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Quantities affecting the methane and VOC emission

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Abstract heading
Quantification and subsequent reduction of methane and other volatile organic compounds (VOC) emissions from storage, loading, transport and discharge of crude oil and condensate requires an understanding of the gas emission behaviour. Quantities affecting the methane and VOC mass emission factors include e.g. the VOC composition in the loaded fluid and its temperature, the loading time and filling degree, the allowed pressure in the cargo tank gas phase as well as the initial gas phase hydrocarbon content. Ship movement roll and pitch affect the large-scale mixing effects along with other mixing mechanisms.

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1 Introduction

1.1 Background and objective

Methane and other volatile organic compounds (VOCs) including benzene are released during storage, loading, transportation and discharge of crude oil and condensate. While benzene primarily pose a health and working environment problem, all non-recovered VOC emissions collectively increase the greenhouse gas problem as well as representing a lost natural resource. Non-methane VOC emissions have been regulated on the Norwegian shelf since the early 2000's, however global focus has been given methane recently through e.g. OGMP 2.0 requirements on quantification, reporting, and subsequent emission reductions.

The behaviour of VOC gas emissions from cargo tanks has been studied since the 1980's. SINTEF Ocean has conducted over one hundred measurement campaigns and developed a simulation software, VOCSim, to predict the gas emission behaviour when only limited information is at hand. Various quantities that affect the gas emissions are taken as inputs, and numerous simulations as well as some measurements show how these quantities affect the emissions.

The objective of this document is to summarise how the various quantities affect the methane and VOC emission, including examples from previously conducted simulations and measurement campaigns. A summary of quantities affecting the methane and VOC mass emission factors are shown in Table 1.

Table 1 Summary of quantities affecting the methane and VOC gas mass emission.

Quantity	Symbol	Change in quantity	Response in emission factor	Section
VOC composition in fluid	x_j (-)	Increase	Increase	3.1, 10.3
Fluid temperature	T_l (K)	Increase	Increase	3.2, 5.1, 5.2, 9.1
Filling time	τ (h)	Increase	Increase	4.1, 4.2
Filling degree	h/H (-)	Increase	Decrease	4.3, 6.2, 7.1,
Pressure in gas phase	P_g (bar)	Increase	Decrease	6.1, 9.2, 10.1
Initial hydrocarbon content	α_0 (-)	Increase	Increase	9.3, 10.2
Ship movement roll, pitch	Φ, Θ (°)	Increase	Increase	7.1

Mixing, i.e. mass transfer processes driven by diffusion, advection, and turbulent dispersion in both liquid and gas bulk phases, increases the emission factor as described in Section 7.1 for ship movement and sloshing, Section 7.2 for inflowing fluids, and Section 7.4 for buoyancy induced convection. Section 7.5 deals with situations with stratification in the gas phase, which reduces the mixing. Flashing of gas as a result of pressure drop is discussed in Section 7.3. Increasing the evaporation surface area due to sloshing, splash loading, and free gas in the loading line increases the possible mass transfer, as mentioned in Section 8.

This document is a deliverable in the Low Emission Case Study (Føre & Krause, Update of VOCSim for OGMP 2.0 reporting of methane emissions - Case study suggestion 2025-26, 2025) and serves a basis for the use case demonstrator in VOCSimPRO (Føre & Holm, VOCSimPRO - improved quantification and abatement of methane and VOC emissions, 2025).

1.2 Definitions and abbreviations

Bar absolute (bar a) is absolute pressure measured in bar, whereas **bar gauge** (bar g) is the pressure difference between ambient and absolute pressures measured in bar.
Emission factors (EF) are based on the emitted mass of methane or VOCs, per standard cubic meter (Sm^3, the volume at 15°C and 1.01325 bara) loaded volume of fluid.
Empty tank means a tank with no liquid content. The tank gas phase may still contain hydrocarbons and other greenhouse gases.
A **fluid** can be in its liquid and/or gaseous state
Mixing is a collective term for mass transfer driven by diffusion, advection, and turbulent dispersion in bulk gas and liquid phases.
Release denotes the mass transfer of methane and other VOCs from the liquid, while **emission** means the gas flowing out from the tanks.

COW	crude oil washing
EF	emission factor (mass emitted VOC/volume loaded fluid)
EOS	equation of state
NMVOC	non-methane volatile organic compound
PVT	pressure-volume-temperature
TVP	true vapour pressure
VOC	volatile organic compound
STTA	sequential transfer of tank atmosphere

2 Behaviour of methane and VOC gas emissions from tanks

The gas emission during loading typically shows a variable gas flow rate (Figure 1), and a varying content of hydrocarbons in the emitted gas (Figure 2). The relative content of the individual VOC components varies normally throughout the loading (Figure 3), such that the VOC molecular weight will change accordingly (Figure 4). While the cargo tank pressure is normally controlled and inert gas added if cargo tank pressure decreases below a given limit, such as during the discharging operation, tank temperatures are usually not controlled. During transportation and storage, gas emission is normally absent or intermittent and low. This is particularly the case for newer shuttle tankers that can operate with cargo tank pressure around 0.5 bar g.

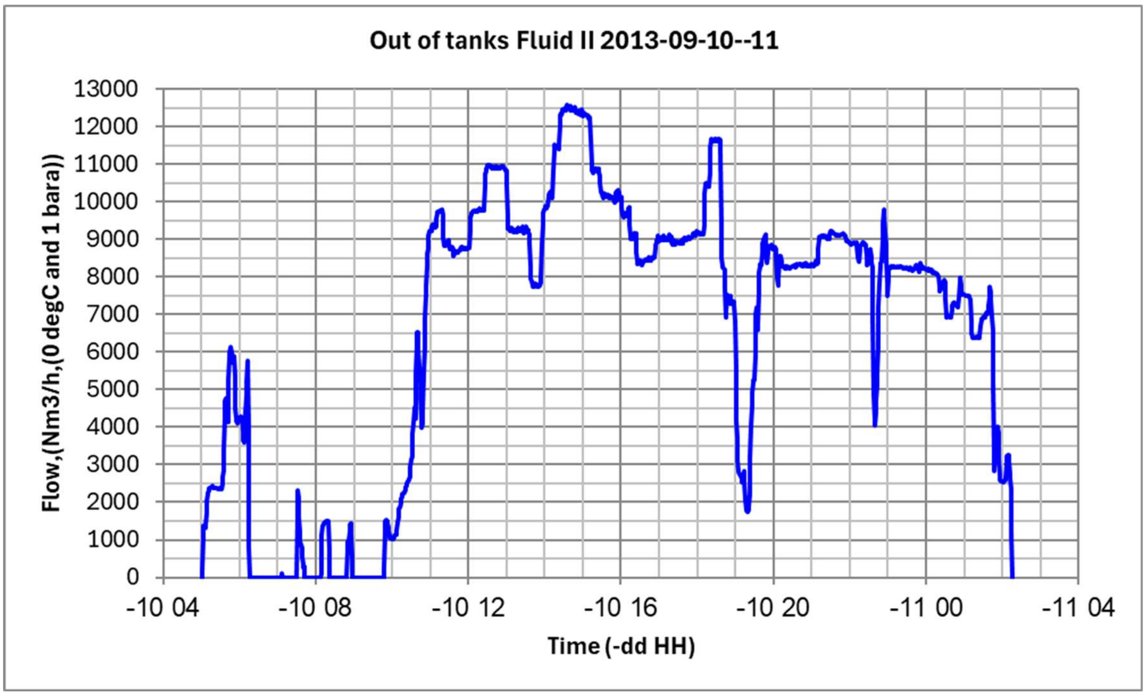

Figure 1 Emitted gas flow rate measured for a loading of Fluid II.

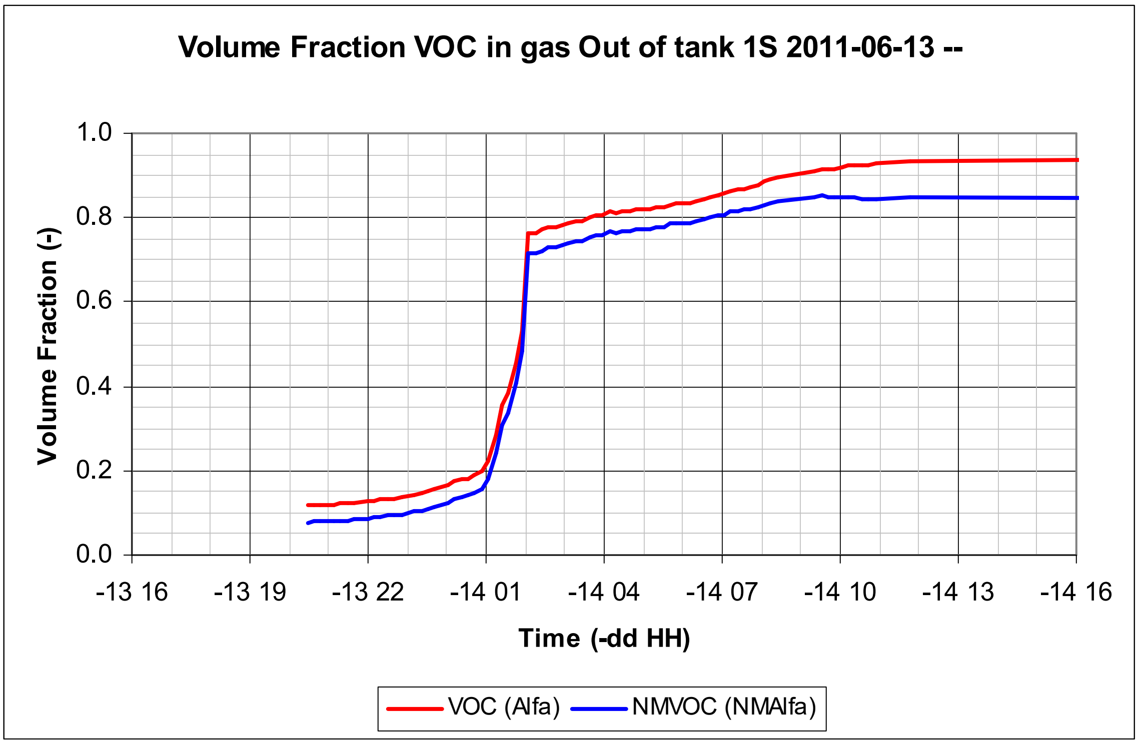

Figure 2 Measured hydrocarbon content in emitted gas for a loading.

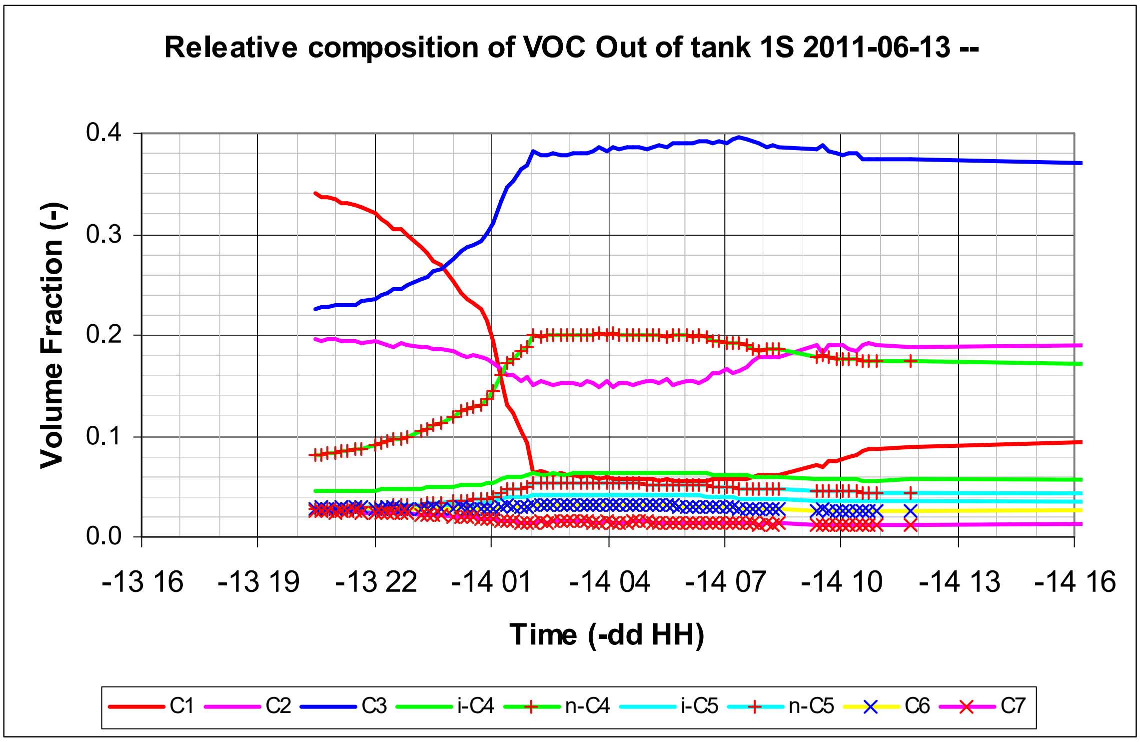

Figure 3 Measured gas composition, hydrocarbon compounds, in emitted gas.

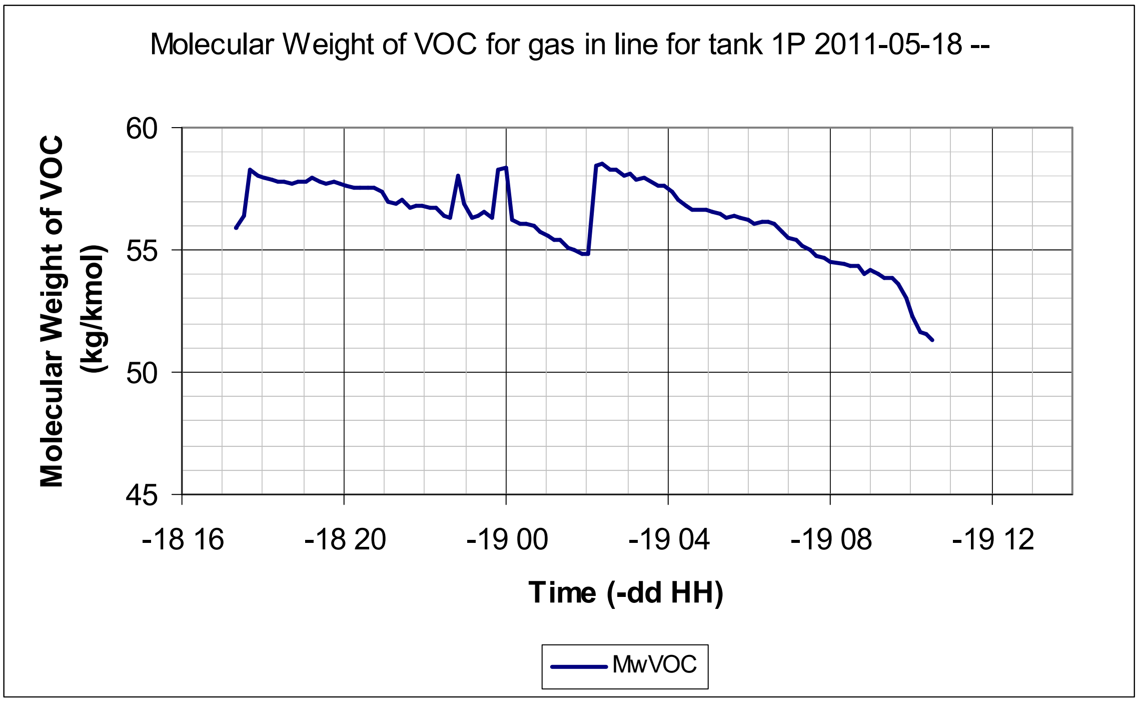

Figure 4 Measured molecular weight of hydrocarbons in the emitted gas.

3 Fluid properties

3.1 Fluid composition

How to best determine the fluid composition, component properties and tuning Equation of States (EOS) is an area of current research (Føre & Oldervik, EOS characterisation and matching PVT data, 2025).

3.1.1 Example: comparing emissions from Fluid I and Fluid II

In a set of simulations using a model calibrated to actual field measurements (Oldervik, Report No. 222230.00.05, 2011), loading a shuttle tanker on a Norwegian offshore field showed that different crude oil compositions result in different methane and VOC emissions. More light end components imply higher volatility and a larger emission if under equal conditions. In this case, Fluid II is the more volatile as shown by the composition in Table 2 as well as the measured equilibrium curves in Figure 5. Equation of state (EOS) tuned component properties and $C6^+$ characterisations are reported separately (Oldervik, Report No. 222230.00.03, 2011).

Table 2 Composition for Fluid I and Fluid II, mole fraction per component.

Component	Fluid I composition (mole fraction)	Fluid II composition (mole fraction)
methane	0.000570	0.000820
ethane	0.003200	0.004200
propane	0.025000	0.030500
i-butane	0.020000	0.012500
n-butane	0.058000	0.055000
iso-pentane	0.036000	0.031000
n-pentane	0.047000	0.049000
hexane	0.060000	0.056000
C7	0.100000	0.120000
C8	0.110000	0.108800
C9	0.070000	0.075800
C10+	0.469430	0.455722
N2	0.000450	0.000600
CO2	0.000350	0.000058
O2	0.000000	0.000000

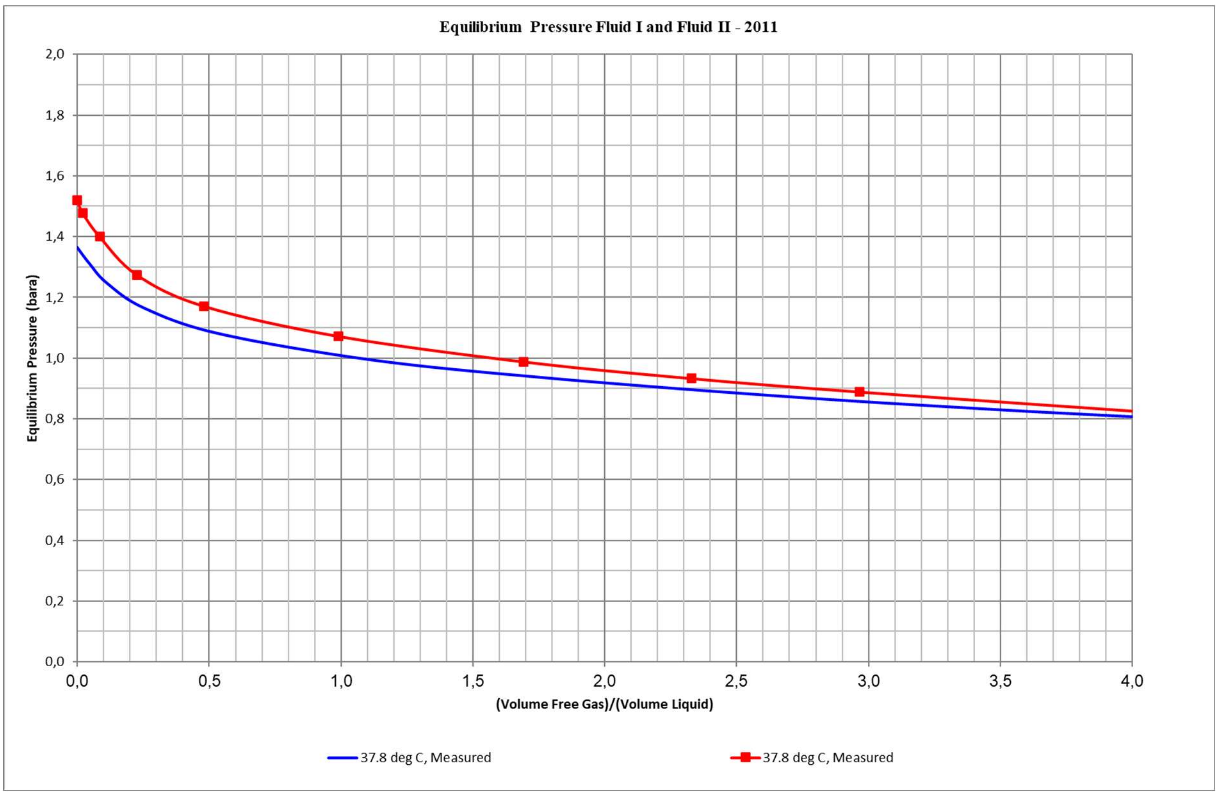

Figure 5 Equilibrium curves expressing the volatility of the fluid. Fluid I (blue) is less volatile than Fluid II (red), if at the same temperature.

In all simulated cases, the gas emissions of methane and VOC were larger for the more volatile Fluid II, as shown in Table 3 for methane and Table 4 for all VOCs.

Table 3 Methane emissions in various cases for Fluid I and Fluid II.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	Kg	kg/Sm^3	kg	kg/Sm^3	Kg	kg/Sm^3	kg	kg/Sm^3
Fluid I	1 807	0.015	3 117	0.026	1 657	0.014	2 863	0.024
Fluid II	2 171	0.018	3 469	0.029	2 005	0.017	3 196	0.027

Table 4 VOC emissions in various cases for Fluid I and Fluid II.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
Fluid I	125 484	1.07	156 507	1.33	101 153	0.86	126 603	1.08
Fluid II	133 113	1.13	161 871	1.37	113 070	0.94	133 961	1.14

3.1.2 Example: comparing emissions from various compositions of Fluid III

In a simulation of loading a shuttle tanker on a Norwegian offshore field (Oldervik, Report No. 238169.00.07, 2004), the last stage separator pressure on the exporting facilities was reduced resulting in a volatility reduction with less light end components in the exported fluid as shown in Table 5. The gas emission was reduced as shown in Table 6 for methane and Table 7 for VOC.

Table 5 Composition for three different volatilities for a fluid, mole fraction per component.

Volatility of fluid	High	Medium	Low
Component	(mole fraction)	(mole fraction)	(mole fraction)
C1	0.0033	0.00277	0.00201
C2	0.0082	0.00779	0.00696
C3	0.0292	0.02884	0.02801
iC4	0.0125	0.01245	0.01234
nC4	0.0360	0.03592	0.03569
iC5	0.0220	0.02200	0.02199
nC5	0.0280	0.02801	0.02802
C6	0.0480	0.04806	0.04818
C7	0.0950	0.09515	0.09544
C8	0.1106	0.11079	0.11116
C9	0.0783	0.07844	0.07870
C10+	0.5285	0.52945	0.53128
N2	0.0003	0.00022	0.00014
CO2	0.0001	0.00009	0.00008
O2	0.0000	0.00000	0.00000

Table 6 Methane emissions for various volatilities of Fluid III.

Quantity	Mass C_1	EF C_1
Unit	kg	kg/Sm³
High	13 898	0.10
Medium	11 641	0.08
Low	8 498	0.06

Table 7 VOC emissions for various volatilities of Fluid III.

Quantity	Mass VOC	EF VOC
Unit	kg	kg/Sm³
High	276 802	2.02
Medium	260 795	1.90
Low	234 071	1.71

3.2 Fluid temperature

Fluid temperature affects the true vapour pressure (TVP) of the fluid, such that the volatility, and thereby the gas release, increase with increased temperature.

3.2.1 Example: comparing emissions for various fluid temperatures

In a set of simulations using a model calibrated to actual field measurements (Oldervik, Report No. 222230.00.05, 2011), loading a shuttle tanker on two Norwegian offshore fields (Fluid I and Fluid II) showed that different fluid temperatures result in different methane and VOC emissions. As shown in

Table 8 for methane and Table 9 for VOC for Fluid I and in Table 10 for methane and Table 11 for VOC for Fluid II, the emission is larger for all cases with a higher temperature.

Table 8 Methane emissions for various temperatures of Fluid I.

	Case 1		Case 2	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm^3	kg	kg/Sm^3
T=306 K	1 279	0.011	1 201	0.010
T=312 K	1 311	0.011	1 230	0.010

Table 9 VOC emissions for various temperatures of Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
T=306 K	75 735	0.644	59 723	0.508	113 082	0.961	95 538	0.812
T=312 K	91 885	0.784	69 285	0.591	143 680	1.226	121 665	1.038

Table 10 Methane emissions for various temperatures of Fluid II.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
T=306 K	2 171	0.018	3 469	0.029	2 005	0.017	3 196	0.027
T=312 K	2 282	0.019	3 609	0.031	2 079	0.018	3 312	0.028

	Case 5		Case 6		Case 7		Case 8	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
T=306 K	3 076	0.026	4 349	0.037	2 704	0.023	3 798	0.032
T=312 K	3 350	0.028	4 678	0.040	2 881	0.024	4 048	0.034

Table 11 VOC emissions for various temperatures of Fluid II.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
T=306 K	133 113	1.129	161 871	1.373	113 070	0.959	133 961	1.136
T=312 K	167 217	1.424	197 935	1.685	135 601	1.155	158 423	1.349

	Case 5		Case 6		Case 7		Case 8	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
T=306 K	155 516	1.319	184 634	1.529	122 567	1.040	141 909	1.172
T=312 K	209 757	1.786	241 765	2.059	151 712	1.292	173 625	1.444

4 Loading rate, tank dimensions, loading pattern and procedures

4.1 Loading rates and procedures

Production or loading and discharging rates and procedures affect the gas emission. Increasing the loading rate to a tank will reduce the emission. Loading and discharge procedures such as ramp-up and -down of pump flow rates and topping-up the tanks must be taken into account.
Distribution of the fluid flow to several tanks results in a lower flow rate to each tank, implying a longer loading time for the individual tank.

4.1.1 Example: comparing emissions for various loading rates for Fluid III

In a simulation using a model calibrated to an actual field measurement, loading a shuttle tanker on a Norwegian offshore field showed that reducing the loading rate increased the methane and VOC emissions according to Table 12 for methane and Table 13 for VOC (Oldervik, Report No. 238169.00.07, 2004). Note however, that a reduction in loading rate also may reduce the emitted gas flow rate, as shown in Figure 6, which can be a desired outcome in for example design of vapour recovery systems. Refer to the discussion in Section 11.

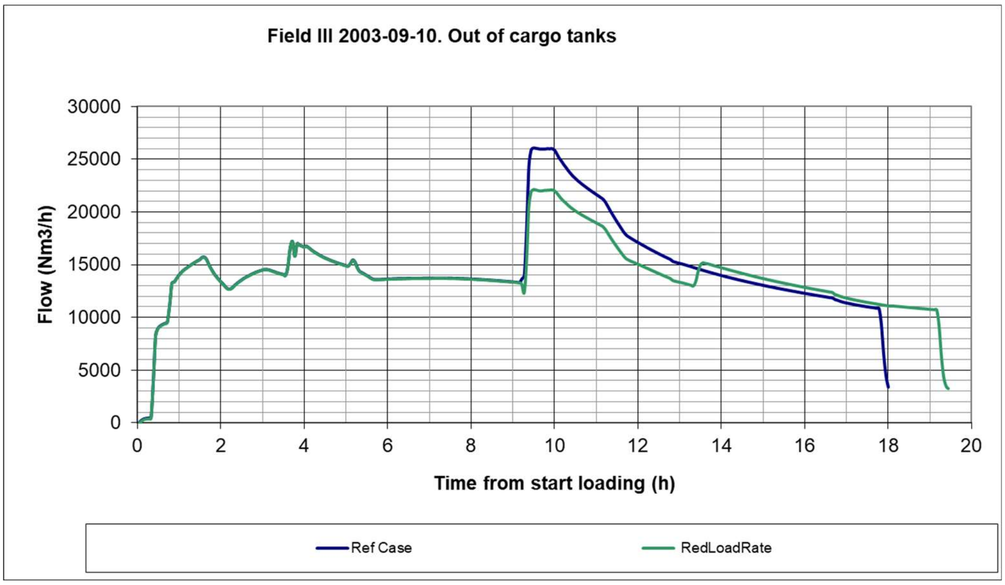

Figure 6 Simulated emission gas flow rate during a shuttle tanker loading Field III.

Table 12 Methane emissions for various loading rates for Fluid III.

Quantity	Mass C_1	EF C_1
Unit	kg	kg/Sm^3
High	13 575	0.10
Low	13 898	0.10

Table 13 VOC emissions for various loading rates for Fluid III.

Quantity	Mass VOC	EF VOC
Unit	kg	kg/Sm^3
High	264 990	1.93
Low	276 802	2.02

4.2 Tank dimensions and arrangement, loading pattern

While tank dimensions are given for a particular asset, new designs should aim for tanks being loaded in as short time as possible. Due to ship stability and hull strength issues, tanks are commonly loaded in parallel or in a particular manner if loaded in series. Wing tanks are loaded in pairs. Given the fluid flow rate, a loading pattern distributing the fluid to as few tanks as possible, i.e. in series, will result in the lowest emissions due to shorter loading time, refer to Section 4.1.

Loading arrangement affects the emission such that, e.g., individual droplines to each tank results in a larger emission than in case of a bottom-line distribution system. Refer also to Section 7.2.

The tank gas outlets are mostly interconnected allowing for flow of gas to tanks not loaded into, in case of a pressure increase in tanks loaded to. Refer also to Sections 9.2, 10.1 and 10.2.

4.3 Filling degree, storage and voyage

To reduce the gas emissions, tanks should be either empty (no liquid content), or as full as possible. Tanks with some liquid content will release and emit gas, and the filling degree can affect the emissions as explained in Section 7.1.

During storage and voyage, the liquid flow rate is zero, implying no displacement of the tank gas due to loaded fluid thus generally a lower emission.

4.3.1 Example: measured methane emissions from voyage compared to loading

The laden voyage has been measured several times (Føre, Methane - data analysis and acquisition, Report No. DT9_2019_04, 2019). An overview of the methane emissions during 40 voyages is shown in Figure 7 where each bar represents one voyage at a given date time span. Compared to emissions during loading, as shown in Figure 8, voyage emissions are generally much smaller.

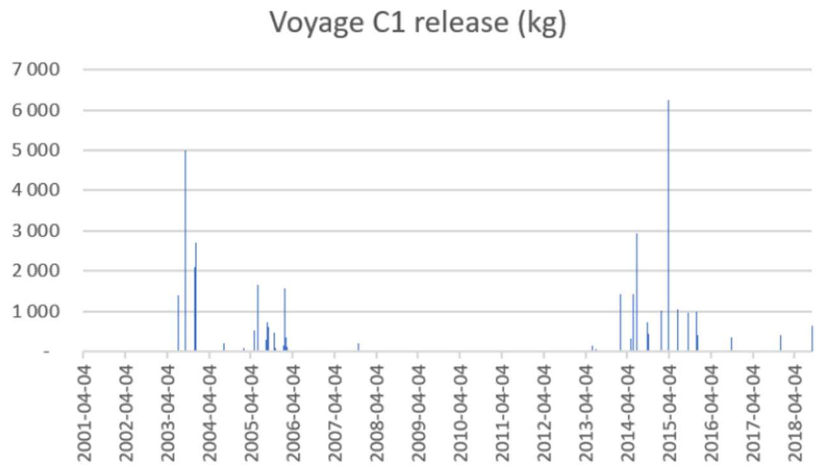

Figure 7 Methane emissions measured at the laden voyage (40 measurements).

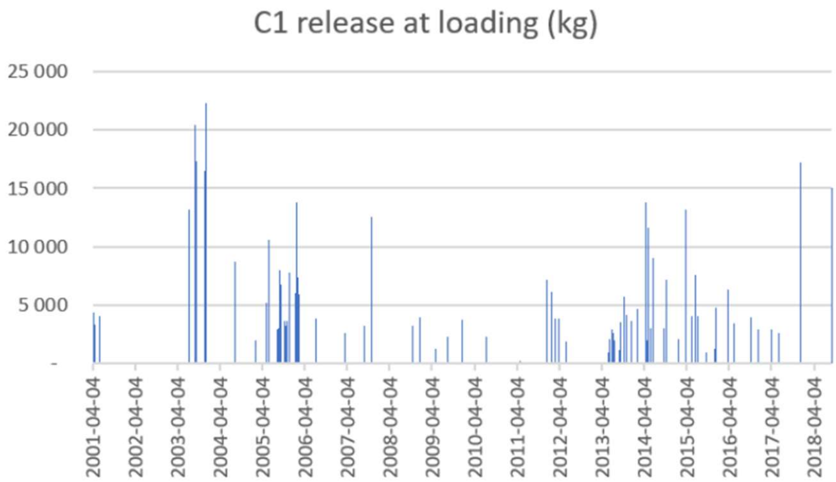

Figure 8 Methane emissions from loading shuttle tankers (79 measurements).

5 Temperatures

5.1 Temperatures in the tank

Temperatures in the gas and liquid phases vary spatially and temporally and are affected by temperatures of the surfaces surrounding the fluids, refer to Section 5.2. Cooling the liquid will reduce the release of hydrocarbons, as shown in Section 3.2.

Temperature variations may also cause density variations and in favourable conditions, natural convection (buoyancy) will occur as shown in Section 7.4.

5.1.1 Example: tank temperatures measured during a measurement campaign

Tank temperatures logged by sensors in the tank are shown before, during and after one loading for tanks 1S and 1P top (Top) and bottom (Bot) in Figure 9 (Oldervik, Report No. 222230.00.06, 2011). The measured temperature is in the gas phase until the sensor is submerged in the loaded fluid; then the liquid temperature is measured as indicated by a significant jump in temperatures between around 00 o'clock (hh) and 10 o'clock (hh) on the 17^{th} (-dd) where both bottom sensors register an increase in temperature before the top sensors, eventually ending at about the same temperature in the liquid phase for each tank.

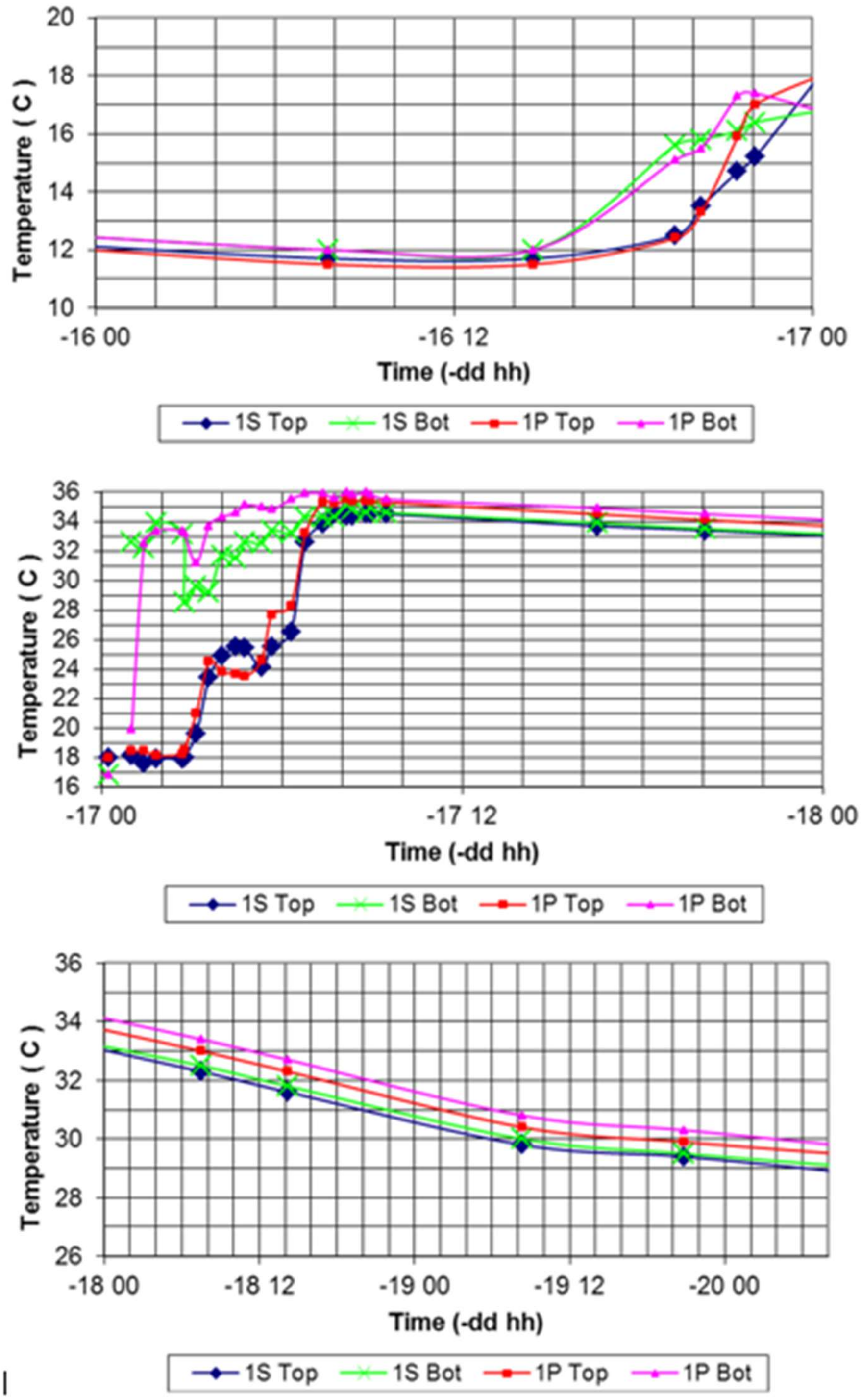

Figure 9 Measured gas or liquid temperatures of cargo tanks 1S & 1P at tank bottom (Bot) and top (Top), before loading (upper diagram), during loading (middle diagram) and during voyage (lower diagram).

Higher resolution temperature measurements are presented in Figure 10 for tank 1P during voyage prior to loading and Figure 11 during and after loading at various tank heights. The air temperature varied between 7 and 11°C while the loaded fluid had a temperature of around 35°C. The sea water temperature is not known; however, the measurement was done in mid-October indicating a sea water temperature in the lower range.

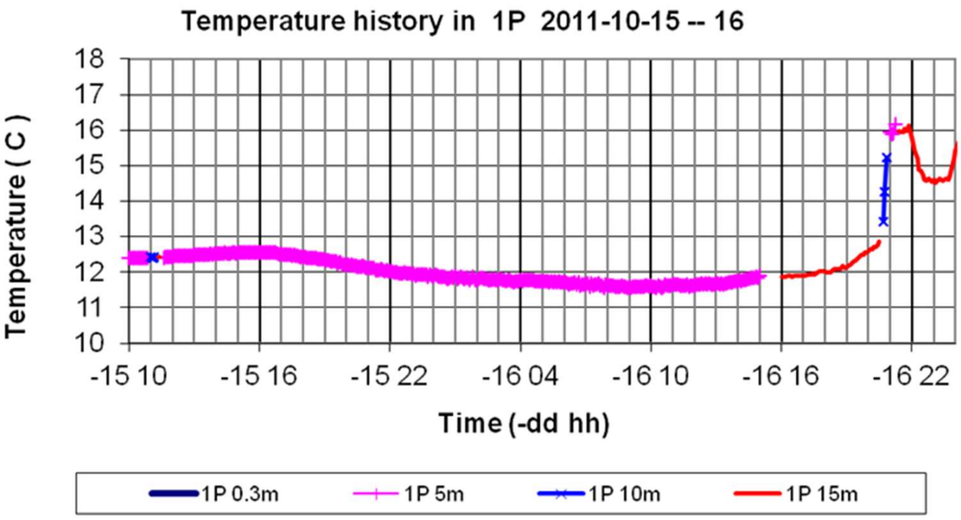

Figure 10 Temperatures in tank 1P measured before loading started, at some distances below deck.

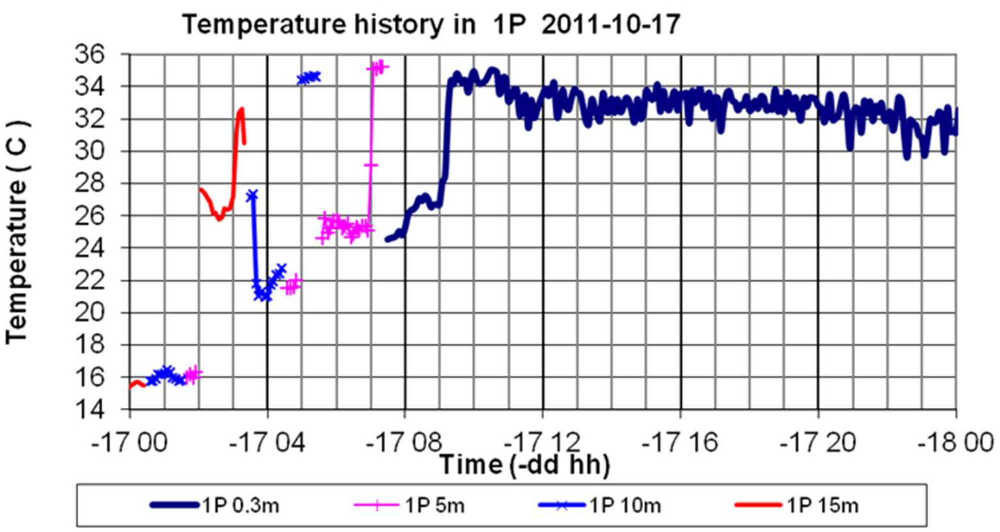

Figure 11 Temperatures in tank 1P measured during and after loading, at some distances below deck.

5.1.2 Example: measured gas phase temperature in empty tanks

Tank temperatures were measured for various vertical locations in an empty tank pair (tanks 1P and 1S) during a flow meter testing in 2011 (Oldervik, Report No. 222230.00.01, 2011), refer to Figure 12, showing the variation in time and between tanks and levels 5, 10 and 15 m below deck. Note e.g. how the temperature in tank 1P at the 10 m level experiences a drop in temperature from around 7.5°C to 3.5°C within about an hour, then rises to nearly 6°C within the next hour. While it may look like temperatures at 10 and 15 m below deck remain about 6°C from around 15 o'clock and onwards, temperatures near deck

(5 m) are significantly higher and, at least for tank 1P, stable around 8°C for the measurement time span of one hour.

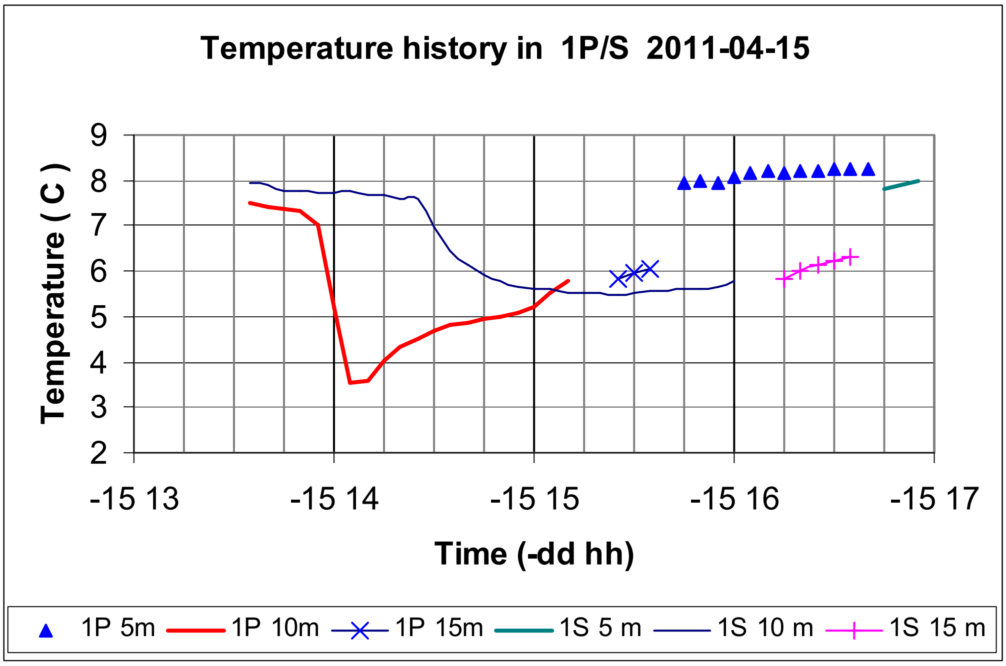

Figure 12 Temperatures measured in tanks 1P&S of a shuttle tanker with no liquid in it.

5.2 Temperatures of tank walls, deck, and sea water

In addition to ambient temperatures and possible solar irradiation to the ship deck, the content of neighbouring tanks impact tank wall temperatures. A neighbouring tank may contain ballast water, gas, or crude oil. Tank top and bottom temperatures must be considered, and in the gas phase, radiation should also be included. Convective effects due to variations in temperature is discussed in Section 7.4.

5.2.1 Example: measured ballast water levels

Ballast water with its cooling effect impacts the temperature of the neighbouring cargo tank wall, resulting in a distinct wall temperature difference corresponding to the ballast water tank level. Figure 13 shows measured levels in ballast water tanks 1P, FWD, and 1S during loading a shuttle tanker on a Norwegian field (Oldervik, Report No. 222230.00.06, 2011).

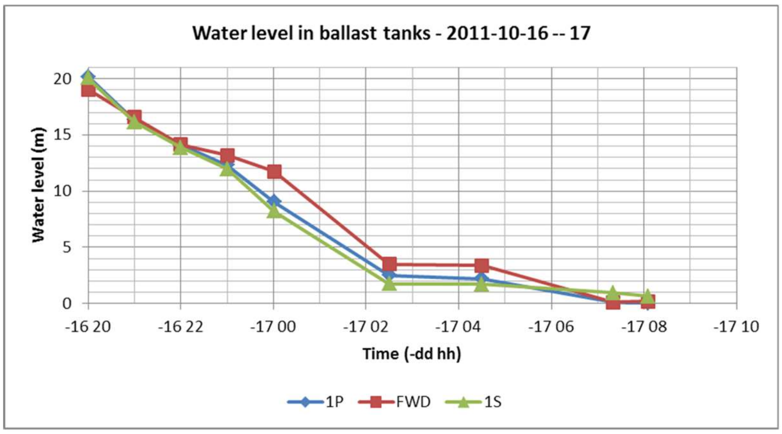

Figure 13 Measured water level in ballast tanks 1P, FWD and 1S during loading.

6 Tank pressures

6.1 Pressure in the tank gas phase

Tank set pressures in gauge in combination with the ambient pressure gives the absolute pressure of the gas. Traditional cargo tanks operate in a set pressure interval of 30-110 mbar g. Ambient pressure can be considered constant for the relevant time span of interest.

6.1.1 Example: tank pressure measurements for Field II

The tank pressures for a tank pair on a shuttle tanker were measured during loading as shown in Figure 14 and voyage as shown in Figure 15 (Oldervik, Report No. 222230.00.06, 2011). The tank pressure was allowed to rise to about 0,5 bar g (set pressure) in tank 1P (red) while manually controlled to about 0,06 bar g in tank 1S (blue). Due to friction losses in the piping, the measured pressure before, during and shortly after the loading shown in Figure 14 and the measured pressure during 32 h of the laden voyage shown in Figure 15 are lower than the actual tank pressures.

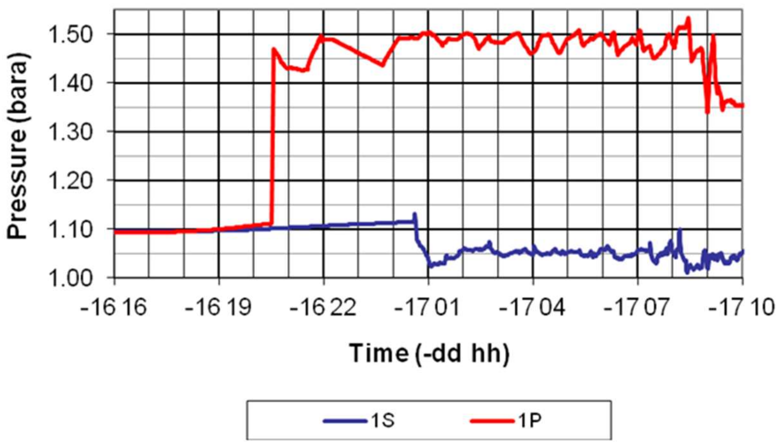

Figure 14 Measured pressure in piping downstream tanks 1S&P during the loading and one hour after.

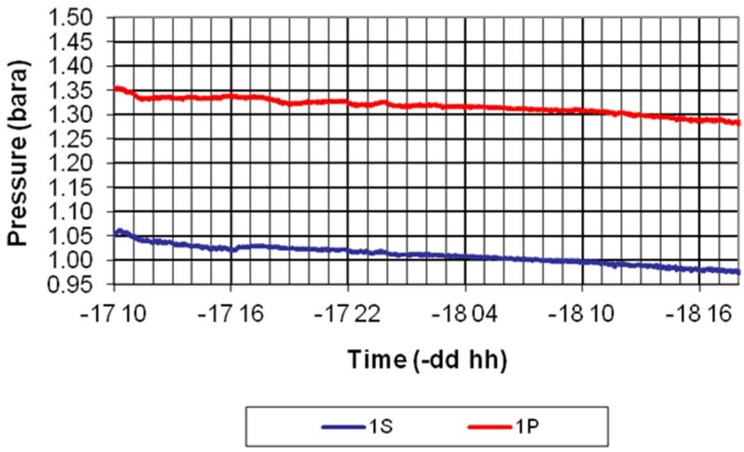

Figure 15 Measured pressure downstream tanks 1S&P during 32 h of the laden voyage.

6.1.2 Example: comparing emissions for normal and elevated tank pressure

In simulations using models calibrated to actual field measurements, loading a shuttle tanker on two Norwegian offshore fields (Fluid I and Fluid II) showed that an increased tank pressure reduces the methane and VOC emissions for Fluid I in Table 14 and Table 15 and Fluid II in Table 16 and Table 17 (Oldervik, Report No. 222230.00.05, 2011).

Table 14 Methane emissions for various tank set pressures for Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
P=1.08bara	1 279	0,011	2 628	0,022	1 311	0,011	695	0,006
P=1.51bara	1 201	0,010	2 506	0,021	1 230	0,010	650	0,006

	Case 5		Case 6	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm^3	kg	kg/Sm^3
P=1.08bara	1 807	0,015	3 117	0,026
P=1.51bara	1 657	0,014	2 863	0,024

Table 15 VOC emissions for various tank set pressures for Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
P=1.08bara	75 735	0,644	113 082	0,961	91 885	0,781	143 680	1,221
P=1.51bara	59 723	0,508	95 538	0,812	69 285	0,589	121 665	1,034

	Case 5		Case 6	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm³	kg	kg/Sm³
P=1.08bara	125 484	1,066	156 507	1,330
P=1.51bara	101 153	0,860	126 603	1,076

Table 16 Methane emissions for various tank set pressures for Fluid II.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³
P=1.08bara	2 171	0,018	3 469	0,029	2 282	0,019	3 609	0,031
P=1.51bara	2 005	0,017	3 196	0,027	2 079	0,018	3 312	0,028

	Case 5		Case 6		Case 7		Case 8	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³
P=1.08bara	3 076	0,026	4 349	0,037	3 350	0,028	4 678	0,040
P=1.51bara	2 704	0,023	3 798	0,032	2 881	0,024	4 048	0,034

Table 17 VOC emissions for various tank set pressures for Fluid II.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³
P=1.08bara	133 113	1,129	161 871	1,373	167 217	1,418	197 935	1,679
P=1.51bara	113 070	0,959	133 961	1,136	135 601	1,150	158 423	1,344

	Case 5		Case 6		Case 7		Case 8	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³
P=1.08bara	155 516	1,319	184 634	1,566	209 757	1,779	241 765	2,051
P=1.51bara	122 567	1,040	141 909	1,204	151 712	1,287	173 625	1,473

6.2 Pressure from the liquid column

While the pressure can be assumed uniform in the tank gas phase, gravitational effects in the liquid column should be added. With a full tank and liquid column of 20 meters, the bottom tank pressure exerted on the fluid is typically 1,65 bar g, linearly decreasing with the liquid height.

6.2.1 Example: calculated pressure from the liquid column for a fluid

Pressure from the liquid column in Figure 16 illustrates the bottom tank pressure (red) increase during loading (Oldervik & Føre, Methane and NMVOC release caused by flashing, Report No. OC2022 F-102, 2022). It rises nearly linearly from atmospheric to 2.4 bar a for this case. Pressure in the gas phase increases only slightly during loading.

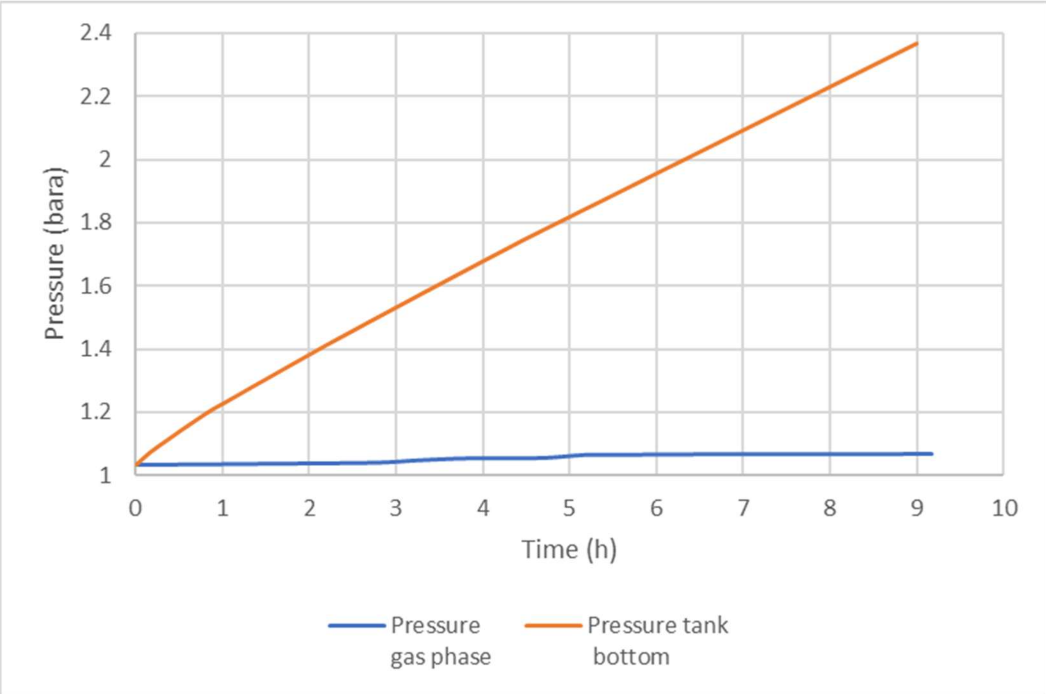

Figure 16 Pressure in gas phase and at bottom of cargo tank.

7 Additional mixing

7.1 Ship movement

While ship movement generally increases fluid movement inside the tank, resonance effects may result in sloshing at some liquid levels. In simulations, this is modelled as an additional contribution to the mixing of the liquid phase and based on numerous calibrations to field measurements.

Ship movement induced sloshing may also increase release of methane and VOC due to enlargement of the evaporation surface area.

7.1.1 Example: measured ship movements for a loading on Field II

Ship movement was measured during one shuttle tanker loading on a Norwegian offshore field (Oldervik, Report No. 222230.00.06, 2011). Roll and pitch angles were measured 2 times per second. The time series was then split in intervals of approximately 15 minutes and mean, standard deviation, maximum and significant angles were calculated for this interval. Result for roll is shown in Figure 17 whereas pitch is given in Figure 18. Recordings of sea weaves are given in Table 18.

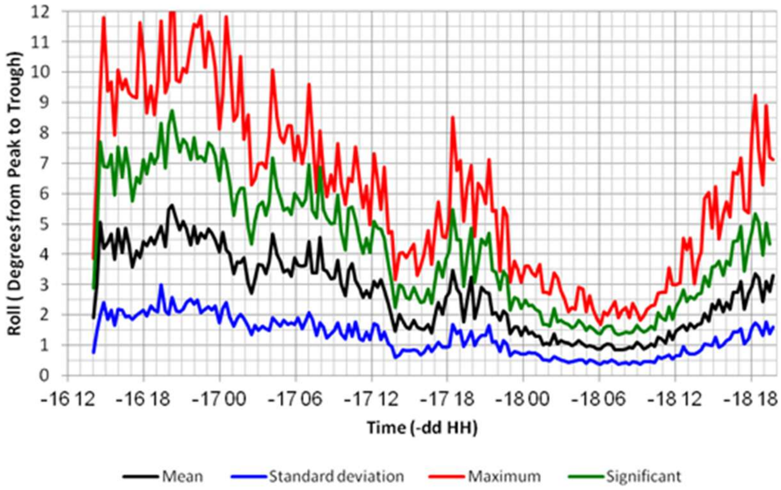

Figure 17 Measured roll of the tanker.

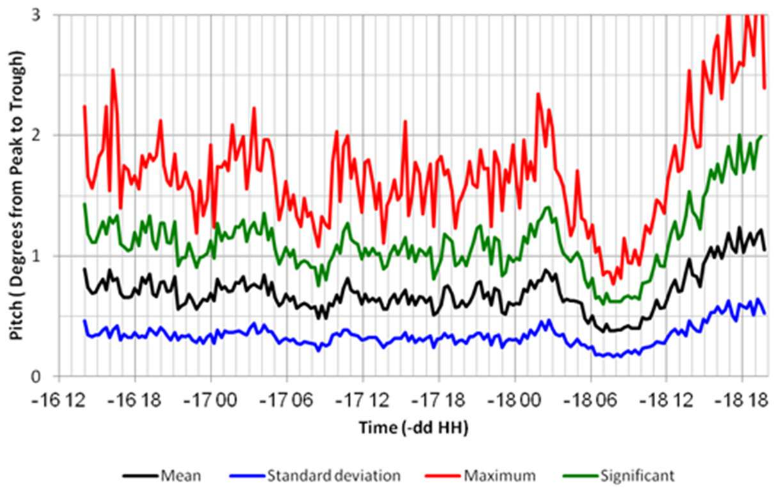

Figure 18 Measured pitch of the tanker.

Table 18 Measured sea state and loaded volumes.

Date+Time	Waves				Loaded volume	Loading rate
	Sign		Max			
(yyyy-mm-dd hh:mm)	Height (m)	Per (s)	Height (m)	Per (s)	(m3)	(m3/h)
2011-10-16 18:00	3.2	6.8	5.1	14	5900	
2011-10-16 19:00	3.8	8	4.9	14	15000	9100
2011-10-16 20:00	3	8	4.9	14	22500	7500
2011-10-16 21:00	2.7	8	4.3	15	29700	7200
2011-10-16 22:00	2.4	8	3.9	1	36900	7200
2011-10-16 23:00	3.4	7	3.8	14	44300	7400
2011-10-17 00:00	2.6	7	4.2	14	50200	5900
2011-10-17 01:00	2.6	10.4	4.2	13.5	58300	8100
2011-10-17 02:00	2.6	10.6	4.2	13.6	65700	7400

2011-10-17 03:00	2.7	10.6	4.4	13.3	70000	4300
2011-10-17 04:00	2.9	10.6	4.6	13.1	80300	10300
2011-10-17 05:00	3	8.2	4.7	13	87700	7400
2011-10-17 06:00	3	6.4	4.8	12.9	95100	7400
2011-10-17 07:00	3	7	4.5	13	102300	7200
2011-10-17 08:00	3.1	7	4.9	15	110600	8300
2011-10-17 09:00					118100	7500
2011-10-17 10:00	3.1	7	5.1	13	118900	800
Average	2.94	8.16	4.53	12.90		
Average while loading 1S&P	2.89	8.64	4.60	13.38		

7.1.2 Example: calibrated mixing coefficients for Fluid I

Table 19 shows the contribution of additional mixing in the liquid phase due to different sea states in VOCSim for Fluid I (Oldervik, Report No. 222230.00.05, 2011). Largest mixing is expected around 20% filling degree for a calm sea situation and between 13 and 20% for an annual mean situation, but note how the mixing remains high with a slight decrease with filling level in case of a more rough sea condition.

Table 19 Mixing coefficients for various sea states and tank filling degrees for Fluid I.

Sea state: calm sea		Sea state: annual mean	
Tank filling degree (%)	Mixing coefficient (m^2/s)	Tank filling degree (%)	Mixing coefficient (m^2/s)
0	0 000010	0	0 000010
3	0.000060	2	0.000050
10	0.000150	6	0.000250
20	0.000200	13	0.001000
40	0.000150	20	0.001000
80	0.000100	24	0.000900
98	0.000050	36	0.000800
		74	0.000600
		91	0.000450
		98	0.000350

7.1.3 Example: comparing emissions for various ship movements for Fluid I

In a simulation using a model calibrated to an actual field measurement, loading a shuttle tanker on a Norwegian offshore field showed that increasing the ship movement, which implies augmented mixing of the fluid in the cargo tanks, the methane (Table 20) and VOC (Table 21) emissions increased for all simulated cases (Oldervik, Report No. 222230.00.05, 2011). For Fluid I, the fluid temperature is constant for all cases.

Table 20 Methane emissions for various sea states for Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
Calm sea	1 279	0.011	2 628	0.022	1 201	0.010	2 506	0.021
Mean sea	1 807	0.015	3 117	0.026	1 657	0.014	2 863	0.024

Table 21 VOC emissions for various sea states for Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3	kg	kg/Sm^3
Calm sea	75 735	0.644	113 082	0.961	59 723	0.508	95 538	0.791
Mean sea	125 484	1.066	156 507	1.330	101 153	0.860	126 603	1.076

7.2 Agitation from inflowing fluids

Cargo entering the ship on deck level is transported to tank bottoms typically by one or more drop lines that convey the cargo down to a bottom-line system which again distributes the cargo to the cargo tanks. This is most usual on crude oil carriers. For product tankers, the typical configuration is a single drop line that conveys the cargo down to each cargo tank. In both configurations, inflowing fluids contribute to significant agitation of the liquid phase, in particular for low liquid levels. Similar to ship movement induced sloshing as mentioned in Section 7.1, splash loading may also increase release of methane and VOC due to enlargement of the evaporation surface area.

7.3 Free gas in inflowing fluids

A pressure drop in the loading line may result in gas release in the droplines, and free gas entering the cargo tank for low liquid levels. A bottom-line system will re-absorb more free gas before the fluid enters a cargo tank than an individual drop-line configuration.

7.3.1 Example: calculated gas released in loading lines for a fluid

Gas release in the fluid loading lines was investigated for some cases in 2022 (Oldervik & Føre, Methane and NMVOC release caused by flashing, Report No. OC2022 F-102, 2022). The study concluded that a minor contribution to the gas emission is possible in the beginning of loading if the pressure in the bottom-line is lower than the fluid TVP. Contrary, as long as the bottom-line pressure is higher than the fluid TVP, any free gas generated in the drop line pressure drop have been reabsorbed, i.e. no free gas will exist in the fluid. The tank bottom pressure will increase with the liquid column, refer to Section 6.2, such that free gas will be possible only until the bottom pressure is equal to the fluid TVP. This is illustrated in Figure 19 where accumulated moles of gas released from the cargo has an impact only for the first period during loading and generally does not contribute much to the total gas emission. Free gas is no longer present from around 1.25 h after start loading.

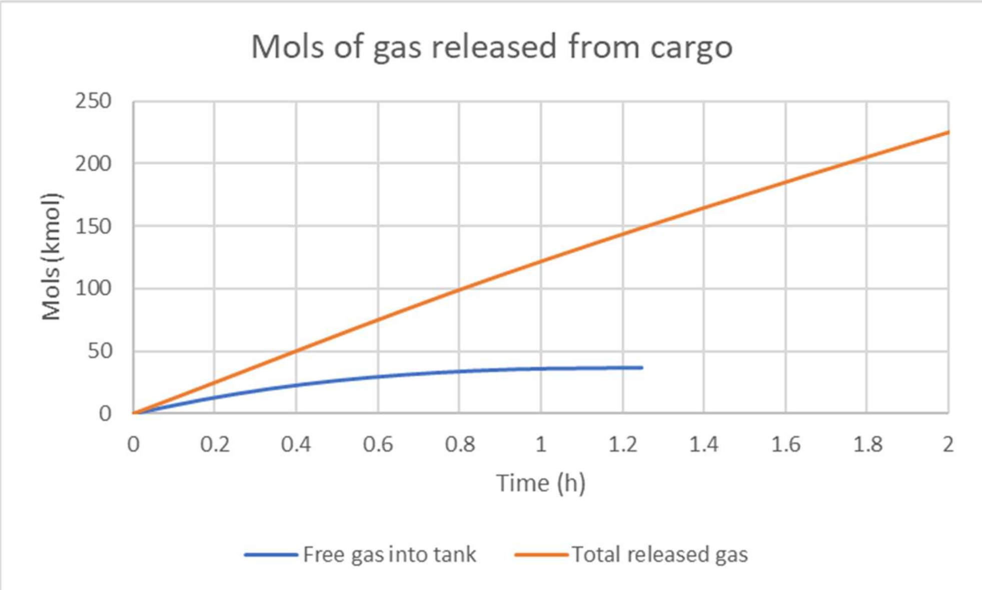

Figure 19 Accumulated moles of gas released from the cargo.

Increasing TVP by, for example increasing the temperature of the fluid, will increase the mass of released gas as illustrated in Figure 20 for 303 K and Figure 21 for 313 K for the same fluid, resulting in a TVP of 1.15 bar a and 1.45 bar a, respectively. When pressure in the tank equals TVP, mass of released gas and mass fraction is zero.

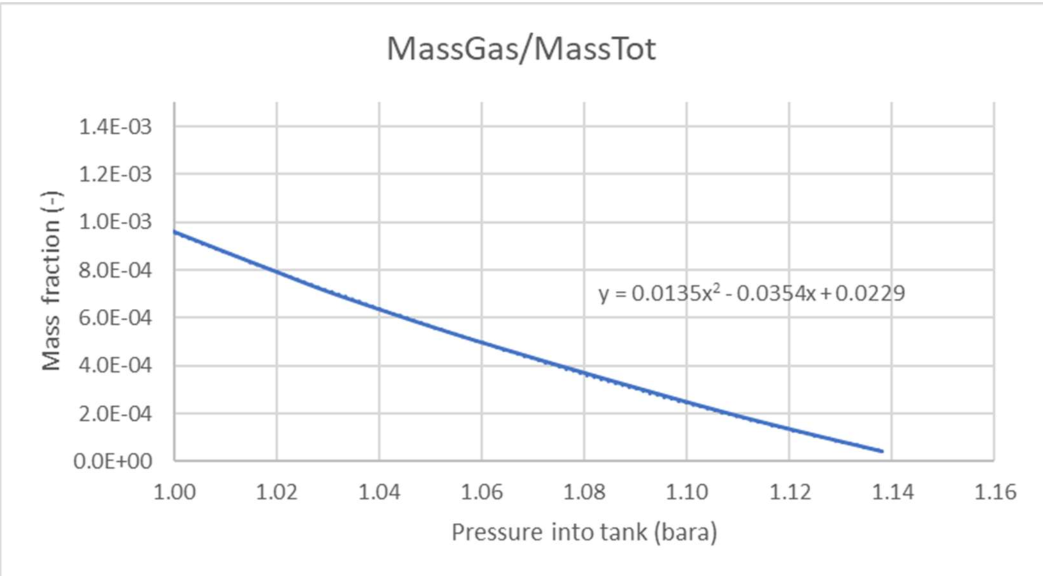

Figure 20 Mass fraction of free gas to total mass at 303 K and TVP 1.15 bar a.

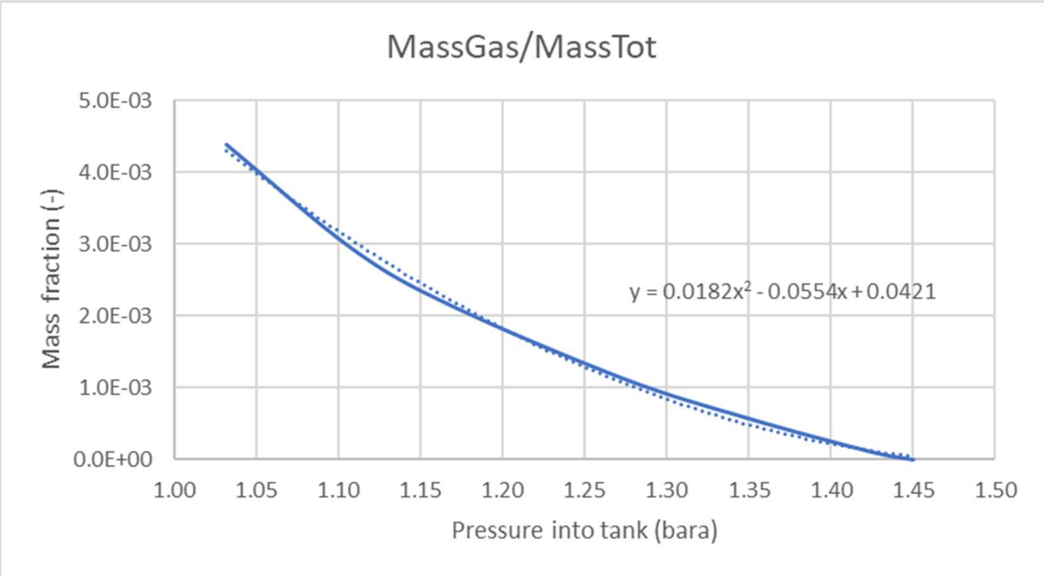

Figure 21 Mass fraction of free gas to total mass at 313 K and TVP 1.45 bar a.

7.4 Convective effects in the gas phase

Convective mixing occurs also in the gas phase and may be a result from variations in composition or temperatures.

7.4.1 Example: comparing tank gas phase mixing due to tank wall temperatures

Current research shows how temperature-induced mixing in the gas phase of a cargo tank affects evolvement of the hydrocarbon content in the tank for various cases (Espelund, 2025). While the cases and their quantities are listed in Table 22, the results of a CFD simulation for case C (solid) and E (dashed) are shown in Figure 22.

Table 22 Specification of case parameters.

Case	Aft temperature °C	Oil surface temperature °C	Bottom VOC concentration m^3/m^3	Fill level m^3/m^3
A (3)	8	22	0.2	0
B (13)	35	35	0.2	0
C (14)	8	22	0.55	0
D (15)	35	35	0.55	0
E (16)	8	22	0.55	50%

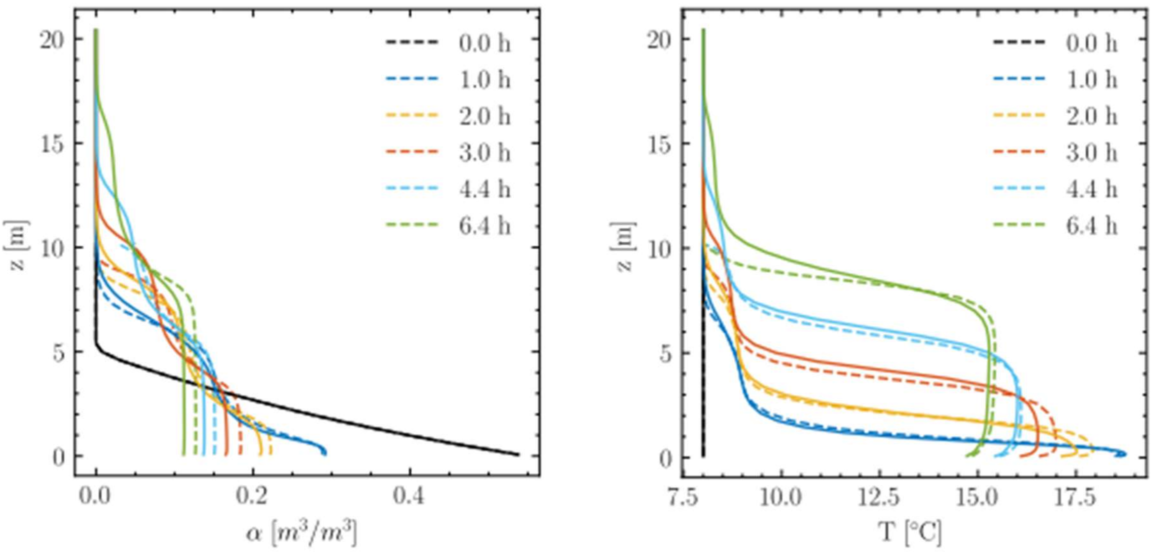

Figure 22 Horizontally averaged vertical profiles for Case C (solid) and Case E (dashed) of VOC volume fraction (left) and gas temperature (right).

7.5 Small mixing – stratification of the gas phase

Small mixing in the gas phase occurs when the gas released from the fluid has a higher molecular weight than the gas already in the tank. While stratification is a temporary condition, it may still have a significant effect on the continued release of hydrocarbons.

7.5.1 Example: measured stratification in the gas phase

Stratification in the gas phase has been confirmed in field measurements (Oldervik, Report No. 222128.00.03, 2007) as shown in, e.g., Figure 23, where the hydrocarbon content is about the same at all heights in tanks 2S (black marks) and 3S (red marks), while tank 5P (blue marks) contains more hydrocarbons near the tank bottom than from about 13 meters below deck. The stratification disappeared after a few days, as shown in Figure 24 where content of tank 5P (blue marks) has become the same for all levels, and section 9.3.3.

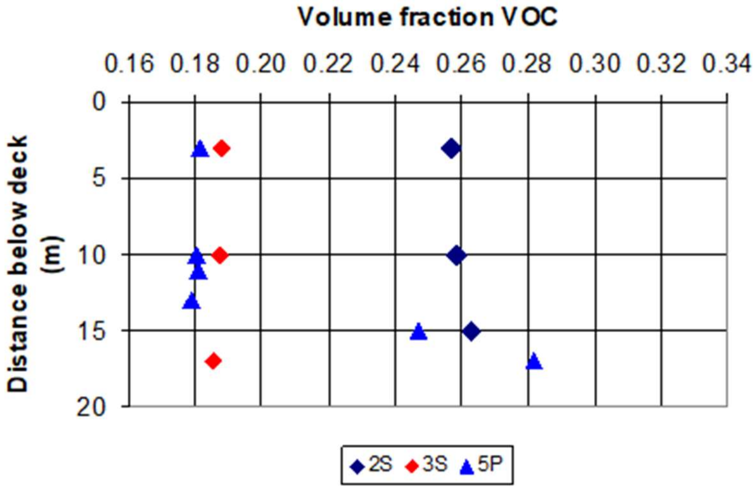

Figure 23 Measured volume fractions of hydrocarbons in various tanks.

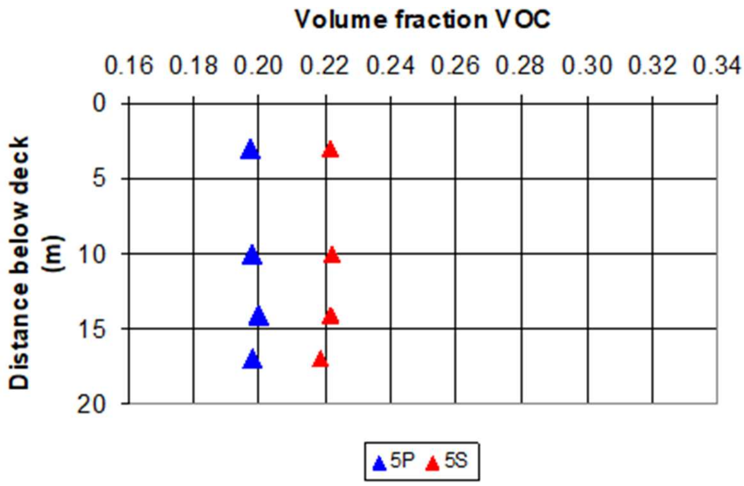

Figure 24 Measured volume fractions of hydrocarbons in various tanks.

8 Evaporation surface area

8.1 Sloshing

Enlargement of the evaporation surface area due to sloshing increases the emission, but this has not been quantified yet.

8.2 Splash loading

Enlargement of the evaporation surface area due to splash loading increases the emission, but this has not been quantified yet.

8.3 Free gas in loading line

Enlargement of the evaporation surface area due to bubbles in the loading line enhances mass transfer between the phases, but this has not been quantified yet.

9 Initial conditions

9.1 Initial temperatures in tank

The effect of initial tank gas temperature on gas release and emission to be considered as discussed in Section 5.

9.2 Initial gas phase pressure

The effect of initial tank gas phase pressure on the gas release and emissions must be considered in connection with available gas volume in addition to ambient and tank set pressure as discussed in Section 6 and Section 10.1.

9.2.1 Example: released and emitted hydrocarbons during loading

Using measured quantities for a loading, released and emitted hydrocarbons were calculated as a function of time for a loading as shown in Figure 25 (Oldervik & Føre, Calculating release of VOC from cargo, 2021). The bars represent a mean mass release or emitted rate per hour after start loading, and shows that while release starts almost instantly, the emissions from the tanks begin 7 hours later, due to a pressure build-up in the tanks.

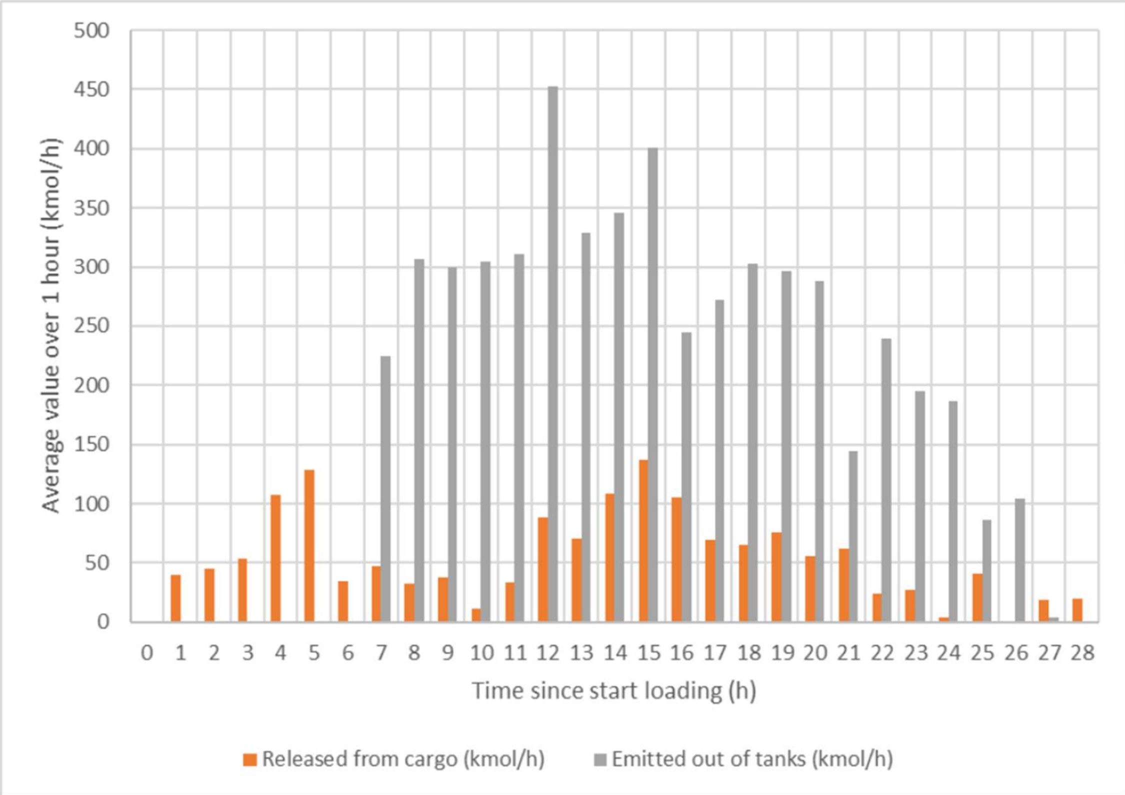

Figure 25 Calculated mole flow rates released from the fluid and emitted from the tanks.

9.3 Initial hydrocarbon gas content

A tank gas atmosphere containing hydrocarbons will reduce the release of hydrocarbons from the fluid. Some initial hydrocarbon content generally, however, increases the emission, as the mass of hydrocarbons in the displaced gas volume comes in addition to mass of the released gas. This may be a significant contribution to the total methane and VOC emission (Oldervik & Føre, Calculating release of VOC from cargo, 2021) and (Oldervik & Føre, Methane and NMVOC release caused by flashing, Report No. OC2022 F-102, 2022). While discharge normally implies some hydrocarbons to be released from the fluid, crude oil washing (COW) the tanks results in the largest hydrocarbon content in the gas phase whereas purged and inert gas filled tanks causes the lowest emissions.

As shown in Section 7.5 and Section 9.3.3, the tank gas composition may have a lateral variation.

9.3.1 Example: measured initial hydrocarbon gas content for several fields

Initial hydrocarbon gas content in the tanks has been measured on several occasions. Results from 12 different previous cargos at 17 loading points and a total of 23 measurements have been published (Oldervik & Føre, Methane emissions from loading crude oil, Memo., 2024) as summarised in Figure 26 showing initial methane (blue marks) and VOC concentrations (red marks) per field and Figure 27 giving an overview of how large a share of the total mass emitted hydrocarbons originating from the previous cargo.

The measurements show that initial hydrocarbon content may contribute to up to around 70% of the total emitted hydrocarbon mass. Note that the field/fluid ID shown on the x-axis is for previous cargo in Figure 26 but for the current loading in Figure 27.

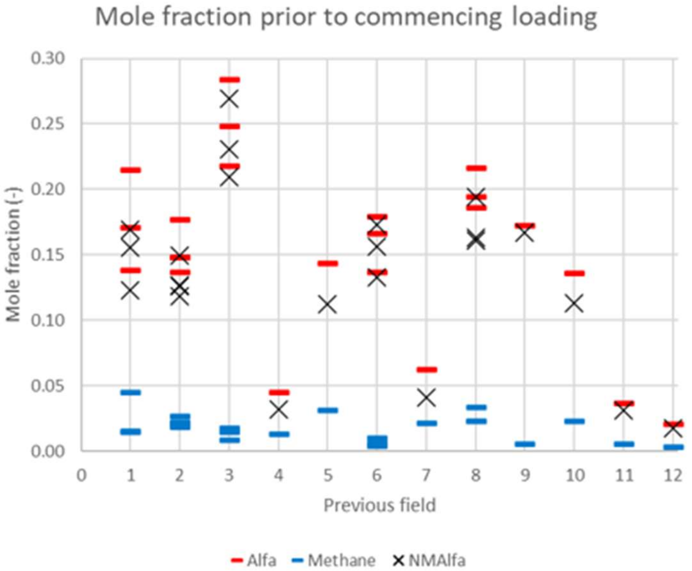

Figure 26 Mole fraction of VOC (Alfa), methane, and NMVOC (NMAlfa) in tanks measured prior to loading.

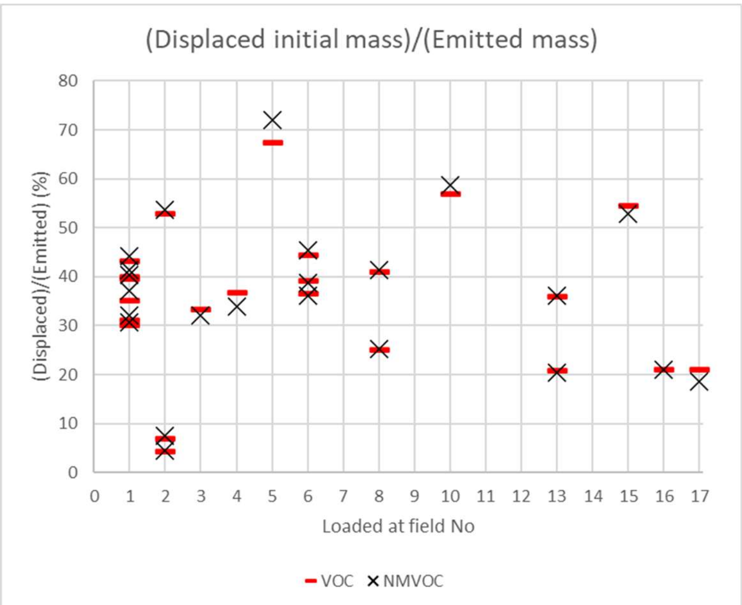

Figure 27 Contribution of initial tank hydrocarbon content to total gas emission with (VOC) and without (NMVOC).

9.3.2 Example: measured hydrocarbon gas content for empty tanks

Two measurements showed only minor compositional variation in time as given for tanks 1S and 1P in Table 23 (Oldervik, Report No. 222230.00.01, 2011). At the given sample location (height in tank), the hydrocarbon content increased slightly during the around 20 hours that elapsed between the measurements, from 3.9% to 4.1% for tank 1S and from 5.1% to 5.7% for tank 1P. The VOC molecule weight decreased slightly from 45.5 to 45.3 kg/kmol for tank 1S and 45.2 to 45.0 kg/kmol for tank 1P.

Table 23 Measured gas composition for tanks 1S&P.

Date	Time	Tank	Methane	Ethane	Propane	i-butane	n-butane	i-pentane	n-pentane	C6	C7	Nitrogen	CO2	O2	Alfa	MWHc
2011-04-15	14:52:47	1S	0.0053	0.0072	0.0130	0.0036	0.0051	0.0017	0.0011	0.0012	0.0010	0.7999	0.1129	0.0482	0.039	45.5
2011-04-15	14:37:26	1P	0.0066	0.0096	0.0174	0.0049	0.0070	0.0023	0.0015	0.0013	0.0009	0.7897	0.1113	0.0476	0.051	45.2
2011-04-16	10:20:38	1S	0.0057	0.0079	0.0128	0.0038	0.0053	0.0018	0.0012	0.0013	0.0009	0.7977	0.1135	0.0481	0.041	45.3
2011-04-16	10:15:30	1P	0.0074	0.0114	0.0179	0.0055	0.0079	0.0027	0.0017	0.0015	0.0009	0.7851	0.1108	0.0473	0.057	45.0

9.3.3 Example: measured hydrocarbon gas content for empty tanks and levels

A larger variation of the hydrocarbon gas content was shown in another measurement campaign, demonstrating also stratification in several tanks and the effect of COW in tank 2S (Oldervik, Report No. 222128.00.03, 2007). In Figure 28, measured volume fraction of VOC is largest in the bottom and decreases towards the deck for all tanks 4P, 4S, 5P, 5S, 6P, and 6S, the VOC concentration varies between the individual tanks and levels. While e.g. tank 5S has the highest bottom concentration of around 33% VOC but only around 16% at the top, tank 4P has most hydrocarbons in the top increasing to and maintaining at around 24% from 10 meters below deck and further to the bottom. Refer also to Figure 23 and Figure 24 in Section 7.5.

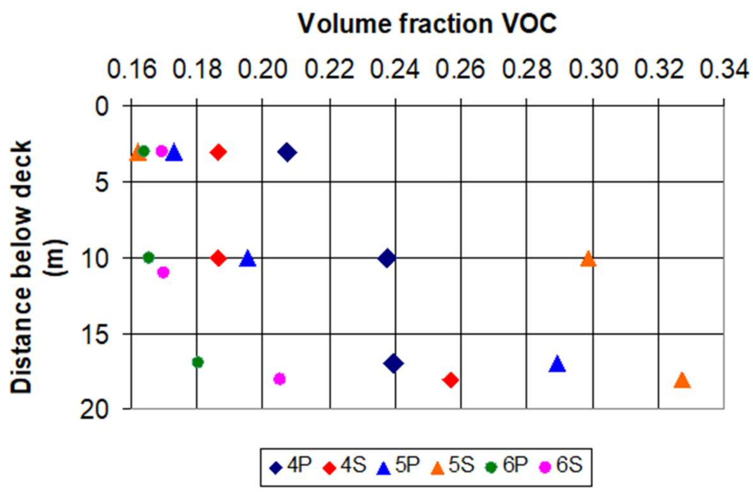

Figure 28 Measured volume fractions of hydrocarbons in various tanks.

9.3.4 Example: comparing emissions with different initial hydrocarbon content for Fluid I

In a simulation using a model calibrated to an actual field measurement, loading a shuttle tanker on a Norwegian offshore field showed that a higher initial hydrocarbon content in the tanks increases the methane and VOC emissions (Oldervik, Report No. 222230.00.05, 2011). According to Table 24 for methane and Table 25 for VOC, this applies for all simulated cases.

Table 24 Methane emissions for various initial hydrocarbon contents for Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1	Mass C_1	EF C_1
Unit	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³
Low alpha	1 279	0.011	1 807	0.015	1 201	0.010	1 657	0.014
High alpha	2 628	0.022	3 117	0.026	2 506	0.021	2 863	0.024

Table 25 VOC emissions for various initial hydrocarbon contents for Fluid I.

	Case 1		Case 2		Case 3		Case 4	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³	kg	kg/Sm³
Low alpha	75 735	0.644	125 484	1.066	59 723	0.508	101 153	0.860
High alpha	113 082	0.961	156 507	1.330	95 538	0.812	126 603	1.076

	Case 5		Case 6	
Quantity	Mass VOC	EF VOC	Mass VOC	EF VOC
Unit	kg	kg/Sm³	kg	kg/Sm³
Low alpha	91 885	0.784	69 285	0.591
High alpha	143 680	1.226	121 665	1.038

9.3.5 Example: comparing emissions due to initial hydrocarbon content for Fluid II

A similar example as in Section 9.3.4 can be extracted for Fluid II from simulations (Oldervik, Report No. 222230.00.05, 2011).

10 Emission reduction or recovery initiatives

An overview of methane and VOC emission reduction initiatives for cargo tanks of crude oil tankers, and examples of their emission reduction, has been published recently (Oldervik, Technologies for reduction of VOC emission, Report No. OC2023 F-077, 2023). While some initiatives handle the emitted gas downstream the vent of the cargo tanks, others affect the VOC emission out of the tanks.

10.1 Elevated tank pressure

High-pressure tankers have additional steel reinforcement to allow a set pressure of at 450-550 mbar g. Elevated pressure is one of the major VOC emission reduction initiatives for shuttle tankers on the Norwegian sector (VOCIC Administrator, 2024).

10.1.1 Example: simulated emissions at elevated pressure

As exemplified in several of the foregoing sections, a simulation using a model calibrated to an actual field measurement, loading a shuttle tanker on a Norwegian offshore field showed that an elevated tank pressure reduced the emissions for methane and VOC for all simulated cases (Oldervik, Report No. 222230.00.05, 2011) and (Oldervik, Technologies for reduction of VOC emission, Report No. OC2023 F-077, 2023). The emission reduction was close to 30% in some cases.

10.2 Transfer of gas

With sequential transfer of tank atmosphere (STTA), tank atmospheres are transferred from one group of tanks to another on the same ship given that the gas piping arrangement of the tanks (refer to Section 4.2) allows for such operation.

10.2.1 Example: simulated emission reduction due to STTA

The effect of using STTA has been determined for four different cases (Oldervik, Simulation of STTA, Report No. OC2020 F-123, 2020). For each case, the VOC emission reduction effect was calculated by comparing the VOCSim simulated result with STTA to the simulated result without STTA, showing that STTA reduces the emission in all cases as listed in Table 26 and illustrated in Figure 29 and Figure 30. Figure 29 shows that the accumulated mass VOC released from the cargo is nearly 120 tons without STTA, but reduced to 100 tons with STTA in simulation case 1, and Figure 30 shows that accumulated mass VOC released from the cargo is above 140 ton without STTA and reduced to below 120 tons with STTA in simulation case 4.The last three columns of Table 26 imply that transfer of hydrocarbon rich gas reduces the methane and VOC emissions in all simulated cases.

Table 26 Reduced emissions of methane and VOC due to STTA.

Simulation No	Crude Type	Tank Pressure (bar a)	Parameters or gas mixture	(Emitted mass with STTA)/ (Emitted mass without STTA)		
				VOC	C1	NMVOC
1	A	1.48	Table C.1	0.857	0.957	0.853
2	A	1.09	Table C.1	0.873	0.966	0.871
3	B	1.48	Table C.1	0.822	0.940	0.821
4	B	1.48	Table C.2	0.764	0.917	0.763

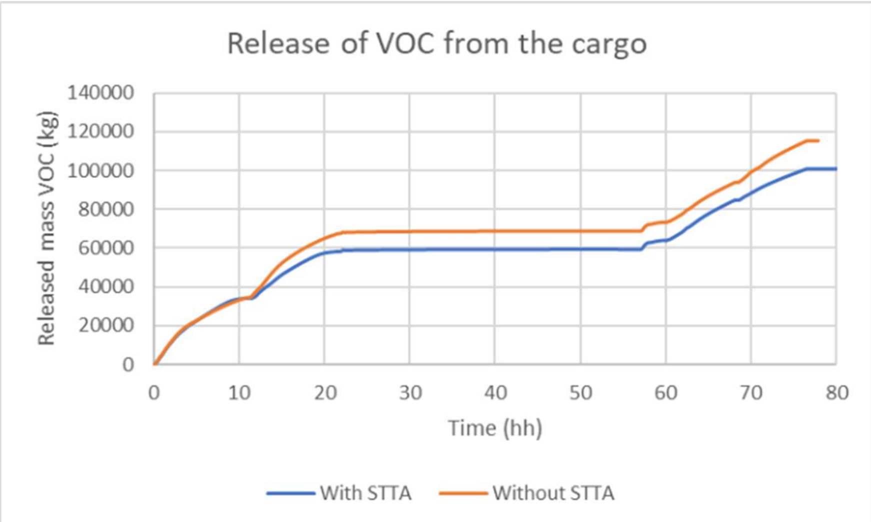

Figure 29 VOC released from the cargo compared for case 1 with and without STTA.

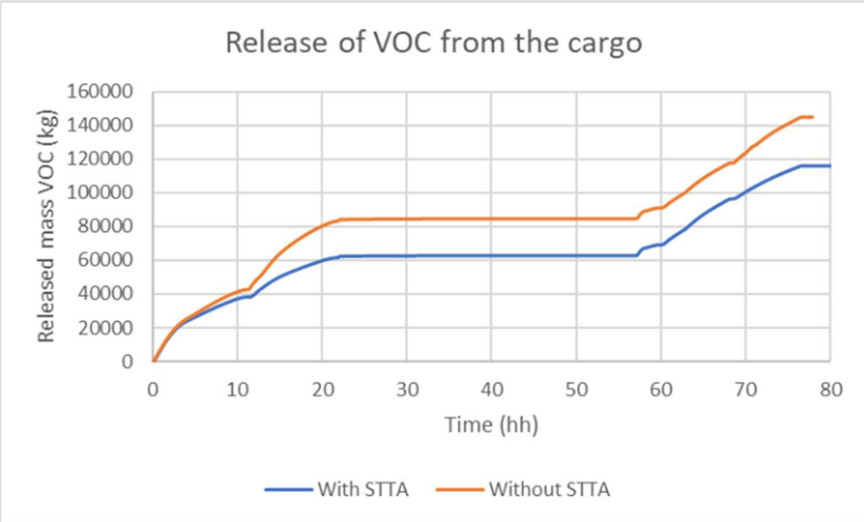

Figure 30 VOC released from the cargo compared for case 4 with and without STTA.

10.3 Vapour recovery units (VRU)

The largest reduction of methane and VOC emissions from cargo operations is achieved using a vapour recovery unit. Typical recovery plants are based on absorption, adsorption, or condensation processes (Oldervik, Technologies for reduction of VOC emission, Report No. OC2023 F-077, 2023).

10.3.1 Example: methane and VOC emission reduction using absorption

In the absorption technology, the liquid that has absorbed some methane, other VOCs and inert gas, is returned to loading line and back into the cargo (Oldervik, Technologies for reduction of VOC emission, Report No. OC2023 F-077, 2023). This alters the fluid composition inside the cargo tanks.

11 Discussion

As defined in Section 1.2, a low emission factor implies low mass emission, and no consideration is taken to other properties of the emitted gas, such as gas volume flow rates, VOC gas molecular weight, molar fraction of VOC in the gas, or the compositional variations. These properties could be important design criteria, e.g., for vapour recovery units where flow rates may not be too high or too low for process equipment to work properly. Also, in case of combustion, the hydrocarbon content of the gas is important with respect to the flammability levels. In some cases, a change in one quantity will reduce the emission in all ways, such as a reduction of the temperature resulting in a less volatile fluid. In other cases, a change will decrease one gas emission property but increase another. The example of Section 4.1.1 shows how a reduction in loading rate will increase the emission but reduce the maximum gas flow rate. Another example is given by the initial gas phase composition; while initial hydrocarbon content reduces the release of gas from the loaded fluid, the total gas emission becomes larger the higher the content due to the contribution from what is already present in the tank. In an optimisation problem it is therefore necessary to evaluate all quantities simultaneously. A future update of this document may include the other properties and behaviour of the emitted gas more thoroughly.

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