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CONTROL OF VOC EMISSION FROM CRUDE OIL TANKERS.

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ABSTRACT

The paper presents results from a preliminary study on some concepts for the prevention of VOC emission from crude oil tankers, with special reference to shuttle tankers and floating production units. The evaporation rate of the individual volatile hydrocarbon components as well as gas volume flow and gas composition during loading and discharging of crude oil cargo are modelled and computed by means of a comprehensive simulation program. Emission is controlled through a series of optional combinations of control techniques, including depression of evaporation at the outset through sequential transfer of tank atmosphere (STTA), condensation of oil vapour and absorption of oil vapour in the cargo oil.

INTRODUCTION

The emission of oil vapour, or Volatile Organic Compounds (VOC), to the atmosphere from tankers world wide is not known to have been measured and assessed systematically. Evidently, the emission represents a loss of considerable monetary value. The harmful consequences to the environment of emission of the individual light hydrocarbons (HC), are known to some extent. This is supposed to be of greater importance than the monetary loss. It is known that the compounds of VOC represent climate gases. They also react with NOx and forms ozone when exposed to sunlight. In some cases the strong poison H_2S is present in the oil vapour.

The International Maritime Organisation (IMO) has adopted a goal of 30% reduction of the emission of Non Methane Volatile Organic Compounds (NMVOC) at the end of 1999 compared to 1989. In MARPOL Annex VI of 1997 it is stated that the individual countries are free to decide on requirements, and to initiate efforts for the reduction of NMVOC emission in their harbours and territorial waters. Norway is among the countries that have adopted a national goal of 30 % reduction in NMVOC emission. Plans are made to require the emission control to be carried further to 37% reduction by 2010.

Nearly one half of the total Norwegian emission comes from the offshore loading of shuttle tankers in the North Sea. As this is also the sector where reduction can be achieved in the most cost efficient way, it is evident from a national standpoint that the efforts should be concentrated on the prevention of emission from shuttle tankers. Floating production, storage and offloading units (FPSOs and FSOs) are also responsible for heavy VOC emission.

Some actions have been taken. Installations are made, believed to be the first of their kind:

- A VOC recovery plant for crude oil has been in operation at the Sture terminal for three years (2). A gas return system has been installed on the tankers, in accordance to the MARPOL requirements to Vapour Emission Control System (VECS).
- A prototype of a plant for reabsorption of VOC in the cargo oil has been installed on M/T “Anna Knutsen” recently (3).

- A prototype of a plant for recondensation of VOC and the use of it as fuel for the main engine has been installed on M/T ”Navion Viking” recently (4).
- A pipe line system for sequential transfer tank atmospheres (STTA) is in use on the combined storage and transport tanker “Wilma Yukon” on the Banff field.
- Several R&D projects and measurement series have been performed at SINTEF and MARINTEK since 1983. The latest one is the VOCON project, some results of which are reported below.

The main problem in the recovery of VOC from tankers is that the evaporated hydrocarbons (HC) are diluted in vast amounts of inert gas when the gas mixture is displaced by the inflow of oil during loading of the cargo tanks. The project team has consequently made studies on the feasibility of a set of concepts which are based on the application of measures to depress the evaporation at the outset, combined with conventional processes for recovery of the oil vapour. Hence, the concepts consist of certain combinations of measures, which are separately known, but the combinations have not been evaluated before, or come into practical use so far. Simulation programs have been used extensively in the evaluation of the concepts.

The philosophy of the project team is that the equipment for recovery of VOC can be made simpler and cheaper than solutions for recovery that have appeared so far. The size of the process plant, and the energy consumption, are reduced if the amount of gas to be handled in the process can be reduced, and the fraction of HC in the mix-gas at the inlet to the processing plant can be increased. The challenge is to find a solution, which implies good total economy and no sacrifice to the emission reduction potential.

Gas return from the cargo tanks to the oil terminal is practised in Sture. The gas return system is made in accordance to the MARPOL requirements to Vapour Emission Control System (VECS). VECS is not feasible for fixed offshore platforms or loading buoys, but might be applied when a FPSO or FSO is offloaded to a shuttle tanker.

THE VOCON RESEARCH PROJECT.

Organisation.

The project was started 1997, sponsored by private enterprises and governmental agencies (see Appendix). The overall objective was partly to advance the competence in the industry for development of cost effective solutions for reduction of VOC emission from crude oil storage and tanker transport, based on known technology, and partly to provide a footing for governmental authorities to formulate appropriate requirements. The research was performed in collaboration between the four units of the SINTEF Group, presented through the authors of this paper.

The project was divided into two parts:

- Part 1: Measurements onboard and development of the simulation program HCGas for computation of the evaporation rate and emission.
- Part 2: Preparation and evaluation of a set of concepts for VOC emission control, and evaluation of the power requirement, energy consumption, complexity, and functionality of the individual concepts, under the condition of a given emission control efficiency being required. The threshold for reduction of VOC emission is set to 75% of the emission in a base case, i.e. the emission when no precautions against emission are made.

The Simulation Program HCGas.

HCGas computes the transportation in the vertical direction of individual components both in the liquid and the gas phase within a cargo tank by solving the following one dimensional diffusion/ convection equation for each component *i*:

$$\frac{\partial \overline{C}_i}{\partial t} + \frac{\partial}{\partial z}(W\,\overline{C}_i) - \frac{\partial}{\partial z}\left((D_{im} + D_{Unr\_Vel})\frac{\partial \overline{C}_i}{\partial z}\right) = 0 \quad \textbf{(1)}$$

where C_i is the unknown molar concentration (kmol/m^3) of species *i* in the mixture, *t* is time (s), *W* is vertical velocity (m/s) and *z* is vertical directions (m). D_{im} is the (effective) diffusion coefficient (m^2/s) for species *i* in the mixture, and D_{Unr_Vel} may be looked upon as a diffusion coefficient due to all unresolved velocities. These are velocities typically created by liquid waves inside the tank when the vessel is rolling and pitching, thermal driven circulation in gas and liquid due to temperature differences and impulse from fluid flowing into the tank.

Equation 1 is solved for the following species : C1, C2, C3, i-C4, n-C4, i-C5, n-C5, C6, C7, C8, C9, C10+, N_2, CO_2 and O_2 , by approximating the partial derivatives with finite differences. 100 computational points typically cover the height of the tank. At the free surface between liquid and gas, an equilibrium flash gives the mass transfer of each component between the phases.

HCGas computes the gas flow between a tank and the environment, and a neighbouring tank in case of STTA, by solving the mass continuity equation in each tank together with an equation of flow for each pipe. Loading and discharging rates are usually specified as functions of time.Temperature of each phase may be specified as function of time and vertical dimension, or it can be computed in the gas phase.

Typical input data are as follows:

- geometry of tanks and pipes,
- initial composition at each computational points within a tank, and initial liquid level,

- rate, cargo composition and cargo temperature during loading, and during discharging,
- data for specification and/or computation of fluid temperature,
- values of D_{Unr_Vel} as function of time.

For the user of HCGas, the challenge is to find which values to use for D_{Unr_Vel} , because D_{Unr_Vel} is typically a function of ship movement, ship geometry, operational procedures and density of gas released from the cargo.

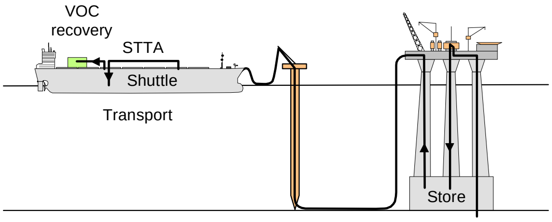
During several loadings of shuttle tankers offshore, flow rate, composition and temperature of the gas emitted to the atmosphere have been measured. Some of these loadings have also been simulated with HCGas, and by trial and error values of D_{Unr_Vel} have been found that produce simulation results in good agreement with the measured ones. As more data from measurements are received, it is possible to find D_{Unr_Vel} values for more typical situations.

Definition of concepts.

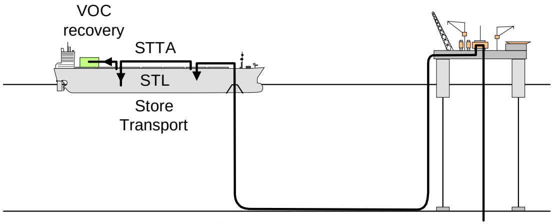
For offshore loading and transport of crude oil, the configuration of VOC emission control systems is in the first hand dependent on the overall systems layout, as illustrated through the four typical field situations shown on Fig. 1. From this, there are basically two different configurations, which can be regarded as similar when seen from a VOC control viewpoint:

1. A shuttle tanker is loaded from a fixed production and storage platform through a loading buoy (A), or a combined storage and transport ship with submerged turret loading (STL) is loaded from a fixed production platform (B). In cases A and B the VOC recovery plant is installed *on the transport unit*. The recovery plant is only operated during loading of the shuttle.
2. A shuttle tanker is loaded from a floating storage (FSO) or from a floating production and storage unit (FPSO). In the cases C and D the gas is conveyed through a floating hose from the shuttle tanker to a VOC recovery plant installed *on the storage unit*, and to its cargo holds, during offloading of the latter. In this case the recovery plant is operated continuously during loading of the FPSO/FSO, and partly during offloading to the shuttle.

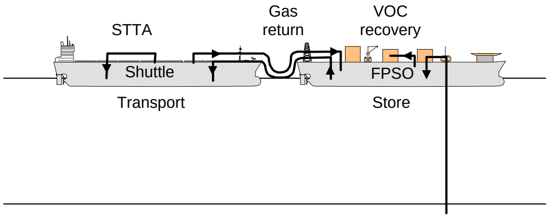
The evaporation from the surface of the crude in the cargo tanks may be depressed through various measures, some of which are particular to the design of the ship's integral cargo tanks, and some to the equipment design and the operational procedures. Effective measures are found to be application of sequential transfer of tank atmospheres (STTA), described in a paper at an earlier ICMES conference (1), and possibly through somewhat heightened tank pressure during loading, secured through the installation of a pressure controlled valve in the gas riser.



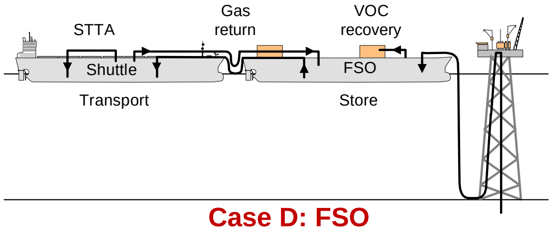
Case A: GBS



Case B: STL



Case C: FPSO



Case D: FSO

Figure 1 Typical layouts for offshore production, storage, offloading and transport

It is presupposed that pipelines for STTA is installed on the transport unit (shuttle tanker and STL) in all the cases shown on Fig. 1, and applied during discharging as well as loading of the crude cargo to and from these vessels. It is assumed that the cargo tanks in these vessels are grouped in three sections of similar volume, which are discharged and loaded in series. When STTA is applied, it is secured that most of the VOC evaporated during discharging is collected in the last of the sections that has been unloaded. Loading is in its turn commenced to the tank section containing the VOC rich atmosphere. The evaporation during loading of that section is thereby depressed through the higher HC partial pressure above the oil surface. When the rich atmosphere is displaced by the flow of oil into the section, it is then transferred to the next section to be loaded. The evaporation is again depressed when the next section is loaded, and the procedure is repeated sequentially as illustrated on Fig.2.

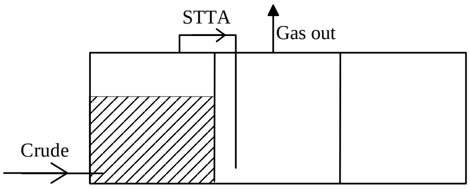


Figure 2. Schematic outline of STTA during loading

Most of the gas is finally conducted to a VOC recovery plant. The peak gas flow occurs during the initial phase of the loading of cargo. During this phase the VOC content at the gas outlet is at its lowest when STTA is applied. It is consequently justifiable to restrict the capacity of the process plant to a level lower than corresponding to the peak flow, and release the excess lean gas to the atmosphere during periods when the gas flow exceeds the compressor capacity. The VOC fraction of the gas mixture is high in subsequent periods, and the recovery efficiency is correspondingly high.

For the situations illustrated in Figure 1 the following concepts are identified as being of interest:

Configurations A and B:

1. The VOC recovery plant is located on the shuttle tanker or STL respectively. The process is based on absorption of NMVOC in the cargo oil. STTA is applied on the shuttle tanker/STL.
2. The VOC recovery plant is located on the shuttle tanker or STL respectively. The process is based on recondensation of NMVOC through compression and cooling, with application of refrigeration when required for attaining the requested recovery rate. STTA is applied on the shuttle tanker/STL. The condensate may be discharged with the cargo oil, or stored onboard and used as fuel for the main engine.
3. Similar to concept no.2 above, but the recovered VOC is used as blanket gas in the shuttle cargo tanks. The condensate is stored onboard during the loaded voyage, and it is evaporated and conveyed to the cargo tanks instead of inert gas during the first part of the discharging period. The evaporation is then effectively depressed when STTA is applied during discharging and loading.

Configurations C and D:

4. The VOC recovery plant is located on the FPSO or FSO respectively. STTA is applied on the shuttle tanker, and most of the gas from the shuttle is transferred through a hose to the FPSO/FSO during offloading of crude to the shuttle. Surplus gas is released to the atmosphere from the shuttle tanker during periods with peak gas flow and low VOC content. VOC recovery can hardly be obtained through absorption in the crude in this case, but with recondensation. The VOC recovery process is similar to concept no. 2 above. However, the condensate should not be offloaded to the shuttle tanker with the cargo, but should be used as fuel. The process plant is run almost continuously in this case.

RESULTS FROM SIMULATIONS AND EVALUATIONS

Line of action.

In order to procure a basis for an evaluation and comparison of the individual concepts, a series of simulations have been made. Most of the above configurations and concepts are covered. The following steps are taken for each concept:

- Computation of evaporation rate and emission for a Base Case, i.e. the emission when no measures are taken to reduce the emission.
- Computation of gas flow and composition of the gas when STTA is applied during loading and discharging. Pumping rates and other conditions are identical to the base case.
- Configuration and dimensioning of processing equipment for VOC recovery. Computation of energy consumption and efficiency. The threshold for reduction of VOC emission is set to 75% of the emission in the base case.
- Assessment of relative complexity of equipment.

Simulations are made under the following conditions:

- All ships have the same cargo carrying capacity of 140.300 m^3.
- The shuttle tanker and the STL are loaded to and discharged from three similar tank groups in series, 46.766 m^3 each, (also in base case).
- Loading and offloading of FSO and FPSO are to and from all tanks in parallel.
- Loading rate to the shuttle tanker is 2.2 m^3/s. Offloading rate is 2.7 m^3/s.
- The loading rate to the STL, FSO, and FPSO is a production rate of 0.308 m^3/s. Offloading rate is similar to the shuttle tanker.
- The prevailing sea conditions during offshore loading is average.
- Crude oil washing (COW) is performed for 60 minutes in one third of the cargo tanks.
- Cargo temperature is 33°C during loading, and 29°C during discharging of the shuttle tanker and STL.
- Simulations are made for two different crude types. The results presented below are for one type only, namely the so-called Statfjord C, which is a fairly volatile crude.

VOC emission from a shuttle tanker. Base Case and application of STTA.

Some results from simulations of loading of the shuttle tanker in configuration “Case A” in Figure 1 are given below. The initial HC concentration in the respective tank groups when loading starts, has been found through simulation of the preceding discharging

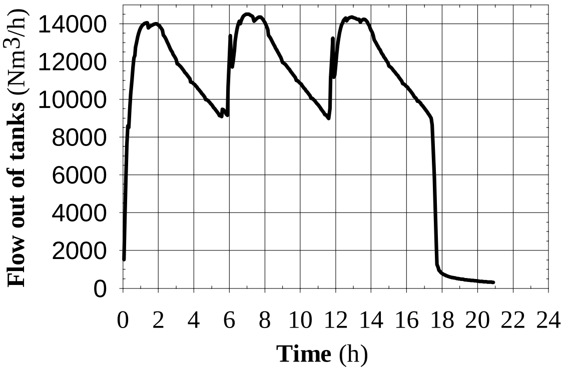


Figure 3 Gas flow out of tanks - Base Case

of a similar crude from the same tank groups (not shown). Simulated gas flow rate out from the tanks during loading is shown in Figure 3.

Loading is concluded after 17.4 hours. It is observed that the flow rate decreases as a tank group is filled up. This typical behaviour is mainly caused by :

- increased volume fraction of hydrocarbons in the tank atmosphere,
- reduced fluid mixing, leading to reduced D_{Unr_Vel} values,
- some stratification in the liquid and gas phase.

Gas composition out of the tanks can be found in Figure 4. C6 and heavier components have been summed to C6+, and N_2 and O_2 have been summed. The relative composition of hydrocarbon gas is shown in Figure 5. The content of C3 is as high as around 37 vol %. Volume fraction (Alfa) and molecular weight of hydrocarbon gas out of the tanks are given in Figure 6 and Figure 7 respectively. The latter varies from 48 to 50 most of the time. The released hydrocarbon gas is therefore heavier than the inert gas, which has a molecular weight close to 30. As a result, the tank atmosphere becomes somewhat stratified as shown in Figure 8. An Alfa value of 1.0 means that the computational point in question is below the liquid surface.

Finally, Figure 9 gives the accumulated values of emitted hydrocarbon (HC), inert (IN) and methane (C1) gas from the tanks. The values for HC includes C1.

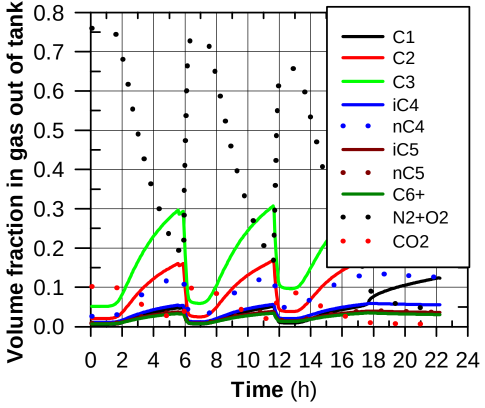


Figure 4 Composition of gas out of tanks - Base Case

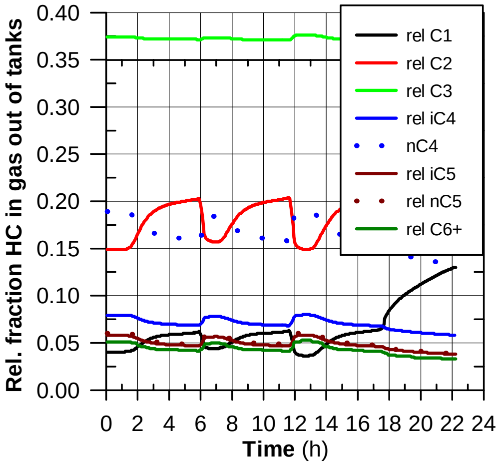


Figure 5 Relative composition of hydrocarbon gas out of tanks - Base Case

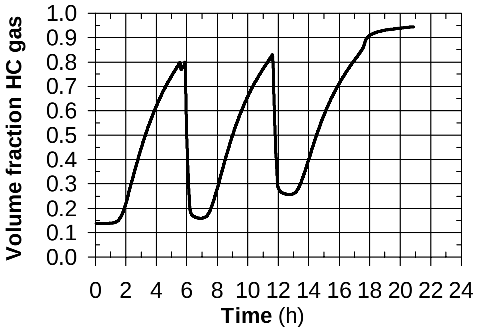


Figure 6 Volume fraction of hydrocarbon gas emitted from tanks - Base Case

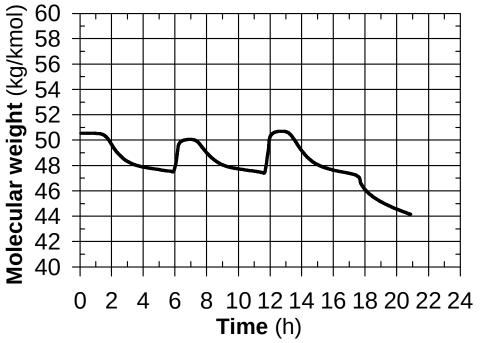


Figure 7 Molecular weight of hydrocarbon gas emitted from tanks - Base Case

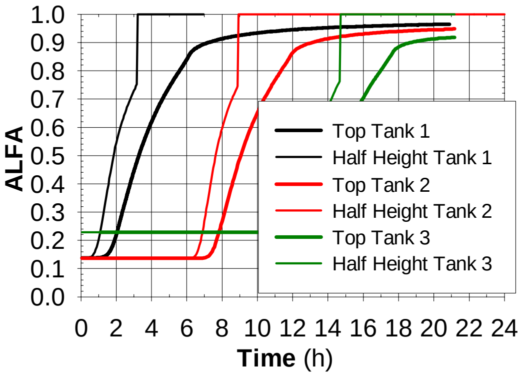


Figure 8 Volume fraction hydrocarbon gas at two levels inside the tank - Base Case

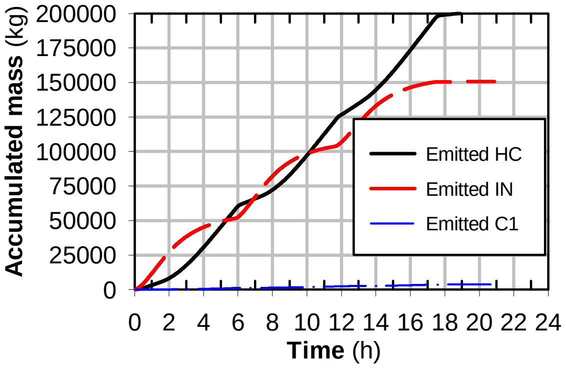


Figure 9 Mass of gas emitted from tanks - Base Case

When STTA is applied both during discharge and during loading, the volume fraction of hydrocarbon gas emitted from the tanks becomes quite low for approximately the first half of the loading, see Figure 13. The flow rate becomes smaller, and the emitted mass of hydrocarbon gas is reduced compared to Base Case.

In the STL case, where the vessel also acts as storage, the loading rate is reduced to only 0.308 m^3/s. STTA is applied also now. Due to the 7 times longer loading time, the tank atmospheres becomes more mixed than in the Base Case with STTA, and the volume fraction of hydrocarbon gas out of the tanks becomes higher, compare Figures 13 and 10. The emission of hydrocarbon gas increases with 38% because of the increased loading time.

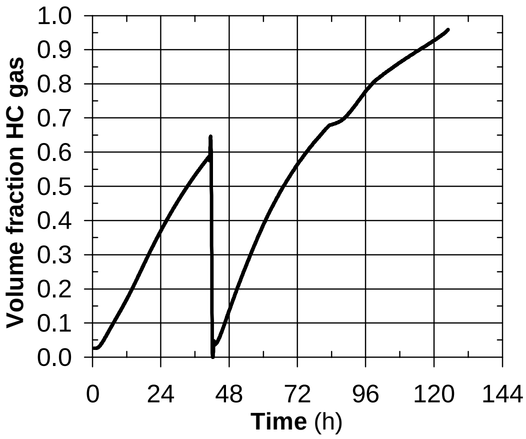


Figure 10. Volume fraction of hydrocarbon gas emitted from tanks - STL with STTA.

Reliquefication of VOC on a shuttle tanker

For the case of loading the shuttle tanker and application of STTA (Case A on Fig. 1), the requirements for a recovery plant based on cooling and condensation have been evaluated. The requirement is to recover 75 wt.% of the NMVOC emission related to the amount emitted in the base case.

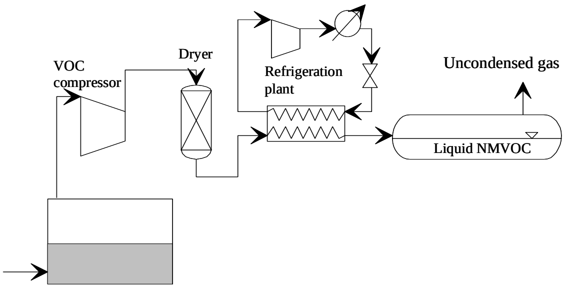


Figure 11. Reliquefaction plant in principle.

The principle of the recovery plant is shown in Figure 11. The mixture of inert gas and VOC is compressed to a given pressure. The inert gas filled to the tanks during the previous unloading is saturated with water. The water should be removed in the case of cooling below the hydrate formation and freezing point temperature. Much of the water can be removed by cooling and separation. For this study it is assumed that the gas is dry and pre-cooled to 15 ^{0}C (no removal of condensate at this temperature) before entering the condenser(s) in the refrigeration plant. In the figure a simple one-stage refrigeration plant is indicated.

Emission figures from HCGas simulations, and the adopted requirement for emission reduction, give the requirements for the recovery plant as follows:

NMVOC emission in base case : 192 823 kg
Requirement for recovery (0.75*192 823) : 144 617 kg

NMVOC emission with STTA : 168 702 kg
Reduced emission (192 823 – 168 702) : 24 121 kg
Requirement for recovery unit
(144 617 – 24 121) : 120 496 kg
Recovery on recondensation plant
(120 496/168 702) : 71.4 wt. %

For the calculations of recovery rate, the total flow is assumed to be cooled to a given temperature at a given end pressure. The standard SRK equation of state is used for the flash calculation. The calculation of recovery rates is based on the total flow rate and gas compositions as calculated for base case with

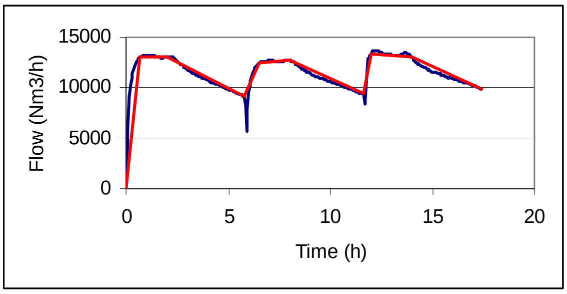


Figure 12. Flow of emitted gas calculated by HC Gas and corresponding fit for recondensation calculations.

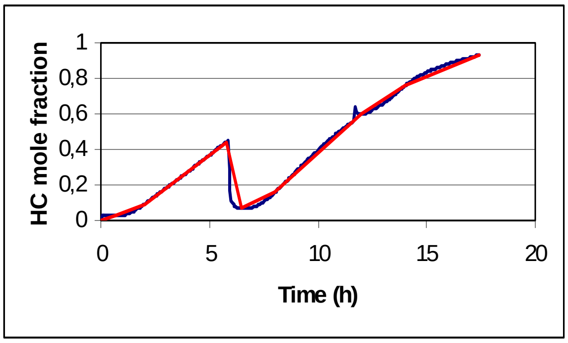


Figure 13 Hydrocarbon mole fraction calculated by HCGas and corresponding fit for recondensation calculations.

STTA. The calculations are performed stepwise after the curve fit of the HCGas data as shown on Figures 12 and 13. The total mass of recovered NMVOC is the sum of the recovered mass in each step.

For the calculation the loading period is divided into time steps based on calculated values for the described parameters. The results of the calculations are given in Table 1. All combinations fulfil the requirement of a recovery rate of 71.4 %.

Table 1 Calculated recovery rates for Case 1

Combination	End temperature (^{0}C)	End pressure (bar)	Recovered NMVOC (wt %)
a	-20	7	71.4
b	-30	5	72.6
c	-40	3.5	74.0

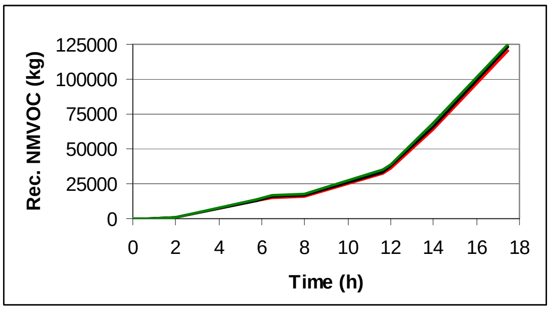


Figure 14. Accumulated recovered NMVOC.

The profile of the accumulated recovery of NMVOC during the loading time is shown in Figure 14. As shown, the recovery in the first period (0-2 h) is very low. The same can be seen in the middle period (6-8 h). The reason for this is the very low fraction of hydrocarbons in these periods. It would not be recommended to run the plant during these conditions.

The swept volume for the VOC compressor is dependent on the inlet gas volume flow and on the volumetric efficiency for the compressor. The volumetric efficiency for a screw compressor is only slightly dependent on the pressure ratio, with a variation of about 3% for a change in pressure ratio from 3.5 to 7.5, and the inlet gas volume flow will be almost independent of the pressure ratio for a given compressor.

Thus, the installation costs for the VOC compressor itself is almost independent of the pressure ratio for the compressor. Since the power requirement increases with increasing pressure ratio, the cost for the compressor motor will increase with the pressure ratio.

The power requirement for the refrigeration plant has been calculated with the following assumptions: One stage plant with screw compressor, without economizer, with propylene as refrigerant. Condensing temperature 20 ^{0}C. The results are given in Table 2. The total power requirement includes the VOC compressor.

Table 2 Approximate maximum refrigeration compressor inlet flow and power requirements.

Case	Evap. temp. ^{o}C	Refrig. Power kW	Refrig. Compress. inlet flow m^3/h	Refrig. Compress Power kW	Total compr. power kW
3.5 bar/-40^{o}C	-47	2034	10907	1330	2071
5 bar/-30^{o}C	-37	1640	5657	746	1673
7 bar/-20^{o}C	-28	1218	2911	407	1521

The case with 7 bar/-20 ^{0}C in the flash tank seems to be the most favourable condition. The total power requirement for the VOC compressor and the refrigerating compressor is at a minimum, and the refrigerating compressor has the smallest swept volume and thus the lowest cost.

The total compressor power requirement together with the energy consumption have been calculated and is shown in Figure 15. The isentropic efficiency of the VOC compressor is set to 78% for all calculations while the efficiency of the refrigeration plant is calculated as a function of the cooling duty.

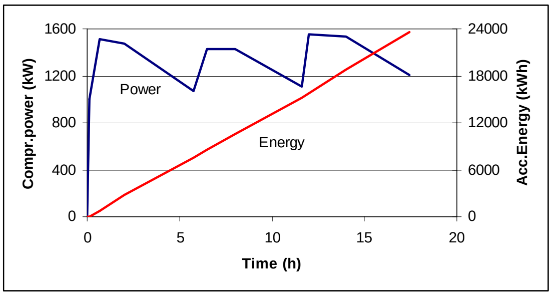


Figure 15. Compressor power and energy consumption.

Based on the given assumptions, the maximum power requirement for the compressors is about 1600 kW. The accumulated energy consumption is about 24000 kWh. For evaluation of optimal operation of the recovery process the energy consumption per kg NMVOC recovered has been calculated and the result is shown in Figure 16.

It confirms the rationale of the recommendation not to run the plant the 2 first hours or so of the loading. This will only give a modest reduction on the total recovered amount of NMVOC (~500 kg), but a

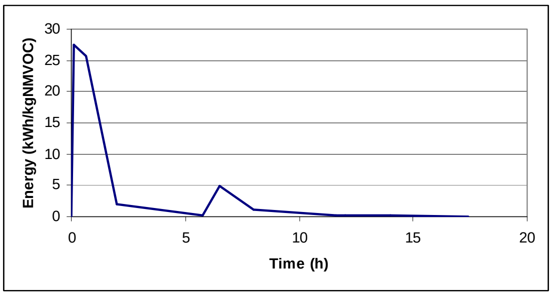


Figure 16. Relative energy consumption.

substantial reduction of the total energy consumption (~3000 kWh).

By using a more complex refrigeration plant, and using the cold in the uncondensed gas and/or condensed liquid, the power requirement would be reduced but the investments cost would be higher and operation of the plant more challenging.

The results above should be compared to the base case without STTA. The combination of 7 bar/-20 ^{0}C in the flash tank would give a recovery of only about 67 wt.% NMVOC. To obtain a recovery rate of 75 wt.% NMVOC, the pressure has to be increased to approximately 10 bar, at –20 ^{0}C in the flash tank. This gives a maximum power requirement for the compressors of ca.1900 kW and an energy consumption of about 28 000 kWh (using the same bases and compressor efficiencies as before).

Reabsorption of VOC on a shuttle tanker and STL

The idea behind reabsorption is to recover a substantial part of the emitted VOC by absorbing it in crude oil. In order to achieve this, the absorption has to take place at an elevated pressure. Initial studies indicated that a pressure of 10 bara might be optimal. The same studies indicated that the absorber should have 4 theoretical plates and that the crude flow should be at least 6.5-7.0 kg crude/Nm^3 gas. A schematic outline of an absorption plant is shown in Figure 17.

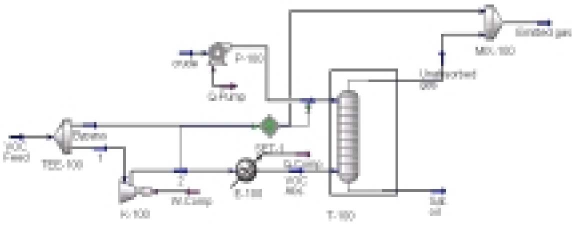


Figure 17. Schematic outline of absorption plant.

The VOC feed is compressed to 10 bara in compressor K-100 and then cooled in cooler E-100 before it is fed to the absorber column T-100. The model has the option of letting part of the VOC bypass the absorber. However, this option is not used. Crude oil is pumped to the same pressure as the gas and then sent to the absorber. The saturated oil from the absorber is returned to the cargo tanks.

Two loading sequences, with different loading rates, were simulated in detail, namely loading of shuttle tanker and STL (Cases A and B on Figure 1). The simulations of absorption with gas compression and crude pumping were performed with the HYSYS 2.1.1 process simulator.

VOC emissions from the shuttle tanker, with and without STTA, are simulated with HCGas. The requirement of recovery by absorption is 120 496 kg, similar to the requirement to the reliquefication plant above. Actually removed amount is calculated to 130 903 kg. Through combining STTA and absorption, the NMVOC emission is reduced by

$$\underline{(130\,903+24\,121)/192\,823 *100 =80.4\%}$$

There is an "over-recovery" in relation to the goal of 75% NMVOC reduction. A better correspondence to the goal might be obtained by reducing the pressure and the crude flow. This would entail somewhat reduced power requirement and energy consumption. However, a complete re-simulation is time consuming, and was not deemed to be necessary.

Key parameters like crude and gas flow rates, power requirements and absorber dimensions were estimated. The results of these calculations are shown in tables 3,4,5 and 6 below. In the tables are also included results of similar calculations made for the STL case ("Case B" in Figure 1), where the loading rate is very much lower. Two different figures of crude flow to the absorber have been applied in this case.

Table 3. Summary gas and crude flows.

Case	Crude (ton/h)	Gas flow average (Nm^3/h)	Maximum Gas flow (Nm^3/h)
Shuttle Base Case	170	11950	14500
Base Case with STTA	116	11500	13700
STL Case	20	1850	4040
STL with increased crude	116	1850	4040

Table 4. calculated recoveries

Case	%rec. NMVOC	%rec. HC	average alpha
Shuttle Base Case	75.0	-	0.48
Base Case with STTA	77.6	74.1	0.53
STL Case with STTA	80.2	78.7	0.51
STL with increased crude	94.8	91.8	0.51

The recoveries in Table 4 are given as weight per cent, and is by absorption only. I.e. emission reduction due to STTA comes in addition.. "Alpha" is the volume fraction of hydrocarbons in the emitted gas, and the average is given here as general information. The simulations were made with the actual gas composition at each time step.

Table 5. Calculated pump and compression power requirements.

Case	Pump duty	Compressor duty Average/ peak	Loading time	Pump total energy requirement	Compressor Total energy requirement
	kW	kW	Hours	kWh	kWh
Shuttle Base Case	66.4	1247/1513	17.4	1155	21750
Base Case with STTA	45.3	1202/1432	17.4	788	20920
STL Case	7.7	184.4/402.7	125	963	23050
STL with increased crude	66.4	184.4/402.7	125	8300	23050

The total energy requirement for the compressor is based on the average duty

Table 6. Absorber dimensions, based on peak conditions.

Case	Diameter (m)	Height (m)
Base Case	2	3.5
Base Case with STTL	2	3.5
STL Case	1	2
STL with increased crude	1.5	2.5

Gas return from shuttle tanker, with VOC reliquefaction on FPSO/FSO

All tanks on the FPSO/FSO are loaded in parallel with a loading rate of 0.305 m^3/s. The discharge rate to the shuttle tanker is 2.2 m^3/s. STTA is performed on the latter. The loading capacity is equal on both vessels. The gas returned from the shuttle tanker is used as blanket gas on the FPSO. The excess gas (there will be more return gas than the need of gas for blanketing) is either released to the atmosphere or led into the recovery unit.

Figure 18 shows the emitted flow rate from the FPSO/FSO. The first 125 h (period 1) is during loading of the FPSO/FSO, the rest (period 2) is during gas return from the shuttle tanker.

The gas returned from the shuttle tanker contains much hydrocarbons at the latter part of the returning period. Due to movement of the FPSO/FSO during discharging, a relatively large amount of hydrocarbon gas is also released from the cargo during the discharge. As a result, the volume fraction of hydrocarbon gas in the tanks of the FPSO/FSO is as high as 70 % when the discharge is finished, see Figure 19. The high content of hydrocarbons in the gas vented from the FPSO/FSO improves the condition for a recovery plant.

The requirement for the recovery of NMVOC for the total operation is set to 75 wt.%. The calculations are based on the same type of crude as for the shuttle tanker case.

For this system the flow rate of the emitted vapour is lower during the loading of the FPSO than during the loading of the shuttle tanker. Most of the emissions of NMVOC are related to the loading of the FPSO. For the design of the recovery unit, the conditions during the FPSO loading should be dimensioning.

The calculated volumetric flow rate and hydrocarbon fraction and the fit used in the recovery calculations are shown in Figures 18 and 19 .

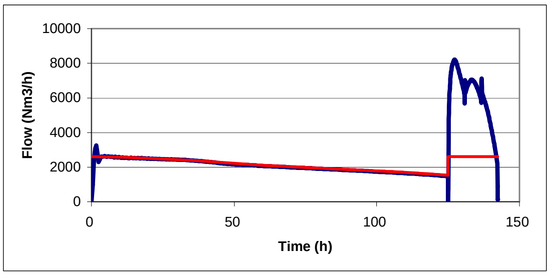


Figure 18 Calculated volumetric flow rate of vapour from the FPSO to the recovery unit and fit used for recovery calculations

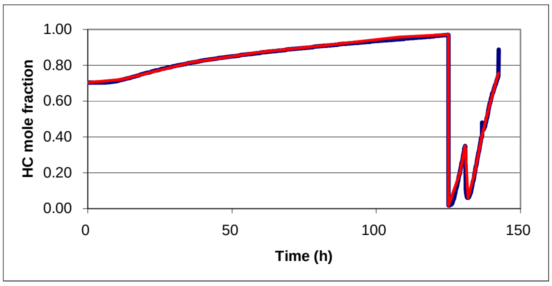


Figure 19 Calculated mole fraction of hydrocarbons of vapour from FPSO and fit used in the calculations on recondensation plant

The amount of released NMVOC together with the requirement for recovered amount is shown below:

Total amount of NMVOC	:511 140 kg
Amount NMVOC in period 1	:450 665 kg
Amount NMVOC in period 2	: 60 475 kg
Required recovery (0.75*511 140)	:383 355 kg

The emissions on period 1 is the dominant. In period 1 the HC fraction in the released gas is high, giving a possibility of a high recovery rate. To obtain a total recovery of 75 wt.% NMVOC, it is first checked if this can be obtained doing the recovery only in period 1. A total recovery of 75 wt. % then requires a recovery rate for period 1 of 85 wt. %.

Period 1 is divided into 6 steps which is summed up to calculate the recovered amount of NMVOC. The results are given in Table 7.

Table 7. Calculated recovery rates

Comb	**Temp.** [^{0}C]	**Pres.** [bar]	**NMVOC recovery period 1** [wt.%]	**Total NMVOC recovery** [wt.%]
a	-20	7	87.4	77.1
b	15	20	87.8	77.4

As the results show, both combinations recover about 77 % of the total amount of NMVOC, which is somewhat higher than the requirement and it is not necessary to run the recovery plant in period 2. However, because a new period 1 is commenced without any interruption in crude production, it is natural that the recovery plant is started when the HC concentration has reached say 30 % in period 2, and then run without interruption into the subsequent period 1.

It is also a possibility to reduce the pressure and/or increase temperatures in the recovery plant, and reaching a recovery rate of 75 wt. %. But in any case it will be recommended to dimension the VOC compressor based on the conditions in period 1 (maximum inlet flow of 2600 Nm^3/h).

Combination b in Table 7 seems to be a preferable choice because of the simplicity of the recovery plant. Since the lowest temperature is 15 ^{0}C, drying may not be necessary. No refrigerant plant will be needed, only seawater cooling. The VOC is compressed to 20.25 bar (or some lower in the case of 75 % recovery). This may require two compressors in series, but it might be possible to do the compression in one stage.

The power requirement is calculated, based on one compressor compressing from 1 bar (at 25 ^{0}C) to 20.25 bar with an isentropic efficiency of 75 %. The power requirement together with the accumulated amount of recovered NMVOC and the accumulated energy consumption are shown in Figure 20.

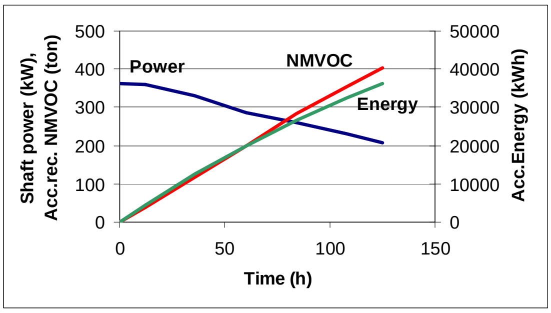


Figure 20. Power requirement, accumulated recovered NMVOC and accumulated energy consumption for case 2.

The peak power is about 365 kW and total energy consumption is about 36 000 kWh or in average 0.09 kWh/kg recovered NMVOC. 400 tons of NMVOC is liquefied.

SUMMARY OF RESULTS

Table 8. Reliquefaction.

Case	NMVOC emission reduction (wt. %)	Reduced emisson (ton NMVOC)	Maximum compressor power (kW)	Energy consumption (kWh)	Relative average energy consumption (kWh/ kgNMVOC)	Plant complexity
BaseCase without STTA. Recovery on shuttle	75	145	1 900	28 000	0.19	- VOC compressor. - Refrig.plant. - Requires drying of VOC/inert gas
BaseCase with STTA. Recovery on shuttle	75	144	1 600	21 000 (no operation the first two hours)	0.15	- VOC compressor. - Refrig. plant. - Requires drying of VOC/inert gas - STTA
Gas return. Recovery on FPSO. STTA on shuttle	77	400 (Liquefica-tion only)	400	36 000 (No operation in period 2)	0.09	- VOC compressor - No refrig. plant (only sea water cooling) - No drying required - STTA

Table 9. Absorption in crude.

Case	NMVOC emission reduction (wt. %)	Reduced emisson (ton NMVOC))	Maximum compressor power (kW)	Energy consumption incl. crude pump (kWh)	Relative average energy consumption (kWh/ kgNMVOC)	Plant complexity
BaseCase without STTA. Recovery on shuttle	75	145	1 500	22 905	0.16	- VOC compressor. - Crude pump. - Absorption column
BaseCase with STTA. Recovery on shuttle	80	131	1 450	21 708	0.14	- VOC compressor. - Crude pump. - Absorption column - STTA
STL Case with STTA. Recovery on STL	80 (Absorption only)	182 (Absorption only)	400	24 013	0.13	- VOC compressor - Crude pump. - Absorption column - STTA

CONCLUSIONS

When STTA is applied on the shuttle tanker or STL, in combination with a process plant for VOC recovery (cases A and B on Fig. 1), the power requirement and energy consumption is reduced. The dimensions of process equipment for VOC recovery are also somewhat reduced. No general conclusion can be drawn on whether these attributes of the outlined combinations will justify the investment costs of a pipeline system for STTA on the tanker. This has to be evaluated in the individual cases.

The power requirement and energy consumption, as well as the complexity of process equipment, is somewhat higher for reliquefication than for absorption in crude. The said disadvantage of the reliquefication process may be outweighed, however, if the recovered VOC is used as fuel.

When a FPSO or FSO and a shuttle tanker are regarded as one system (cases C and D), the total VOC emission can be reduced effectively when a relatively small and simple reliquefication plant is installed on the FPSO. A hose for gas return from the shuttle to the floater is applied. When this is combined with STTA on the shuttle tanker, the required diameter of the hose is reduced, and so is the emission.

The complexity, the power requirement and the energy consumption of a reliquefication plant on the tanker will be reduced when the recovered VOC is used as blanket gas in the cargo tanks, in combination with STTA in cases A and B. The liquefied VOC is then stored onboard during the loaded voyage. It is evaporated and fed into the tanks during discharge of the cargo. However, this case has not yet been simulated, and the safety aspects have not been assessed. The VOC content in the cargo tanks during the ballast voyage will be increased from typically 20% without STTA, to typically 33% when the cargo tanks have been divided into three groups. Practically all the VOC is then collected in the last of the tank groups which had been discharged.

Some of the VOC control concepts described above might be applicable also on ordinary crude tankers with gas return to shore terminals, and for offshore lightering.

The simulation program HCGas is a powerful tool for computing the evaporation and emission from various crude types and procedures of cargo handling. The efficiency of optional measures to depress evaporation and prevent emission is computed. However, the effect of STTA has not yet been measured. Consequently the accuracy is not known of the computations when STTA is applied.

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APPENDIX .

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