loa	Length over all(of vessel)	(m)
Lpp	Length between particulars (of vessel)	(m)
1	Length (of tank)	(m)

Symbol	Name	$\mathbf{Unit}$
$\overline{\dot{m}}$	Mass flow	$(kgs^{-1})$
М	Moment	(Nm)
MARVS	Maximum allowable relief valve setting	
$N_2$	Inert with nitrogen only	
$N_2I$	Inert with nitrogen or other inert gas	
OH	Time offhire	(Days)
р	Pressure	$(bar), (Nm^{-2})$
$\mathbf{p}_0$	Maximum allowable vapour pressure	(bar)
$\mathbf{p}_{ed}$	External design pressure	(bar)
$\mathbf{p}_f$	Fuel price	(USD)
PE	Polyethene, polyethylene	
ppm	Parts per million	
Q	Annual ship transport capacity	$(t), (m^3)$
q	Vessel cargo capacity	$(t), (m^3)$
q	Volume flow	$(m^3 s^{-1})$
r	Radius	(mm)
R	Radius, inside of shell	(mm)
$\mathbf{R}_{e}$	Reynolds number	(mm)
RPT	Rapid Purge Technology	
S	Standard req.: Liquid free cargo tanks	
S	Distance between axes of openings in tank	
SFC	Specific fuel consumption	$(g(kW)^{-1})$
SOLAS	Safety of Life at Sea Convention	
$\mathbf{t}$	Thickness of wall, shell	(mm)
$t_a$	Thickness of tank, with reinforcements	(mm)
$t_b$	Thickness of branch	(mm)
$t_{ba}$	Thickness of branch, with reinforcement	(mm)
Т	Draught (of vessel)	(m)
Т	Roundtrip time	(days)
$T_q$	Glass temperature	$(^{\circ}C)$
$T_p$	Time in port	(days)
V	Vessel speed	(kn)
V	Visual inspection	
V	Volume	$(m^3)$
$V_T$	Volume of tank	$(m^3)$
W	Axial force on shell	(N)
W	Water wash	
х	Distance, longitudinal	(m)
Z	Distance, vertical	(m)
Ζ	Height at specified location	(m)
$Z_{eta}$	Largest liquid height in $\beta$ direction	(m)

### Definitions

Expressions written in this colour are defined alphabetically.

- **Barg** is a unit of gauge pressure, i.e. pressure in bars above ambient or atmospheric pressure." [36]
- Change of grade is the operation, after completion of discharge of a certain type of cargo, of which the vessel is employed for another type of cargo [9].
- **Charterparty** A transportation contract which includes the full and exclusive use of the airplane, vehicle or vessel for the duration of the transportation of either goods or persons [14].
- Chemical gases The chemical gases do not belong to a particular family, and have thus chemical properties that varies considerably. Some, like ammonia, are highly reactive and can form explosive compounds several substances, as well as being prone to cause stress corrosion on cargo tank shells, or polymerization [24].
- **Dedicated trade** is when a vessel is only transporting one type of cargo [24]. No operations of cleaning, purging or changing of grade are performed [9].
- Fail-safe valve means that the valve will close automatically upon loss of actuating power.
- **Failure mode** describes the physical or functional part of the result of the failure of a unit.
- **Fixed support** is the most restrictive way of supporting a beam as both translation and rotation is prevented [20]
- Flash point The lowest temperature at which a liquid gives off sufficient vapour to form a flammable mixture with air near the surface of the liquid [24].
- Function specification A specification is defined as an explicit set of requirements, or characteristics, to be satisfied [37]. A function specification is therefore considered to be the description of the required function of the system in question. It should not be confused with *design specification*, which also provides explicit information about *how* the system is to function, in opposition to the *what* in a function specification.
- Gas Lock (GL) is the designation for a suitable container from which a bellow is inserted into the cargo tank. The GL will thus serve as a connection between deck and cargo tank, with the primary function of housing the mechanisms for storing, inserting and evacuating the bellows into or from the cargo tank respectively.
- Generatrix is a line parallel to the centre line of the cylindrical or conical shells.

- **Independent tanks** are completely self-supporting and will neither form part of the ship's hull structure nor contribute to its strength [24].
- Inert gas is a gas such as nitrogen, or a mixture of non-flammable gases containing insufficient oxygen to support combustion [24].
- **Isoquant** is a contour line at which the same quantity of output is produced, while changing the quantities of two or more inputs.
- Liquefied gas is the liquid form of a substance which, at ambient temperature and pressure would be gas. [24]

Liquefied gas is a cargo with a vapour pressure equal to or above 2.75 bar absolute at  $37.8^{\circ}C[3, Sec.1, B122]$ 

- **Phase** refers to a quantity of matter that is homogeneous throughout in both chemical composition and physical structure, which means that the matter is either all solid, all liquid or all vapour. A system can contain one or more phases [25].
- Saturated hydrocarbons Hydrocarbons are substances comprising hydrogen and carbon atoms only. They are said to be saturated when there is a full complement of hydrogen atoms as for the alkanes which are in accordance with the formula  $C_nH_{2n+2}$ . All saturated hydrocarbons are flammable and will burn in air or oxygen. They may also form hydrates when in presence of moisture [24].
- Saturated state A state at which a phase change begins or ends is called a saturated state [25].
- Saturated vapour pressure is the absolute pressure exerted when the liquid is in equilibrium with its own vapor at a given temperature. [24]
- Simply supported beams are pinned at one end and roller-supported at the other [20].
- **Slow steaming** is the reducing of vessel velocity to minimize fuel consumption and thus reduce both expenditures and emissions. [38]
- State refers to the condition of a system as described by its properties [25]. Most substances can exist in either the solid, liquid or vapour state [24].
- Tank dome is the upward extension of a portion of the cargo tank. In the case of below deck cargo containment systems the tank dome protrudes through the weather deck or through a tank cover." [3, Sec.1, B133]
- **Unpumpables** is the term for the liquid residue, often found in the sump of the cargo tank. It is disposed of by either heating or pressurization.
- **Unsaturated hydrocarbons** Hydrocarbons are said to be unsaturated when there is less than the full compliment of hydrogen atoms. In addition of being flammable, they are chemically more reactive than the saturated compounds. This includes

possible reaction with air leading to polymerization, as well as incompatibilities with several metallic materials [24].

Vacuum pressure is pressure between 0 and 1 bar (or below 0 barg).

Volatile Organic Components Hydrocarbon compounds that have low boiling points, usually less than 100°C, and therefore evaporate readily. Some are gases at room temperature. Propane, benzene, and other components of gasoline are all VOCs [32].

### 1 Introduction

A major challenge concerning the operation of ships transporting liquefied gases is that they spend much of their time in ballast condition, thus not transporting any cargo.

The main reason for this situation is the large amount of time and high cost connected to the current procedures for cargo change on liquefied gas carriers [33]. With the recent focus on climate change, there is also a concern regarding the negative environmental impacts from such procedures. [22][26].

The procedures for cargo change are designed to make sure that the cargo tanks are in such a condition that charterers and/or suppliers can accept the vessel to load without delay and risk for cargo contamination [9]. This often include an extensive cleaning process, and sometimes also a visual inspection [9]. This cleaning process usually include displacing the vapour phase of the previous cargo (subsequent to discharging the liquid phase) with inert gas, usually nitrogen or exhaust gases from a dedicated inert gas generator.

Depending on the difference in density between cargo and inert gas, it is common to use up to 400 % of the cargo tank volume to displace the cargo gas phase. The gas mix is then released into the atmosphere [24], and the vessel is ready to perform a change of grade.

The high costs connected to the loss of time, cargo and inert gas, usually result in these procedures being performed only in connection with maintenance of the ship at a shipyard when tank cleaning is required. This, in turn, results in liquefied gas carriers usually being in a dedicated trade.

Cargo change is therefore done only for long distance operations in which the cargo change costs can be justified by a correspondingly longer transportation time. There is a new Norwegian technology called Rapid Purge Technology (RPT), being developed by Environgas  $AS^1$ , that may offer an alternative to the current procedures. In short, it works by separating the vapour phases from each other in such a way that there is no mixing of gases. This will allow the said gases to be reclaimed, and thus avoiding release of gas to the atmosphere as well as drastically shortening the time usage. This new technology utilises disposable bellows of PE-film that are inserted into the cargo tank from Gas Locks (GL).

The bellows are filled with nitrogen, which is an inert gas, through the GL. When fully inflated, the bellows will have displaced the previous cargo gas from between the outside of the bellow and inside of the tank. This displaced gas is either transferred to terminal, or liquefied and transferred to a deck tank for later use. The nitrogen gas in the bellows is transferred to an adjacent deck tank for reuse or vented to atmosphere.

<sup>&</sup>lt;sup>1</sup>Environgas AS will henceforth be called the "Company"

This is done as the bellows are deflating and retracted with the execution of change of grade operations.

The RPT will thus give substantial cost reductions as well as significant reductions in the emissions of carbon dioxide and Volatile Organic Components (VOC).

### 1.1 Introduction

The RPT is still under development, and the goal of this Master thesis is to establish a basis upon which a proper detailed design specification of the GL system can be made. Due to potential issues with patent rights, the detailed design of the bellow insertion-, storage- and retraction devices (which are located inside the GL) shall not be subject to consideration in this thesis, though in-principle methods of execution will be mentioned.

### 1.2 Task

As defined in the Task Definition of the assignment, I am to establish the basis for a detailed design of the GL by:

- 1. Make a function specification for a Gas Lock by:
  - a) Describing a typical cargo tank type 'C' and its design criteria<sup>2</sup>.
  - b) Describing the bellow system and its operation.
  - c) Discussing relevant problems and challenges, and viable solutions by means of in-principle methods of execution.
  - d) Establishing the boundary conditions and requirements for the GL based on a), b) and c).
- 2. Carry out a preliminary design study for integration of a GL into a cargo tank by:
  - a) Evaluating the effect of three or more GL's in addition to penetrations for pump, piping and access openings in the tank.
  - b) Identifying problems associated with connection and use of GLs and the bellows system in a tank, and propose design changes to make the tank more suitable for use in combination with the bellows technology described above.
  - c) Performing a preliminary structural analysis for incorporation of a GL into the tank design using DnV classification society rules.

<sup>&</sup>lt;sup>2</sup>Design criteria is here meant to include factors influencing the tank design, such as internal pressure and wall thickness as well as bending moments in the tank arising from its method of support. These factors will often limit the tank design, which will be further affected by the introduction of tank wall penetrations for the GL's.

### 1.3 Assumptions and definitions

The Task Definition requires that, in addition to evaluations of general systems and principles, specific analyses are to be performed as well. In order to perform these properly, and to ensure that I stay within the scope, specific background material is required. This comprise:

- Gas Lock
- Principal ship particulars
- Cargo containment system
- Liquefied gas cargoes

The liquefied gases to be carried and their properties was established in the pre-Master project [33]. Any other information presented in this subsection is, however, found during the course of working on this Master thesis. It is presented here that it may serve as a foundation for calculations performed in this thesis.

### 1.3.1 Owner's requirements for Gas Lock

The Company has decided that the GL's connection to the cargo tank is to include a gate valve in order to secure it as gas tight. The inner diameter is to be 300 (mm). The valve is not to have any obstructions or sharp edges that may harm or interfere with the bellow.

When fully closed, the GL is to be filled with  $N_2$  as inert gas. The pressure is to be slightly higher than that of the tank design pressure in order to give extra security to maintaining inert environment of the GL.

#### 1.3.2 Principal vessel characteristics

### 1.3.3 Cargo systems

The values in this section is collected from the Carbon Chain Gas Carrier [18], which is a design for a full-scale liquefied gas carrier. The values are presented only to give plausible values for numerical calculations that may occur later in this report.

#### 1.3.4 Tank Type C

As data from external sources comprise drawings for a tank Type C of 3500  $(m^3)$ , this will be used in considerations for structural analyses and function specification of a GL, as well as case studies found later in the report. The drawing is found in appendixA.

Hull dimension	Symbol	Value	Unit
Length overall	Loa	228.0	m
Length between Perpendiculars	Lpp	220.0	m
Breadth	В	31.0	m
Draught	Т	12.1	m
Sailing distance	d	500.0	nm
Vessel speed	V	16.7	kn
Days offhire	OH	4.0	days

Table 1: Principal characteristics

Item	Value	Unit
Cargo tank capacity	$6,\!667$	$\mathrm{m}^3$
Number of tanks	6	
Vessel cargo capacity	40,002	$\mathrm{m}^3$
Minimum allowable tank temperature	-55	$^{\circ}\mathrm{C}$
Maximum allowable tank pressure	6	bar
Maximum cargo density	$1,\!100$	$\rm kgm^{-3}$
Max rate of cool-down	10	$^{\circ}\mathrm{C}\cdot h^{-1}$
Discharge rate (per tank)	445	$\mathrm{m}^{3}h^{-1}$
Loading rate (total)	$3,\!333$	$\mathrm{m}^{3}h^{-1}$

Table 2: Cargo systems

For said cases, data from tables 1 and 2 are used when necessary. The values used will be presented when necessary, in order to avoid confusion.

### 1.3.5 Liquefied gas cargoes

Though, in principle, the RPT is applicable to all liquefied gases, the main focus is to be on *propane*  $(C_3H_8)$  and *carbon dioxide*  $(CO_2)$  as specified by Environgas AS. Though propane is a common cargo, carbon dioxide is not, and has been selected in order to identify special requirements and considerations that must be made.

		Liquid phase	Vapour phase
Temperature	$(^{\circ}C)$	-55.0	-55.0
${\bf Pressure}, {\bf absolute}$	(bar)	6.0	1.0
Density	$(kgm^{-3})$	1150.0	2.3

The properties of these cargoes during transport are as follows:

Table 3: Properties of *carbon dioxide* during transport [33]

		Liquid phase	Vapour phase
Temperature	$(^{\circ}C)$	-42.0	-42.0
Pressure, absolute	(bar)	1.13	1.0
Density	$(kgm^{-3})$	582.0	2.4

Table 4: Properties of *propane* during transport [33]

### 2 Liquefied gases

### 2.1 Liquefied gas introduction

Transportation of liquefied gases is different from the transportation of other liquids; in order to reach the desired saturated liquid state of the gas, it is either pressurized, refrigerated, or a combination of both [9][24].

The cargo tank contains cargo in the two phases liquid and vapour [9][24], which are being separated by a phase boundary [25][24].

Common name	Simple formula	Critical temperature	Atm. boiling point
Methane	$CH_4$	- 161.5	- 82.5
Ethane	$C_2H_6$	- 88.6	32.1
Propane	$C_3H_8$	- 42.3	96.8
n-Butane	$C_{4}H_{10}$	- 0.5	153.0
Ethylene	$C_2H_4$	- 103.9	9.9
Propylene	$C_3H_6$	- 47.7	92.1
Butylene	$C_4H_8$	- 6.1	146.4
Butadiene	$C_4H_6$	- 5.0	161.8
Isoprene	$C_5H_8$	34.0	211.0
Vinyl chloride (VCM)	$C_2H_3Cl$	- 13.8	158.4
Ethylene oxide	$C_2H_4O$	10.7	195.7
Propylene oxide	$C_3H_6O$	34.2	209.1
Ammonia	$NH_3$	- 33.4	132.4

The most common liquefied gases are listed in table 5.

Table 5: Common liquefied gases [24]

Furthermore, the liquefied gases can be divided in categories of saturated and unsaturated hydrocarbons, as well as chemical gases.

Another type of gas often encountered with liquefied gas handling is inert gas.

Inert gas is used on board liquefied gas carriers to inert cargo tanks and to maintain positive pressures in hold and inter-barrier spaces [24]. The reason for this is to prevent formation of flammable mixtures by limiting both oxygen and hydrocarbon contents. Inert gas is either nitrogen (from shore or produced on board), or produced on board by a combustion inert gas generator (IGG). Other gases, like CO<sub>2</sub>, are also inert, but are not commonly used. This may change where ships are transporting  $CO_2$  in an established full-scale CCS scenario (as  $CO_2$  with high purity is more easily obtained).

Component	IG from IGG	$N_2$ Membrane Separating Process
Nitrogen	85 - 89 %	up to 99.5 %
$CO_2$	14 %	
СО	$0.1~\%~({\rm max})$	
$O_2$	1 - $3~%$	> 0.5~%
$\mathrm{SO}_X$	0.1~%	
$NO_X$	traces	
Dew point	- 45 °C	- 65.%
Ash and Soot	present	
Density $(air = 1)$	1.035	0.9672

The different forms of inert gas has the following properties:

Table 6: Inert Gas compositions[24]

The different chemical properties of the liquefied gases results in different operational and structural requirements of cargo containment systems on liquefied gas carriers, depending on the cargo transported. Table 7 shows both common hazards and materials that the common liquefied gases may react with as a result of their chemical properties. These intrinsic properties result in some of the boundaries, and ultimately the principles, that are to be adhered to with liquefied gas handling.

Key properties and compatibilities of the more common liquefied gases are shown in tables 7 and 12  $^{3}$ .

It is impossible to completely discharge a liquefied gas from a cargo tank due to its physical properties [9]. As will be explained in a later section in this report, this calls for certain procedures in order to perform the change of grade

In addition to the gas handling equipment, with change of grade it is necessary to regard the (in)compatibility of the cargoes in question as shown in table 8. This has resulted in

### 2.2 Cargo properties

As stated in Ch 1.3, the cargoes to be considered for transportation in this report are the liquefied gases carbon dioxide and propane. Necessary considerations as well as their properties will therefore be described in this section.

 $<sup>^{3}</sup>x = Incompatible$ 

	Methane	Ethane	Propane	Butane	Ethylene	Propylene	Butylene	Butadiene	Isoprene	Ammonia	Vinyl chloride (VCM)	Ethylene oxide	Propylene oxide	Chlorine
Flammable	х	х	x	x	х	x	x	х	х	x	x	x	x	
Toxic								х		x	x	x	x	x
Polymerisable								х	х		x	x		
Magnesium								х	х			x	x	
Mercury								х	х	x		x	x	x
Zinc										x				x
Copper								х	х	x		x	x	
Aluminium								х	х	x	x	x	x	x
Mild carbon steel	x				x									
Stainless steel												x		
Iron												x	x	
PtFE										x				
PVC										x				
Polyethylene (PE)	x	x	x	x			x							
Ethanol														x
Methanol														x

Table 7: Chemical properties and reactive materials [24]

	Methane	Ethane	Propane	Butane	Ethylene	Propylene	Butylene	Butadiene	Isoprene	Ammonia	Vinyl chloride	Ethylene oxide	Propylene oxide	Chlorine	Water vapour	Oxygen or air	$CO_2$
Methane														х			
Ethane														х			
Propane														х			
Butane														х			
Ethylene														х			
Propylene														х			
Butylene														х			
Butadiene														х	x	x	
Isoprene														х	x	x	
Ammonia												х	х	х			х
Vinyl chloride														х		х	
Ethylene oxide										x						х	
Propylene oxide										x							
Chlorine	х	х	х	x	х	х	х	х	х	x					x		
Water vapour								х	х		х			х			
Oxygen or air								х	x		x	x					
$CO_2$										x							

Table 8: Chemical compatibilities of liquefied gases[24]

#### 2.2.1 Propane

Propane  $(C_3H_8)$  is a saturated hydrocarbon, which makes it flammable as shown in table 7.

Of the cargoes of propane and carbon dioxide, only the former is flammable. Combustion is a chemical reaction (initiated by a source of ignition), in which a flammable vapour combines with oxygen to produce carbon dioxide, water vapour and heat. The reaction can be written as follows [24]:

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O + Heat$$
 (2.2.1)

The table also shows that it may react to PE, and that it is neither toxic nor polymerizable, though it may form hydrates when in presence of moisture. It is a common liquefied gas, and when mixed with butane, they are referred to as Liquefied petroleum gases (LPG) [24]. During transportation the properties of propane are as shown in table 9.

		Liquid	Vapour
Temperature	$[^{\circ}C]$	-42.0	-42.0
Pressure, absolute	[bar]	1.13	1.0
Density	$[kg/m^3]$	582.0	2.4

Table 9: Properties of propane during transport [33]

The DNV Rules states that a ship transporting propane is of either type 2G or 2PG.

### 2.2.2 Carbon dioxide

Carbon dioxide is an inert gas, and is (of the common liquefied gases) only chemically incompatible with ammonia [24].

Today, there is only small-scale transport of  $CO_2$  (mainly in the food industry), and there is no definite standard for its transportation[17]. Audun Aspelund[17] states that  $CO_2$  should be transported in liquid phase near the triple point, which is at 5.5 bar and -55 [°C]. Investigations on large-scale transport of  $CO_2$  suggest that the properties of  $CO_2$  at the mentioned condition are near those of propane, and that the same equipment, with slight modifications may be used in ship transportation[17]. During loading and discharge it should be noted that let-down of pressure from said condition can lead to dry ice-formation<sup>4</sup>, which should be avoided[17].

The conditions of  $CO_2$  at liquid and vapour phase are shown in table 10.

<sup>&</sup>lt;sup>4</sup>Dry ice is  $CO_2$  in solid state

		Liquid phase	Vapour phase
Temperature	$[^{\circ}C]$	-55.0	-55.0
${\bf Pressure}, absolute$	[bar]	6.0	1.0
Density	$[kg/m^3]$	1150.0	2.3

Table 10: Properties of  $CO_2$  during transport [33]

The DNV Rules states that a ship transporting carbon dioxide is of type 3G, though the more stringent type will apply for ships transporting more than one cargo. The ship will therefore be of type 3G.

Furthermore, for this cargo, the following Rules (Pt.5 Ch.5 Sec.15) must be considered:

- A302 Independent tanks
- B1000 Carbon dioxide

They state explicitly that the cargo is to be carried in independent tanks Type C due to the high pressure. Moreover, due to the inert nature of the cargo, some requirements need not be followed in the construction of the system. In this case, however, more than one cargo is to be transported, and these Rules will therefore not be subject to further consideration.

### 2.3 Cargo change procedures

The properties of the liquefied gases to be carried dictates the boundary conditions for the procedures for cargo change.

On change of grade operations the following rules applies as seen in tables 11 and 12.

On a liquefied gas carrier, there are several cargo handling operations. They are explained as presented in the pre-Master report [33]:

- 1. Discharge of cargo
- 2. Removal of remaining liquid
- 3. Warming-up
- 4. Inerting
- 5. Aerating
- 6. Inspection
- 7. Drying

	Butane	Butadiene	Butylene	C-4 Raff	Ethylene
O <sub>2</sub>	< 0.5%	$<\!0.2\%$	< 0.3%	$<\!0.3\%$	< 0.3
Dew-point	-10	-10	-10	-10	-50
LAST CARGO					
Ammonia	Loading a	fter ammoni	ia is often sul	oject to specif	ic terminal reqs
Butane		$N_2, < 5\%$	$N_2I$	ET	$V,N_2$
Butadiene	ET		$N_2I$	$N_2 I < 25\%$	$V,N_2$
Butylene	ET	$N_2, < 5\%$		ET	$V,N_2$
C4-Raff	ET	$N_2, < 5\%$	S		$V,N_2$
Ethylene	S, Heat	$N_2, < 5\%$	$N_2, < 5\%$	S	
Propane	ET	$N_2, < 5\%$	N <sub>2</sub> I	ET	$N_2 < 10^3 \text{ ppm}$
Propylene	ET	$N_2, < 5\%$	$N_2, < 5\%$	ET	$N_2 < 10^3 \ \rm ppm$
Propylene Oxide	$W,V,N_2I$	$W,V,N_2I$	$W,V,N_2I$	$W,V,N_2I$	$W,V,N_2$
Propane Propylene	ET	$N_2, < 5\%$	$N_2I$	ET	$V,N_2$
Vinyl Chloride	$V,N_2I$	$V,N_2$	$V,N_2I$	$V,N_2I$	$V,N_2$
Butane and Propane	S	$N_2, < 5\%$	$N_2, < 25\%$	ET	V,N <sub>2</sub>
C3/C4	ET	N <sub>2</sub>	$N_2, < 25\%$	ET	$V,N_2$

Table 11: Tank Cleaning Procedures pt. 1/2 [24]

	Propane	Propylene	Propylene Oxide	Propane Propylene	Vinyl Chloride	C4-Crude
O <sub>2</sub>	$<\!0.1\%$	$<\!0.3\%$	< 0.1%	< 0.3%	$<\!0.3\%$	
Dew-point	-10	-10	-10	-10	-10	-10
Ammonia	Load	ling after ammonia i	s often su	bject to spe	cific terminal re	eqs
Butane	$V,\!N_2<5\%$	$V,N_2I$	ET	$V,N_2$	S	$V,N_2$
Butadiene	ET	$V,N_2$	$V,N_2$	$V,N_2$	$V,N_2$	$\mathbf{ET}$
Butylene	ET	$V,N_2$	$V,N_2$	$V,N_2$	$V,N_2$	$\mathbf{ET}$
C4-Raff	ET	$V,N_2$	$V,N_2$	$V,N_2$	$V,N_2$	ET
Ethylene	S	$N_2 < 3 \cdot 10^3 \text{ ppm}$	$V,N_2$	ET, Heat	$N_2 < 10^3 \ pp$	S, Heat
Propane		ET	$V,N_2$	ET	$N_2 < 10^3 \ pp$	S
Propylene	ET		$V,N_2$	ET	$N_2 < 10^3 \text{ pp}$	S
Propylene Oxide	$W,V,N_2I$	$W,V,N_2I$		$W,V,N_2I$	$W,V,N_2I$	$W,V,N_2I$
Propane Propylene	$N_2 < 25\%$	$N_2 < 25\%$	$V,N_2$		$N_2 < 10^3 \ pp$	S
Vinyl Chloride	$V,N_2I$	$V,N_2$	$V,N_2$	$V,N_2$		$V,N_2$
Butane and Propane	ET	$V,N_2$	$V,N_2$	S	$V, N_2$	
C3/C4	S	$V,N_2$	$V,N_2$	$V,N_2$	$V,N_2$	

Table 12: Tank Cleaning Procedures pt. 2/2 [24]

Code	Description
W	Water wash
V	Visual inspection
$N_2$	Inert, with nitrogen only
$N_2I$	Inert, with nitrogen or other Inert Gas.
$\mathbf{ET}$	Empty Tank, which is as far as the pumps can go
$\mathbf{S}$	Standard Requirements: Cargo tanks and cargo piping are to be liquid free
	and with $0.5$ bar overpressure (depending on ship type) prior to loading,
	but based on terminal or independent cargo surveyors advice.

Table 13: Explanation to tables 11 and 12 [24]

- 8. Inerting
- 9. Gassing-up
- 10. Cool-down
- 11. Loading

Which of these operations are performed will depend on the cargoes in question, as presented by tables 11 and 12. Save for a few special ones, I have identified four different sets of cargo change procedures [24][29]:

- i) Both current and new cargoes are saturated hydrocarbons (like propane, butane and mixtures of these). After discharge of liquid phase, or emptying of tank (ET), no more procedures are necessary as cross contamination is of little or no consequence.
- ii) In the cases where avoidance of cross contamination is required, but no remnants of solid phase is expected, the tank has to be heated above the flash point of the previous cargo in order to remove said remnants. For most of these cargoes, there is also need for inerting. The IG is then displaced by vapour phase of the next cargo before loading of liquid phase will commence.
- iii) When solid residue is expected as with (vinyl chloride, among others), there is a need for a visual inspection before new cargo may be introduced. This will, in turn require that the cargo tank is filled with breathable air after inerting. After inspection is complete, inerting is performed again before vapour phase of new cargo is introduced and the tank is ready for loading of liquid phase.
- iv) Some cargoes, like propylene oxide, requires water wash in addition to what has been explained in case iii).

Each individual process is explained in greater detail below (in Chapters 2.3.1 through 2.3.10).

In order to show typical times for each of the procedures that these cases comprise, the change from propane to the cargoes of carbon dioxide, butane and ammonia are considered. All numerical calculations and solutions are shown in coloured boxes such as this.

As has been explained in table 12, ammonia are subject to specific terminal requirements. In this report, the procedures for ammonia is considered similar to those on the gas carrier Clipper Hebe [8].

Cross contamination of carbon dioxide and saturated hydrocarbons such as propane is to be avoided. Carbon dioxide is, however, an inert gas and additional inerting procedures are therefore not required. Of this reason, gassing-up and cool-down may commence directly after heating.

### 2.3.1 Discharge

The method of discharge will vary depending on ship type, and thus on tank type design, cargo specifications and terminal storage. The basic methods used are:

- Discharge by pressurising cargo space
- Discharge by pumps
- Discharge via booster pump and cargo heater

Discharge by pressurising cargo space is done using either shore vapour supply, or a vaporizer and compressor on board. This is possible only in which tank type 'C' is used. It is considered slow and inefficient, and is only used on small ships of this reason. By supplying vapour to the cargo tank above the liquid the pressure will increase, thus expelling the liquid.

**Discharge by pumps** is the method adopted by most ships. This is done with submerged or deepwell centrifugal pumps.

Discharge via booster pumps and cargo heater is used when cargo is being discharged from a refrigerated ship to a pressurised storage.

The rate of discharge by use of pumps is often adjusted to the cargo capacity of the tank.

For a cargo tank with 6,667 $(m^3)$  and a discharge rate of 445 $(m^3h^{-1})$ , discharge is completed after: 6667 $(m^3)$ 

$$\frac{6007(m^2)}{555(m^3h^{-1})} = 12.01(h) \approx 12(h)$$
(2.3.1)

### 2.3.2 Warming-up

Depending on tank temperatures and design considerations, it is often necessary to warm up the tanks prior to inerting when aerating will be performed. This is to avoid freezing of  $CO_2$  from within the inert gas, to save inert gas, or dispose of unpumpables. On ships where cargo tanks are at very low temperatures (like LNG ships), warming-up is necessary as the equipment is designed to handle warm gas. This procedure may be done by either circulating warm cargo vapours through the cargo tank [24] or use heat coils in the sump. Normally, however, it is sufficient to pause the cooling and allow for the liquid in the sump to boil off by itself. For a typical ship as described in the introduction, this process will take 12 hours [8] [29].

### 2.3.3 Inerting after discharge

Inerting is performed by introducing inert gas into a tank after cargo discharge and warming-up with the object of reducing existing vapour content to a level [24]:

- i) below which combustion cannot be supported if aeration takes place
- ii) suited to gassing-up prior to the next cargo
- iii) stipulated by local authorities if a special gas-free certificate for hot work is required

Inerting at this stage is done depending on [24]:

- i) desire to gain entry for inspection
- ii) next and last cargo
- iii) charter party terms
- iv) requirements of loading terminal
- v) requirements of receiving terminal
- vi) permissible cargo admixture

There are two procedures that can be used for inerting of tanks[24]:

**Displacement** method relies on stratification by using the differences of density between the inert and cargo gases. The heavier gas is introduced beneath the lighter gas at low velocity to minimise turbulence and dilution. If done properly, only one gas tank volume of inert gas is needed.

Dilution method works by mixing the inert and cargo gases. It can be done by:

- Repeated pressurisation: By using a cargo compressor, the inert gas is pressurised into the tank, and the compressed gas mix is released into the atmosphere. This must be done repeatedly, and can only be done with Type C tanks.
- Dilution by repeated vacuum: Works by using a cargo compressor to repeatedly drawing a vacuum in the tank. The vacuum is broken by insertion of inert gas. This can only be done with Type C tanks where some degree<sup>5</sup> of vacuum is permitted.

 $<sup>^{5}</sup>$ Depending on design, vacuum-breaking valves are set to permit vacuums in the range from 30 to 70 per cent[24]

• Continuous dilution: The process is as described with the former two, but continuous instead of cyclic by releasing the gas mix simultaneously with introduction of inert gas.

These procedures are shown in fig 2 in which LPG vapours are displaced by inert gas from IGG.



Figure 2: Inerting after discharge[24]

For typical capacities (as mentioned in Ch 1.3.3) inerting is likely to take 24 hours is necessary for capacities [8] [29].

### 2.3.4 Aerating

Aerating is the ventilating of tanks with air. This can be done after inerting, but requires ambient conditions. This is shown in fig 3

For aerating a typical tank from fully inert condition to fully breathable air with fans, it will take 24 hours.

### 2.3.5 Visual inspection

A visual inspection of the tank is performed.



Figure 3: Aerating after inerting[24]

Visual inspections are expected to last five hours [29].

### 2.3.6 Drying

Drying is done prior to loading. All free water and water vapour is removed from the system in order to avoid icing and hydrate formation with residual moisture. It is done by using[24]:

**Inert gas from shore**. This is done as a part of the inerting procedure. Moisture contents are lowered to required dew point and oxygen contents are lowered simultaneously. A disadvantage is that more inert gas is used than when simply lowering the oxygen content.

Inert gas from ship's inert gas generator. The same principle as when taken from shore. Inert gas generator (IGG) must create inert gas of a certain quality, though not all specifications are always a design feature of this equipment. **On-board drying systems.** Air is drawn from cargo tank by a compressor and passed through a refrigerated drier. The air is cooled, and the water is condensed and drained off. The air is heated and sent back to the tank.

As the most common way of drying is with inerting (before loading), it will not be subject to consideration in time calculations.

#### 2.3.7 Inerting before loading

This procedure is performed the same way as "Inerting after discharge". In some cases there are special considerations to be taken. Before loading ammonia, it is required to use nitrogen as inert gas.

Time considered taken from fresh air to inert condition is 36 hours [8].

### 2.3.8 Gassing-up

Gassing-up is done by introducing vapour from the next cargo, at ambient temperature, to the tank while venting the inert gas. This is done until the concentration of cargo vapour has reached approximately 90 per cent (or as specified by compressor manufacturer). The main reason for performing this procedure is that the main constituents of inert gas, namely  $CO_2$  and  $N_2$ , can not be condensed by the ship's reliquefaction plant as they are above their critical temperatures at cargo temperatures. They must therefore be removed. Venting alongside or near shore is not always permitted. Gassing-up is therefore done either at sea, using liquid from deck storage tanks (as shown in fig 4 or alongside if a vapour return facility is provided (as shown in fig 5).

Gassing-up is usually done with cool-down, but may take between 6 and 12 hours for typical capacities [29].

### 2.3.9 Cool-down

Before refrigerated cargo is loaded, the tanks are slowly cooled down as the cargo liquid is sprayed in slowly. The vapours are either taken ashore, or sent to the ship's reliquefaction plant as shown in fig 6. This is done in order to minimize thermal stresses, and the rate is therefore dependent on the design of the tank, typically being around 10°Cper hour [24].


Figure 4: Gassing-up with liquid from shore[24]



Figure 5: Gassing-up with vapour from shore[24]



Figure 6: Cargo tank cool-down using liquid from shore[24]

For a tank going from ambient temperature (considered to be 5°C according to DNV [4]) to -55°C, the minimum required time is 6 hours.

## 2.3.10 Loading

When the cargo tank is filled with vapour from the cargo and the cool-down procedure has been completed, the liquid phase of the cargo may be loaded. This is done either with or without vapour return as seen on figs 7 and 8. When vapour return line is unavailable, the rate is dependent on the ship's reliquefaction plant.

For a total cargo tank capacity with  $40,002(m^3)$  and a loading rate of  $3,333(m^3/h)$ , discharge is completed after:

$$\frac{40,002(m^3)}{3,333(m^3h^{-1})} \approx 12(h) \tag{2.3.2}$$



Figure 7: Loading with vapour return[24]



Figure 8: Loading without vapour return[24]

## 2.3.11 Summary of current procedures

As seen from the previous chapters, the current procedures for cargo change include the procedures as shown in table 14, all together with the purpose of preparing the gas handling systems for a new and different type of cargo in a safe manner. The common denominator for these procedures is the displacement of the vapour remnants which occupies the volume inside the cargo tank. As mentioned earlier in this section, this is done by introducing vapours of a new type, which mixes with the current one. By requiring the ship to leave harbour for releasing these gas mixes<sup>6</sup> into the atmosphere <sup>7</sup>, these procedures are not only costly and very time consuming, but also polluting.

The cases to be considered in this report are i), ii) and iii), as they require ET;  $N_2$ , I;  $N_2$ , I, V respectively (as explained in table 13).

Procedure	Unit	Case i)	Case ii)	Case iii)
Discharge	[h]	12	12	12
Warming-up	[h]	12	12	12
Inerting	[h]	0	24	24
Aerating	[h]	0	0	24
Inspection	[h]	0	0	5
Inerting	[h]	0	0	36
Cool-down and Gassing-up	[h]	12	12	12
Loading	[h]	12	12	12
Sum	[h]	48	66	131

Cases i) through iii) are represented by change between propane as previous cargo and the new cargoes of carbon dioxide, butylene and ammonia respectively.

Table 14: Time for cargo change procedures, for cases i), ii) and iii)

Some of the aforementioned procedures includes emissions of cargo vapours, inert gas (IG) or air, depending on the cargoes in question. As stated earlier, with up to 400% of the total cargo tank volume being necessary for purging, it is clear that each such procedure gives up to three times the cargo tank volume of emissions. Thus, emissions of IG and cargo vapours during cargo change procedures are shown in tables 15, 16 and 17 in terms of cargo tank volumes.

<sup>&</sup>lt;sup>6</sup>The gas mix is between 100 and 400 % of the tank volume, resulting in significant volumes [24]. <sup>7</sup>As is the case with most harbours, save for a very few, in which a return facility is available alongside [24]

Procedure	Unit	Previous cargo	IG	Air
Inerting	$(V_{Tank})$	0	0	0
Aerating	$(V_{Tank})$	0	0	0
Inerting	$(V_{Tank})$	0	0	0
Gassing-up	$(V_{Tank})$	3	0	0

Table 15: Emissions for cargo change procedures, Case i)

Procedure	Unit	Previous cargo	IG	Air
Inerting	$(V_{Tank})$	3	0	0
Aerating	$(V_{Tank})$	0	0	0
Inerting	$(V_{Tank})$	0	0	0
Gassing-up	$(V_{Tank})$	0	3	0

Table 16: Emissions for cargo change procedures, Case ii)

Procedure	Unit	Previous cargo	IG	Air
Inerting	$(V_{Tank})$	3	0	0
Aerating	$(V_{Tank})$	0	3	0
Inerting	$(V_{Tank})$	0	0	3
Gassing-up	$(V_{Tank})$	0	3	0

Table 17: Emissions for cargo change procedures, Case iii)

# 3 Tank Type C

This chapter will give an account of the principles and, ultimately, the design criteria of a typical tank type C. These criteria includes (as specified in the Task Definition) factors influencing the tank design such as:

- internal pressure
- wall thickness
- bending moments arising from the tank's method of support
- tank penetration for the GLs.

Where other relevant design criteria are found, they will be mentioned accordingly.

A tank Type C is designed by use of Det Norske Veritas (DNV) "Rules for Classification of Ships - Newbuildings"<sup>8</sup>, making any further analyses extraneous [12]. All analyses in this report is therefore to be done according to the Rules.

## 3.1 Cargo containment system

The Code that applies to new gas carriers (built after 1986) is the International Code for the Constriction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC), by the International maritime organization (IMO) [21], and includes amendments to the Safety of Life at Sea Convention (SOLAS) [24]. The IGC describes several basic cargo tank types. They are of either independent or membrane type [24]:

- Independent type A
- Independent type B
- Independent type C
- Membrane

Independent tank Type A is primarily made of flat surfaces, giving a prismatic cross section. A secondary barrier is required for this type. For temperatures between  $-10^{\circ}$ C and  $-55^{\circ}$ C the ship's hull may serve as second barrier. Furthermore, tank Type A has a a maximum allowable tank design pressure of 0.7 barg, which usually means that cargoes must be carried in a fully refrigerated condition [24].

<sup>&</sup>lt;sup>8</sup>The DNV "Rules for Classification of ships - Newbuildings" is henceforth denoted the "Rules"

Independent tank Type B can be of either spherical or prismatic type. They are subject to much more detailed stress analysis compared to Type A systems, and need only a partial secondary barrier in the form of a drip tray. The Type B spherical tank is almost exclusively applied to LNG ships; seldom featuring in the LPG trade. The prismatic Type B tank has the benefit of maximizing ship-hull volumetric efficiency and having the entire cargo tank placed beneath the main deck. Where the prismatic shape is used, the maximum design vapour space pressure is, as for Type A tanks, limited to 0.7 barg [24].

Independent tank Type C tanks are normally spherical or cylindrical pressure vessels having design pressures higher than 2 barg and are always used for semi- and fully pressurized gas carriers. In the case of the semi-pressurized ships it can also be used for fully refrigerated carriage, provided appropriate low temperature steels are used in tank construction and proper isolation and/or refrigeration is in place. No secondary barrier is required for Type C tanks [24].

As specified in the introduction, the liquefied gases  $CO_2$  and propane are to be considered for cargoes in this report. The properties of which they are to be stored are as specified in the tables 10 and 9 respectively. As specified, it is clear that only an independent tank Type C will meet the requirements due to the pressure of both cargoes at transport conditions.

The cargo containment system is the total arrangement for containing cargo, and comprises, where fitted [24]:

- Primary barrier (cargo tank)
- Secondary barrier (if fitted)
- Associated thermal insulation
- Intervening spaces
- Adjacent structure for support of these elements (if necessary)

A typical arrangement of a cargo containment system for a tank Type C is shown in fig. 9.

### 3.1.1 Tank arrangements

## [24]

There are many different versions and shapes of tanks Type C as they are usually custom made for each ship [24]. A simple version is cylindrical parallel as shown in fig 10.

In some cases the cargo area involves an obstacle or elevation of the hull, and a conical end section is fitted as shown in fig 11.



Figure 9: Arrangement, independent tank Type C







To exploit the breadth to a more full extent, a bilobe construction is used as shown in fig 12.



Figure 12: Type C, bilobe illustration [30]

Typical arrangements are shown in figs 14 and 13 for cylindrical and bilobe tanks type 'C'.



Figure 13: Type C, bilobe arrangement



## No secondary barrier required

Figure 14: Arrangement, independent tank Type C

The tank Type C that is to be considered as specified in Ch. 1.3 is of a cylindrical parallel type.

## 3.1.2 Cargo tank subsystems

There are a number of specific requirements in place by Gas Codes and classification society rules to ensure the safety of operations [24].

**Pipelines** It is not permitted for cargo pump room to be placed, or cargo pipelines to be run below upper deck level. There are at several consequences of this; deepwell or submersible pumps have to be used for cargo discharge, and pipelines to the cargo tank are taken through a cargo tank dome that penetrates the deck [24]. This is usually done by means of a flexible and air tight rubber material [13]. Also, a typical liquefied gas carrier's deck is often somewhat crowded with pipelines as shown in fig 15. The tops of the deck tanks are marked with green.

When starting or stopping flow through pipelines, surge pressures may cause lateral or vertical displacements. Of this reason parts of the pipeline systems are fitted with strong anchor points [24] as shown in fig 16. The major temperature differences between ambient and cargo temperatures, together with little or no insulation make pipelines particularly susceptible to thermal expansion and contraction. A typical solution involves adapting the geometry of the pipe between anchor point and structure (i.e. dome), forming a spool, or z-shaped construction as illustrated in fig 17. Here, the angle due to thermal elongation (or contraction) will be of no or little consequence. If so is considered, it may be necessary with flexible joints as shown in fig 18. It may be necessary to support the weight without transferring forces due to thermal expansion, which may be done with either a hanger or a spring for support [7]. For this purpose, the Rules [5] mentions solid hangers, sway braces and guides.

Tank domes and manifolds are shown in figs 19 and 20, and 21 respectively. It should be noted that (as shown in fig 21) the cargo manifolds are fitted with a double valve arrangement, in which one is remotely controlled, and one of the manual type.

Flow through most pipe systems is turbulent [35], which may be described by a Reynolds number:

$$R_e = \frac{\rho D v}{\mu} \tag{3.1.1}$$

where,



Figure 15: LPG carrier deck level with pipelines



Figure 16: Concept of anchors and flexible joints in a pipeline



Figure 17: Thermal expansion of pipeline



Figure 18: Expansion joint



Figure 19: Cargo tank dome

 $\rho = \text{fluid density } (kgm^{-3})$  D = pipe diameter (m)  $v = \text{fluid velocity } (ms^{-1})$   $\mu = \text{absolute viscosity } (Nsm^{-2})$ 

As pipe systems come with valves, bends, pipe diameter changes, elbows etc., all which contribute to energy (head) loss [35]. This loss needs to be considered when designing pipe systems, and is often done by applying the energy equation, which is based on the Bernoulli equation.

$$\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + Z_1 + h_P = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + Z_2 + h_L$$
(3.1.2)

where,

 $p_1 = \text{pressure } (Nm^{-2}) \text{ at location } 1$   $p_2 = \text{pressure } (Nm^{-2}) \text{ at location } 2$   $\gamma = \rho g \ (kgm^{-2}s^{-2})$   $Z_1 = \text{height } (m) \text{ at location } 1$   $Z_2 = \text{height } (m) \text{ at location } 2$   $h_P = \text{pump head } (m)$  $h_L = \text{head loss } (m)$ 



Figure 20: Cargo tank dome [13]



Figure 21: Cargo manifolds

For  $Z_1=Z_2$ , constant pipe diameter and no pump in operation, we know that  $v_1 = v_2$  such that:

$$\frac{p_1}{\gamma} = \frac{p_2}{\gamma} + h_L$$
 (3.1.3)

$$\begin{array}{c} \gamma & \gamma \\ \Delta p = \gamma h_L \end{array} \tag{3.1.4}$$

which is called the Darcy-Weisbach equation.

The head loss is often divided into major loss,  $h_{L,major}$  and minor loss,  $h_{L,minor}$ . The former is from viscosity (in a straight pipe), while the latter is from energy loss in components such as bends and values.

For fluid flow in a pipe, the pressure loss is dependent on several components, but may be derived from dimensional analysis [35]. This results in:

$$\Delta p = \mathbf{F}(v, D, L, \epsilon, \mu, \rho) \tag{3.1.5}$$

$$\Delta p = f \rho \frac{v^2}{2} \frac{L}{D} \tag{3.1.6}$$

where,

L = Length (m) $\epsilon = \text{surface roughness } (mm)$  It is clear that the friction factor, f, is a key aspect of the major head loss,  $h_{L,major}$ . For turbulent flows, this factor may be found as a function of the Reynolds number. This is often done by help of a moody diagram as shown in fig 22. Here, we have:

$$f = F(R_e, \frac{\epsilon}{D}) \tag{3.1.7}$$

or, more precisely as the Moody formula is expressed [35]:

$$f = 0.0055(1 + (20,000\epsilon + \frac{10^6}{R_e})^{\frac{1}{3}})$$
(3.1.8)



Figure 22: Moody diagram

As mentioned above, the minor losses,  $h_{L,minor}$ , are dependent on the components in the system. These are:

- Valves
- Inlets and outlets
- Bends
- Diameter changes

#### • Branches

The minor loss is usually described by means of the loss coefficient,  $K_L$ . This is defined as [35]:

$$K_L = \frac{h_{L,minor}}{v^2/2g} = \frac{\Delta p}{0.5\rho v^2}$$
(3.1.9)

Typical values for  $K_L$  are 0.5 for 90° bends, 1 for outlet to a tank (regardless of geometry), and between 1 and 0 for inlet from a tank, depending on geometry [35].

The full equation for head loss,  $h_L$  is then:

$$h_L = h_{L,major} + h_{L,minor} \tag{3.1.10}$$

$$= \frac{v^2}{2g} \left( \frac{fL}{D} + \sum K_L \right)$$
 (3.1.11)

Forces and moments are also generated by the flow itself. With an outlet to a large container, for a fluid with density,  $\rho$  ( $kgm^{-3}$ ), where the mass rate,  $\dot{m}$  ( $kgs^{-1}$ ) and fluid velocity v ( $ms^{-1}$ ) are zero (as can be found with most large containers), the thrust due to the change of momentum at the outlet is [34]:

$$F_{outlet} = \dot{m}v - \dot{m}_0 v_0$$
(N) (3.1.12)

$$= \dot{m}v (\mathbf{N}) \tag{3.1.13}$$

where,

$$\dot{m} = \rho q \ (kgs^{-1})$$

In addition to inlets and outlets, there are centrifugal forces and moments arising from the fluid with bends in the pipeline system [34]. For a 90° bend with radius, R, the centrifugal force can be expressed as:

$$F_{centrifugal} = \frac{\pi}{2R} \dot{m} v \text{ (N)}$$
(3.1.14)

The centrifugal force in a  $90^{\circ}$  bend works outward,  $120^{\circ}$  from flow input and output of bend.

**Cargo valves and strainers** [24] For Type C tanks<sup>9</sup> the principal liquid and vapour connections on the tank dome (except relief valve connections) should be fitted with a double valve arrangement. This is to comprise one manually operated globe valve and a remotely operated isolation valve fitted in series. These are of the fail-safe type, usually either ball, globe, gate or butterfly valves that are fitted with pneumatic or hydraulic actuators [24]. Such a valve can be seen in fig 23.



Figure 23: Gate valve

Supports As an independent tank is neither contributing to the hull structure nor strength of the ship, it follows that the supports, or foundation, on which the tank is mounted is to function accordingly.

The Rules [3, Sec.5, A1100 Supports] states that cargo tanks are to be supported by the hull in a manner which will prevent bodily movement of the tank under static and dynamic loads, while allowing contraction and expansion of the tank under temperature variations and hull deflections. This is to be done without undue stressing of the tank or the hull.

Moreover, the Rules prefers horizontal tanks Type C to be supported by two saddle supports only, which are bearing at least 140° of the circumference. All these requirements results in most tanks Type C being simply supported as illustrated in figs 24 and 25, in which the supports are shown in red.

 $<sup>^9\</sup>mathrm{More}$  precisely, for cargo tanks with a maximum allowable relief valve setting (MARVS) greater than 0.7 barg



Figure 24: Simply supported beam principle

The tank is thus constrained from moving in longitudinal, transverse and vertical directions, though allowing for thermal expansion or contraction.



Figure 25: LPG tank, supports

The supports may, however, contribute to tank stresses by form of friction with thermal expansion and contraction, or ship deflection, which is explained in eq 3.2.1.

Stiffening rings Any forces and moments that arise from ship or tank movement (i.e. ship deflection or lifting of tank) need to be transferred between the supports and the tank itself. For this purpose, an independent tank is fitted with stiffening rings as shown in fig 26.

Lifting of a tank by its stiffening rings (from or onto its supports) is shown in fig 25.

The Rules states that for cylindrical shells with uniform external pressure, stiffening



Figure 26: Stiffening rings in a bilobe tank Type C [30]

rings shall extend completely around the circumference of the shell [3, I 705]. There are also requirements to its moment of inertia [3].

Swash bulkhead is installed in order to support stiffeners [3] and to reduce swashing of liquid due to ship movements (see fig 27).

Vacuum rings are installed as circled in fig 28 in order to avoid buckling when there is vacuum pressure in the cargo tank.

Figure 29 gives an indication of the inner topology of a typical tank Type C with all the mentioned equipment present.

## 3.2 Design criteria

As mentioned, a tank Type C may be designed by use of the Rules only. In order to understand these design criteria, the underlying principles are explained first.

According to the SIGTTO Liquefied Gas Handling Principles [24] the most important physical property of a liquefied gas is its saturated vapour pressure-temperature relationship.



Figure 27: Swash bulkhead in bilobe tank [30]



Figure 28: Vacuum rings on tank Type C (from appendix A)



Figure 29: Tank Type C, with inner topology

This property governs the design of the tank containment system by means of direct influence on design stress, and has a strong influence on economic considerations by means of material wall thickness. To a lesser degree, the design is also subject to the compatibility and chemical reactivity with the various cargoes [24]. These considerations are formalized by various Gas Codes agreed by the International Maritime Organization (IMO) and apply to all gas carriers.

## 3.2.1 General requirements

This section deals with the different requirements for a tank Type C as found in the Rules.

**Design stress** The design stresses are determined by using the minimum specified mechanical properties of the material used.

Also, for design against excessive plastic deformation and bursting, the Rules requires the equivalent primary stress to be:

$$\sigma_t \le \frac{\sigma_B}{A}$$
$$\sigma_t \le \frac{\sigma_F}{B}$$

where A and B vary between 1.5 and 4 as given by the Rules [3, Sec.5, I301], and

 $\sigma_F$  = the specified minimum upper yield stress at room temperature (Nmm<sup>-2</sup>)  $\sigma_B$  = the specified minimum tensile strength at room temperature (Nmm<sup>-2</sup>)

Longitudinal stress in the tanks cylindrical shell,  $\sigma_z$ , is given in the Rules [3, Sec.5, I400] as shown in eq. 3.2.1:

$$\sigma_z = \frac{p_0 R^2}{10(2R+t)t} + \frac{W}{\pi(2R+t)t} + \frac{4M*10^3}{\pi(2R+t^2)t}$$
(3.2.1)

Also, for design against excessive plastic deformation and buckling respectively, the Rules requires:

$$\sigma_z \le 0.8\sigma_t e \tag{3.2.2}$$

and

$$\sigma_z \le \frac{0.20E\frac{t}{R}}{1+0.004\frac{E}{\sigma_F}} \tag{3.2.3}$$

where,

t=minimum required thickness of shell, exclusive of corrosion allowance (mm)

 $p_0$ =maximum allowable vapour pressure defined in A300 (bar)

R=inside radius of shell or shell section (mm)

M=longitudinal bending moment (Nm) e.g. due to

-mass loads in a horizontal vessel

-eccentricity of the centre of working pressure relative to the neutral axis of the vessel -friction forces between the vessel and a saddle support

W=axial force on shell, positive if tensile, excluding pressure load due to  $p_0$  (N)

E=Modulus of elasticity (Nmm<sup>-2</sup>)

e=joint efficiency

=1 for tank Type C pressure vessels

Wall thickness There are requirements to both minimum and maximum thickness of a tank Type C.

According to the Rules [4, Sec.4 C200], the thickness of a cylindrical shell shall not be less than:

$$t = \frac{p_{eq}R}{10\sigma_t e - 0.5p_{eq}} + c \;(\text{mm}) \tag{3.2.4}$$

where

$$p_{eq}=p_0 + (p_{gd})_{max}$$
 (bar)  
 $c=$ corrosion margin, (Pt.4 Ch.7 Sec.4 B700)  
 $=1$  for carbon and low-alloy steels

The Rules [3, Pt.5 Ch.5 Sec.5 I1100] dictates that the maximum shell thickness, t, on a tank is 40 (mm). This is in order to allow for mechanical stress release of the tank. Greater thickness may be accepted by parts that can be thermally released of stress, though this is not feasible for the entire tank.

Tank length Due to damage stability considerations, the maximum tank length is found to be around  $40 \pmod{10}$ .

## 3.2.2 Loads

The Rules [3, Pt.5 Ch.5 Sec.5] dictates that the following are to be considered in the design of a tank Type  $C^{10}$ :

- i) Static loads (A600)
- ii) Dynamic loads (A704, A705, A706)
- iii) Sloshing loads (A800)
- iv) Thermal loads (A900)
- v) Vibration (A1000)
- vi) Supports (A1100)

In addition, the Rules [3] consider the hazards of:

<sup>&</sup>lt;sup>10</sup>Independent tanks Type C are tanks meeting pressure vessel criteria as given in the Rules [3, Sec. 1 D700]

- a) Fire
- b) Toxicity
- c) Corrosiveness
- d) Reactivity

The items i) through vi) will therefore be considered as the basis for the design criteria. The hazards will be mentioned but not subject to further consideration.

The stress on a tank is due to its loads, which are mainly from internal vapour pressure. The relevant loads are therefore discussed here. As the requirements and equations in the Rules also contain empirical factors, the principles will be explained first:



Figure 30: Tank type 'C', Hamworthy

The design of a typical tank designed to withstand internal pressure can usually be divided in a cylindrical part with hemispherical ends as shown in fig 30 as given in appendix A. Due to the large radius-to-wall thickness ratio of such tanks, they are considered thin-walled.

From said figure it is noted that the radius,  $r = 6376 \ [mm]$  and wall thickness (at its maximum),  $t = 49.5 \ [mm]$ . This yields:

$$\frac{t}{r} = \frac{49.5}{6376} \approx 0.0078 \ll 1 \tag{3.2.5}$$

Thus it is demonstrated that this tank is thin-walled.

As stated by Irgens [23], the stress experienced for a thin-walled cylindrical tank with:

inner gauge pressure, pthickness, tradius, r

can be written in  $\theta$  and z directions (as shown in fig 31) as found in equations (3.2.6) and (3.2.7) respectively.

$$\sigma_{\theta} = \frac{r}{t}p \tag{3.2.6}$$

$$\sigma_z = \frac{r}{2t}p = \frac{\sigma_\theta}{2} \tag{3.2.7}$$



Figure 31: Stress components of a cylindrical tank

For a sphere, the stress in tangential direction can be written as [23]:

$$\sigma_{\phi} = \frac{\pi r^2 p}{2\pi r t} = \frac{r}{2t} p = \frac{\sigma_{\theta}}{2}$$
(3.2.8)

Thus, it is clear that the radial stress,  $\sigma_{\theta}$ , is the constraining factor from the internal pressure. This is, however, a rather simplified view of a more complex situation where more than a uniform, static, internal pressure is to be considered.

The Rules [3, Pt.5 Ch.5 Sec.5] dictates that the following are to be considered in the design of a tank Type  $C^{11}$ :

- i) Static loads (A600)
- ii) Dynamic loads (A704, A705, A706)
- iii) Sloshing loads (A800)

 $<sup>^{11} \</sup>mathrm{Independent}$  tanks Type C are tanks meeting pressure vessel criteria as given in the Rules [3, Sec. 1 D700]

- iv) Thermal loads (A900)
- v) Vibration (A1000)
- vi) Supports (A1100)

Definition of tank Type C (DNV Pt. 3 Ch.5 Sec.1 D700)

Independent tanks type C (also referred to as pressure vessels) are tanks meeting pressure vessel criteria and having a design vapour pressure  $p_0$  not less than:

$$p_0 = 2 + AC\rho^{1.5} \text{ bar} aga{3.2.9}$$

where,

$$\begin{split} &A = 0.0185 (\frac{\sigma_m}{\Delta \sigma_a})^2 \\ &\Delta \sigma_A = \text{allowable dynamic membrane stress} \\ & (\text{double amplitude at probability level } (Q = 10^{-8}) \\ &= 55 \text{ Nmm}^{-2} \text{ for ferritic-perlitic, martensitic and austenitic steels} \\ &= 25 \text{ Nmm}^{-2} \text{ for aluminium alloy } (5083-0) \\ &C = \text{a characteristic tank dimension to be taken as the greatest} \\ & \text{of the following: h, 0.75 b, or 0.45 l} \\ &h = \text{height of tank exclusive dome (dimension in ship's vertical direction) (m)} \\ &b = \text{width of tank (dimension in ship's transverse direction) (m)} \\ &l = \text{length of tank (dimension in ship's longitudinal direction (m)} \\ &\rho = \text{the relative density of the cargo at the reference temperature} \\ & (\rho = 1 \text{ for fresh water of } 4^\circ\text{C}) \end{split}$$

The dynamic pressure differential  $\Delta p$  shall be calculated as follows:

$$\Delta p = \frac{\rho}{1.02 \cdot 10^4} (a_{\beta 1} Z_{\beta 1} - a_{\beta 2} Z_{\beta 2}) \text{ bar}$$
(3.2.10)

where  $\rho$ ,  $a_{\beta}$ ,  $Z_{\beta}$  are as defined in Sec.5 A706, (see also figs 32 and 32).  $a_{\beta 1}$  and  $Z_{\beta 1}$  are the  $a_{\beta}$  - and  $Z_{\beta}$  -values giving the maximum liquid pressure  $(P_{gd})$  max.  $a_{\beta 2}$  and  $Z_{\beta 2}$  are the  $a_{\beta}$  - and  $Z_{\beta}$  - values giving the minimum liquid pressure  $(P_{gd})$  min.

In order to evaluate the maximum pressure differential,  $\Delta p$ , pressure differentials shall be evaluated over the full range of the acceleration ellipse as shown in figs 32 and 33.



Figure 32: Acceleration ellipse used to evaluate pressure differential 1/2 [3]



Figure 33: Acceleration ellipse used to evaluate pressure differential 2/2 citeDNV505

DNV Rules, Static loads (Pt. 5 Ch.5 Sec.5 A600 Static loads)

The static load is to be considered due to the 98% filling by volume of the tank. The Rules state that the design pressure  $p_0$  shall not be taken less than:

- 1. MARVS setting.
- 2. The pressure of the inert gas for tanks unloaded by means of inert gas.

The design external pressure,  $p_e d$ , shall be based on the difference between the minimum internal pressure (maximum vacuum) and the maximum external pressure to which the tank may be subjected simultaneously. The design external pressure shall be based on the following formula:

$$p_{ed} = p_1 + p_2 + p_3 + p_4 \tag{3.2.11}$$

where,

- $p_1 =$  opening pressure of the vacuum relief valves. For tanks not fitted with vacuum relief valves,  $p_1$  shall be specially considered, but is generally not to be taken less than 0.25 bar.
- $p_2 =$  for tanks or part of tanks in completely closed spaces: the set pressure of the pressure relief valves for these spaces. Elsewhere  $p_2 = 0$
- $p_3 =$ external head of water for tanks or part of tanks on exposed decks, elsewhere  $p_3=0$ .

 $p_3$  may be calculated using the formulae given in Sec.5 E303 multiplied by the factor c given in Pt. 3 Ch.1 Sec.10 C100.

 $p_4 = compressive actions in the shell due to the weight and contraction of insulation, weight of shell, including corrosion allowance, and other miscellaneous external pressure loads to which the pressure vessel may be subjected. These include, but are not limited to, weight of domes, weight of towers and piping, effect of product in the partially filled condition, accelerations and hull deflection. In addition the local effect of the local effect of external or internal pressure or both should be taken into account.$ 

Static forces imposed on the tank from deflection of the hull are also to be considered.

## DNV Rules, Dynamic loads (Pt. 5 Ch.5 Sec.5 A700 Dynamic loads)

Dynamic loads are from accelerations acting on the tanks. According to the Rules, they are estimated at their centre of gravity and include the following components:

• vertical acceleration (motions acceleration of heave, pitch and, possible, roll (normal to ship base)):

$$a_z = \pm a_0 \sqrt{1 + (5.3 - \frac{45}{L})^2 (\frac{x}{L} + 0.05)^2 (\frac{0.6}{C_B})^{\frac{3}{2}}}$$
(3.2.12)

• transverse acceleration (motions acceleration of sway, yaw and roll, as well as gravity component of roll):

$$a_y = \pm a_0 \sqrt{0.6 + 2.5(\frac{x}{L} + 0.05)^2 + x(1 + 0.6\frac{\kappa z}{B})^2}$$
(3.2.13)

• longitudinal acceleration (motions acceleration of surge and pitch, as well as gravity component of pitch):

$$a_x = \pm a_0 \sqrt{0.06 + A^2 - 0.25A} \tag{3.2.14}$$

where,

$$\begin{split} A &= (0.7 - \frac{L}{1200} + 5\frac{z}{L})(\frac{0.6}{C_B}) \\ x &= \text{longitudinal distance from amidships to centre of gravity of the tank with content (m). x is positive forward of amidships, negative aft of amidships. \\ z &= \text{vertical distance from the ship's actual waterline to the centre of gravity of tank with content (m). z is positive above and negative below the waterline. \\ a_0 &= \frac{0.2V}{\sqrt{L}} + \frac{34 - \frac{600}{L}}{L} \\ V &= \text{service speed (knots)} \\ \kappa &= 1, \text{ but may for some conditions and hull forms be written as:} \\ &= \frac{13GM}{B}, \ (\kappa \leq 1, \text{GM} = \text{metacentric height (m)}) \end{split}$$

Omitting sloshing effects, the internal pressure can therefore be expressed as explained in eq 3.2.5.

The internal liquid pressures are those created by the resulting acceleration of the centre of gravity of the cargo due to the motions of the ship. The following formula gives the value of internal liquid pressure, resulting from combined effects of gravity and dynamic acceleration:

$$p_{gd} = \frac{a_{\beta} Z_{\beta} \rho}{1.02 \cdot 10^4}$$
 (bar) (3.2.15)

where,

- $a_{\beta}$ =the dimensionless acceleration (i.e. relative to the acceleration of gravity) resulting from gravitational and dynamic loads, in an arbitrary direction  $\beta$  (as shown in fig 34)
- $\rho$ =the maximum density of the cargo in  $kg/m^3$  at the design temperature
- $Z_{\beta}$ =largest liquid height (m) above the point where the pressure shall be determined measured from the tank shell in the  $\beta$  direction (as shown in fig 35 Tank domes considered to be part of the accepted total volume should be

taken into account when determining  $Z_{\beta}$  unless the total volume of tank domes  $V_D$  does not exceed the following volume:

$$V_D = V_T (\frac{100 - FL}{FL} \ (m^3)$$
(3.2.16)

where,

 $V_T$  = tank volume without any domes  $(m^3)$ FL = Filling limit according to Sec. 17 A101 or 103 in %

DNV Rules, Sloshing loads (Pt. 5 Ch.5 Sec.5 A800 Sloshing loads)

In the event of partial filling of the tank, sloshing induced by the accelerations mentioned in eqs 3.2.12, 3.2.13 and 3.2.14 are to be considered.

DNV Rules, Thermal loads (Pt. 5 Ch.5 Sec.5 A900 Thermal loads)

The Rules dictates transient thermal loads during cooling-down periods to be considered for tanks intended for cargoes with a boiling point below -55°C. Also, stationary thermal loads shall be considered for tanks where design, supporting arrangement and operating temperature may give rise to significant thermal stresses.

Thermal insulation is fitted to refrigerated cargo tanks in order to [24]:

- Minimize the heat flow into the cargo tanks, thus reducing boil-off.
- Protect the ship structure around the tanks from the effects of low temperature.



Figure 34: Resulting acceleration (static+dynamic)  $a_{\beta}$  in arbitrary direction  $\beta$  [3]



Figure 35: Liquid heights,  $Z_{\beta}$ , for check points I-V in the  $\beta$ -direction [3]

The DNV Rules has requirements to material qualities that are determined on basis of the lowest temperatures in the material [3].

Materials for cargo tanks, piping systems and related equipment are to comply with the Rules, and dictates chemical compositions of materials, minimal and maximal thicknesses [3].

## DNV Rules, Vibration (Pt. 5 Ch.5 Sec.5 A1000 Vibration)

Design of hull and cargo tanks, choice of machinery and propellers shall be aimed at keeping vibration exciting forces and vibratory stresses low. Beyond that, calculations are rarely necessary in the case of independent tanks Type C.

## 3.2.3 Openings and reinforcements

Openings and their reinforcements are to be in compliance with the Rules [4, Sec.4 I600].

The following Rules apply to, among others, circular openings where the distance between the axes is more than 1.5 times the average diameter of the openings, and the inside diameter of the opening is not exceeding one third of the shell inner diameter.

For openings with inner diameter,  $d_i$ , greater than 150 (mm), reinforcements are required. On each side of the centre line of the opening the required area of reinforcement,

A, is:

$$A \ge K(\frac{d_i}{2} + t_b)t \ (\mathrm{mm}^2)$$
 (3.2.17)

where

- $t_b$ =thickness in mm of the branch calculated from the formula in Sec.5 G101
  - with c = 0. For elliptical or obround reinforcement rings the chord length
  - in the plane being considered shall be used in determining  $\mathbf{t}_b$
- k=1 for spherical shells and for planes passing through the generatrix for cylindrical and conical shells
  - =0.7 for planes normal to the generatrix for cylindrical or conical shells.

For oval openings in cylindrical and conical shells the reinforcement shall be determined in a plane passing through the generatrix (fig 36) and in a plane normal to the generatrix (fig 37). For spherical shells the reinforcement shall be determined in a plane passing through the major diameter of the opening. All planes shall pass through the centre of the opening and shall be normal to the wall.



Figure 36: Reinforcement area, K = 1

As shown in fig 36, the reinforcement material is to be located:



Figure 37: Reinforcement area, K = 0.7
$$L_S = \sqrt{(D_i + t_a)t_a} \ (\mathrm{mm}) \tag{3.2.18}$$

$$L = 0.8\sqrt{(d_i + t_{ba})t_{ba}} \ (\text{mm}) \tag{3.2.19}$$

The Rules also states that if two openings are sufficiently closed spaced for the limits of compensation in the shell to overlap, the limits of compensation shall be reduced so that no overlap is present.

For cargo tank domes, the Rules [3, Pt.5 Ch.5 Sec.4 A103] state that the minimum distance between a cargo tank dome and other deck structures shall not be less than 150 mm. This is shown in fig 38.



Figure 38: Minimum distance requirement between cargo tank dome and deck structures

The Rules [4, Sec.6 Mountings and fittings]states that Valves exceeding 50 mm in diameter shall be fitted with outside screws, and the covers shall be secured by bolts or studs.

#### 3.2.4 Hazards

As mentioned, the Rules requires the hazards of fire, toxicity, corrosiveness and reactivity to be considered.

Fire As has been found earlier, propane is flammable. Flammability is, however, considered beyond the scope of this report, and will not be subject to further consideration.

Toxicity is related to poisoning of personnel due to exposure [24], but will not be considered any further of same reason as "Fire".

**Corrosiveness and reactivity** Degree of corrosiveness and reactivity may indicate if special concerns are to be given to choice of material and gas handling equipment. Material selection is to be done as specified in the Rules for Metallic Materials [6].

Also, as explained in eq 3.2.5, for the most common materials, there is usually calculated 1(mm) extra thickness due to corrosion.

This subject is also not to be considered any further of same reason as for "Fire" and "Toxicity".

# 3.2.5 Summary of design criteria

With the stress components from the saddle support system considered minor or negligible, the key loads affecting the stress on a tank Type C are the dynamic and static pressures, which constitutes  $p_{eq}$ .

Thus, as is shown in eq 3.2.4, the design criteria can ultimately be described by the maximum tank diameter, which is a function of the variables of pressure, p, allowed thickness, t, and the equivalent primary stress,  $\sigma_t$ . The maximum shell thickness, t, of a tank is 40 (mm). Due to damage stability considerations, the maximal length of a tank is limited to 40 meters.

With a typical tank transporting carbon dioxide at -55°C, density of 1150 (kgm-3) at design pressure, p<sub>0</sub> of 5 (bar), the tank diameter is effectively limited to a maximum of about 15.5 meters [1]. With The calculations for this case is based on a tank volume of 6667  $(m^3)$  and ship characteristics as described in Ch 1.3.2.

In addition to geometry, openings (also referred to as tank penetrations) are governed by their inner diameter. This property will, in turn, govern the need for reinforcements. Reinforcement requirements comprises thickness of both tank and branch, as well as inner diameter of opening.

# 4 Bellow system

This section will contain descriptions of the bellow system, which is a key component of the RPT. First, the very rationale for the technology will be considered, followed by a detailed description of the bellow system and its operation. This section will also account for potential problems and challenges, as well as solutions by means of in-principle methods of execution.

# 4.1 Rationale for Rapid Purge Technology

As stated in Ch 1, the existing procedures for cargo change on liquefied gas carriers are time consuming, expensive and polluting. These economic and environmental aspects forms the rationale for developing new methods, and ultimately, the RPT.

The system is designed to displace the remaining gas phase of the previous cargo. This is to be done by inflating several bellows that will occupy the entire volume of the interior of the cargo tank. During transit and until the liquid in the cargo tank has been discharged, the bellows are stored in containers on top of the cargo tank. When the liquid phase of the cargo has been discharged from the cargo tank, they are released into the cargo tank. They are then filled with inert gas, and only inert gas, which is distributed from a deck tank. When all remaining vapours in the cargo tank have been displaced to terminal or a deck tank, the bellows are deflated while gas phase of a new cargo is introduced. Finally, the bellows are retracted into their respective containers for disposal at a later stage. This will be explained in greater detail later in this chapter.

Moreover, by introducing the RPT there will be no emissions of vapours from the cargo tanks to the atmosphere, and the ship does not need to leave harbour as with some of the current procedures. Implementation of such a technology will therefore greatly reduce the time spent on cargo change, which should be beneficial in both economic and environmental terms. The times consumed for the different cargo change procedures for a certain ship are as found in the pre-Master project[33], from the "Gasform C" for Clipper Hebe from Solvang [8] as well as Environges' application documents for EU FP7 (EU Framework Programme 7) [29].

In Ch. 2.3.11, the cases i) through iv) for procedures for cargo change were explained. The RPT is relevant for the cases ii) through iv) as they include inerting, aerating and other procedures. As cases iii) and iv) are similar (save for the water washing procedures in iv), which the RPT will not have any impact on), only case ii) and iii) will be considered further when determining the rationale with the RPT.

Some procedures with RPT takes place simultaneously and are therefore not to be counted when finding the total time. This applies in particular to the operations of inflating and deflating the bellows. The procedures to be counted (with RPT) are shown in **bold letters** in the table below.

		Case ii)		Case iii)	
Procedure		$(N_2,I)$	(RPT)	$(N_2,I,V)$	(RPT)
Discharge	(h)	12	12	12	12
Warming-up	(h)	12	12	12	12
Inflating of bellows	(h)	0	6	0	6
Inerting	(h)	24	6	24	6
Aerating	(h)	0	0	24	6
Empty bellow	(h)	0	0	0	6
Visual inspection	(h)	0	0	6	6
Inflating of bellows	(h)	0	0	0	6
Inerting	(h)	0	0	36	12
Cool-down and Gassing-up	(h)	12	6	12	6
Empty bellow	(h)	0	6	0	6
Loading	(h)	12	12	12	12
Sum	(h)	72	48	138	78
$T_P$	(days)	6.00	4.00	11.50	6.50

Table 18: Time with procedures for cargo change

#### 4.1.1 Economic and environmental benefits

The evaluation performed in this section is based on a typical industrial shipping agreement for a particular cargo or route service. This is somewhat similar to a Charterparty, save for the exemption of harbour dues, fuel and other voyage related costs. As mentioned, there are both economic and environmental benefits to the use of RPT, though they are of greater significance in the cases ii) and iii) as explained in Ch 2.3.

**Economic benefits** As presented in table 18, the main benefit with use of the RPT is less time spent with procedures for cargo change, which will reduce time spent in port,  $T_p$ .

The different values for $T_p$ for case ii) are:					
	Case ii)		Case iii)		
	$(N_2, I)$	(RPT)	$(N_2, I, V)$	(RPT)	
	6.00	4.00	11.50	6.50	

The effect of a reduction of time in port,  $T_p$  will differ, depending on the overall logistical/supply chain system in question. Possible scenarios where the economical effect of reduced time in port is of no consequence (i.e. improvement of local optima does not affect the overall system) is beyond the scope of this report and will not be subject for consideration. In order to view the potential of the technology it is only of interest to regard cases where the time in port is to be considered a constraining resource.

The reduction of  $T_p$  can therefore be analysed with regard to the annual transport capacity, Q, of a ship. Here, Q is analysed based on production theory. Considering the ship's cargo capacity and the speed as the two primary production factors, the annual ship capacity can be given as shown in eq. 4.1.1 [16]:

$$Q = q \frac{365 - OH}{T}$$
(4.1.1)

$$=q\frac{365 - OH}{T_p + d \cdot (24V)^{-1}} \tag{4.1.2}$$

where,

Q = Annual ship transport capacity	$(t \cdot year^{-1}, m^3 \cdot year^{-1})$
q = Vessel cargo capacity	$(t, m^3)$
d = Sailing distance	(nm)
OH = Days offhire	( - )
T = Roundtrip time	(days)
$T_p = Time in port, per roundtrip$	(days)
V = Vessel speed	$(\mathrm{kn})$

The economical benefits of reduced time in port will therefore be regarded in the two ways:

- i) Q increased, V unaltered
- ii) Q unaltered, V decreased

To examine the effect of a reduction of time in port,  $T_p$ , in a proper manner it will be necessary to eliminate some of the variables. This is done here by setting specific values to the variables that are usually fixed on a ship operating in a specific trade route. These values are here assumed to be as shown in table 1.

 $\begin{array}{ll} q = 40,002 & (m^3) \\ d = 500 & (nm) \\ OH = 5 & (days) \\ V = 20 & (kn) \end{array}$ 

Q increased, V unaltered: For a specific ship in a specific trade route as shown above, we may present the equation for different values of  $T_p$  in a 3D plot as shown in fig 39. Here, the two graphs in green-blue hue is Case ii), while Case i) is represented by the two graphs in grey.

Plausibility check of fig 39 confirms that Q [m<sup>3</sup>/year] increases with higher V [kn] and/or lower d [Nm]. Moreover, it is clear that higher  $T_p$  [days] also yields lower Q [m<sup>3</sup>/year] as expected. It should also be noted that the effect of lower  $T_p$  [days] decreases significantly with longer distances, d [nm]. This indicates that the utilisation of the RPT is more appropriate for trade routes of medium to short distances. This is also supported when regarding a specific case in which  $Q = Q(T_p)$ :

With values given as shown in table 1, and velocities:

$$\mathbf{V}^T = [V_1, V_2, V_3, V_4, V_5, V_6] = [10, 12, 14, 16, 18, 20],$$

we will observe isoquants for different annual transport capacities as shown in fig 40.

Plausibility check confirms that both higher velocities, v, and lower time in port,  $T_p$ , yields higher annual ship transport capacity, Q.

With support from these graphs, these calculations can be said to indicate that a reduction of  $T_p$  may yield higher annual ship transport capacities, increasingly with lower d- $T_p$  ratios, and therefore also corresponding economic benefits.

Q unaltered, V decreased: From eq. 4.1.1, and Q unaltered with different v, we have as shown in eq 4.4.2:



Figure 39: Q(V, d),  $T_p = (4; 6; 6.5; 11.5)$ 



Figure 40:  $Q(T_p)$ 

$$Q_1 = q \frac{365 - OH}{T_{p,1} + \frac{d}{24 \cdot v_1}}$$
(4.1.3)

$$Q_2 = q \frac{365 - OH}{T_{p,2} + \frac{d}{24 \cdot v_2}}$$
(4.1.4)

$$Q_1 = Q_2$$
 (4.1.5)

which yields:

$$T_{p,1} + \frac{d}{24 \cdot V_1} = T_{p,2} + \frac{d}{24 \cdot V_2}$$
(4.1.6)

$$V_1 = V_2 + \frac{d}{24} \left(\frac{1}{T_{p,1}} - \frac{1}{T_{p,2}}\right)$$
(4.1.7)

(4.1.8)

and by inserting the values for procedures for cargo change with standard and RPT methods for Cases ii) and iii), we get:

$$V_{RPT, Case i} = 18.3 (kn)$$
 (4.1.9)

$$V_{RPT, Case \ ii)} = 18.6 \ (kn) \tag{4.1.10}$$

With the following assumptions:

- i) Vessel size fixed
- ii) OPEX fixed, except fuel
- iii) Specific fuel consumption (SFC) constant across load

we know that the cost, C, for a vessel can be expressed as shown in eq 4.1.11 [16]:

$$C = C_0 + C_{fuel} (4.1.11)$$

$$= C_0 + p_f \cdot SFC \cdot kW \tag{4.1.12}$$

$$= C_0 + p_f \cdot SFC \cdot k_1 \cdot C^{\alpha} \cdot v^{\beta} \tag{4.1.13}$$

$$= C_0 + p_f \cdot SFC \cdot k \cdot v^{3.5} \tag{4.1.14}$$

where,

C = Costs	(USD)
$C_0 = Costs except fuel (constant)$	(USD)
$\mathbf{p}_f = $ fuel price	$(\text{USD} \cdot g^{-1})$
SFC = specific fuel consumption	$(\mathbf{g} \cdot kW^{-1})$
kW = installed propulsion power	(kW)

A reduction of speed from v = 20 to v = 18 will give a reduction of  $C_{fuel}$  of [16]:

$$C_{fuel,1} = k \cdot V_1^{3.5} \tag{4.1.15}$$

$$C_{fuel,2} = k \cdot V_2^{3.5} \tag{4.1.16}$$

(4.1.17)

which will give a saving of:

$$C_{fuel,2} - C_{fuel,1} = k(V_2^{3.5} - V_1^{3.5})$$
(4.1.18)

It should be noted that the assumption of constant SFC is not entirely accurate, as slow-steaming usually<sup>12</sup> gives increased SFC.

 $<sup>^{12}</sup>$ With use of new technologies such as tuning, SFC may be reduced for several different engine loads [19]

With basis on either an increased Q or reduced V, which will lead to either increased income or decreased cost, it should be safe to reach the conclusion that the RPT will be economically beneficial. The validity of this statement includes a ship engaged in a dual trade with only two ports of call, and will depend on the cost of installing the RPT.

#### 4.1.2 Environmental benefits

Though a reduction of velocity will have affect the emissions during sailing between ports, the key to the true environmental benefits lies in the new procedures of cargo change.

By using the RPT, there are no mixing of gases with the procedures for cargo cleaning or change of grade. As the gases in question are reclaimed instead of released to the atmosphere (as is usual with today's procedures), there is an environmental benefit as well as economical.

With the current procedures for cargo change, emissions occur with:

- inerting (before aerating or gassing-up)
- aerating
- inerting (after aerating)
- gassing-up

When changing the atmosphere of the cargo tanks, it is usually necessary to supply a volume of cargo vapour equal to 3 to 5 times their volume before reaching the point at which compressors can be started [9]. As there is a full tank volume of vapours left after procedures are finished, the volume of cargo vapour that is released equals 2 to 4 times the cargo tank volume. With use of the RPT, there are in principle no emissions as the vapour phases are not mixed. It is therefore easy to calculate the emissions for each procedure.

With current procedures, and data as given in Ch 1.3.5, the emissions for cargo change from propane to  $CO_2$  are:

 $3 \cdot q \,(m^3)$  propane = 120006 (m<sup>3</sup>) propane = 276 (tonnes) propane (4.1.19)

Correspondingly, the emissions for cargo change from propane to ammonia are:

 $3 \cdot q \ (m^3) \text{ propane} = 120006 \ (m^3) \text{ propane} = 276 \ (tonnes) \text{ propane}$  (4.1.20)

as well as

$$3 \cdot q \ (m^3) \ IG = 120006 \ (m^3) \ IG = 143 \ (tonnes) \ IG$$
 (4.1.21)

where IG is in form of  $N_2$  with properties as described in table 6.

As cargo change with RPT does not yield any emissions, it is clear that the environmental benefits of using this technology are significant.

It has thus been found that the rationale for using the RPT is of both an environmental and economical character, with significant results in a broad spectrum of cases.

## 4.2 Systems overview

This subsection will describe the systems, components and procedures connected with use of the RPT.

I believe the entire RPT system comprises the following subsystems:

- Bellow system
  - Gas Lock
  - Bellow arrangement
- Inert gas system
  - Deck tank
  - Piping system

# 4.2.1 Bellow system

This system comprises the bellows and the containers in which they are stored, released from and retracted to.

**Gas Lock** A GL is, as mentioned in the introduction, the designation for a suitable container from which a bellow is inserted into the cargo tank. The GL will thus serve as a connection between deck and cargo tank, with the primary function of housing the mechanisms for storing, inserting and evacuating the bellows into or from the cargo tank respectively. Part of the goal of this Master thesis is to establish a function specification of this unit. This will therefore not be discussed any further in this section.

Bellow arrangement The bellow arrangement comprises the bellow when stored or folded within a GL. After being released into the cargo tank from a GL, the bellows are filled with inert gas from the deck tank until they are all inflated. When a new gas is introduced into the cargo tank, the bellows are deflated by sending the inert gas back to the deck tank. When empty, they are retracted into their respective containers for disposal. A new bellow arrangement is installed before the next operation.

Material screening reports have been performed by Norner Innovation AS [28] in order to identify materials that can withstand the relevant cargoes, as well as comply with certain requirements from Environgas AS. The potential cargoes are those mentioned in Ch 2 with temperatures between -104 and  $+30^{\circ}$ C, though the relevant ones are carbon dioxide and propane as established earlier.

The requirements for bellow material established by Environgas AS are for chemical resistance, as well as likely temperature range for the transported cargoes. The procedures of the technology will in principle not involve any net pressure on a bellow, and the structural integrity is only required to be sufficient for the bellow to carry its own weight. As the bellow thickness should be very small (in order to keep production costs to a minimum and small required space for bellow arrangement storage inside the GL) there is need for a high strength-to-weight ratio. Though the technology may, in principle, apply to all cargoes, the Company currently focuses on propane and carbon dioxide. The requirements for material for a bellow are therefore found by the Company to be [28]:

- Operational in the temperature range of -55 to +30 °C, plus safety margins
- Chemically resistant to the cargoes in question
- Low swelling
- Low costs

Though there are polymer materials that can withstand all the potential cargoes, many of these have in common that they are fluoropolymers (and thus relatively expensive). Advanced textiles could also be able to fulfil the technical demands, but would also become too expensive. Of these reasons, Norner AS have found that the coating of textiles needs to be compatible with welding due to the large sheets of material required for each bellow [29].

A simple film construction to be used in the bellows would be three layer films with a core layer that gives the majority of the mechanical strength, and top layers suitable for welding [29]. In order to be able to fulfil the different required demands in mechanical strength of the different parts of the bellow, and to keep the overall weight and cost at an optimal level, a single bellow is to be made of several types of film constructions [29]. It is believed that (among others) the bellow inflation tube and parts of the bellow top will be critical highly stressed parts of the bellows, and requiring textiles to ensure sufficient mechanical strength [29]. Though tests are required to establish the required

properties (which primarily is required tensile strength) Norner has assumed that some parts of a bellow will comprise oriented or fibre reinforced films and varying thicknesses [29].

In the case of the cargoes carbon dioxide and propane, the bellows are to be made of a polyethylene (PE) film solution, either reinforced with fibres, by orientation or simply as produced as cast or blown films. A reinforced PE-based film is believed to be capable of meeting the demands for a bellow in this case as its glass temperature,  $T_g$ , is of  $\approx$  -120 to -130 °C[28]. PE is, however, not compatible with Chlorine, but in this case with carbon dioxide and propane it is of no consequence.

The relevant properties of the PE film is found [29] [27] and presented in table19:

Avg. bellow density	$ ho_{PE}$	1	$(kgm^{-3})$
Avg. bellow thickness	$t_{PE}$	100	$(\mu m)$
Max. length-diameter ratio	$(L/D)_{PE}$	2	

#### Table 19: Properties of PE

As the bellows are to be installed into the GL before being released into the cargo tank and, ultimately, evacuated through said GL, they must be organised in some sort of arrangement inside the GL, making these operations feasible. The Company have not yet established a specific arrangement, but this issue will be discussed in Ch 4.4.

Due to the selection of material and method of manufacture of bellows, as well as inner tank topology, there are inherent limitations to the bellows. Norner AS has stipulated a maximum length-diameter (L/D) ratio of 2 (though it is preferred to be closer to unity) [27]. Of this reason, it follows that there is a need for more than one bellow for most cargo tanks. The bellows will of this reason have to accurately fill a designated volume of space inside the tank every time they are deployed as sketched in figs. 41 through 50. The successful deployment of the bellows are also considered dependent on the folding pattern (or bellow arrangement) inside the GL. This issue will also be considered in Ch 4.4.

#### 4.2.2 Inert Gas system

Deck Tank The deck tank is the storage whence IG is supplied to the bellow system. To ensure rapid inflation of bellows, the deck tank should contain enough IG for the entire volume of the cargo tank and piping systems leading to it, with the addition of the vapours required in the deck tank for successfully maintaining a certain pressure, as well as piping systems.

$$V_{DT} = V_{CT} \frac{\rho_{vapour}}{\rho_{liquid}} + V_{Pipes} + V_{DT,vapour}$$
(4.2.1)

As the volume of the piping systems,  $V_{pipes}$ , is unknown, and it as well as the volume for deck tank vapours are very small compared with the volume from density difference, it is reasonable to rewrite the equations with a safety margin of 1.2 [7] to replace these two volume components. The new equation is then:

$$V_{DT} = 1.2 \cdot V_{CT} \frac{\rho_{vapour}}{\rho_{liquid}} \tag{4.2.2}$$

Depending on the conditions (pressure and temperature) of the contents in the deck and cargo tanks, the IG is sent to a vaporiser, heat exchanger or compressor before the flow is directed further. This is to obtain the desired condition of the IG before feeding it to the bellows (or deck tank).

Piping system The piping system comprises all pipes, valves, pumps and similar equipment that is required for transporting liquid or vapour with the RPT system. They should all be according to the IGC and the Rules.

### 4.3 Bellow system operation

First, the principle of the bellow system operations will be explained, before illustrating how the new cargo change procedures would be with the RPT.

#### 4.3.1 Bellow system principle

The purpose of the RPT is to reduce time spent on cargo change procedures on liquefied gas carriers by displacing the remaining gas phase of the previous cargo. This section will comprise a detailed step-by-step overview of the operations of the RPT system. This is illustrated by cargo change from cargo "1" to cargo "2". Note that the deck tank-, cargo tank-, and general gas handling systems have not been described in detail. Only the key components and sub systems are shown in the following section. The IG needs to be sent to either a vaporiser, heat exchanger or compressor (with reliquefaction) to obtain the desired condition of the flow. This component is represented by "Heat Exchanger" (HE).

The initial conditions are as shown in fig 41. The cargo tank has been emptied of liquid phase of cargo 1 as explained in chapter 2, and only vapours are left. The deck tank is filled with IG and the bellows are safely stored in their containers, ready for deployment. All valves are closed, but the connection from the CG to shore is open as some vapours have been displaced.

Step 1 The containers open and the bellows are released into the cargo tank as shown in fig 42.



Figure 41: Initial conditions of Bellow system



Figure 42: Step 1: Release of bellows into cargo tank

**Step 2** Liquefied IG from deck tank prepared for insertion to the bellows. The flow is directed to a HE (or vapouriser) as shown in fig 43.



Figure 43: Step 2: IG is prepared before insertion to bellows

Step 3 The bellows are now to be filled sequentially in order to properly displace all vapours. As bellows are inflated by the IG, the vapours from the tank are displaced as shown in fig 44.

Step 4 The IV3a closes as bellow a is fully inflated. IV3b is then opened in order to inflate the next bellow as shown in fig 45.

Step 5 All belows have been inflated properly, and all vapours have been displaced. As shown in fig 43, the distribution of IG has stopped entirely. The tank is now properly "gas-free" and ready to receive new cargo.

Step 6 Vapour phase of the next cargo is introduced to the tank simultaneously with IG being led from the bellows to the HE. Here the IG is reliquefied before being fed to the IG deck tank. The temperature differences of the cargo and IG may be exploited in the HE for saving energy with the reliquefaction process. This is shown in fig 47



Figure 44: Step 3: Inflating of first bellow



Figure 45: Step 4: Inflating of second bellow



Figure 46: Step 5: Bellows fully inflated



Figure 47: Step 6: Introduction of vapours from cargo "2"

**Step 7** As is shown in fig 48, the first below is completely deflated, and the next below is emptied of IG, all the while vapours are distributed to the tank from shore.



Figure 48: Step 7: First bellow deflated

Step 8 All bellows have been deflated, and as their volume is negligible, virtually the entire cargo tank is occupied by the vapours from cargo "2". This is shown in fig 49

Step 9 All bellows have been retracted into their containers, as is shown in fig 50

## 4.3.2 New procedures

With the bellow system operations as shown in Ch 4.3, the new set of procedures (as opposed to the current set of procedures as shown in Ch 2.3), will be as follows:

The new set of procedures are therefore as follows:

- Discharge
- Warming-up
- Inflation of bellows



Figure 49: Step 8: All bellows deflated



Figure 50: Step 9: Bellows retracted

- Inerting
- Aerating
- Inerting
- Empty bellow
- Visual inspection
- Inflating of bellows
- Inerting
- Cool-down and Gassing-up
- Empty bellow
- Loading

The RPT systems are incorporated into the existing systems as shown in fig 51. As can be seen, in addition to the "Bellow system" and the "Deck Tank", a new header called the "RPT header" is installed. This is to enable vapour transport (to and from the cargo tank) at the same time as IG is transported (to and from the deck tank to the bellows). It should also be noted that pumps and valves have been installed to satisfy the IGC the same way as is shown in the diagrams for the current procedures. Furthermore, the RPT systems are connected to all necessary headers in order to facilitate for use of gas handling equipment like vaporiser, heater, IGG, reliquefaction and vapour compressor.

**Discharge** Discharge is performed as described in Ch 2.3. This is shown in fig 52. Artist's expression of discharge with RPT is shown in fig  $53^{13}$ .

With similar systems as in Ch 2.3, the time for discharge will still be 12 hours.

Warming-up Following discharge of liquid phase of cargo, Warming-up procedures will commence as described earlier. Warming-up will be performed with inflation of bellows.

The time for Warming-up is estimated to be 12 hours.

<sup>&</sup>lt;sup>13</sup>It should be noted that the illustrations with "artist's expression" was made on an early stage in which the concept of RPT was a single bellow that functioned as a fixed installation. As that is not the case here, the illustrations will not be entirely accurate, though the concept still applies.



Figure 51: RPT incorporated in existing systems



Figure 52: RPT: Discharge



Figure 53: RPT, artist's expression: Discharge

Inflation of bellows After insertion, the bellows are inflated (with IG) sequentially (as shown in the previous chapter) in order to properly displace the vapours from the previous cargo. The IG is sent via a vaporiser and heater in order to send vapours (and not liquid) to the bellows. This is shown in fig 54. Artist's expression is shown in 55. When this operation is complete, the tank is "gas-free" and ready to receive vapour phase of a new cargo, as is shown in fig 56.

The time for inflating bellows is estimated to be 6 hours, but will be performed with warming-up.

Cases ii), iii) and iv) In Cases ii), iii) and iv) as explained earlier, there is need for inerting, aerating, visual inspection or other procedures, all that would normally follow at this stage. These are not explained here as they are described in Ch 2.3. Any dissimilarities are due to an inflated bellow that would shorten any following purging procedure.

The time for inerting (after heating) or aerating the tank when bellows are inflated is estimated to be 6 hours.



Figure 54: RPT: Inflation of bellows



Figure 55: RPT, artist's expression: Inflation of bellows



Figure 56: RPT, artist's expression: Bellows fully inflated

Inerting after aerating will take 12 hours [29].

Gassing-up/deflating bellows The vapours of the new cargo is inserted into the cargo tank simultaneously as the bellows are deflated. Cool-down happens simultaneously due to the temperature of the new cargo. The IG from the bellows are sent to the deck tank. When this operation is complete, the bellows are completely deflated, and virtually the entire tank volume consists of said vapours. This is shown in fig 57 and 58.

The time for Cool-down and Gassing-up are 6 hours as with the current procedures. Deflating is performed simultaneously and will also take 6 hours.

Loading The tank is now filled with vapours of the new cargo, and loading of liquid phase can commence. This is done as with current procedures as seen in fig59 and 60.

The time for loading is the same as with the current procedures, which is 12 hours.



Figure 57: RPT: Gassing-up



Figure 58: RPT, artist's expression: Gassing-up and deflating bellows



Figure 59: RPT: Loading



Figure 60: RPT, artist's expression: Loading

Procedure	Unit	Value
Discharge	(h)	12
Warming-up	(h)	12
Inflating of bellows	(h)	6
Inerting	(h)	6
Aerating	(h)	6
Empty bellow	(h)	6
Visual inspection	(h)	6
Inflating of bellows	(h)	6
Inerting	(h)	12
Cool-down and Gassing-up	(h)	6
Empty bellow	(h)	6
Loading	(h)	12

Summary of new procedures With these new procedures in place as explained, the times for each are presented in table 20.

Table 20: Time with new procedures for cargo change

# 4.4 Challenges

The RPT being a new technology still under development, there are several unresolved challenges with the bellow and its operations. Among these are:

- Bellow arrangement
- Bellow deployment
- Bellow evacuation
- Hazards

Each of these unresolved challenges will be discussed in this section, with in-principle methods of solution.

# 4.4.1 Bellow arrangement

One of the GL's functions are to store the bellow arrangement. With release, insertion and filling of bellows into the cargo tank, they have to fill a specific volume. In order to achieve this, a bellow has to be unfolded, erected and oriented accordingly [29]. This requires a specific folding pattern, and certain requirements must be considered. The bellow must be of a specific volume and surface to cover a specific volume of the cargo tank, and it will need to fit inside the GL when folded properly. Also, it needs to be inserted through a gate valve with an inner diameter of 300 (mm).

The Company believes that a feasible method of folding a bellow into a proper arrangement would be in a roll, or series of rolls, depending on the required volume [15]. A single bellow will thus comprise one or more rolls, depending on the limitations of the material and folding method. The folding may not result in an accurate circular crosssection, and deviations of 10 to 20 (mm) may occur [27]. From this, it may be inferred that either a minimum design distance between bellow and inner wall of GL, or use of additional technology that will allow for secure deployment is required. Though inprinciple solutions of using a movable hard cover in the form of a cylinder for ensuring a maximum diameter of the bellow arrangement may be utilised, further considerations on this subject will work with the assumption that a minimum design distance is to be used. The minimum distance between bellow arrangement and GL has been suggested to be 30 (mm)[27], resulting in a design outer diameter of bellow arrangement of

$$d_{ba} = d_{GL,inner} - 2 \cdot \text{safety distance} \tag{4.4.1}$$

Which yields, with the current numerical values:

$$d_{ba} = 300 - 2 \cdot 30 \ (mm) \tag{4.4.2}$$

$$= 240 \ (mm) \tag{4.4.3}$$

In order to ensure successful deployment of the bellow arrangement through the gate valve and into the tank its outer diameter is to be 240 (mm). The Company has determined that the length of each roll is to be maximum 1000 (mm), thus defining the amount of coils in series for a single bellow within each GL.

If possible, the volume of the GL should be reduced in order to minimise material cost and load on cargo tank from GL weight. This volume is dependent on the bellow arrangement. These in-principal solutions are found to be:

- a) Decrease volume of bellow per GL
- b) Maximise possible GL volume

These can be fulfilled by:

- i) Decrease thickness of bellow
- i) Increase effective diameter of bellow arrangement
- i) Increase number of GLs

- i) Optimise bellow deployment space
- i) Maximise height of GL
- i) Maximise diameter of GL

These items will be discussed and evaluated with regard to their individual effect in reducing the bellow volume  $V_0$ .

Decrease thickness of bellow is dependent (among others) on method of construction as mentioned earlier. Though the average bellow thickness is said to be 100 ( $\mu m$ ), the Company believes that a thickness of 50 ( $\mu m$ ) is possible. By inserting this value, the volume will be halved:

$$V = \frac{1}{2}V_0 \tag{4.4.4}$$

Increase effective diameter of bellow arrangement The Company may be able to develop a method of folding the bellow arrangement in a manner that the entire diameter can be used (300 (mm) instead of 240 (mm)). Alone, this will decrease the required GL volume of:

$$V = \frac{240}{300} V_0 = \frac{4}{5} V_0 \tag{4.4.5}$$

Increase number of GLs This will reduce the volume depending on the amount, n, of GLs used, as well as their location with regard to inner topology. This solution is to be avoided if possible. As explained earlier, the cost of the RPT is thought to mainly be connected to the GLs, and as few as possible are to be installed on each tank. This will only be considered if the other items fail to achieve a sufficient reduction in volume.

**Optimise bellow deployment space** This is done in connection with use of more GLs. By having a single bellow on each side of a major inner structure in a tank (like a stiffener ring), much volume is saved. The stiffeners have a larger surface than the vacuum rings, and are better to consider with this.

Maximise height of GL The maximum height of a GL is connected to both the structural integrities of GL connection and the GL itself, as well as requirements with regard to ability to see in front of the vessel from the bridge. In most cases, however, this will not be a issue due to the low bellow volume, and this will not be subject to further consideration in this report.

Maximise diameter of GL Though there is little use of expanding the diameter around the gate valve to the cargo tank, it should be possible to make a design of several interconnected cylinders. This could be done in many ways, but a simple one could include a revolver mechanism from which sets of a single bellow arrangement was launched/dropped. In further considerations and calculations, multiple cylinders will be assumed to be possible, though the exact method will not be subject to further consideration.

All these methods, and possibly others, should be considered further to increase the efficiency and keep the costs of the RPT down.

### 4.4.2 Bellow deployment

The deployment of the bellows are started by opening the corresponding gate valve and unrolling the bellow inside the tank. This is illustrated in fig 61. The folding should be done in a way that minimises kinetic energy from impact of roll to the bottom of the cargo tank, which could harm the bellow.



Figure 61: Schematic drawing of deployment mechanism [29]

With below deployment follows inflation inside the cargo tank. The folding pattern of the below will have had to be made so that the below upon inflation will cover its specified volume. Though not done inside a liquefied gas tanker, the method of execution is established technology and will not be considered further. The specified volume inside the cargo tank is limited by its inner topology (such as rings, pumps, bulkheads etc as explained in Ch 3.1.2) as well as the inherent limitations of the below itself.

An important matter with the latter limitation is the length-diameter ratio (L/D) of 2. The former is covered by the method of orienting the bellow. According to Norner AS [27], a bellow may be constructed and folded in a manner allowing it to position it along and around all aforementioned items in the cargo tank. Sharp edges should be avoided completely as they will very likely puncture the bellow.

If sharp edges cannot be removed, they should (if feasible with regard to accessibility and uncovered cargo tank volume) be covered. For a typical pump as described earlier, sufficient covering may be achieved with a perforated cylinder of a sufficiently hard material. This is illustrated in fig 62. For access with visual inspections, staircases are common. With these (as well as other elements inside a cargo tank), there may be sharp edges that could cause bellow rupture. Such sharp edges should be avoided or eliminated if possible. Where removal of sharp objects are not feasible, cover of said objects should be done. This would need to be explored with each individual tank, and should be subject to further investigation. This will not be considered further in this report, however.



Figure 62: Perforated rolled cylinder

A bellow may be positioned closely around small items like stiffening- and vacuum rings, but the pump (or perforated cylinder around it) is placed in the middle of the tank, thus denying any bellow to do so. Of this reason, there are need of at least two bellows in any cargo tank with one pump. Naturally, a swash bulkhead will deny any bellow to pass through, and there is need of at least an additional bellow in such cases.

In the case where a perforated cylinder is needed, the vapours within it are not displaced by the bellow, and purging by vapours (cargo or inert) are required. Due to the relatively small volume as well as a strictly limited diameter of the inside of the perforated cylinder, the displacement should be performed easily.

#### 4.4.3 Bellow evacuation

As explained in Step 6 in Ch 4.3.1, the bellow is to be deflated by discharging IG to the deck tank while cargo vapours are introduced to the cargo tank, outside the bellow. Due to the nature of the bellow material and method of IG discharge, successful removal of all IG from the bellow will probably be a challenge. The suction on the bellow from the IG system, or even the increasing pressure from the introducing cargo vapours may cause some area of the bellow to be compressed in a manner that will flatten it; effectively discontinuing any further IG flow from the extremities of the bellow.

This should be avoided by gradual introduction of cargo vapours (and correspondingly slow discharge of IG from bellow), which is often the case with Gassing-up and Cooldown procedures, as explained in Ch 2.3.8. If gradual introduction of cargo vapours is insufficient other measures should be taken. One possibility is the deployment into the bellow of a small, perforated straw-like structure. This should ensure sufficient IG flow, though denying the bellow to collapse. The materials for such a device, as well as the mechanism for deploying or storing it, should be explored, though it will not be subject to further consideration in this report.

After emptying a bellow, it is in need of being evacuated. It is not feasible to roll the bellow back into its original arrangement with its evacuation, and a mechanism is needed for this purpose. This procedure is therefore thought of the Company to include a "rolling-up" mechanism as shown in fig 88. Ideally, no IG is left inside the bellow, and the bellow may be rolled completely in, followed by closing of the gate valve and inerting of the GL. After inerting of the GL, it should be ready to be aerated and depressurised before removal and insertion of a new arrangement.



Figure 63: Conceptual sketch of retrieval mechanism [29]

A challenge with the rolling-up procedure would be present if there was IG left inside the bellow. If so is the case, it will not be feasible to recover the IG, and it would be mixed with the cargo vapours upon bellow retrieval. IG should not be a problem with most cargoes neither due to chemical incompatibility nor on account of contamination due to the very large cargo vapour-to-IG ratio.

# 4.5 Hazards

There are several hazards connected with use of the RPT. These are presented with a failure modes, effects and criticality analysis (FMECA) has been performed<sup>14</sup>

The FMECA is a systematic approach for analysing faults in technical systems, and will thus identify potential hazards. This method is a qualitative analysis, but with certain quantitative elements, and is usually performed in the design phase of a system [31].

A failure mode describes the physical or functional part of the result of the failure of a unit. A FMECA is a qualitative analysis, but with certain quantitative elements, and is usually performed in the design phase of a system [31].

A FMECA will describe:

- Potential failure modes for each component in the system
- Cause of these failure modes
- Effect of failure mode on component and system
- Rate of occurrence
- Severity of failure
- How the failure is detected
- Risk associated with each failure
- What can be done to mitigate the risk

In this case, the purpose of the FMECA analysis is to identify properties of the RPT system that should be considered further. This analysis could in another study be used as a basis for a more detailed fault tree analysis (FTA). This analysis contains no description of risk mitigation, contrary to what a FMECA usually contains as.

# 4.5.1 FMECA preliminary steps

The FMECA is executed in three steps [31] [2]:

- 1. Define scope
- 2. Define resolution
- 3. Collect data
- 4. Break the system down

 $^{14}$ The FMECA was performed in my pre-Master thesis [33], but was considered appropriate to be included at this point in the report.

Scope Only the subsystems and components that are functioning with the RPT system are to be evaluated. This is solely a system with technical components, and only primary and secondary faults are of interest (command faults will not be subject to evaluation). In cases where several scenarios can unfold, it is always the worst credible case scenarios are always to be viewed. It is also assumed that all components have been designed, manufactured and installed properly. External sources that may affect the systems are neglected.

**Resolution** The resolution of the analysis will be on a component-level. However, as the RPT system is still under development, data on most components are unavailable, and their parent subsystems will then represent the limit.

**Collect data** The available data has been presented in the introductory chapter about the RPT. Before the next step, however, it is necessary to present the system in a hierarchical structure. Based on the available data, the system is presented in fig 64. The lower-level items in this hierarchy are part subsystems and part components. As the design is not finished, it is not yet possible to describe it in more detail.



Figure 64: Hierarhcical structure of system as presented in the pre-Master

System breakdown From the hierarchical structure, we have a set of lowest-level components (and subsystems). For each of these items, the following steps are performed [2]:

- 1. Define the item being analysed
- 2. Define the functions of the item being analysed
- 3. Identify all potential fault modes for the item
- 4. Determine the causes of each potential fault mode
- 5. Identify the effects of each potential fault mode without consideration of current control
- 6. Identify and list the current controls for each potential fault mode
- 7. Determine the most appropriate corrective/preventive actions and recommendations based on the analysis of risk

Risk Priority Numbers After all items have been gone through, I will assign a rating between 1 and 10 (low and high, respectively) for the attributes "severity", "occurrence" and "detection". As there are little available data, the rating values for these attributes have been determined by their relative importance/impact. The risk priority number (RPN) is then determined by

$$RPN = \text{Severity} \cdot \text{Occurrence} \cdot \text{Detection}$$
(4.5.1)

, and it is used to prioritise their importance.

Though the valid range stretches between 1 and 10, "Occurrence" in this FMECA ranges between "1" to "4". The latter value is given to take into account newly designed and unproven components, contrary to the former. "Severity" ranges from "1" as "Negligible impact on operations", while "10" indicates "Loss of system or personnel". "Detection" ranges from "1" to "2" as both visual detection and well proven sensory systems are available.

# 4.5.2 FMECA procedure

The results of the FMECA procedure is shown in the figs 65 and 66  $^{15}$ 

From fig 65 and 66, it is clear that the potential faults connected to the disposable below pose the greater risks. These risks are all caused by error in design or construction, which is considered to be outside the scope of this report an risk or hazards with the belows will not be subject to further consideration.

<sup>&</sup>lt;sup>15</sup>Please note that this FMECA was performed in the pre-Master, and the GL is referred to as "container valve".
	Unit description		Ë	ailure descriptio	-	Potential fa	ilure effects		Ris	L	
ltem	Function	Operational mode	Potential failure mode	Potential causes	Discover failure how?	On subsystem	On system	0		2 4	0
1	2	3	4	5	6	7	8	9	0 1	1	~
	Store, and release/retract	And a state of the	Fail to release bellow	Any primary or secondary fault	Immediately. Sensor	None	Cargo change done w/ old procedures	2 6	`	4	<b>A</b> 1
container	bellow to/from tank	Normai operation	Fail to retract bellow	Any primary or secondary fault	Immediately. Sensorl	Container system fail	RPT fail. Inerting and aerating with old procedures	2	`	7	
	Open/Close connection	Closed	Fail to open	Any primary or secondary fault	Immediately. Sensor	None	Cargo change done w/ old procedures	2 6	`	1	
Container Valve	from container to cargo tank	Open	Fail to close after bellow removal (after gassing-up with new cargo)	Any primary or secondary fault	Immediately. Sensor	Close manually	Inerting and aerating of tank	2 5	,	7	-
Control system	Controls distribution of inert gas to/from deck tank and individual bellows	Distributing inert gas to bellows	Fail to direct flow to next bellow (continue to distribute gas to full bellow)	Any primary, secondary or command fault	Immediately. Sensors	Bellow rupture	Contamination of cargo	5		-	-
motorio anioi0	Enables/disables gas and	Stand-by	Fail to start	Any primary, secondary or command fault	Immediately. Sensor	No flow	RPT delayed until system is repaired	1 3	`	(F)	
maneke filmli	to/from DT and bellow	Normal operation	Fail to stop	Any primary, secondary or command fault	Immediately. Sensor	Must be stopped manually, or by ESD	RPT delayed until system is repaired	- -		e0	

	RPN	12	24	08	6	20	56
šk	٩	11	-	N	N	5	2
Ris	S	10	ω	9	ω	7	7
	0	6	4	4	4	4	4
lure effects	On system	ø	Cargo change done w/ old procedures	Oxygen levels higher than specified. Risk of explosion; loss of system and personell	Oxygen levels higher than specified. Risk of polymerisation; loss of cargo loss of cargo systems	Contamination of cargo	Contamination of cargo
<b>Potential fai</b>	On subsystem	7	Bellow fail	Loss of system	None	None	None
on	Discover failure how?	9	Immediately. Sensor		<ol> <li>Pressure and temp in bellow not as predicted, or:</li> <li>2) Not until</li> </ol>	occur occur	
lure descripti	Potential causes	5	Design fault		Design fault		
Fai	Potential failure mode	4	Mechanical fail/rupture due to structural weakening by chemical incompatibility		Fail to inflate 100% (displace all remaining vapours)		
Ę	Operational mode	3	Inflation or deflation	Bellow fully inflated, Cargo change. FROM: Flammable cargo gas; cargo gas; versa)	Bellow fully inflated, Cargo change. FROM: Polymerisable TO: air (or vice versa)	Bellow fully inflated, Cargo change. FROM: Any cargo gas; TO: IG (or vice versa)	Bellow fully inflated, Cargo change with incompatible cargoes
Init descriptio	Function	2		ls filled up with IG, inflates and	displaces remaining cargo vapour in cargo tank. Will deflate with introduction of introduction of to cargo gas to cargo tank		
	Item	1			Disposable Bellow		

# 5 Function specification

With descriptions of both the design criteria of a typical tank Type C and the bellow system and its operation, it is possible to establish the boundary conditions (BC) and requirements for a GL.

This is done in this section by considering all of the GL's interfaces and BC (as shown in fig 67).



Figure 67: Tank type 'C' with GL

Note that fig 67 is for illustration and conceptual purposes only. Numbers and scale of both GL and valve are not necessarily to scale in this figure.

As is established in Ch 1, the GL is to function as the chamber in which the folded bellow arrangement is mounted and taken out after use. The following items have been deemed to be relevant for a function specification:

- 1. To cargo tank
- 2. Deck penetration and foundation
- 3. To deck tank
- 4. To services
- 5. Bellow operations

Moreover, each of these items are, when relevant, considered with regard to the different operational modi (of the GL) as found in Ch 4.

These items are covered in Chapters 5.1 through 5.5, with the findings summarised in Ch 5.6.

In order to establish a reasonable limit for the workload, a specific cargo tank Type C is to be considered. As is mentioned in Ch 1.3.3 and shown in Ch A, the cargo tank volume to be considered is 3500  $(m^3)$ . Though the thickness and diameter (and therefore also the volume) of the tank presented in Ch A, the geometry and structure in way of stiffeners and so on is to be used in any considerations or calculations. For any calculations regarding the bellow, the largest possible size is to be considered in order to maintain a conservative profile.

# 5.1 To Cargo Tank

The connection between the GL and the cargo tank is by means of a gate valve as indicated on fig. 67. A typical gate valve is also shown in fig 23. As has been explained in Ch 1.3.1, the opening to the cargo tank, and therefore also the gate valve, is to be circular with an inner diameter of 300 (mm) as specified by the Company.

The opening from the gate value to the cargo tank is to be in compliance with the Rules as explained in Ch 3.2.3. As the GL can be considered an extension of the cargo tank, and a pressure vessel itself, it is prudent to consider the opening between the GL and the gate value to be in compliance with the Rules as well.

Numerical calculations for cargo tank openings and their reinforcements will be shown later in this report.

If the GL is mounted directly on the cargo tank (via the gate valve), any forces and moments from the GL, including thermal, should be considered. This is explored further in Ch 5.2.

A typical connection between GL and cargo tank below deck is shown in fig 68.



Figure 68: Overview of GL and cargo tank

### 5.1.1 Modus operandi

**Cargo tank closed** As specified by the Company in Ch 1.3.1, a closed condition to the cargo tank is achieved by means of a closed gate valve. This gate valve needs to withstand the most extreme design pressures, temperatures and densities that are to be encountered.

Cargo tank open The GL is open to the cargo tank so that the bellow may be released, filled with IG, emptied of IG and finally retracted. Therefore, the gate value is to be without any sharp edges or obstructions that may harm the bellow or hinder its operations as described earlier. The atmosphere inside the GL (and outside the bellow arrangement) will be the same as that inside the cargo tank.

## 5.2 Deck penetration and foundation

Any forces and moments (including thermal, or due to ship accelerations) arising from the GL and connected systems (such as pipelines) needs to be considered with the mounting of the GL. The GL may be mounted directly on the cargo tank (via gate valve), in which case special care needs to be taken to ensure that these forces/moments does not exceed design stress of the cargo tank. In order to avoid larger forces/moments on the cargo tank, the GL may also be mounted on the deck itself.

Mounting GL on deck requires the construction of the foundation to account for thermal expansion/contraction as well as ship deflection while still supporting the GL without causing undue stress on the tank. Also, it is prudent to assume that the minimum distance as described by the Rules for cargo tank domes also applies in this case. Fig 38 illustrates that aspect. As is explained in Ch 4.4.1 and will be further discussed in Ch 5.5, the GL should be designed with a relatively high height-to-diameter ratio (H/D). For support or foundation on weather deck, relative movement between cargo tank (and therefore also GL), as well as thermal forces yields that flexible supports should be used. This eliminates use of simple guys/wires for support, and more complex systems with springs or dampening features allowing for both relative movement and structural support is needed.

As an independent cargo tank Type C is designed to not be affected by ship movements, it would be natural to assume that this also goes for appendices and add-ons like a GL due to, among others, the aforementioned reasons. Therefore, the GL is to be installed on top of the cargo tank with no supports from ship hull construction or deck level.

By using this method, no extra structures (for support of GL) are needed on a deck in which available volume may be sparse as indicated on fig 15.

In order to minimise the penetrations of the weather deck and corresponding weakening of structural integrity of same, it is assumed that the GL is placed on the dome as recommended by the DNV [13]. Where that is not possible, it is assumed that a certain length of pipe is required between the cargo tank and the GL. This is explored later in this report.

Mounting GL on cargo tank should result in greater care to be taken when considering the additional forces/moments to the cargo tank that arises from the GL and its connected systems. This is due to the relatively small area (that is already reinforced from tank penetration) that will take up these forces and moments. As the weight of the GL is relatively small, which is a valid assumption, it may be disregarded with calculations with its connection to the cargo tank [13]. The final design of the GL could, however, in a more thorough study be subject to the rules of ASME Div 1 and sec. 2 [13], or a FEM analysis to ensure a proper connection and foundation.

The forces and moments may be accounted for by finding the accelerations on the centre of gravity of the GL due to ship movement and accelerations as defined in the Rules (as described in Ch 3.2.2. The Rules[3, Pt. 5 Ch.5 Sec.5 A600 Static loads] takes these forces into account with  $p_4$  as found in eq 3.2.11. This states that  $p_4$  comprises compressive actions in the shell due to the weight and contraction of shell and structures. These include, but are not limited to, weight of domes, towers and piping. It is therefore assumed that this also applies to the GL structure.

# 5.3 Deck tank

The GL needs to be connected to the IG system, or more specifically, the deck tank from which the bellow is supplied with IG. The pipelines from the deck tank will run above the weather deck as explained earlier, and into the GL. The deck tank and the pipelines are connected directly to the weather deck and therefore the ship's hull and exposed to the same accelerations. The weight of the pipelines needs also be considered. These, as well as thermal forces from the pipes (as are explained in Ch 3.1.2) must be accounted for so that they don't affect the GL (and its foundation).

As explained in Ch 3.1.2, flexible joints and z-shaped spools may be used to reduce stresses due to relative movement due to pressure changes, thermal expansion or ship accelerations. The weight, save for the final length of pipe between anchor point and GL, should be supported by hangers or anchor points, as are flow induced forces due to change of momentum at bends.

The gas handling procedures described in Chapters 3 and 4 are to be performed within given periods of time. Pipeline characteristics by way of diameter, surface roughness, length etc. are to be designed accordingly to these given times, as well as pump characteristics and corresponding flow capacities. They shall otherwise be designed as specified by the Rules [5, Pt. 4 Ch.6].

Calculations for the above-mentioned aspects are performed in Ch 5.3.2.

#### 5.3.1 Modus operandi

Deck tank closed As specified by the Company in Ch 1.3.1, a closed condition to the cargo tank is achieved by means of a closed gate valve. This gate valve needs to withstand the most extreme design pressures, temperatures and densities that are to be encountered. Though only gas, and not bellows is to pass through, it would be natural to assume that a valve with similar characteristics as the one bordering to the cargo tank would be suitable for this task.

As the GL is to be filled with IG when it is closed (in order to create a non-hazardous space as specified by the DNV Rules), an opening to the inside of the GL (and outside of the bellow) is required. This feature could be obtained by an additional opening into the GL, or by simply having the bellow arrangement disconnected from the valve when not in use.

**Cargo tank open** The GL is open to the deck tank so that the bellow may be filled with, or emptied of IG. This is achieved by means of a gate valve similar to that connected to the cargo tank, but with an inner diameter corresponding to that of the pipelines to the deck tank.

### 5.3.2 Pipeline characteristics

As mentioned above, this subsection contains the calculations for the pipelines connected to the GL. In order to account for any of these when finding the BCs for the GL, the following aspects are considered:

- Pipeline weight
- Pipeline expansion
- Valve and flange characteristics

These are derived from, among others, the pipeline diameter and thickness. In order to perform the necessary calculations to find these values for the relevant pipeline, the following assumptions have been made<sup>16</sup>  $^{17}$ :

- Fluid to be transported is nitrogen  $(N_2)$  vapours @ 5.5 bar and -55 °C.
- Pipeline length, L = 20 meters
- Surface roughness,  $\epsilon = 0.0015 \text{ (mm)}$  (as for drawn tubing)
- Reynolds number,  $R_e$ , of  $10^5$ , which is not unusual for turbulent gas flows [35]

Though the nitrogen is considered to be liquefied in the deck tank, it is considered sent to the GL and bellows via a heat exchanger as explained earlier in this report. Therefore, only the last length of pipeline will be considered in this section.

With nitrogen with properties as found in table 6, and a cargo tank with capacity of 3500  $(m^3)$  to be filled with gas according to procedures as shown in Ch 4.3.2, the following values are given:

<sup>&</sup>lt;sup>16</sup>Pipeline length, L, denotes typical total length of pipeline between vaporiser (or heat exchanger) and GL

<sup>&</sup>lt;sup>17</sup>Though fig. 70 shows another value for the surface roughness of said object, the value used in this report is as given in the Course Notes of TMR 4310 Marine Technology 4 - MACHINERY [35]

$ \rho_{N2} = 1.19 \; (\text{mm}) $	(5.3.1)
$V = 3500 \ (m^3)$	(5.3.2)
t = 21600 (s)	(5.3.3)
$q = 0.3087 \ (m^3 s^{-1})$	(5.3.4)
	(5.3.5)

These assumptions are also illustrated in fig 69 in which a pipeline arrangement between deck tank and cargo tank is shown. In this figure, area A illustrates the concept of a z-spool (as mentioned in Ch 3.1.2), intended to eliminate thermal expansion/contraction. Area B shows the length of pipe that is to be considered in this section. Hangers or suitable supports, as well as branches and valves are assumed to be located at appropriate locations. The figure is not to scale and should not be considered an accurate description, but an illustration of the concept.



Figure 69: Pipeline arrangement

When the fluid and its properties, as well as flow rate and head loss is known, and the pipe size is to be found (as is the case here), the more correct approach is to solve the (in this case) non-linear energy equation for pipe diameter, D, versus head loss,  $h_L$ . This is to be iterated until  $h_L$  is equal to the known value [35].

As no actual values are known, and any values present in this report are estimates, a more simplified approach will be used here. Plausibility checks with head loss will be performed to ensure that the results are proper and of a plausible order of magnitude.

By starting with the Reynolds number (as defined in eq 3.1.1), we get:

$$R_e = \frac{\rho D v}{\mu} = 10^5 \tag{5.3.6}$$

and with

$$v = \frac{Q}{A} = \frac{4Q}{\pi D^2} \tag{5.3.7}$$

in addition to the numerical values as presented above, we get:

$$D = 3.558D^2 \tag{5.3.8}$$

$$= 140.5 \text{ (mm)}$$
 (5.3.9)

It is recommended to choose a pipe diameter that is slightly larger than the exact pipe diameter extracted from the equation [35].

The pipe diameter, D, is set to be 150 (mm) = 0.15 (m)

This value will be subject to a plausibility check by considering the head loss as presented in the energy equation (see eq 3.1.2).

First, the friction factor, f needs to be found. In fig 70 the values  $Re = 10^5$  and  $\epsilon/d = 10^{-5}$  gives a friction factor, f = 0.018. This is a reasonable value, given that f = 0.02 is plausible for many pipe problems [35].

We find that with the current pipeline arrangement, there are 8 90°C bends. In reality, there should be at least two valves to allow for flow between deck tank and GL, as well as branches at relief valves. By assuming that there is one gate valve only, the  $K_L$  values are as follows:

Item	Quantity		$K_L$	
Valve	1	$1 \cdot 1$	=	1
Bends	4	$4 \cdot 1.5$	=	6

This gives:

$$h_L = h_{L,major} + h_{L,minor} \tag{5.3.10}$$

$$h_L = \frac{v^2}{2g} \left( \frac{fL}{D} + \sum K_L \right)$$
(5.3.11)

$$h_L = 15.5838(6+6) \tag{5.3.12}$$

$$h_L = 187$$
 (5.3.13)

With a total head loss of 187 (m), this corresponds to a pressure difference of:

$$187 \cdot g = 1835(kPa) = 18.35(bar) \tag{5.3.14}$$



Figure 70: Moody diagram<sub>2</sub> friction factor, f = 0.018

It is clear that the fluid velocity, v, is the factor that contributes the most to this high value, and this may indicate that an even larger pipe diameter should be considered. This report will not consider this subject any further as this value is found only so that further calculations regarding the GL can take place.

Also, though the pressure difference is found to be 18.35 (bar), it will not be considered further, and a working design pressure of 6 (bar) will still be used as stated initially in this report. A material used for low temperature service, and specially recommended for the temperature and pressures of liquefied  $CO_2$  cargoes are the NV 4-4L carbonmanganese steel [6] [11]. Due to the lack of chrome, this material is not considered a stainless steel.

Thus, the initial information needed for this section of the report is<sup>18</sup>:

Material:		NV 4-4L
Density of material	$(kgm^{-3})$	7800
Design pressure	(bar)	6
Diameter of pipe	(mm)	150

With the diameter fixed, the thickness needs to be found in order to do any further calculations. The DNV Rules [5, Sec. 6, A. Pipes] state that wall thicknesses shall comply with the requirements in said section. The relevant Rules are presented as considered appropriate.

The minimum wall thickness is found (for non-stainless steel pipes in general) for pipes with a diameter between 152.4 and  $168.3 (mm)^{19}$  to be 4.0 (mm) [5].

Moreover, the Rules dictates that a corrosion allowance, c, is to be added to the basic thickness. This depends on cargoes and materials. No category covers nitrogen vapours, and the closest piping service is for compressed air, which has a corrosion allowance of 1. Save for cargo oil, sea water or feed water in open circuit systems, all values are below 1 [5]. It should therefore be safe to assume that c = 1. This corrosion allowance is added to the nominal thickness that is mentioned earlier.

For pipes with an internal pressure (as is the case), the Rules [5] state that the strength thickness,  $t_0$  is not to be less than:

$$t_0 = \frac{pD}{20\sigma_t e + p} \tag{5.3.15}$$

where,

<sup>&</sup>lt;sup>18</sup>The density of the NV 4-4L is unknown, and a typical steel density has been used for illustration purposes with numerical calculations. Moreover, the NV 4-4L

<sup>&</sup>lt;sup>19</sup>The diameter range lower than this is below 150 (mm) and is therefore not considered.

e = strength ratio, assumed to be 1 (*mm*) in this case [5]  $\sigma_t =$  Permissible stress

The permissible stress,  $\sigma_t$ , is based on the lower value of:

$$\frac{\sigma_b}{2.7} and \frac{\sigma_{ft}}{1.6} \tag{5.3.16}$$

We have the following properties for NV 4-4L:

Minimum yield stress 
$$(Nmm^{-2})$$
,  $\sigma_{ft} = 335$   
Minimum tensile strength  $(Nmm^{-2})$ ,  $\sigma_b = 550^{20}$ 

which gives:

$$\frac{\sigma_b}{2.7} and \frac{\sigma_f t}{1.6}$$
  
203.7 and 209.4

This gives  $\sigma_t = 203.7 \ (Nmm^{-2})$ , which is put into eq 5.3.15:

$$t_0 = \frac{6 \cdot 150}{20 \cdot 203.7 \cdot 1 + 6}$$
(5.3.17)  
$$t_0 = 0.22(mm)$$
(5.3.18)

This being lower than the minimum value set initially, we get:

$$t = t_0 + c \tag{5.3.19}$$

$$t = 4 + 1 \tag{5.3.20}$$

$$t = 5$$
 (5.3.21)

 $<sup>^{20}</sup>$ This value is in reality between 490 and 610, and the mean is presented here.

This gives a pipe wall thickness of 5.0 (mm).

#### 5.3.3 Moments due to pipeline mass

The total mass of the pipeline between GL and anchor may now be found:

$$M_{pipeline} = \rho V \ (kg) \tag{5.3.22}$$

$$= 7800 \cdot (L \cdot A) \ (kg) \tag{5.3.23}$$

$$= 7800 \cdot (20\pi \cdot d \cdot t) \ (kg) \tag{5.3.24}$$

$$= 367.6 \ (kg) \tag{5.3.25}$$

(5.3.26)

As the exact geometry and pipeline arrangement is unknown, these calculations will follow the example of the preceding ones and simplified systems are used.

It is therefore assumed that the weight of the pipeline is evenly distributed along the entire length of the pipeline, and that hangers and supports are placed with regular intervals along it. As is indicated in fig 69, the bend closest to the GL is about 10 meters away. It is assumed that a fixed support (in form of an anchor) is situated here as well. With a gate valve as a method of connection to the GL, it can be considered a fixed support, and a simplified system can be used for further analysis. By assuming fixed support in both ends (A and B), and an evenly distributed load, we have from simple mechanics (see fig 71) [20] that:

$$M_A = M_B = \frac{qL^2}{12} \tag{5.3.27}$$

where,

$$q = M_{pipeline} \cdot \frac{g}{L} = 180.3 \ (Nm^{-1})$$
 (5.3.28)

$$L = \text{Length of pipeline (m)}$$
 (5.3.29)

Thus, the moment,  $M_A$  on the GL is

$$M_A = \frac{180.3 \cdot 10^2}{12} \ (Nm) \tag{5.3.30}$$

$$= 6010 \ (Nm) \tag{5.3.31}$$



Figure 71: Fixed supports

The moment on the GL from mass of a 10 (m) pipeline is 6.01 (kNm).

Calculations on moments due to accelerations also need to be performed, but this cannot be done until the form of the GL has been determined. These calculations are found in Ch 5.6.5.

# 5.3.4 Moments due to flow

5.3 Deck tank

As described in Ch 3.1.2, and eqs 3.1.14 and 3.1.12, fluid flow through a pipeline will generate forces. With values as shown in eq 5.3.1, it is found that:

$$\dot{m} = \rho q \ (kgs^{-1})$$
  
= 0.367  $(kgs^{-1})$ 

and

$$v = Q/A \ (ms^{-1})$$
  
= 17.47  $\ (ms^{-1})$ 

This is inserted into the above mentioned equations:

$$F_{outlet} = \dot{m}v \text{ (N)}$$
(5.3.32)  
= 6.42 (N) (5.3.33)

$$F_{centrifugal} = \frac{\pi}{2R} \dot{m} v \text{ (N)}$$
(5.3.34)

$$= 134.37 (N) \tag{5.3.35}$$

Forces due to flow are 6.42 (N) and 134.37 (N) at outlet and 90° bends respectively.

It is assumed that the centrifugal forces are accounted for by hangers and supports in appropriate positions. The inlet force is small compared to other forces/moments found. It is therefore considered negligible and will not be subject to further considerations in this report.

### 5.4 To Services

As the GL is to be fully automated, and functions such as retracting (and possibly also deploying), in addition to numerous sensors as required by the DNV, are in need of a power source, there will be certain connections providing this.

In this report it is assumed that the electrical (and any hydraulic or pneumatic) connections will not influence the structural integrity of the GL in any way.

With no knowledge of the exact design of the bellow arrangement and its equipment, it is difficult to make any considerations of these aspects. Though it should be explored further at a later stage when the equipment and motors are known, it will not be subject to further consideration in this report.

### 5.5 Bellow operations

The main issues to be considered with the bellow arrangement are:

- Storage of bellow arrangement
- Evacuation of the bellow into the GL
- Replacement of bellow arrangement

#### 5.5.1 Bellow arrangement storage

As specified earlier in this report, the bellow arrangement is stored by way of connected coils or rolls, all with these properties:

Bellow material:	$\rm PE$
Avg. bellow density: $(kgr)$	$n^{-3}$ ) 1
Bellow thickness $(\mu m)$	) 100
Diameter of bellow arrangement (mm	a) 240

By regarding the bellow arrangement itself, it is possible to find the total volume, and therefore also the total mass of the GL. As is defined in the beginning of this chapter, the largest possible bellow for the tank in question is to be considered with the GL function specification. As explained in Ch 4.4.2, a minimum of three bellows are required. Fig 72 shows the three different bellow spaces that are considered for volume calculations. The total bellow volume is found by multiplying the surface area and thickness, the latter being 100 ( $\mu m$ ) = 0.1 (mm). Area A1 and A2 are separated by a pump column, while A2 and A3 are separated by a swash bulkhead<sup>21</sup>. The GLs on the illustration are not to scale, but merely indicators of possible locations. It is assumed that the bellow is folded and shaped in a manner that allows it to be wrapped around each item inside the cargo tank (such as stiffeners and rings) when deployed <sup>22</sup>. In order to calculate the entire surface area, the surface of each of these items are added to that of the cylindrical and hemispherical parts.



Figure 72: Area for three bellows in a tank Type C

The different areas A1, A2 and A3 are therefore determined by the hemisphere, their respective cylindrical portions, vacuum rings, stiffener rings, swash bulkhead and (virtual, or real) cylinder around pump. Calculations from figure yield the following:

<sup>&</sup>lt;sup>21</sup>The separations are marked with vertical, hatched areas

<sup>&</sup>lt;sup>22</sup>As is explained earlier in this report, this should be explored further, and be subject to rigorous testing and analyses as it is key to the success of the RPT.

 $SW = \pi R^2$ Swash bulkhead,  $(mm^2)$ (5.5.1)

Vacuum rings, (mm²)
$$VR = 2(\pi R^2 - \pi (R - 300)^2)$$
(5.5.2)Stiffener rings, (mm²) $SR = 2(\pi R^2 - \pi (R - 1500)^2) + 2(2\pi R \cdot 350)(5.5.3)$ Hemisphere, (mm²) $HS = 2\pi R^2$ (5.5.4)Cross section by pump, (mm²) $P = \pi R^2 + 2R(2\pi 500 - 500)$ (5.5.5)

ross section by pump, (mm<sup>2</sup>) 
$$P = \pi R^2 + 2R(2\pi 500 - 500)$$
 (5.5.5)

$$A1 = 2\pi R \cdot 3100 + HS + P \ (\mathrm{mm}^2) \tag{5.5.6}$$

$$= 5.07 \cdot 10^8 \; (\mathrm{mm}^2) \tag{5.5.7}$$

$$A2 = 2\pi R \cdot 8525 + P + SW + SR + VR \ (\text{mm}^2) \tag{5.5.8}$$

$$= 7.55 \cdot 10^8 \; (\mathrm{mm}^2) \tag{5.5.9}$$

$$A3 = 2\pi R \cdot 9750 + SW + SR + 2 \cdot VR + HS \ (\text{mm}^2) \tag{5.5.10}$$

- $= 9.55 \cdot 10^8 \; (\mathrm{mm}^2)$ (5.5.11)
  - (5.5.12)

As is seen from figure 72, these areas, with A3 being the larger, are plausible compared to one another. A3 is larger and will therefore be considered further. The limit of L/Dof maximum 2 is subject to control, with the results as follows:

$$D = 2R = 12752(mm) \tag{5.5.13}$$

The total length is noted as

$$L = R + 9750(mm) = 16126(mm) \tag{5.5.14}$$

$$\frac{L}{D} = \frac{16126}{12752} = 1.26 < 2 \tag{5.5.15}$$

It is therefore established that A3 can be occupied by a single bellow.

With a thickness, t, of 100  $(\mu m) = 0.1$  (mm), the volume for the bigger below is:

$$V_{bellow} = A \cdot t \tag{5.5.16}$$

$$=\frac{9.55\cdot10^{7}\cdot0.1}{1000^{3}}(m^{3}) \tag{5.5.17}$$

$$= 0.0955(m^3) \tag{5.5.18}$$

With a bellow arrangement with the suggested maximum diameter of 240 (mm), the required height for the bellow arrangement in the larger GL is found to be minimum:

$$H = \frac{V}{d_i} \tag{5.5.19}$$

$$0.0955(m^3)$$
 (5.5.20)

$$=\pi 0.240^2(m^2)$$
 (0.0.20)

$$= 0.398(m) \tag{5.5.21}$$

The required volume and height from bellow arrangement is  $0.0955 \ (m^3)$  and  $0.398 \ (m)$  respectively.

# 5.5.2 Reclaimed bellow

Said bellow will also occupy space in the GL when reclaimed from the tank.

We have from earlier calculations:

 $V_{bellow} = 0.0955 \text{ (m}^3)$ H = 0.398 (m) $d_i = 0.300 \text{ (m)}$ 

By assuming a method of retrieval as specified in Ch 4.4.3 and fig 88, the bellow is, when rolled up, assumed to take shape of a rather crude cylinder with a height,  $h_{roll}$  equal to the opening diameter,  $d_i$ :

$$h_{roll} = d_i \tag{5.5.22}$$

With the given volume and height, the diameter of the rolled-up below after use is:

$$d_{roll} = 2\sqrt{\frac{V}{h\pi}} \tag{5.5.23}$$

$$= 0.712(m) \tag{5.5.24}$$

This indicates that with the assumed method of retrieval of the bellow, there should be a cylinder (either horizontal or vertical) with diameter,  $d_{roll}$  of 0.712 (m) on the GL<sup>23</sup>. Other methods of retrieval will have other impacts on the GL and its requirements. As

<sup>&</sup>lt;sup>23</sup>The diameter,  $d_r oll$  is based on the assumption of the bellow being rolled up in a perfect cylinder, which is unlikely. Due to the lack of information, this value is still used.

there should be equipment and connections to this cylinder where the bellow is rolled up, there will be additional space occupied (and therefore additional mass). In order to simplify further calculations, the total volume of the roll-up section is to be increased by assuming a height of 1.2 times the original. The actual values should be found in further studies on the subject, when more is known about the GL and its equipment.

=

The total volume of the roll-up section is:

$$V_{roll-up} = A \cdot 1.2 h_{roll} \ (m^3)$$
 (5.5.25)

$$= \pi (d_{roll}/2)^2 \cdot 1.2h_{roll} \ (m^3) \tag{5.5.26}$$

$$= 0.143 \ (\mathrm{m}^3)$$
 (5.5.27)

Its surface area is

$$A_{roll-up} = 2 \pi (0.712/2)^2 + 0.712\pi 1.2 \cdot 0.3 \ (\text{m}^2) \tag{5.5.28}$$

$$= 1.602 \ (m^2) \tag{5.5.29}$$

### 5.5.3 Bellow arrangement replacement

For the bellow arrangement to be replaced an opening suitable for this needs to be present. Depending on the method of retrieval, the former bellow arrangement will be removed from the GL. With the GL completely empty, a new bellow arrangement may be inserted. Method of replacement is unknown and dependent on method of bellow folding and retrieval, though it is assumed that a suitable opening, such as either a valve, or a gas tight lid or door, may be used. Therefore, a volume with diameter and height equal to that of the gate valve is to be considered for this purpose.

# 5.6 Summary of function specification

The calculations not belonging to any of the previous subsections are performed in the following. This subsection will conclude with the principal characteristics as a summary of the function specification for the GL.

## 5.6.1 Design of Gas Lock

It has been established that the GL consists of two compartments, one for bellow storage before deployment, and one for rolling-up with evacuation after use. The former requires a geometrical shape of at least 300 (mm) in diameter and 398 (mm) in height (as shown in fig 87), while the latter requires a geometrical shape with at least 360 (mm) height and 712 (mm) diameter (as shown in fig 89).



Figure 73: 3D rendering of GL storage section with bellow arrangement

In order to save space and material costs, the possibility of integrating these into one unit should be explored further. This is, however, beyond the scope of this report, and further calculations and consideration are based on a possible design that is proposed here. As the entire GL storage section could fit into the GL retrieval section, a modified version of the latter will be considered as the GL in entirety. The GL with a combined storage and retrieval section is shown in figs 75 and 76.

In fig 76, it should be noted that the bellow is attached to the top of the GL so that flow of IG is secured. Attaching the bellow this far up is necessary if the rolling-up method of retrieval is to be used. The green shapes indicates valves that are connected to the GL in both ends. Method of replacing the bellow arrangement has not been considered, though it may be possible to construct the GL such that the entire rolling-up section could be opened from the side. A method for holding the bellow arrangement in place in such a way that proper deployment is ensured needs to be found. It is assumed that



Figure 74: 3D rendering of GL retrieval (roll-up) unit



Figure 75: Design of GL (2D) in the y-z plane



Figure 76: Design of GL (2D) in the x-z plane

such a method is in work in this case.

This design is considered for further calculations and considerations.

# 5.6.2 Thickness calculations of Gas Lock

With the form of the GL established, further calculations may be performed as specified in Ch 5.3.3.

As a minimum, the shell thickness for a cylinder with inner diameter,  $D_i$ , shall[4, Sec.4 B600] not be less than:

$$t = 3 + \frac{D_i}{1500} \text{ (mm)}$$
(5.6.1)

The Rules [4, Sec.4 C200] state that plate thickness of cylindrical shell<sup>24</sup> can be written as:

<sup>&</sup>lt;sup>24</sup>This value is used to calculate plate thickness for cylindrical part of domes, and is therefore considered sufficient for the purpose of finding required thickness for GL as well.

$$t = \frac{R \cdot p}{10\sigma_t e - 0.5p} + c \tag{5.6.2}$$

where,

$$R = 2d_i \tag{5.6.3}$$

$$e = \text{joint efficiency}$$
 (5.6.4)

Thickness of GL storage section With  $D_{i,storage} = 300 \text{ (mm)}, \sigma_t = 203.7 \text{ (Nmm^{-1})}$  and  $p = p_{max} = 6$  (bar), and a corrosion allowance, c, of 1.0 (mm) [4, Sec.4 B700] we get from eqs 5.6.1 and 5.6.2:

$$t_{storage,min} = 3 + \frac{D_{i,storage}}{1500}$$
(mm) (5.6.5)

$$= 3.2 \text{ (mm)}$$
 (5.6.6)

$$t_{storage} = \frac{2 \cdot 300 \cdot 6}{10 \cdot 203.7 \cdot 1 - 0.5 \cdot 6} + 1 \tag{5.6.7}$$

$$= 2.47 \text{ (mm)}$$
 (5.6.8)

$$\approx 2.5 \text{ (mm)} \tag{5.6.9}$$

This is less than the 3.2 (mm) found to be the minimum allowed thickness. Thus, the shell thickness of the GL storage cylinder with the storage section is to be 3.2 + c = 4.2(mm).

Thickness of GL retrieval section With  $D_{i,roll} = 712 \text{ (mm)}, \sigma_t = 203.7 \text{ (Nmm^{-1})}$  and p =  $p_{max} = 6$  (bar), and a corrosion allowance, c, of 1.0 (mm) [4, Sec.4 B700] we get from eqs 5.6.1 and 5.6.2:

$$t_{roll,min} = 3 + \frac{D_{i,roll}}{1500} \text{ (mm)}$$

$$= 3.48 \text{ (mm)}$$
(5.6.10)
(5.6.11)

$$= 3.48 \text{ (mm)}$$
 (5.6.11)

$$t_{roll,cylinder} = \frac{2 \cdot 712 \cdot 6}{10 \cdot 203.7 \cdot 1 - 0.5 \cdot 6} + 1 \tag{5.6.12}$$

$$= 5.2 \text{ (mm)}$$
 (5.6.13)

The required thickness for the cylinder part of the GL will therefore be 5.2 (mm).

The thickness of the unstayed, flat end plates is determined by a formula from the Rules [4, Sec.4 C600]:

$$k \le \frac{14\sigma_t}{p} \tag{5.6.14}$$

where,

$$t = \text{thickness of end plate (mm)}$$
 (5.6.15)

$$t_1 = \text{thickness of cylindrical shell (mm)}$$
 (5.6.16)

$$D_i = \text{inside diameter of cylindrical shell (mm)}$$
 (5.6.17)

The coefficient k is determined from fig 77.

With

$$\frac{14\sigma_t}{p} = 475.3\tag{5.6.18}$$

and

$$\frac{100(t_1 - c}{D} = 0.59\tag{5.6.19}$$

we get from the chart that this is outside the given parameters, and a flat end cannot be unless the thickness,  $t_1$  is increased. Though the possibility of a concave end should be explored, this will not be done here due to the time constraint of this report.

The Rules [4, Sec.4 C500] state that the thickness of dished ends, without stays are not to be less than:

$$t = \frac{pD_0}{20\sigma_t e} K + c \;(\text{mm}) \tag{5.6.20}$$

where,

$$t =$$
thickness of end plate (mm) (5.6.21)

- $D_0 =$ outside diameter of end plate (mm) (5.6.22)
  - e = joint efficiency(5.6.23)
- K = shape factor from fig 78 (5.6.24)



Figure 77: Calculation factor, **k** 



Figure 78: Calculation factor, K

With

$$\frac{H}{D_0} = 475.3\tag{5.6.25}$$

and

$$\frac{100(t_1 - c)}{D} = 0.59\tag{5.6.26}$$

An analysis of the use of materials with a dished, versus a flat end should be performed in order to keep the material costs down. The use of stays with both flat and dished ends should be explored as this most likely would result in less total material use. For this report, however, a flat unstayed end will be used out of simplicity of calculations.

In order to use a flat end, the thickness,  $t_1$  needs to be increased to at least 8.12 (mm). This yields:

$$\frac{100(t_1 - c)}{D} = \frac{100(8.12 - 1)}{712} = 1 \text{ (mm)}$$
(5.6.27)

This yields a parameter of 0.2 from fig 77, and we therefore have:

$$\frac{t_1 - c}{t - c} = 0.2\tag{5.6.28}$$

that yields:

$$t = \frac{t_1 - c}{0.2} + c = 36.6 \text{ (mm)}$$
(5.6.29)

It should be noted that the thickness of 36.6 (mm) is very high, which is due to the ends being flat. As is mentioned earlier, the ends should be dished, or hemispherical for the extreme case if the thickness should be reduced. This should be considered with further work on the subject.

The shell thicknesses of the GL is therefore 36.6 (mm) and 8.12 (mm) for flat and cylindrical parts respectively.

The volume of this section of the GL (excluding the values) is given as:

$$V = A_{cyl} \cdot t_{cyl} + A_{flat} \cdot t_{flat} = 0.0357 \ (m^3) \tag{5.6.30}$$

It is assumed that the construction is made of the material NV 4-4L with a density of 7800  $(kgm^{-3})$  as described earlier. The mass is therefore:

$$M_{GL} = \rho V \tag{5.6.31}$$

$$= 278.5 \text{ (kg)} \tag{5.6.32}$$

The roller and other equipment has not been accounted for, and this additional equipment is assumed to increase the mass such that: The mass of this section of the GL is 300 (kg).

#### 5.6.3 Reinforcements from penetration

The section between the gate valve and the cargo has, out of simplicity and the time constraint, been assumed to be subject to the same stresses as the cylindrical portion of the GL that has been evaluated earlier in this report. Thus, the required thickness for this cylindrical section is 4.2 (mm).

The distance (height),  $h_{cylinder}$ , between cargo tank and gate value is assumed to be 450 (mm) as is a requirement for many distances between surfaces and cargo tank[3, sec.4 A].

The penetration of the cargo tank being larger than 150 (mm) in inner diameter needs to be reinforced as specified by the Rules (see Ch 3.2.3 in this report).

Symbol	$\mathbf{Unit}$	Value.
h <sub>cylinder</sub>	(mm)	450.0
$d_i$	(mm)	300.0
$\mathrm{D}_i$	(mm)	12752.0
$\mathbf{t}$	(mm)	40.0
$t_b$	(mm)	4.2

With geometry as indicated in fig 79, we have K = 1. Thus, the required area A, needs to be:

$$A \ge K(\frac{d_i}{2} + t_b)t = 7600 \ (\mathrm{mm}^2) \tag{5.6.33}$$

As shown in Ch 3.2.3, this area, A, is to be distributed as follows:

$$L_S = \sqrt{(D_i + t_a)t_a} \text{ (mm)}$$
$$L = 0.8\sqrt{(d_i + t_{ba})t_{ba}} \text{ (mm)}$$

The thicknesses  $t_{ba}$  and  $t_a$  need to be found, and by evaluating them with regard to minimum total reinforcement area (where  $A \ge A_{req}$  as shown in fig 80), it is found that the optimum solution is with the following:



Figure 79: Reinforcement area, K = 1

Symbol	Unit	Value.
$t_a$	(mm)	15.0
$t_{ba}$	(mm)	0.0
$\mathbf{L}$	(mm)	0.0
$L_S$	(mm)	437.6
$A_{req}$	$(mm^2)$	6168.0
А	$(\mathrm{mm}^2)$	6564.2

The area, A, is slightly larger than the required area,  $A_{req}$ , as it should be due to the Rules.

With this, the total mass of this section is found as:

$$m_{cylinder} = \rho(h_{cylinder} \cdot t_a \cdot \pi d_i) \tag{5.6.34}$$

$$\approx 50 \text{ (kg)} \tag{5.6.35}$$



Figure 80: Reinforcement thicknesses,  $\mathbf{t}_{ba}$  and  $\mathbf{t}_{a}$ 

# 5.6.4 Mass and centre of gravity

With all masses and dimensions known, the total mass and COG of the GL can be found.



Figure 81: 3D rendering of GL with valves and connection to cargo tank

For these calculations, it is assumed that the bellow is not installed in the GL until harbour has been reached as undue stress would be inflicted on the bellow arrangement. When in harbour where bellow is installed, it is assumed that any accelerations from ship movement is negligible.

The mass of the gate values are unknown, but it is assumed that the weight from similar pumps from Piping World [39] is representative. Each gate value is therefore assumed to have a mass of 300 (kg)  $^{25}$ . The GL is presented with dimensions in fig 81.

The total mass of the GL is found to be:

$$M = m_1 + m_2 + m_3 + m_4 \tag{5.6.36}$$

$$= 50 + 3 \cdot 300 \tag{5.6.37}$$

$$= 950$$
 (kg) (5.6.38)

The GL's COG is from this figure found to be:

$$COG = M^{-1} \sum_{i=1}^{N} (m_i x_i)$$
 (5.6.39)

$$= \left(\frac{450}{2}\right)50 + \left(\frac{300}{2} + 450\right)300 + \tag{5.6.40}$$

$$= +(\frac{712}{2} + 450 + 300)300 + (\frac{300}{2} + 450 + 300 + 712)300) \cdot M^{-1} (5.6.41)$$

$$= 1059.6 \text{ (mm)}$$
 (5.6.42)

The mass and COG of the GL is 950 (kg) and 1059.6 (mm) respectively.

### 5.6.5 Moments due to accelerations

With the form of the GL established, further calculations may be performed as specified in Ch 5.3.3.

Accelerations of the ship (as explained in "Dynamic loads" with eqs 3.2.12 through 3.2.14 in Ch 3.2.2) will affect the GL. These accelerations, with a resultant working on the centre of gravity (COG) of the GL, will create a force (with the mass of the GL), and therefore a moment that will be transferred to the connection between GL and cargo tank.

<sup>&</sup>lt;sup>25</sup>It is uncertain if both gate valves are of equal mass as the one leading to the deck tank is not of the same inner diameter. Out of simplicity, they are assumed to be of equal mass.

Symbol	Item	Unit	Value.
L	Ship length	(m)	147.7
В	Ship breadth	(m)	22.7
$L_S$	Length of reinforcements	(mm)	437.6
х	Distance (longitudinal) from amidship	(m)	0.
у	Distance (transverse) from amidship	(m)	0.
$\mathbf{Z}$	Distance (vertical) from waterline to GL's COG	(m)	7.5
$C_B$	Block coef.	(-)	0.82
V	Service speed	(kn)	14.0
GM	Metacentric height	(m)	1.0
$\kappa$	Form factor	()	1.0

For the calculations of accelerations, the following values have been used  $^{26}$ :

The design acceleration vectors working on the GL can be found from the Rules as specified in eqs 3.2.13 and 3.2.14:

$$a_x = 0.025 \ (\mathrm{ms}^{-2}) \tag{5.6.43}$$

$$a_y = 0.067 \ (\mathrm{ms}^{-2}) \tag{5.6.44}$$

$$a_z = 0.038 \ (\mathrm{ms}^{-2}) \tag{5.6.45}$$

With the assumption that the static weight of the GL need not be taken into consideration (as specified earlier in this report), and with  $a_z$  being only 0.38 per cent of the gravitation, g, it will not be taken into consideration. Thus, the resultant,  $a_R$  from the design accelerations  $a_x$  and  $a_y$  needs to b found:

$$a_{res} = \sqrt{a_x^2 + a_y^2} = 0.071 \ (\text{ms}^{-2})$$
 (5.6.46)

With mass, m, the force arising from the accelerations are given as:

$$F = m \cdot a_{res} = 67.9 \text{ (N)} \tag{5.6.47}$$

With the distance from the COG to the foundation on the cargo tank, the moment , M, from this force can be found. The moment is given as

$$M = F \cdot z = 75,095 \text{ (Nm)} \tag{5.6.48}$$

A simplified, but sufficient[13] method of considering these forces will be to find the required reinforcements from required moment of inertia.

$$I_{req} = \frac{M}{\sigma} z = 4.08 \cdot 10^5 \; (\mathrm{mm}^4) \tag{5.6.49}$$

<sup>&</sup>lt;sup>26</sup>Hull characteristics have been found from Clipper Hebe[8]. Values not available from Clipper Hebe have been assumed. They are only in place so that proper calculations can be performed for this report.

With Steiner's theorem as given in eq 5.6.50, where A is area of cross section:

$$I'_{z} = I_{z} + a^{2}A \ (\mathrm{mm}^{4}) \tag{5.6.50}$$

as well as moment of inertia of a rectangular cross section with height, h, and breadth, b, where:

$$I_z = \frac{hb^3}{3} \ (\mathrm{mm}^4) \tag{5.6.51}$$

It is believed, however, that a better solution would be to support the construction with regard to the moments in another way that requires less material than the simplified method of above. A typical way of doing so would be by installing brackets (as shown in fig 82, preferably two for each of the x and y axes; thus having four in total. The requirements of said brackets should be found by means of FEM analyses, but that is beyond the scope of this report, and will not be performed here. Also, whichever method is found suitable, an appropriate safety factor should be included.



Figure 82: Reinforcement by way of brackets

It has been found that the reinforcements due to the accelerations on the GL should be by way of four brackets, two for each of the x- and y axes.

### 5.6.6 Principal characteristics

With the considerations and calculations performed in this chapter, we have established the following:

The GL is in contact with the cargoes of  $CO_2$  and  $C_3H_8$ , as well as the inert gas  $N_2$ . The properties of these are described in table 10. The properties of nitrogen gas is explained

in table 6. From these, as well as below requirements, it is clear that the more extreme <sup>27</sup> temperatures, pressures and densities the GL will encounter is as shown in table 7.

		Maximum	Minimum
Temperature	$(^{\circ}C)$	30.0	-55.0
Design pressure, absolute	(bar)	6.0	1.0
Density	$(kgm^{-3})$	1150.0	1.0

The largest required volume due to bellow arrangement storage is found to be 0.0955  $(m^3)$ . With a required maximum diameter of the bellow arrangement of 0.240  $(m^2)$ , the required GL height due to bellow arrangement storage is 0.398 (m). The required space for bellow retrieval by means of roll-up is 712 (mm) diameter and height of 360 (mm). It has been found in this report that an efficient way of reducing the total volume of the GL (and therefore also total mass and material costs) is to store the bellow arrangement inside the retrieval (roll-up) section. It is assumed that a method of holding the bellow arrangement such that it will deploy successfully, though it has not been described in this report.

Between GL and cargo tank, the opening is sealed (and opened when necessary) by means of a gate valve of 0.3 (m) in diameter, and 0.3 (m) in length. To the deck tank (via a heat exchanger) the GL is connected via a pipeline of 0.15 (m) diameter and 3.3 (mm) thickness. This pipeline exerts (in this given case) a moment on the GL of 6.01 (kNm). This moment needs to be accounted for with reinforcements, preferably by way of four brackets mounted on top of the reinforcements required for the penetration of the cargo tank itself.

With the above-mentioned BCs and requirements, the function specification of a GL can be established. The results are presented in table 7 and figs 90 and 91.

<sup>&</sup>lt;sup>27</sup>As explained in Ch 1.3.1, the GL is to have a "slightly" higher pressure than the cargo tank design pressure. Due to the inaccuracy of this statement, it has been assumed that this gauge pressure is negligible and has of this reason not been considered any further.


Figure 83: 3D rendering of GL, xz-plane



Figure 84: 3D rendering with dimensions

### 6 Gas Lock case study

As specified in the Task Definition in Ch 1.2, a preliminary design study for integration of a GL into a cargo tank is to be performed. Part of this has been done in Ch 5 as a possible design for a GL has been found. The effect of three or more GL's (in addition to penetrations for pump, piping and access openings in the tank) are to be evaluated. This will be done in this section  $^{28}$ .

As has been specified in Ch 3.2.3, openings and reinforcements are to be in accordance with the Rules [4, Sec.4 I600].

They state that the Rules [4, Sec.4 D102] only apply to openings in cylindrical shells where the distance between the axes is no less than 1.5 times the average diameter of the openings. They [4, Sec.4 D304] also state that where two openings or branches are sufficiently closely spaced for the limits of compensation in the shell to overlap, the limits of compensation shall be reduced so that no overlap is present. These are found to be the only relevant requirements with regard to multiple openings.

It is for this case assumed that all GLs are to be mounted on the very top of the cylindrical part of the cargo tank, though the possibility of GLs on other parts of the surfaces should be explored. This is not done in this report, but should be done if there proves to be no available space on the top.

With an opening of 300 (mm) as suggested by the Company, the required distance, s, between openings are as shown in fig 85. From this, it is clear that the minimum distance between the axes of two GL openings are 450 (mm).

$$s = 1.5d_i \text{ (mm)}$$
 (6.0.52)

$$=450 \text{ (mm)}$$
 (6.0.53)

With further considerations, the distance, a, from the centre of a typical opening for a pump (not a GL related opening) will be used to determine possible locations for a GL opening in accordance with the Rules as specified above. With fig 86, it is shown that there are three different openings not related with the GL. They have diameters  $\mathbf{d_i} = [d_1, d_2, d_3] = [500, 1500, 630]$  (mm).

$$a = s - \frac{d_2}{2} \tag{6.0.54}$$

With distance, a, as given in eq 6.0.54, the distances of  $\mathbf{a_i} = [a_1, a_2, a_3] = [450, 1200, 547.5]$  (mm). The available space for GL openings in the tank considered in this case is therefore as shown in fig 86

<sup>&</sup>lt;sup>28</sup>All analyses are to be performed according to the Rules



Figure 85: Multiple openings, with non-overlapping reinforcements. Top view.



Figure 86: Openings and available space. Side view.

With the available spaces being 778 (mm), 1091 (mm), 654 (mm), 3127 (mm), 3124 (mm), 3040 (mm), 959 (mm) and 579 (mm), and the distance between the axes of each GL opening being 450 (mm), the available numbers,  $n_1$ ,  $n_2$  and  $n_3$  of GLs for each of the areas A1, A2 and A3 (as shown in fig 72 are respectively:

$$n_1 = 2$$
 (6.0.55)

$$n_2 = 10$$
 (6.0.56)

$$n_3 = 17$$
 (6.0.57)

With the different required surface areas for a bellow as found in Ch 5.5.1, each of the areas A1, A2 and A3 can be covered with bellows down to the following sizes:

$$\frac{A1}{n_1} = 2.54 \cdot 10^8 \text{ (mm}^2 \text{ per bellow)}$$
(6.0.58)

$$\frac{A2}{n_2} = 7.55 \cdot 10^7 \text{ (mm}^2 \text{ per bellow)}$$
(6.0.59)

$$\frac{A3}{n_3} = 5.62 \cdot 10^7 \text{ (mm}^2 \text{ per bellow)}$$
(6.0.60)

The largest possible volume and surface area of a bellow should, if a tank of the type and size used here is to be considered, be accordingly to the surface areas found in eqs 6.0.58, 6.0.59 and 6.0.60. In this case, however, it will be assumed that the number of bellows is to be kept at a minimum in order to reduce the amount of the required GLs, and therefore also the cost of use of this technology.

With only one GL for each of the areas A1, A2 and A3, the optimal position should be found. The location with regard to bellow depends on the physical properties of the bellow itself, as well as its deployment capabilities. Neither are known at this point, but it is assumed that a mid-position is favourable. Also, location of a GL is dependent on the available space on deck, which is rarely, if ever, the same on different liquefied gas carriers. With this information unknown for this special case, it will be assumed that there is available space where needed.

The effect of three or more penetrations on the tank is considered negligible if the Rules as specified above are followed. As stated earlier in this report,

A tank Type C with all appendices and add-ons is, as stated earlier in this report, designed by use of the Rules, making any further analyses extraneous. The Rules as described in this Chapter shows that the effect on the cargo tank of three (or more, up to 2 + 10 + 17 = 29) GLs is negligible. If necessary, more GLs could be installed using the surface of sides of the cargo tank. This would require special considerations to be taken with the design of these GLs to ensure proper deployment and retrieval of bellows.

## 7 Conclusion

For the liquefied gas cargoes of propane and carbon dioxide in a cargo tank with dimensions as specified in Appendix A, and with basis on the information as shown in Chapters 1, 2, 3 and 4, the basis for a function specification of a GL is presented in Chapters 5 and 6.

A GL is to be able to store, deploy and retrieve a bellow, as well as being able to function in the given environment.

**Deployment of bellow** Deployment of bellow requires the GL to have an opening from the GL into the cargo tank. This is to be done by way of a gate valve with 300 (mm) inner diameter. Such a valve is shown in fig 23.

Storage With storage of the bellow inside the GL as described in Ch 4.2.1, 4.4.1 and 5.5.1, it is clear that the minimum required dimensions are as shown in fig 87.



Figure 87: 3D rendering of GL storage section with bellow arrangement

**Retrieval** Retrieval of bellow happens through the gate valve of which it was deployed. This is assumed to be done by means of a roll-up mechanism as shown in fig 88.



Figure 88: Conceptual sketch of retrieval mechanism [29]

When rolled up with such a mechanism, the bellow is thought to resemble a cylinder with the same height as the diameter of the gate valve. The concept and dimensions are as shown in figs 90 and 91 respectively. It should be noted that the bellow arrangement itself is the bottom cylinder shape, while it has one thin drape-like end attached to the top of the GL in order to allow for IG flow through it, as well as retrieval by means of rolling-up.



Figure 89: 3D rendering of GL retrieval (roll-up) unit

**Environment** With regard to the environment, a GL needs to be dimensioned for the properties as shown in table 7.

		Maximum	Minimum
Temperature	$(^{\circ}C)$	30.0	-55.0
Design pressure, absolute	(bar)	6.0	1.0
Density	$(kgm^{-3})$	1150.0	1.0

This will affect the design mainly by required thicknesses and method of manufacture, but also by use of compatible materials. The material NV 4-4 L has been found to be suitable for the temperature and pressure, both for the cargo tank, and the GL construction.

With this material, a design with dimensions as shown in fig 81 is proposed. Though the design is probably not the optimal one, it has been made in accordance with the Rules, and should be a possible solution. This design is presented in figs 90 and 91 in Ch 5.6.6.

With this, it is concluded that designing a GL in accordance with the Rules is possible with a negligible effect on the cargo tank. Care should be taken in order to optimise the GL and minimise material costs.



Figure 90: 3D rendering of GL, xz-plane



Figure 91: 3D rendering with dimensions  $% \left( \frac{1}{2} \right) = 0$ 

#### 8 Further studies

Though conclusions were reached in this report as described in Ch 7, there are many aspects that should be explored further. These aspects include, but are not limited to, further development of the RPT based on said conclusions, as well as the checking of all assumptions used to find these conclusions.

The consequences of use of the RPT have been shown in this report for a limited number of idealised cases with many and crude assumptions. With further studies on this technology there should be a focus on establishing economic and environmental benefits for more types of cases, and apply them to more realistic ones than what have been found in this report. These analyses should be performed with actual values from relevant and real-life trade routes, cargoes and their corresponding liquefied gas handling procedures. Cooperating with a shipping company, or others with access to the same information, would be key in performing these analyses successfully.

As the RPT is under development, the design specifications of many components are merely conceptual at this stage. In order to properly direct the effort of further developments, proper and thorough risk analyses should be performed. This would typically involve a FMECA (or HAZOP or similar procedures, but more accurately than what was performed in this report) by key personnel<sup>29</sup> in order to identify the potential risks with the RPT. It would be prudent to follow up such analyses with detailed FTAs for the more serious risks, as well as ETAs.

Some of these aspects would influence the development of the bellow and the corresponding equipment. They would, in turn, influence the success or failure of procedures such as deployment and retrieval of bellow. Successful deployment and inflation of a bellow is dependent on its design, as well as the absence of sharp edges as mentioned earlier. Each cargo tank the RPT would be installed on should be thoroughly checked for sharp edges that should be either removed or covered up. Methods for doing so should therefore be explored. It follows that different mechanisms for retrieval should be explored in order to find the better method. This is linked directly to the arrangement of the bellow, the GL and the deflation of the bellow. These, and especially the latter should be set up for further studies. With these components in place, a more thorough function specification can be given for a GL. This should result in an actual design specification. With requirements from a function specification, different materials and designs can be explored with regard to cost, hopefully resulting in a RPT being efficient and inexpensive for both installation and use.

As mentioned earlier in this report, the proposed design for a GL with dimensions as presented in Ch 7 should neither be considered efficient nor final; it is merely used for calculations with the case study as required by the Task Definition in Ch 1.2.

 $<sup>^{29}</sup>$ Key personnel with the design and concept of the technology in question, as is usual with these kinds of risk assessments

This report will therefore conclude with that further studies are necessary to ensure a functional and optimal design of both bellow arrangement, GL and their related equipment. With proper studies carried out, an economically viable solution should be found such that the RPT can be successfully commercialised.

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# Appendices

A Tank type 'C'



Figure 92: Appendix A