Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Jakob Synes Nordvik

Measurement, characterisation and simulation of VOC emissions from crude oil loading, transport and discharge from Persian Gulf by ship

VOC emissions in relation to a VLCC voyage from the Persian Gulf

Master's thesis in Marine Technology
Supervisor: Eilif Pedersen, Ole Oldervik and Knut Brødreskift
June 2020

Sunset on board m/t Arosa

NTNU
Norwegian University of Science and Technology

WÄRTSILÄ

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MASTER THESIS IN MARINE TECHNOLOGY

SPRING 2020

FOR

STUD.TECHN. JAKOB SYNES NORDVIK

MEASUREMENT, CHARACTERISATION AND SIMULATION OF VOC EMISSIONS FROM CRUDE OIL LOADING, TRANSPORT AND DISCHARGE FROM PERSIAN GULF BY SHIP

Work description

Around 2000 million metric tons of crude oil is transported by sea every year with this accounting for nearly a third of global maritime trade. During transport as well as during loading and offloading a large quantity of volatile organic compounds (VOC), that have high CO2-equivalent factor, are released to the atmosphere. These light hydrocarbon compounds at the same time have rather high calorific value and can be used to produce heat or other forms of energy which can be further used for different purposes on board. The thesis will provide estimation of amount and composition of VOC emissions during crude oil loading and transport from Persian Gulf to China, give the assessment of applicability of available technologies to utilise energy from these emissions and develop measurement techniques to improve future measurements.

The Master Thesis is a product of cooperation between Wärtsilä Gas Solutions, Department of Marine Technology and the student.

Scope of work:

1. Familiarisation with the considered crude oil carrier and the arrangements for cargo handling and control of its conditions (pressure, temperature)
2. Prepare, test, calibrate and verify all the equipment required for the measurement campaign (gas chromatograph, ambient and tank conditions logger, measuring hoses, measuring points, etc.)
3. Perform measurements of VOC composition during whenever vapour is released from the VLCC (loading and voyage)
4. Develop models to estimate quantity of weight and volume of VOC-gasses which are released from the VLCC
5. Elaborate on problems met during measuring (if any) and sources of error.
6. Familiarisation with a VOC emission simulation program (VOCSim).
7. Challenge measurement results using the VOC emission simulation program (VOCSim).
8. Develop simulation scenarios to challenge hypotheses.

The report shall be written in English and edited as a research report including literature survey, description of mathematical models, simulations results, discussion and conclusion including a proposal for further work.

The Department of Marine Technology, NTNU, can use the results freely in its research work by referring to the students work.

The thesis should be submitted in three copies within 5 months after the registered start-up of this thesis.

Trondheim January, 2020

Eilif Pedersen	Ole Oldervik	Knut Brødreskift
Associate Professor (Advisor)	Senior research engineer (Co-Advisor)	Product owner (Wärtsilä)

Abstract

Light hydrocarbons evaporate from crude oil when stored and is also released during turbulent flow and flashing in droplines during loading into crude oil carriers. As these volatile organic compounds (VOCs) are released, they occupy the spacing between the crude and roof of storage tank. When crude oil is loaded to the tanks or stored, these hydrocarbons are often vented out into the atmosphere. This type of emission creates severe local air pollution and has health damaging effects. At the same time, valuable hydrocarbons are lost from the crude oil. VOC emissions draws more attention as climate change is a hot topic around the world and many countries have signed regulations and protocols to reduce these emissions. Still, there are many large oil producing countries which are not part of such regulations and oil set for export from these countries lead to high VOC emissions. As part of Wärtsilä Gas Solutions' and NEDA Maritime's vision to liquefy VOC emissions from a very large crude carrier (VLCC) to fuel in the middle east region, this study estimates the amount of VOC emissions released from a VLCC during loading, sailing and discharging from Ras Tanura, outside the coast of Saudi Arabia, to Quanzhou in China. A model was developed and used to estimate VOC emissions by analysing measurements of samples done with a gas chromatograph together with ship tank data. Results showed that the VLCC emitted substantial amounts of hydrocarbons into the atmosphere during loading. However, the ship did not release any VOC emissions during sailing or discharging. To validate the measurement results, the VOC emission simulation program, VOCSim, was implemented and used to test different hypotheses. The simulation gave different results than the measurements and is further discussed in the report. Suggestions for future measurement projects was given together with sources of error. This work can help shipowners and process plant designers to scale VOC processing plants to be installed on crude oil carriers operating in the middle east region and beyond.

Sammendrag

Lette hydrokarboner fordamper fra råolje når den lagres og frigjøres også under turbulent strømning når den lastes om bord oljetankere. Når disse flyktige organiske forbindelsene frigjøres, opptar de volumet mellom oljen og taket i oljetanken. Når råoljen blir lastet eller lagret, blir disse hydrokarbonene oftest sluppet rett ut i atmosfæren som et resultat av å redusere trykk i tankene. Denne typen utslipp skaper alvorlig lokal luftforurensning og har helseskadelige effekter. Samtidig går verdifulle hydrokarboner tapt fra oljen. Utslipp av flyktige organiske forbindelser vekker stadig mer oppmerksomhet ettersom klimaendringer er et hett tema rundt om i verden og mange land har signert forskrifter og protokoller for å redusere disse utslippene. Fortsatt er det mange store oljeproduserende land som ikke er en del av slike forskrifter. Dermed fører olje som er øremerket eksport fra disse landene til store utslipp av flyktige organiske forbindelser. Denne studien estimerer mengden slike utslipp som slipper ut i atmosfæren fra en veldig stor oljetanker under lasting og seilas fra Ras Tanura utenfor Saudi Arabia, og lossing i Quanzhou langs kysten av Kina. Oppgaven er en del av Wärtsilä Gas Solutions og NEDA Maritimes visjon om å prosessere disse utslippene fra en veldig stor oljetanker (VLCC) om til flytende drivstoff i Midtøsten regionen. En utslippsmodell ble utviklet og brukt for å estimere utslipp av flyktige organiske forbindelser ved å analysere målinger av gassprøver gjort med en gasskromatograf sammen med temperatur- og trykkdata fra skipets tanker. Resultatene viste at skipet slapp ut betydelige mengder hydrokarboner ut til atmosfæren under lasting. Skipet slapp imidlertid ikke ut slike utslipp under seilas eller lossing. For å validere måleresultatene ble utslippsprogrammet "VOCSim" implementert og brukt til å teste forskjellige hypoteser som ble utviklet underveis. Simuleringen ga andre resultater enn målingene, noe som videre blir diskutert i rapporten. Forslag til fremtidige måleprosjekter innen utslipp av flyktige organiske forbindelser ble gitt sammen med feilkilder. Denne oppgaven kan hjelpe redere og prosessanleggsdesignere med å skalere prosessanlegg som skal installeres om bord veldig store oljetankere og som opererer rundt om i verden, spesielt Midtøsten området.

Preface

This thesis has been done as part of the 2-year Master of Science in Marine Technology program at the Norwegian University of Science and Technology (NTNU), with Marine Machinery as specialisation. The idea of the thesis was introduced by Hans Jakob Buvarp from Wärtsilä Gas Solution. The Master Thesis is a product of cooperation between Wärtsilä Gas Solutions, Department of Marine Technology and the student. The thesis was partly carried out at the offices of Wärtsilä Gas Solution in Asker, Wärtsila's facility in Vaasa, on board a VLCC sailing from the Gulf of Persia to the coast of China and campus at the Department of Marine Technology in Trondheim.

My motivation for this thesis was to be part of solving problems related to climate change and to gain maritime experience on board a crude oil tanker.

I have learned a lot within Volatile Organic Compounds which I previously underestimated as a climate problem. The learning curve have been steep as I have been introduced to new areas of science I did not have much affiliations with earlier, and to that I am grateful.

Acknowledgement

First and foremost, I would like to thank Wärtsilä Gas Solutions for the opportunity to work on this exciting project. Thanks are given to Hans Jakob Buvarp at Wärtsilä Gas Solutions for choosing me to write this thesis. I would like to thank Knut Brødreskift for unending support during training and execution of measurements. I am grateful for my Gas Chromatograph training teached by Jens Sandelin at the Wärtsilä facility in Vaasa, Finland. My stay on board Arosa would not be as pleasant as it was if not for the amazing crew from NEDA Mritime, and many thanks are given to them.

I am eternally grateful to all my academic supervisors. Sergey Ushakov helped me in the early stages in making sure my interests were taken care of by Wärtsilä before any work on the project happened. I am thankful for the good relationship we have. Eilif Pedersen helped me greatly in structuring the thesis and figure out new ways to solve problems occurring. I always had a good feeling that I had done well after meetings with him. Ole Oldervik have brought immense amounts of experience to the thesis and is the inventor of the simulation program "VOCSim". Without him, the project would not be the same, and many thanks are given for his efforts.

I would like to thank my mother and father for their loving support and raising me into the man I am today. Without them, I would not have the analytical curiosity I have today. I would also like to thank my fellow students for support through rough times writing this thesis.

Contents

List of Figures

List of Tables

List of Abbreviations

AHCO	Arabian Heavy Crude Oil
AMCO	Arabian Medium Crude Oil
AXLCO	Arabian Extra Light Crude Oil
C.O.T	Crude Oil Tank
COW	Crude Oil Wash
EEA	European Environment Agency
GC	Gas Chromatograph
GWP	Global Warming Potential
IG	Inert Gas
IMO	International Maritime Organization
LNG	Liquid Natural Gas
LVOC	Liquid Volatile Organic Compound
NMVOC	Non Methane Volatile Organic Compound
NOC	Number of Components
NSV	Net Standard Volume
PLOT	Porous-Layer Open Tubular column
PR EOS	Peng Robinson Equation Of State
SCOT	Support-Coated Open Tubular column
SVOC	Surplus Volatile Organic Compound
TCD	Thermal conductivity detector
UNCTAD	United Nations Conference on Trade and Development
UNECE	United Nation Econimic Commission for Europe
VER	Voyage Emission Reduction
VLCC	Very Large Crude Carrier
VOC	Volatile Organic Compound
WCOT	Wall-Coated Open Tubular column

1 Introduction

Around 2000 million metric tons of crude oil is transported by sea every year accounting for nearly a third of global maritime trade. During storage and transport, as well as during loading and offloading, a large quantity of volatile organic compounds (VOC) are released to the atmosphere. These emissions have high CO2-equivalent factor and can damage the local climate as well. In many areas around the world VOC emissions are regulated, especially onshore and port areas, but there are exceptions. In this case, Ras Tanura outside the coast of Saudi Arabia is not regulated. VOCs are emissions with large variety of drawbacks. VOCs will react with molecules in the atmosphere and create ozone and act as a passive greenhouse gas which harm the climate in various ways. Since VOCs are hydrocarbons, the emissions can also be utilised as fuel after being processed. If VOCs are treated from industrial processes it is common to incinerate the VOCs. A more environmental friendly way of treating VOCs emissions is to process and cool the emissions and use it as fuel for power and heat generation. This is an effective solution to lower the greenhouse emissions from many oil tankers and more examples are beginning to appear.

The purpose of this thesis is to try and quantify how much volatile organic compounds a very large crude carrier (VLCC) emits during loading and voyage from the gulf of Persia to the coast of China to confirm the viability of different VOC processing installations on board the ship. In this case, the voyage is from Ras Tanura to Quanzhou with departure in early August 2019. A sampling and analysis program for VOC emissions are performed on board m/t Arosa, owned by NEDA Maritime, during loading, sailing and discharging operation of the vessel. VOC development models are developed to help analyse the data collected. To validate the results from the measurements and VOC development model, a simulation study is also performed with the simulation program named "VOCSim". Parameters that match Arosa's are used in the simulation in an effort to digitally replicate the loading process and emission development. Other tests are also performed with the program to challenge hypotheses made during the project. This project is part of Wärtsilä Gas Solutions' and NEDA Maritime's vision to liquefy VOC emissions from VLCCs to fuel in the middle east region and beyond.

2 Background

2.1 Volatile Organic Compounds

Volatile Organic Compounds (VOCs) are a group of organic compounds which have high vapour pressure in room temperature. This comes from the low boiling temperature of the compounds and leads to evaporation and release of hydrocarbon gasses. These compounds also have an impact on climate and environment. Light hydrocarbons, such as methane, ethane and propane are considered as part of these organic compounds [1]. The lightest components, mainly methane, have a significant effect on global warming with respect to CO_2 equivalents. Another subgroup is Non-methane VOCs (NMVOCs) such as ethane, propane, butane, pentane and hexane. These gasses react with NO_x to form ground level ozone, commonly termed "smog", which is known to have significant effects on human health as well as on vegetation and materials. Ground ozone can in fact decrease the productivity of crops, injure flowers and shrubs, and contribute to forest decline [2]. Even as the greenhouse gas CO_2 gathers most of the worlds attention, VOCs have in recent years become one of the greatest concerns for oil and process industries in countries where VOC emissions are tightly regulated [1]. Today, IMO's Marine Environment Protection Committee, MECP, further considers concrete proposals to reduce methane slip and emissions of Volatile Organic Compounds from the shipping industry. Reducing such emissions are therefore earning more focus from shipowners.

2.1.1 Tropospheric Ozone

Photochemical pollution in the troposphere, also known as smog, are created from emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and volatile organic compounds in the presence of sunlight radiation. Ozone is one of the major photochemical pollutant and is enhanced by VOC emissions [3]. Complex photolytic reactions happen to VOC in the presence of sunlight and nitrogen oxides to form ozone. O_3 is produced by photochemical splitting of NO_2 as the free oxygen atom formed rapidly combines with molecular oxygen O_2 as shown in equation 1 and 2.

$$NO_2 + hv \Rightarrow NO + O \tag{1}$$

$$O + O_2 \Rightarrow O_3 \tag{2}$$

The reaction of VOCs and NO_x with sunlight also produces O_3 in a more complicated way. The reactions can be simplified in the following steps [4, 3].

$$O_3 + hv \Rightarrow O_2 + O^* \tag{3}$$

$$O^* + H_2O \Rightarrow 2OH \tag{4}$$

$$VOC + OH + O2 \Rightarrow RO_2 + H_2O \tag{5}$$

$$RO_2 + NO \Rightarrow RO + NO_2 \tag{6}$$

$$NO_2 + hv \Rightarrow NO + O \tag{7}$$

$$O + O_2 \Rightarrow O_3 \tag{8}$$

Ozone undergoes photolysis to form a free oxygen atom O^* which again reacts with water to create two hydroxyl radicals (equation 3 and 4). Two VOCs react with the hydroxyl radicals and oxygen to form two peroxy radicals(RO_2) in equation 5. The peroxy radicals then react with NO to form NO_2 as seen in equation 6. The previously mentioned cycle then begins again in equation 7 and 8. It can be observed from these reactions that each ozone molecule produces two hydroxyl radicals (OH), and each hydroxyl radical results in the formation of two ozone molecules. The fact that VOCs have many hydrogen atoms to react means that each VOC molecule can start many chain reactions as the leftover RO can enter into more reactions to form ozone [4].

Tropospheric ozone can cause damage on vegetation and crops. Events with high ozone levels or prolonged periods with moderate levels of ozone can cause both permanent and acute damage. Ozone damages a number of processes in plants and vegetation, such as reducing the photosynthesis process and growth, and accelerate aging and leaf drop [5]. Together with NO_2 and SO_2, ozone deteriorates the strength and durability of materials as well. They cause corrosion damage on buildings and materials, especially rubber and plastic [5].

Ozone can also affect human health by causing inflammation and damage to the respiratory tracts, as well as impair respiratory function and increase respiratory ailments [6]. Population studies have shown a link between ozone exposure and increased mortality from respiratory diseases, cardiovascular diseases and increased morbidity for people with respiratory disease [6].

2.1.2 Global warming potential of VOC

Interferences with earth's radiation budget leads to the phenomenon called global warming otherwise known as the greenhouse effect. The earth absorbs energy in the form of ultraviolet, infrared and visible radiation from the sun and emits radiation to outer space. These two processes are always in balance. A variety of trace gasses absorb some of the outgoing infrared radiation and thereby disturbs the radiative balance and causes radiative forcing. Radiative forcing of a gas is defined as the process where the earth and atmosphere are warming to re-establish the radiative balance as a result of the isolative effect of the gas. The most important radiatively trace gasses in the atmosphere are water vapour and carbon dioxide [4].

There are possible climate change consequences of VOC emissions to the atmosphere and from their control by incineration [7]. It is difficult to define VOCs effect on global warming as certain VOCs have different impacts than others and that it is a challenging field of study. It is normal to compare the relative effectiveness of a compound to cause radiative forcing with carbon dioxide and can be expressed in terms of Global Warming Potentials (GWPs). The GWP of a certain mass of a VOC is a measure of its climate change impact relative to the same mass of carbon dioxide over a given time period. Most of organic compounds are not themselves radiatively active gases, but they do have the potential to react in the atmosphere and cause indirect GWP. VOCs can behave like secondary greenhouse gasses by reacting to produce methane, water vapour and ozone in the troposphere [4]. All these gasses are highly potent greenhouse gasses. VOCs are also responsible for reacting with hydroxyl radicals (OH), which leads to less OH and thereby longer atmospheric lifetime of methane (CH_4) [8].

Since the beginning of the industrial era, the non-methane volatile organic compounds ethane, propane and butane have increased to abundant levels [8]. These NMVOCs are highly relevant emissions for the petroleum industry. Direct GWP for these gasses are less than 1, while the indirect GWPs are much more substantial in value. Hodnebrog et al. [8] concluded that the net

GWPs over 100-year time horizon are 10 for ethane and propane, and 7 for butane.

2.1.3 Sources of VOC

VOC emits into the atmosphere from many different sources. The atmosphere has a natural equilibrium with sinks and sources of VOCs. Sources of biogenic VOC emissions include both flora and fauna. Natural sources are geophysical processes only, such as volcanic eruptions and biomass burning. Anthropogenic sources result directly from human activities. According to Goldstein and Galbally [9], nonmethane biogenic emissions from terrestrial ecosystems and the ocean accounts for 1150 Mt of carbon each year, while anthropogenic emissions account for 142 Mt of carbon each year. VOC emissions from biomass burning and plant decay are a small additional source in comparison. Attention is given to the fact that these numbers are highly uncertain.

Even though VOC emission from anthropogenic sources are relatively small globally, they can contribute to the atmospheric burden significantly in local and regional areas. Anthropogenic sources mostly come from the extraction, storage and use of fossil fuels. Many VOCs are compounds of fuels, solvents, hydraulic fluids, paint thinners etc. Anthropogenic VOC emissions are in a way product of industrial activity. Figure 1 shows the different sectors of anthropogenic NMVOC emissions from the 33 member countries of European Environment Agency (EEA-33) totalling 8151 kt in 2017 [10].

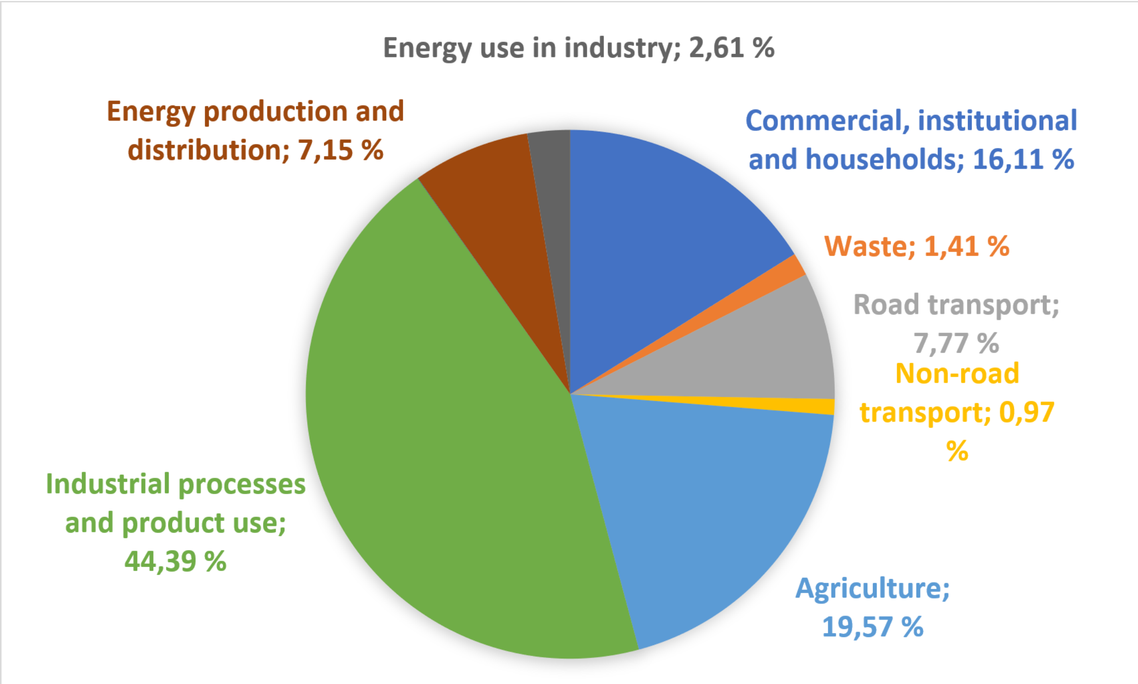


Fig. 1: Anthropogenic NMVOC emissions in European EEA-33 countries by sector in 2017

Industrial processes and product use counts for almost half of all anthropogenic VOC emissions in EEA-33 countries and can be correlated with use of fossil fuels.

2.1.4 VOC emissions from crude oil industry

Within the oil industry there are two main sources of VOC emissions. The first source is emissions from storage tanks, both on land and on ships, where volatile organic compounds emits from the crude oil. When this happens, the gas atmosphere in the tanks will increase in pressure and the operator will have to release the gas either into the atmosphere or into a process facility to make sure the pressure is below maximum strain for the tanks. The second source is emissions from loading/unloading operations into crude oil tankers. In this process, high turbulence and "flashing" in the drop lines release the gas compounds from the crude oil in addition to evaporation in the tanks. When the gas compounds is released from the crude oil it occupies the spacing between the oil and the storage tank roof and walls. As pressure increases parallel to rise of displacement of oil in the tanks and more gas compounds evaporating, the gasses need to be vented out through a vent facility. This vented gas can either be processed or released straight into the atmosphere. What is most common today is to release the volatile organic compounds into the atmosphere without any treatment.

The Energy Institute's Hydrocarbon Management Committee 4A collects and analyses worldwide crude oil shipping data. For the year 2018 they presented a volumetric loss of 0.168 % of transported cargo volume (NSV – Net Standard Volume) due to the emission of VOC to the atmosphere [11]. The United Nations Conference on Trade and Development (UNCTAD) reports that around 2000 million metric tons of crude oil are transported by ship every year [12]. This further suggest that around 3.36 million metric tons of crude oil are lost as VOC emissions every year from maritime crude oil transportation, given that 0.168 % of the volume is lost. These are mostly high quality light hydrocarbons released with high calorific value.

Oldervik and Lerstad [13] performed measurements on board shuttle tankers loading offshore in the Norwegian sector to figure out parameters that effect VOC emissions from each loading. The model tests were conducted in the 1990s and provided qualitative relationship between VOC emissions and several important parameters. The full scale measurements showed that the VOC emissions from a cargo tank is mainly a function of the following parameters:

- Composition of loaded cargo
- Temperature of the cargo in the tank
- The level of mixing in the liquid and gas phases inside the tank
- The volume fraction of VOCs (α) in the tank as the loading starts
- Cargo tank pressure
- Operational procedures such as loading rate and crude oil washing during discharge

Lower cargo temperature, higher pressure, higher loading rate which gives shorter loading procedure, and less movement of ship which leads to less mixing are possible measures to reduce VOC emissions.

2.2 LVOC as a fuel

VOCs released from crude oil tankers have high calorific value and can help save money if processed and used. If VOC gasses are processed there are different ways to reduce emissions, such as adsorption, cryogenic condensation, absorption, thermal oxidation, catalytic oxidation and membrane separation [1]. The most current and prosperous method today is to store liquid VOC (LVOC) as a fuel through a cryogenic condensation process of NMVOC. The surplus methane is not condensed, due to high energy demand for cooling, but can instead be burnt directly together with the inert gasses as surplus VOC (SVOC) in a boiler etc. The LVOC fuel can be used in gas turbines to produce electricity, in mix with LNG in dual fuel engines for propulsion or used as fuel in specialised boilers. Another effective method is as mentioned absorption, which is to reinject the VOC back into the cargo tanks to be absorbed by the crude oil. This method prevents the loss of cargo for the charterer which also saves them money in the process. Since regulations are not in place in certain ports, terminals and loading sites around the world, economic motivation are and could further drive the desire to reduce VOC emissions, and the above recovery methods are therefor highly relevant.

2.2.1 Real world examples of processing VOCs

Wärtsilä already have a cutting-edge Voyage Emission Reduction system (VER) which can process VOC emissions into LVOC. Up to 96% of the boil-off emissions during voyages can with this system be converted back into fuel [14]. The system process is illustrated in a simple manner in figure 2 [14]. Wärtsila also have a larger sized system for loading operations.

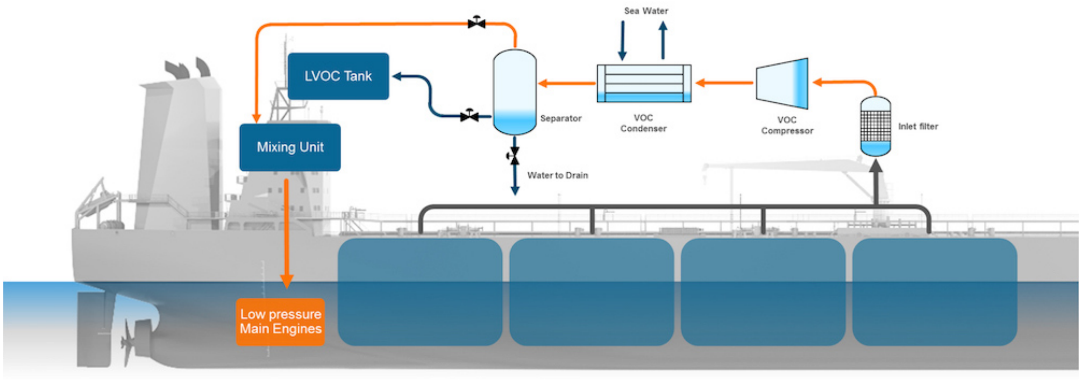


Fig. 2: Schematic representation of Voyage Emission Reduction system (VER)

Gasses from the cargo tanks enter the inlet filter to dispose any liquids. The gasses are compressed and then cooled with a condenser using sea water. The gasses are then separated as some LVOC is going to a storing tank, SVOC with inert gasses is going to mixing unit and water is to be drained. Mixing unit mixes the SVOC and/or LVOC with LNG to be injected into low pressure dual-fuel engines. The dimensions of such systems are important to specify whether to focus on volumes released during loading or boil-off volumes during voyage. The latter requires much smaller and less expensive modules compared to a processing plant focusing on loading volumes. This is because plants focusing on the loading procedures must be able to handle much larger volume flows and be able to cool more VOCs to store in the LVOC tanks for later use.

Examples of moderate sized processing plants can be seen on the 4 new Teekay shuttle tankers being delivered in 2020, with the first already delivered in January 2020. Teekay's new generation of "E-Shuttles" use their own waste gasses from cargo tanks as fuel as well as having a hybrid propulsion system with an included battery storage system [15]. The first two shuttles are to be operating for Equinor in the North Sea. Figure 3, gathered from DNVGL[15], shows how the shuttle's VOC recovering system works and aids the ship in reducing its environmental footprint.

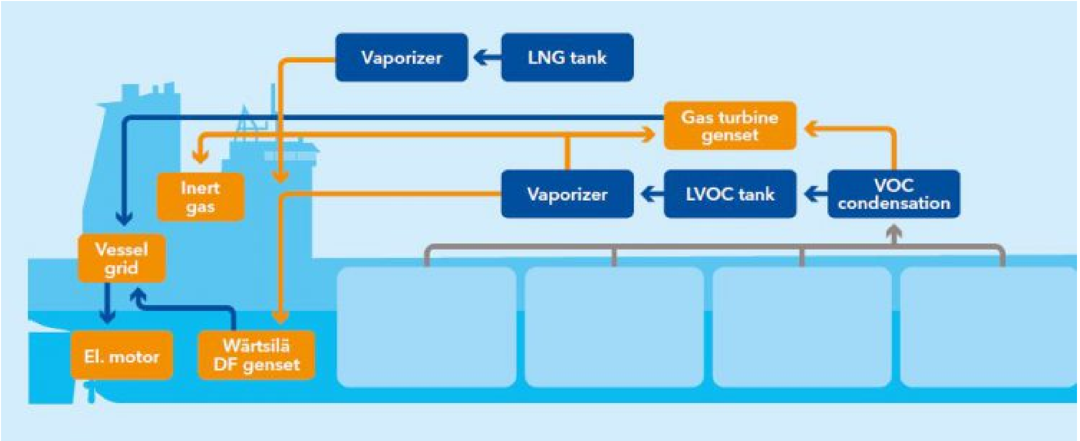


Fig. 3: Schematic representation of VOC recovering system on Teekay's E-Shuttle tankers

During a cargo loading procedure the system will condensate the heavier hydrocarbons into LVOC and send the lighter hydrocarbons to a gas turbine generator set which produces electricity for the vessel grid. In most situations, the vessel also has the possibility to use a mix of LNG and LVOC to fuel its dual fuel generator sets which powers the electric propulsion motors and the rest of the vessel grid. LVOC can also be vaporised and directed into the inert gas system when offloading cargo to fill the atmosphere of the cargo tanks with VOCs instead of inert gasses from exhaust of the generator sets. This helps reduce the evaporation of VOCs from the crude oil during next loading procedure as higher VOC fraction in tank atmosphere sets an equilibrium between gas phase and liquid phase. This was also shown in results from the measurements done by Oldervik ands Lerstad [13]. These capabilities together with other features of the ship are estimated to reduce the fuel consumption by 22% and reduce CO_2 emissions by 42%, NO_x emissions by more than 80% and SO_x emission by more than 95% compared to traditional shuttle tankers [15]. With this technology, Teekay says "once on the water, they (the E-Shuttles) will be the most environmentally friendly shuttle tankers ever built"[16].

When deciding the size of such processing plants, it is important to have quantified VOC development in relevant situations and locations, and for different crude oil types. Ensuring profitability of VOC recovery systems is today the single most important criteria as global regulations on VOC emissions are neither strict or sufficient enough.

2.3 Regulations

The work to reduce air pollution has been ongoing for many years. As this type of pollution is spreading over long distances and across borders, pollution prevention calls for international cooperation. This was the background for the United Nation Econimic Commission for Europe's (UNECE)1979 convention on Long-Range Transboundary Air Pollution. 30 European countries, EC, USA and Canada signed to this convention and agreed that the parties shall limit and gradually reduce air pollution. This agreement have later been detailed in several protocols, of which the Geneva Protocol (1991) and Gothenburg Protocol (1999) deals with VOC.

2.3.1 Geneva Protocol 1991

The Geneva Protocol specifically focuses on VOC emissions and targets the reduction of such emissions. The participating countries were given three options on how to reduce its VOC emissions, of which are the following:

1. *30% reduction in emissions of volatile organic compounds (VOCs) by 1999 using a year between 1984 and 1990 as a basis.*
2. *The same reduction as for (1) within a Tropospheric Ozone Management Area (TOMA) specified in annex I to the Protocol and ensuring that by 1999 total national emissions do not exceed 1988 levels.*
3. *Finally, where emissions in 1988 did not exceed certain specified levels, Parties may opt for a stabilization at that level of emission by 1999.* [17]

2.3.2 Gothenburg Protocol 1999

The Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone was signed by most countries in Europe and USA in 1999 and entered into force in 2005. The protocol deals with sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and non-mehtane organic compounds (NMVOC). In May, 2012, the parties of the protocol agreed on new commitments towards 2020. One of the most important goals was to get the countries of Eastern Europe, the Caucasus and Central Asia to join the protocol, which was a success. These countries have more time to adapt to the strict comitments. Because of such regulations, new technologies for controlling the escape of VOCs have emerged. On January 1^{st}, 2012, the Norwegian Climate and Pollution Directorate, now called the Environment Directorate, imposed an emission limit of 0,45 kg NMVOC/Sm^3 loaded crude oil per loading point as a mean value through one calendar year for the Norwegian continental shelf. The scope of the emissions shall be documented by implementation of measurement programs[18]. Norway have since the top of 2001 reduced its NMVOC emissions by around 60% but still reported emissions of 173 000 tonnes in 2018 [19].

2.3.3 MARPOL Annex VI Regulation 15

In September 1997, the International Maritime Organization (IMO) adopted the Protocol of 1997, later known as "MARPOL Annex VI - Regulations for the Prevention of Air Pollution from Ships". Entering into force 19^{th} of May 2005, the protocol regulates and sets limits on sulphur oxide and nitrogen oxide emissions from ship exhaust and prohibits deliberate emissions of ozone depleting substances. So far 53 countries have ratified the regulations, representing 81,88% of the gross tonnage of the world's merchant shipping fleet. The MARPOL 73/78, Annex VI, Regulation 15 deals with VOC emissions and only facilitates the possibility of VOC regulation. If a party state of the IMO decides to regulate certain ports and terminals, regulation 15.1-15.5 imposes that emissions of VOCs from a tanker are to be regulated in accordance with regulation 15 at given terminals or ports. The party shall notify the organisation with details regarding the tanker size, cargoes requiring vapour emission control systems and the effective date of such control. The party shall also ensure that vapour control systems, approved by the organisation in regards to the standards in MSC/Circ.585, are provided in given ports and terminals and operated safely without causing delay to a ship. If the emission of VOCs from a tanker are to be regulated, the tanker shall be provided with a vapour emission collection system approved by the administration and shall use this system during the loading of relevant cargoes. If a port or terminal have installed vapour emission control systems in accordance with the regulation, it may accept tankers not fitted with vapour collection systems for a period of three years after the effective date notified to the administration. Regulation 15.6 demands that all tankers carrying crude oil have an approved and effectively implemented

VOC Management Plan for each specific ship covering at least the points given in the regulation. The IMO has later published technical information guidelines on systems and operations to assist development of VOC management plans in MEPC/Circ.680 (27^{th} July 2009), supplementing the resolution MECP.185(59) that came into effect on 1^{st} July 2010 [20]. The purpose to this resolution is to ensure that the operation of a tanker prevents or minimises VOC emissions during loading, sea passage and discharge of cargo to the extent possible.

In short, this means that it is up to each individual state to regulate its ports and terminals for VOC emissions and whether to install vapour collection systems or not. No upper limit on VOC emissions are set by the IMO, but the regulation helps facilitate the means on how to regulate such emissions. However, IMO's Marine Environment Protection Committee are currently considering concrete proposals to reduce methane slip and emissions of Volatile Organic Compounds from the shipping industry.

2.4 Experimental techniques - Gas Chromatography (GC)

To be able to measure VOC emissions from crude oil tankers, samples are taken and analysed either from the vent riser or a vapour control valve for a certain tank. The results may then be coupled with an analysis model to quantify the emissions. But first, once a gas sample has been collected it must be chemically analysed to reveal the VOC content of the sampled gas. In this thesis, one instrument were used to analyse several gas samples. The instrument used is a mobile gas chromatograph (GC).

Gas Chromatography is a quantitative separation technique to find different compounds of an analyte. The analyte components are vaporised and fractionated while transported with a gaseous mobile phase through either packed columns or hollow capillary columns containing a polymeric liquid stationary phase [21, p. 543]. The fractionation of the analyte components are selectively distributed between the stationary phase and the mobile phase (also referred to as the carrier gas) based on the partition coefficient (K_c) described in equation 9. The partition coefficient are also referred to as the distribution coefficient.

$$K_c = \frac{C_S}{C_M} \tag{9}$$

Here C_S is the concentration of the analyte in the stationary phase and C_M is the concentration of the analyte in the mobile phase. Due to different characteristics of different analytes, they interact differently with the stationary phase and traverse the length of the column at different speeds and is thereby separated as they elute the column [21, p. 542]. Since its invention, the GC has found applications in a host of industrial, environmental, pharmaceutical and biochemistry analytical laboratories. In the petrochemical industry, GC applications include gasoline characterisation and fraction quantitation, natural gas analysis, aromatics in benzene, etc. Environmental GC applications include detection of pollutants such as smoke stack emissions and detect VOC emissions as in this project [22].

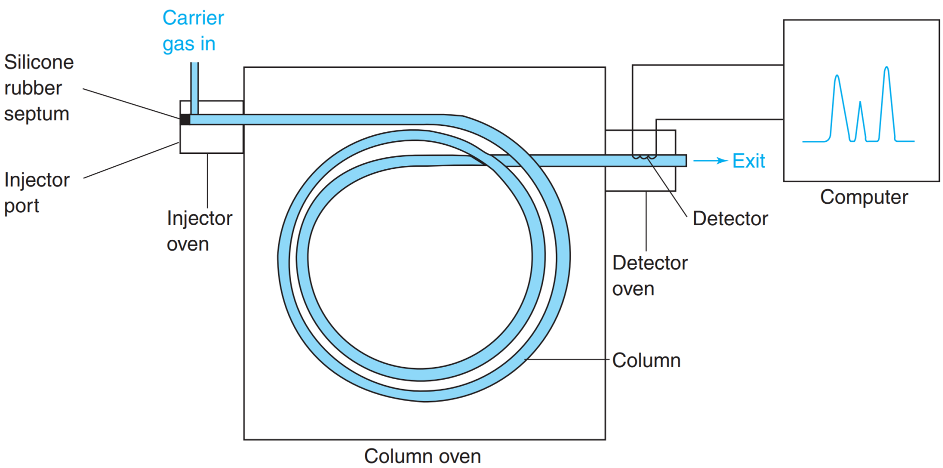


Fig. 4: Schematic diagram of gas chromatograph

Figure 4, gathered from Harris [21], illustrates in a simple manner the components of a GC. A GC is made up of a carrier gas inlet, sample injector system, column and detector, which will be further explained in detail below. Gas chromatographs come in various forms with different features, all from different carrier gasses, injector types, column types and detectors to be able to separate different analytes.

2.4.1 Inlet

Carrier gasses are fed from cylinders through piping to the instrument. The gas supply is often externally regulated to a maximum pressure as well as actively regulated in the instrument to ensure an appropriate supply pressure. Helium (He) is the most common carrier gas as it is compatible with most detectors. Nitrogen (N_2), hydrogen (H_2) and sometimes argon (Ar) are also used carrier gasses for specific uses [21, p. 574].

2.4.2 Sample injection

In figure 4, volatile liquid or gaseous sample is injected through the septum (rubber disk) into a heated port. Here the sample rapidly evaporates. Depending on what the sample is, the temperature is regulated accordingly so that the sample evaporates. After the analyte is evaporated it is injected into the stream of carrier gasses flowing through the column. Gas samples are often compressed into a sample loop before injected. If samples are in liquid form at room temperature and pressure it is injected with a needle where different injection strategies can be used. If analytes of interest are >0,1% of a sample, split injection is used where most of the sample is vented out (split from the rest) and only a small fraction is sent through the column. In trace analysis of analytes that are <0,1% of a sample, splitless injection is used. For samples that decompose above their boiling points, on-column injection is used to limit decomposition at higher temperatures. On-column injection is also best for quantitative analysis [21, p. 577-579, 589].

2.4.3 Column

Columns for GCs come in two configurations: Packed and open tubular. A packed column is filled with fine particles of solid support coated with nonvolatile liquid stationary phase. Packed columns are typically 3-6 mm in diameter and 1-5 m in length. They provide great sample capacity and are often used for preparative separations [21, p. 571].

An open tubular column is a narrow, hollow capillary with stationary phase coated on the inside walls. The vast majority of analysis uses these long narrow columns made of fused silica and coated with polyimide. Open tubular columns have inner diameters of typicaly 0,1 to 0,53 mm and lengths from 15 to 100 m. These columns offer higher resolution, shorter analysis time and greater sensitivity than packed columns, but they also have less capacity. There are three types of open tubular columns, of which is wall-coated open tubular column (WCOT), support-coated open tubular column (SCOT) and porous-layer open tubular column (PLOT). The wall-coated column has a 0,1 to 5 μm thick film of stationary liquid phase on the column inner wall. The support-coated column features solid particles coated in liquid stationary phase and attached to the inner column wall. The porous-layer columns have solid particles which themselves are the active stationary phase attached to the inner wall of the column. SCOT and PLOT have higher surface area and can handle larger samples than WCOT [21, p. 566].

2.4.4 Detector

There have been many different detector types since the inception of the GC, and the choice is based mainly on application, analyte chemistry and required sensitivity. It is also important to consider whether quantitative or qualitative data is required.

Thermal conductivity detectors (TCD) have been common in gas chromatography because they are simple and universal responding to all analytes. The TCD responds to the difference in thermal conductivity between the carrier gas and the sample components. Normally helium is used as carrier gas for thermal conductivity detectors as it has the second highest thermal conductivity (after hydrogen). This means that when any analyte other than hydrogen mixes with helium, the thermal conductivity of the gas stream becomes lower. The process of reading a signal is when the thermal conductivity of the gas stream reduces, a hot electrified filament increases in temperature because of the lower thermal conductivity. As a result, the filaments electrical resistance increases and the voltage across the filament changes. The detector thereby measures the change in voltage [21].

2.4.5 Chromatogram

As the components elute from the column and pass into the detector, the detector's signal is amplified and plotted against time. This gives the rise to a chromatogram as illustrated in figure 5.

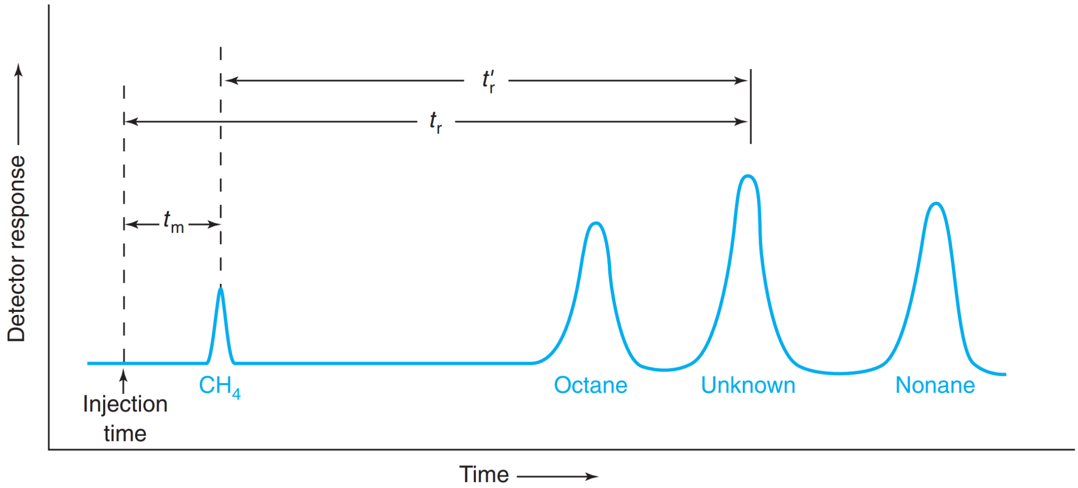


Fig. 5: Figure of a chromatogram with retention times

Figure 5, gathered from Harris [21], shows what might be the result when a mixture of methane, octane, nonane and an unknown are separated by gas chromatography. Components that are not retained within the column elute at the minimum possible time t_m, also called "dead time" or "hold up time". This is the same time as the carrier gas uses to travel through the column. Unretained compounds such as methane and hexane can be used to find t_m, as seen in figure 5 [22]. The retention time, t_r, provides the qualitative aspect of the chromatogram as the retention time of a compound will always be the same under identical chromatographic conditions. The quantitative aspect of the chromatogram comes from the analytes peak height or peak area. To determine the actual amount of the compound, the area or height is compared against a reference chromatogram of known concentration.

3 The VLCC - M/T Arosa

The measurements for this report were done on m/t Arosa, sailing under Greek flag. The ship is owned and operated by NEDA Maritime. Table 1 lists some details about the vessel.

Table 1: Ship details

IMO	9784386
MMSI	241478000
Call Sign	SVCN4
Flag	Greece [GR]
AIS Vessel Type	Tanker
Gross Tonnage	150978 [t]
Deadweight	299323 [t]
Length Overall	330m
Breadth Extreme	60m
Year Built	2017

One of the most essential ship parameters for this project are the tank volumes and how much they were filled at the end of loading. When crude oil is loaded into the tanks, the displaced tank atmosphere volume has to be vented out as well as additional vapour development from cargo. Table 2 shows volume capacity and height for all of the ship's cargo tanks.

Table 2: Tank volumes at 100% filled and internal tank height

Tank	**Volume** [m^3]	**Height** [m]
NO.1 C.O.T.(C)	24 459,9	28,63
NO.1 C.O.T.(P)	16 224,9	28,02
NO.1 C.O.T.(S)	16 224,9	28,02
NO.2 C.O.T.(C)	32 233,9	28,64
NO.2 C.O.T.(P)	20 720,7	28,03
NO.2 C.O.T.(S)	20 720,7	28,03
NO.3 C.O.T.(C)	32 233,9	28,63
NO.3 C.O.T.(P)	20 909,6	28,03
NO.3 C.O.T.(S)	20 909,6	28,02
NO.4 C.O.T.(C)	32 233,9	28,63
NO.4 C.O.T.(P)	20 818,6	28,03
NO.4 C.O.T.(S)	20 818,6	28,02
NO.5 C.O.T.(C)	27 017,2	28,63
NO.5 C.O.T.(P)	14 752,1	28,08
NO.5 C.O.T.(S)	14 752,1	28,10
SLOP T. (P)	4 784,4	22,82
SLOP T. (S)	4 784,4	23,02
Total	**344 599,4**	

The ship's cargo capacity is divided into 15 crude oil tanks and 2 slop tanks. It has a vapour emission collection system which is connected to all tanks and the inert gas(IG) system.

4 Equipment

For this project there were some equipment that was essential. A mobile gas chromatograph, with associated equipment, was necessary to be able to measure the sample composition in close to real time. If a sample was stored for a prolonged time, for example to after the voyage was done, the composition of the sample could change due to absorption to the Tedlar sample bag or chemical reactions within the sample. Table 3 shows the equipment brought on board.

Table 3: Equipment brought on board M/T Arosa

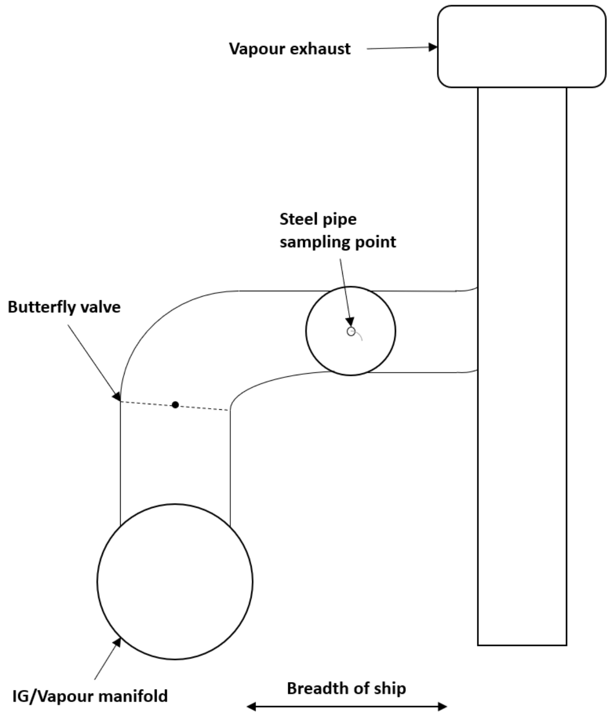
No. off	**Equipment**	**Weight [kg]**	**Dim. LxWxH [m]**
1	Gas chromatograph (4-channel)	15	0.5x0.3x0.4
1	Logging PC	2	0.3x0.3x0.1
1	Helium bottle	20	0.6x Ø0.2
1	Argon bottle	20	0.6x Ø0.2
1	Plastic (Acrylic) tube	0.2	1x Ø0.008
50	Sample bags	1	0.15x0.15x0.1
1	Plastic Hose	1	25x Ø0.008
1	Steel pipe	0.5	1x Ø0.01
50	Hose clamps	0.1	Dim. 0.1x0.01x0.005

The Arosa have pressure sensors and cargo level sensors for all tanks. It was assumed before embarking the Arosa that there also were temperature sensors for all tanks, but this was only the case for the slop tanks at an unknown height. This lead to some consequences for the results later in the report.

4.1 Equipment arrangement on board

The steel pipe was inserted into the vent riser piping and was used as a sampling point. Figure 6a shows how the sampling point looked. The sampling point was inserted after the vent riser valve which is illustrated in figure 6b.

(a) Picture of sample steel pipe setup



(b) Illustration of vent riser

Fig. 6: Sample setup at vent riser

It is assumed that the valve controlling the vapour flow is a butterfly valve. The opening of the valve was controlled with high precision through a percentage meter in the cargo control room to keep the tank pressure in the interval 400-800 mm$H_2$0. Normally the valve was set to 10-20% open during loading.

To take samples from each individual tank, a long hose was needed. This hose, shown in figure 7a, was attached to the tank to be measured via a vapour control valve, shown in figure 7b. After attachment, the hose could be lowered down to desired depth of 0 to 25 meters.

(a) Picture of sample plastic hose

(b) Picture of vapour control valve for C.O.T 2(S)

Fig. 7: Sample setup for tank sampling

When samples were taken, they needed to be analysed by the mobile gas chromatograph (GC). The GC had to be stored in a safe, well ventilated room on board the ship, as the samples that were tested were flammable and high concentrations could lead to dangerous situations. Figure 8 shows the arrangement of the sampling points and GC on board Arosa.

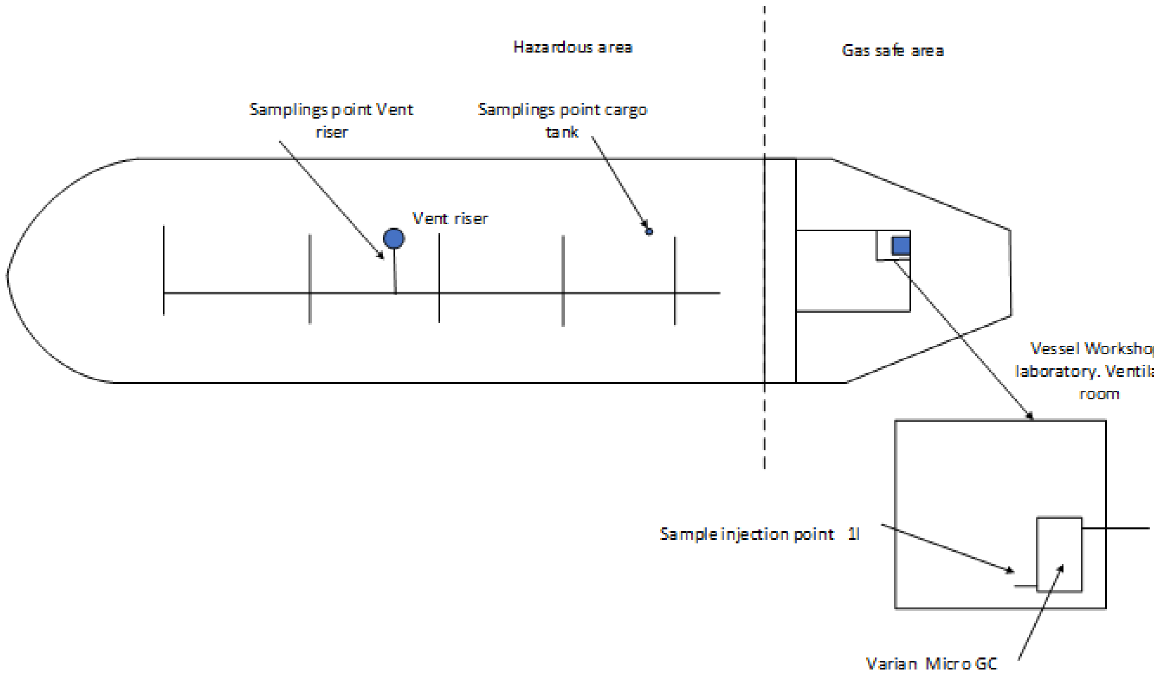


Fig. 8: Equipment and sample point arrangement

4.2 Gas chromatograph - Varian 4900 Micro-GC

The gas chromatograph used in this project is a Varian 4900 Micro-GC. It is relatively small and mobile, and has 4 column channels, each having the task to measure a group of gasses. Channel 1 focuses on the separation of oxygen, nitrogen and methane. Channel 2 focuses on carbon dioxide and ethane. Channel 3 focuses on propane, i-butane and n-butane. Channel 4 focuses on the heavier compounds, such as i-pentane, n-pentane and n-hexane. The setup is shown in picture 9 and illustrated more clearly in figure 10.

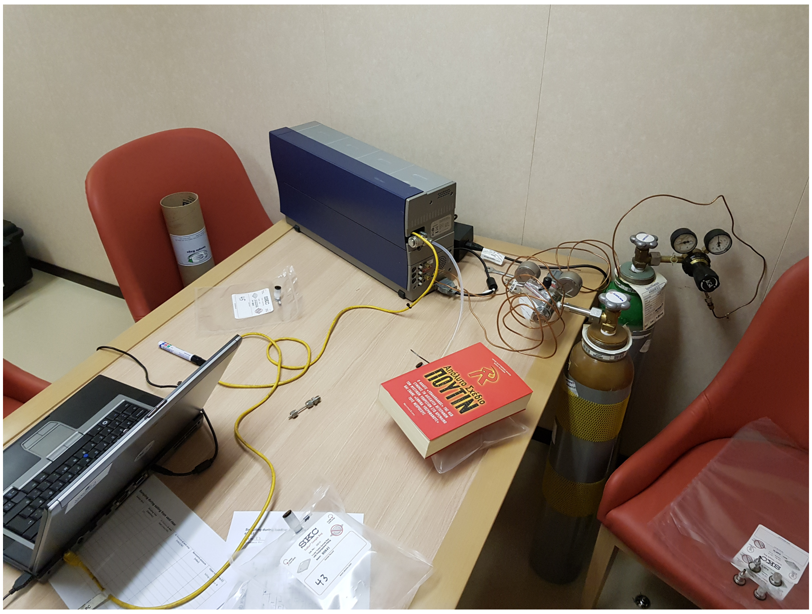


Fig. 9: Picture of GC setup

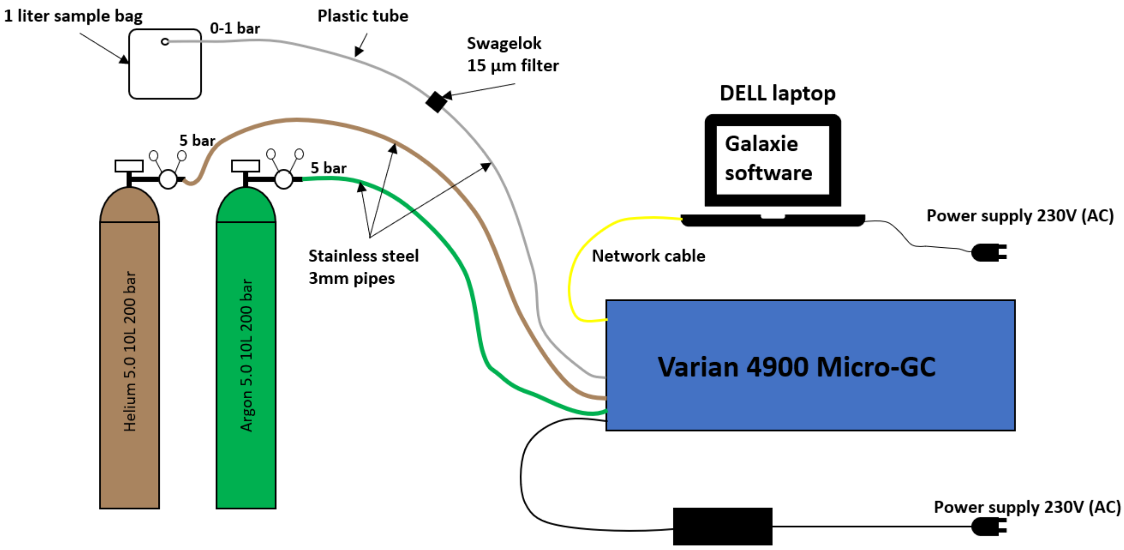


Fig. 10: Illustration of GC setup

Fig. 11: GC setup

Helium is used as carrier gas for channel 1, 2 and 3, while argon is used for channel 4. The GC has built-in micro electronic gas control regulators that adjusts to get constant pressure control, which results in constant flow through the injectors, columns and detectors. The injector has a built in 10 μl sample loop that is filled with the gaseous sample. Pressure of sample should be 0-100 kPa. The book on top of the sample in figure 9 is therefore used to create pressure difference between the sample bag and GC intake. After starting the sequence, a vacuum pump draws the gas sample through the sample loop and the injector then injects the sample gas into the gas system. The detector type used in this GC is thermal conductivity detector. The TCD have been elaborated in section 2.4.4. All information gathered from the GC is then sent through a network cable to its associated DELL laptop, illustrated in figure 10. The software program "Galaxie" is then used to analyse the samples and create a multi-channel report for further use. Multi-channel reports are covered in the result section.

Tedlar sample bags of 1l from "SKC" were used in this project as shown in figure 12. Duct tape were applied to the nozzle of the sample bag in/outlet to make a snug fit for when plastic tubes were connected.

Fig. 12: Inflated sample bag

5 VOCSim - Functions of the simulation program

In order to validate the results from the measurements and analysis, a simulation study is performed. The study is done using a VOC emission simulation program, named VOCSim, developed by Ole Oldervik at the Norwegian Marine Technology Research Institute(MARINTEK).

The simulation program's main tasks is to simulate the emission of gas from the cargo tanks of crude oil carriers. VOCSim takes into consideration all the main components of the gas mixture that is emitted. There are three main simulation parts in VOCSim:

- Transportation inside the liquid and the gas phases
- Equilibrium at the free surface
- Gas flow out of or into the tanks.

The third part is solved by continuity and flow equations where friction, pipe dimensions and valve dimensions are taken into consideration. However, it is not further covered in this thesis. VOCSim was first developed in 2005 and has been used regularly by MARINTEK to supplement measurements in the North Sea. The program has been gradually improved over the years by comparing its results to real measurements done on crude oil tankers. From these experiences, new versions and fixed parameters have been made so that the program results coincide with measurements done on crude oil tankers. The program provides the opportunity to choose and control a variety of parameters to match the operation characteristics of different crude oil tanker systems. The program can replicate the emissions from numerous amounts of crude oil loading, voyage and offloading procedures on different tank and piping setups.

5.1 Governing equations

5.1.1 Liquid and gas transportation

VOCSim is one-dimensional in the vertical direction (z) and is using an adaptive grid that moves with the free surface in the vertical direction (z). The program equations can be formulated both with molar density and molar fraction as free variables. Since molar fraction formulation has given good results, it is currently used in VOCSim. A central part of the program is to simulate the movement of molecules within the liquid and gaseous state. Diffusion and convection theory is consequently used for this purpose. The transportation of molecules within the two fluids are based on a diffusion-convection equation formulated from equation (1.3.9) and (6.1.1) in *Multicomponent Mass Transfer*[23]. This gives that in a fixed coordinate system (z,t), the diffusion equation can be written as in equation 10

$$C_{tot}\left[\frac{\partial X_i}{\partial t}+\frac{\partial}{\partial z}(W\cdot X_i)\right]-\frac{\partial}{\partial z}\left[C_{tot}(D_{im}+D_{Unr\_Vel})\frac{\partial X_i}{\partial z}\right]=0 \tag{10}$$

where C_{tot}[kmol/m^3] is total molar density of the fluid, X_i is mole fraction of component No i, W[m/s] is velocity in z direction, D_{im}[m^2/s] is molecular diffusion of component i in the mixture and D_{Unr_Vel}[m^2/s] is apparent diffusion caused by not resolved velocities. As the program only calculates velocities in vertical direction, D_{Unr_Vel} is needed to simulate the turbulence and other non resolved velocities in the fluids caused by roll and pitch motions of the ship, impulses from fluids entering the tank and buoyancy forces caused by heat differences between fluids and the tank wall [24]. The sum of the diffusion coefficients are later referred to as D_i. To solve the diffusion-convection equations, a finite difference method is used which requires that the tank height is divided into several computational points k. Since the program is using an adaptive grid in z direction that moves with the free surface, new sets of independent variables are introduced in both liquid and gas phase. This means that the mole fraction X_i now becomes a function of time and the height ratio, ZDL, where ZDL for liquid is defined in equation 11 and for gas in equation 12

$$ZDL_{liq}=z/z_{surface} \tag{11}$$

$$ZDL_{gas}=\frac{z-z_{surface}}{HG} \tag{12}$$

where z is the height of a point, $z_{surface}$ is the height of the surface of loading crude oil in tank and HG is the height difference between tank ceiling and surface of crude oil ($z_{surface}$). The assumption of constant cross section area of the tank means that in the liquid phase, one may put $W_k - W_{k-1} = 0$ for computational point k. This would not be the case for the gas phase because of its compressibility [24].

5.1.2 Free surface equilibrium

The most essential factor in this program is the flux at the surface between the two phases. This directly leads to VOCs emitting from liquid to gas phase. There are two conditions that apply at the free surface between the liquid and the gas phases:

- "The component of the molar flux of species i normal to the interface must be continuous across the interface.
- Local equilibrium exists at the interface."[24]

According to Taylor and Krishna [23, p. 12], the first condition can be noted as in equation 13

$$C_{i,k} \cdot (u_{i,k} - W_{Surf}) = C_{i,k+1} \cdot (u_{i,k+1} - W_{Surf}) \tag{13}$$

where $C_{i,k}$ is the molar density of species i at computational point k which is in the liquid phase, $C_{i,k+1}$ is the molar density of species i at computational point $k+1$ which is in the gas phase, $u_{i,k}$ is the velocity with respect to a stationary coordinate reference frame of species i at computational point k, $u_{i,k+1}$ is the velocity with respect to a stationary coordinate reference frame of species i at computational point $k+1$ and W_{Surf} is the vertical velocity of the free surface [24]. Further, the average molar velocity in equation 14 is introduced together with Fick's first law on diffusion expressed as equation 15 [23, p. 50]

$$u_k = \sum_{i=1}^{NOC} X_{i,k} \cdot u_{i,k} \tag{14}$$

$$C_{i,k} \cdot (u_{i,k} - u_k) = -\left(C_{tot} \cdot D_i \frac{\partial X_i}{\partial z}\right)_k \tag{15}$$

where effective diffusivity is introduced based on the assumption that diffusion of species i depends only on the concentration gradient of species i [24]. Finally, as the molar flux is continous across the interface, the first condition is expressed in equation 16.

$$-C_{tot,k} \cdot D_{i,k} \frac{\partial X_{i,k}}{\partial z} + C_{i,k} \cdot (u_k - W_{Surf}) = -C_{\text{tot },k+1} \cdot D_{i,k+1} \frac{\partial X_{i,k+1}}{\partial z} + C_{i,k+1} \cdot (u_{k+1} - W_{Surf}) \tag{16}$$

The second condition states that local equilibrium exists at interface and is represented by equation 17 [25, p. 112].

$$X_{i,k+1} = K_i \cdot X_{i,k} \tag{17}$$

The equilibrium constant K_i is a function of pressure, temperature and composition for each species. These variables are calculated by Peng Robinson Equation Of State (PR EOS). In VOCSim, Wilson's modified equation is used to find K_i [25, p. 123 Eq. 3.67].

5.1.3 Equation system

Oldervik [24] further explains that the diffusion-convection equations (Eq 10 for both gas and liquid phase) are approximated by Finite Differences (FD). Implicit formulations are used for space derivatives of X_i, which leads to a three diagonal equation system for the liquid phase and another one for the gas phase. The finite difference approximation of equation 16 gives 4 unknowns and equation 17 is therefore used to solve one of these unknowns. Together the finite approximation of equation 10, for both liquid and gas phase, and the conditions at the surface forms an equation system for the unknowns $X_{i,k}$ with three diagonals. The equation system is solved by forward and backward substitution. Appropriate boundary conditions at top and bottom of the cargo tank are also needed for the equation system.

One equation system is solved for each species of i at each time step. The fact that the sum of all mole fractions, $\sum_{i=1}^{NOC} X_{i,k}$, equals 1 for all computational points k is further used to normalise all $X_{i,k}$. Here NOC represents number of components.

5.2 Boundary conditions

To fulfill the equation system, some boundary conditions are necessary. Conditions applied for the bottom of the tank would be liquid flow and composition into the tank and liquid flow out of the tank. At the top of the tank, conditions applied would be:

- Pressure outside of the tank
- Back pressure control valve that is opened or closed at specified set points to control the gas flow in or out of tank
- Specified flow out of or into the tank
- Composition of the gas that may flow into the tank

6 Measurement strategy

The measurement strategy and analysis method determines the outcome of the project, which is why it is chosen carefully. Measurement tubes and pipes are always flushed before samples are taken to minimise the risk of contaminating the vapour gas with air trapped in the tubes.

6.1 Gas sample handling

Gas samples are taken with 1l plastic tedlar bags in hazardous area on cargo deck and brought to the GC position in the workshop for analysis. The gas content in each sampling bag is in the range of bellow 1 gr of hydrocarbon fractions (50kJ). The gas is vented to atmosphere after analysis. If several samples are taken within short time, they are stored in hazardous area, and brought to the GC for analysis one by one.

6.2 Gas sampling

6.2.1 Cargo tanks upper and lower level

The vapour control valves are used for sampling lower, middle and upper levels of relevant cargo tanks. When taking samples, a sample hose is lowered to the required level and purged for some time to assure correct gas composition in hose before filling the sample bag. An illustration of this method is shown in figure 13. This sampling method is used to measure individual tank conditions. This is needed for example to measure the hydrocarbon fraction before loading initiation.

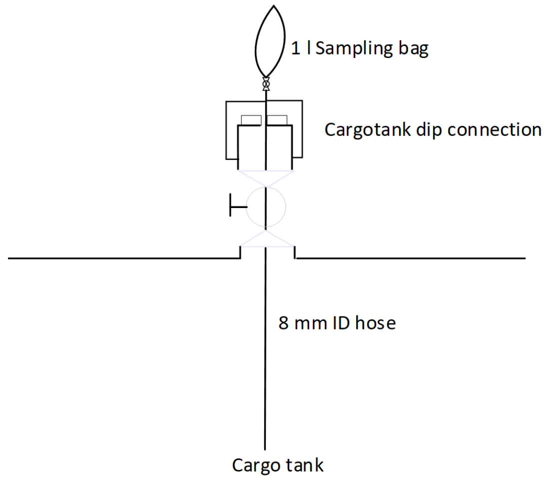


Fig. 13: Tank measurement illustration

6.2.2 Vent riser

When common sampling from all cargo tanks, the samples are to be taken at the vent riser position. All tanks have an inert gas inlet/outlet connected to the inert gas manifold which leads to the vent riser. This is also known as the vapour emission control system. It is drilled a hole through the vent riser piping with threads to fit a sample pipe as depicted in figure 6a. The sample pipe has a rectangular cut on the side facing the vapour flow. An illustration is shown in figure 14. A problem later discovered is that no vapour came out of the steel pipe during venting when the valve of the vent riser is set to partially open. A reason for this may be because of the partially opened valve of the vent riser, turbulence is produced and the pressure at steel pipe inlet is lower than in the inert gas system. A solution to this problem is to open the valve to 100% during short periods when measuring.

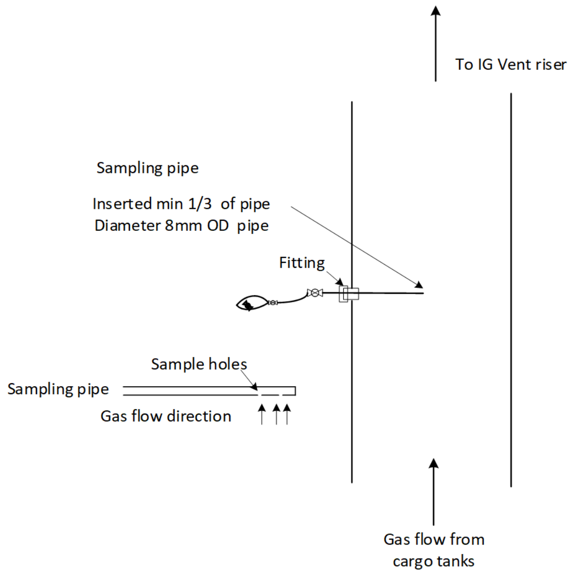


Fig. 14: Illustration of steel pipe into vent riser

6.2.3 Sampling before loading

Verification of tanks condition is done to ensure hydrocarbon composition before loading starts. On the Arosa, all tanks have been crude oil washed during unloading when the last parts of cargo were pumped to shore. Measurements of tanks pre-load conditions are done just before loading initiation at loading terminal with the sample hose lowered through tanks vapour control valve. It is measured one tank per segregation of previous loaded voyage, which leads to measurement of crude oil tank 4 starboard and 5 starboard which had the AMCO and AXLCO segregations respectively from previous loading. A sample sheet is used to cover necessary data for the different measurements. These data include sample number, tank number, height level of measurement, status of COW and previous crude loaded. This sheet is given in section 8.2.

6.2.4 Sampling during loading - Vent riser

The sample point for loading procedures is positioned at the common vent riser. Samples are taken with even intervals with 10 samples for each loaded segregation. So for approximately each 10% increase of sounding level for the given segregation, a sample is taken. Information from each sample is written in a sheet for further analysis, including time, sample identity, gas temperature, gauge pressure, ambient pressure, crude oil sounding levels for every tank and loading rate. This sheet is also given in section 8.2.

6.2.5 Sampling during voyage

If pressure in tanks increase beyond the pressure limit during voyage, the ship would release the gas through the vent riser. This could happen from increasing gas temperature during the day when the sun warms up the deck or from further VOC formation in the tanks. Each time such a release finds place, measurements are done and logged. Information from each sample is written in a sheet, as shown in appendix A.1, for further analysis. To get the normalised volume released during a venting sequence, the pressure in the inert gas (IG) manifold is logged before and after each venting sequence together with the gas temperature. However, no vapour releases happened during the voyage.

7 Method

After taking a sample, measurements of the sample are done with the gas chromatograph. The measurements are taken as soon as possible after sampling to avoid any degradation of the sample content. This degradation could happen as a result of reactions between the sample bag and gas, or reactions of the gasses inside the sample bag. Sample measurements are then put into a data modeling and analysis set to quantify the emissions. Figure 15 shows a flowchart that illustrates the procedure done to quantify VOC emissions and compare the results to simulation results done by VOCSim in a simple manner.

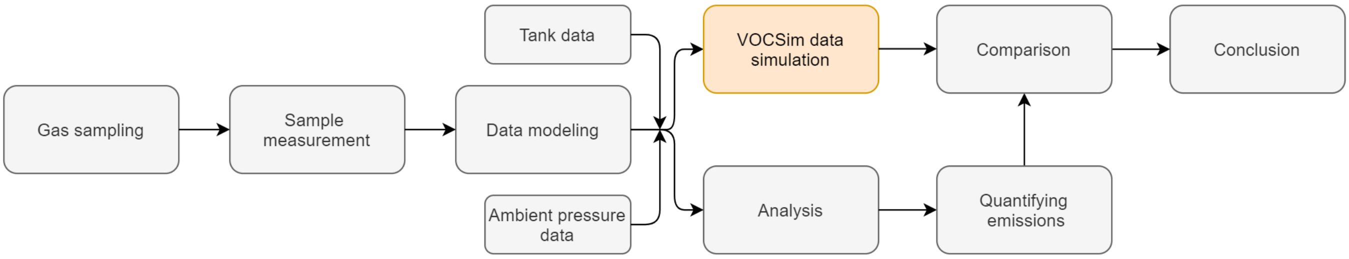


Fig. 15: Flowchart illustrating procedure done to quantify VOC emissions and compare with VOC-Sim simulation results

In order to validate the measurements and analysis, VOCSim is used in parallel as a comparison tool. From the results of the two emission measurement strategies, a conclusion is made.

7.1 Gas composition

Every measurement of a sample gives details about the composition of the vapour gas. This information is put into spreadsheets for further analysis, and an example of such spreadsheets are given in table 4.

Table 4: Part of sample analysis table

	1 (10% loaded)	2 (20% loaded)	3 (30% loaded)	... →
Sample id				
Time				
Methane				
Ethane				
Propane				
i-Butane				
n-Butane				
i-Pentane				
n-Pentane				
n-Hexane				
Nitrogen				
Oxygen				
CO_2				
α-value				
HC molar mass				
Tank gas volume				

When gas composition is known, an α-value can be obtained to illustrate the volume percentage of hydrocarbons in the gas. Since composition is given in volume fractions, i.e. mole fractions, the α-value can be calculated through adding all the hydrocarbon fractions together, as in equation 18.

$$\alpha = \sum_{X=1}^{8} X_{\%} \tag{18}$$

The hydrocarbon molar mass is then calculated in equation 19

$$MM_{HC} = \frac{\sum_{X=1}^{8}(X_{\%} * MM_X)}{\alpha} \tag{19}$$

where $X_{\%}$ is the molar fraction for different hydrocarbon gas components as methane, ethane and so forth. MM is the molar mass and α is the hydrocarbon fraction of the sample. This equation calculates only the molar mass for the hydrocarbon part of the gas, as if it was isolated from the inert gasses (oxygen, nitrogen and carbon dioxide). The reason for this is that later in the model it is only the hydrocarbon part of the gas that is quantified as emission from the tanks.

7.2 Emission model during loading

In order to estimate the amount of hydrocarbons that have been emitted with the inert gas from the tanks, the cargo tank gas volumes and α-value is used. Each group of tanks loaded, i.e. each segregation, must be analysed separately. The model used to quantify the amount of emission are based on adding hydrocarbons emitted due to cargo displacement difference between samplings with hydrocarbon vapour growth in tanks between samplings. Hydrocarbon vapour growth means that the α-value of the vapour have increased between the samplings, which means that the fraction of hydrocarbons have increased in the gas. An illustration of the model are shown in figure 16.

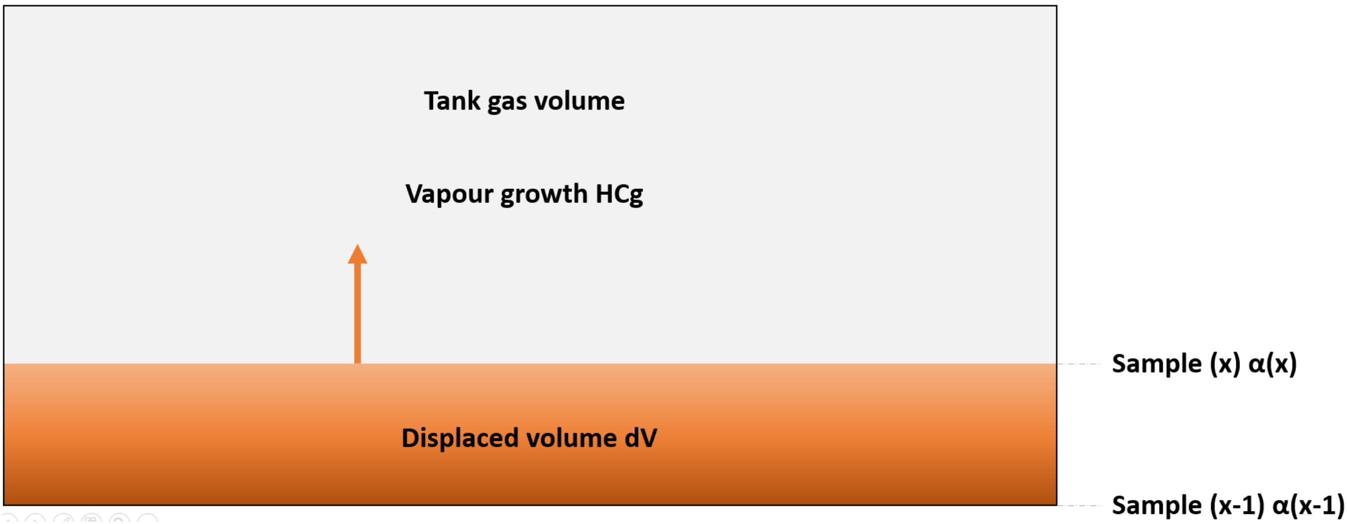


Fig. 16: Hydrocarbon emission model during loading

This model is based on stable loading process, well mixed homogeneous gas and on the assumption that the loading tanks are only connected to each other and the vent riser through the inert gas system.

The model hinges on two central equations, HC_g and HC_d given in equation 20 and 21

$$HC_g[V] = \left(TV_{gas}(x) + \frac{dV_{cargo}}{2}\right) * \frac{\alpha(x) - \alpha(x-1)}{2} \tag{20}$$

$$HC_d[V] = dV_{cargo} * \left(\alpha(x-1) + \frac{\alpha(x) - \alpha(x-1)}{2}\right) \tag{21}$$

where TV_{gas} is the gas volume in the tanks, dV_{cargo} is the cargo displacement difference in the tanks between samplings and α is the hydrocarbon fraction value. Adding equation 20 and 21 will result in total hydrocarbons released between two samplings. This is done for every sampling and accumulated to a final emission calculation for the given segregation as shown in equation 22.

$$HC_{total}[V] = \sum_{X=0}^{10} HC_g(x) + HC_d(x) \tag{22}$$

$(X = 0)$ represents the measurements taken before loading initiation and is needed to obtain initial α-value at 0% loaded. This iteration in the model does not result in any emission since loading have not yet started, but is crucial as it counts as $(x-1)$ in the first measurement/iteration after loading initiation.

7.3 Standardising volume and pressure

Gas is compressible and expands when temperature rises and contracts when cooled. When the incompressible cargo displaces a certain volume in the tank which again presses the same volume of gas out of the tank, the number of molecules released would not be the same in two different scenarios with different gas temperatures. The same counts for pressure difference. Higher pressure will increase gas density in the same given volume. As conditions in the cargo tanks are dynamic, this fact calls for the need to standardise pressure and temperature. Avogadro's law says that equal volumes of gases, measured at the same temperature and pressure, contain equal numbers of molecules. There are several alternative definitions for standard reference conditions. For this paper, the IUPAC (International Union of Pure and Applied Chemistry) STP (Standard Temperature and Pressure) definition is used because of its common use in chemical and physical processes. The STP standardising method is defined as air at 1 bar and 0 C° [26]. At these conditions, ideal gas law, from equation 23, says that there are 22,711 cubic meter of space per kmole of molecules $[m^3/kmole]$. This reference value is calculated through equation 24

$$\frac{V}{n} = \frac{RT}{P} \tag{23}$$

$$\frac{V}{n}\Big[\frac{m^3}{kmoles}\Big] = R * \frac{T_{STP}}{P_{STP}} = 8.314462\Big[\frac{J}{K * mol}\Big] * \frac{273,15[K]}{100[kPa]} \tag{24}$$

where V is volume, n is number of moles, R is the universal gas constant, T_{STP} is the defined reference temperature and P_{STP} is the defined reference pressure.

7.4 Defining the gas density and weight

The model is now able to quantify the volume of hydrocarbons released, but to be able to determine the weight of all hydrocarbons released, a method of deriving the density of the hydrocarbon fluid is necessary. A method for defining the total molar mass of the hydrocarbon gas have been obtained in equation 19, and together with tank temperature and pressure related to the STP reference value from equation (24), the density of the hydrocarbon gas in the gas sample can be obtained. To be specific, this is the density of hydrocarbons as if the other inert gasses are not present. For each sample, equation 25 gives the density of the hydrocarbon gas as

$$\rho_{HC} = \frac{MM_{HC}}{\frac{V}{n} * \frac{T_{smpl}}{T_{STP}} * \frac{P_{STP}}{P_{smpl}}} = \frac{MM_{HC}}{22,711 * \frac{T_{smpl}}{273,15[K]} * \frac{100[kPa]}{P_{smpl}}} \tag{25}$$

where T_{smpl} and P_{smpl} are tank temperature and pressure for when the given sample is taken, $\frac{V}{n}$ equals the given STP reference value and MM_{HC} is the molar mass of the hydrocarbon gas. A new density is then measured for every sample as composition, tank temperature and tank pressure varies during loading. Total weight of emissions are estimated by multiplying ρ_{HC} with HC_{total} as in equation 26.

$$HC_{mass} = \rho_{HC} * HC_{total} \tag{26}$$

7.5 Data simulation method

Simulations in VOCSim are directly based on data and measurements done on board the vessel and are used as a "verification of measurement" tool. VOCSim is a difficult program to be introduced to and does not have a commercial friendly interface. As seen in figure 15, data and parameters from the ship are needed to simulate a similar loading process, and the colored box in the flowchart can be extended to the flowchart in figure 17.

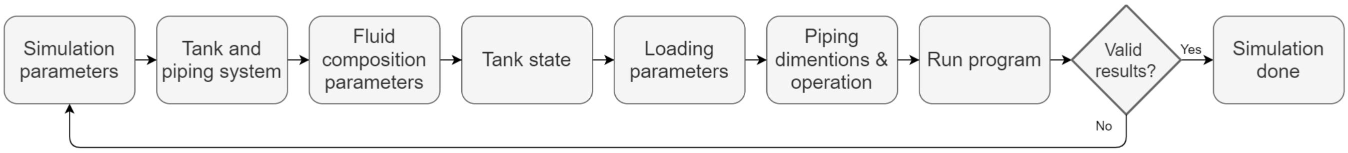


Fig. 17: Flowchart illustrating procedure in VOCSim simulation

The figure illustrates that parameters for the program, such as time step between simulation points, length of the simulated time, number of molecule components needed for simulation, maximum number of computational points in the vertical direction in each tank and other maximum limit parameters are first defined. The actual numbers of the "limited" parameters are later specified and will be explained further. Tank and piping system are then defined as from how many tanks, pipes, pipe nodes (defined as junctures) and valves the system is made up from. Fluid composition parameters are then defined for every hydrocarbon where accentric factor, molecular weight, critical pressure and temperature, and density of component in liquid phase are given. If not provided, the program will insert default values. The next steps are done for every tank in the system, and starts with defining the previously "maxed" parameters. Width, height and length of the given tank are defined. Initial tank liquid height, gas temperature and pressure, and component fractions are given. Loading parameters such as volume flow and composition of crude over time are then decided for each tank. Lastly, the valve and piping dimensions are set before running the program. Results from the simulation are evaluated to see if some parameters need change or have been typed wrong.

7.5.1 Simulation parameters

The simulation parameters are the baseline of which the program further builds upon. Parameters to be decided are:

- Simulation time start and stop
- Length of time step
- Number of molecule components that are accounted for in simulation
- Maximum number of computational points in the vertical direction in each tank
- Max number of positions in vertical direction in a cargo tank for which temperature and composition are specified as initial values
- Max number of simulation times for which additional diffusion coefficients for the liquid phase is specified. (Same for gas phase)
- Max number of times for which flow is specified in a liquid pipe
- Max number of times for which pressure and temperature is specified in a "Gas environmental tank"
- Max number of times for which the fluid composition is specified in a "Liquid" or "Gas environment tank"
- Max number of times for which liquid/gas temperature is specified in a cargo tank.
- Max number of positions in the vertical direction for which the liquid/gas temperature is specified in a cargo tank

- Max number of different boundary conditions (Loading parameters)

Environmental tanks are hypothetical external tanks to define conditions of the ambient air and the storage tank for which the crude is loaded from at terminal. The gas environment tank can be used as an infinite drain for when vapour is vented out from the crude oil tanks during loading or storage, and as an infinite source when inert gasses are flushed into the tanks during offloading or an event where tank pressure decreases.

7.5.2 Tank and piping system

To replicate the real process as representable and simple as possible, a good design is necessary. The program works in a way that if a segregation is loaded into for example 5 different tanks or 1 tank with the same total volume, the emission results would be the same as it works in one dimension. That is why 1 larger tank for each segregation is preferred instead of several tanks to make the simulation as clear and concise as possible. An example of a VOCSim tank and piping model is shown in figure 18, given that 3 segregations are loaded.

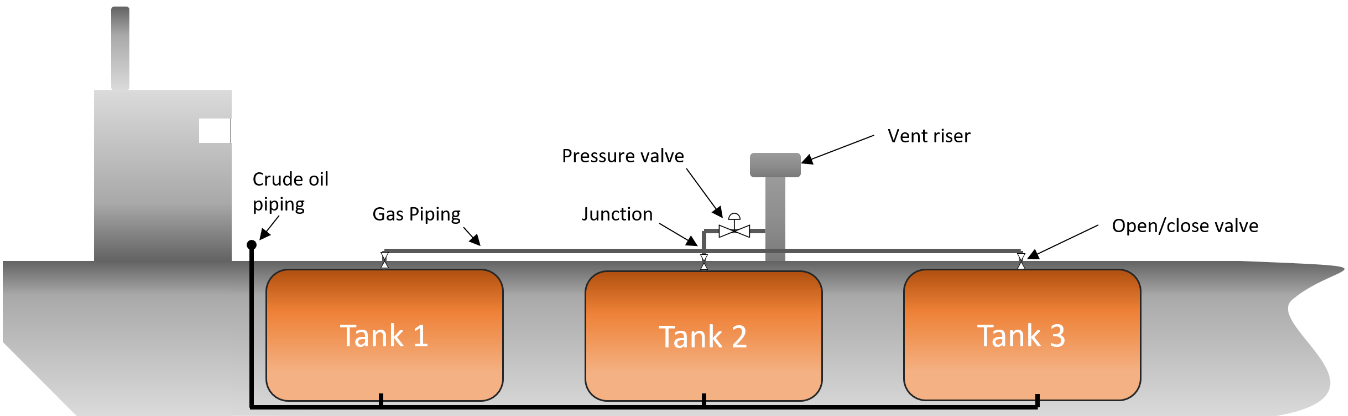


Fig. 18: Tank and piping setup in VOCSim

In the above figure, each tank represents a segregation of crude oil and has one liquid inlet/outlet at bottom and one gas inlet/outlet in ceiling, but it is possible to have more inlets/outlets for both phases. Gas flow out of each individual tank is controlled by an open/close valve which leads to the piping network. On tankers these are normally always open. The piping network leads to a junction to collect the different gas streams and further sends gas out of vent riser. The overall flow out of the vent riser is controlled by a pressure valve which opens and closes in between predetermined pressure values to keep the pressure in the tanks at a determined interval.

7.5.3 Fluid composition parameters

This section defines the different molecular components that are needed for the simulation, of which are different hydrocarbons and the inert gasses oxygen, carbon dioxide and nitrogen. Parameters needed to be defined for each component are accentric factor, molecular weight, critical pressure and temperature, and density of component in liquid phase. This is a difficult area which has a large effect on the final emission results. An example of the difficulties of this area is that when the equilibrium constant K_i, calculated with Wilson's modified equation, is compared with values calculated with Peng Robinson equation of state, the values for critical temperature of the lighter hydrocarbons must be slightly reduced to give good compliance in the program [27]. Default values for the parameters are gathered from literature, stored in the program and used if no other value for a parameter is given.

In this project, the fluid composition parameters are gathered from the "Aspen HYSIS" oil database and are chosen based on name of origin of the crude oil and API value that is closest to the segregations measured on board Arosa. As only distinctive values are set for these parameters and can not change during simulation, loading 2 or more segregations will cause inaccuracies. If 2 or more segregations are to be loaded, the parameters would be a mix of weighted values from each segregation.

7.5.4 Tank state

This and later sections focuses on individual tanks and has to be repeated for all tanks included in the simulation. The parameters which were assigned max values in section 7.5.1 are now given specific values all depending on level of detail wanted in the simulation. Tank dimensions such as height, width and length are set as desired to match the volume of each segregation group. The area of the gas and crude pipe inlet/outlet are also set, with the gas outlet preferably matching the pipe dimensions witch are later defined. If tanks is partly filled before loading initiation, liquid surface height above tank floor must be defined. The initial conditions of tank atmosphere are also needed where gas temperature and component fractions are to be defined at one or more height levels above floor. These initial conditions are set to match the measurements from before loading procedure of Arosa. Initial pressure is also set for each tank.

7.5.5 Loading parameters and variables

During loading, the diffusion coefficient changes while the tank is filling. Both liquid and gas diffusion changes. From measurements done and experiences made by Oldervik, diffusion values for certain ship movements during loading (roll, pitch, etc.) at different loading percentage levels of a tank have been found through trial and error [27]. Note that this is mostly from Suezmax shuttle tankers. In the gas phase there is a constant artificial diffusivity and added artificial diffusivity if the density gradient reaches different set values. The timing of each diffusion change must be edited after an initial simulation run as the tanks fill at different times of simulation and that the timing must match certain loaded percentage levels of a given tank. Temperature development throughout the simulation for both liquid and gas phase are also set, preferably reflecting actual values from real measurements. The temperature can be set for several height levels in the tank and linear changes between the levels are done by the program.

The loading itself are defined by two files. One file defines the crude oil flow, temperature and pressure throughout the simulation, while the other determines the composition of the oil. These two types of files must be made for each tank. After this is done, the same types of files are made for the environment "tank", where the first determines the pressure and temperature, and the other defines the composition of the environment "tank".

7.5.6 Piping and valve dimensions and operations

Now all the necessary inputs on the loading of the tanks should be in place. In this section, the dimensioning and orientation of the piping are defined. Diameter, length and internal roughness of each pipe section are needed inputs. The orientation of each valve, i.e. what tank or junction is upstream and downstream, also have to be decided. Each pipe has a valve, and the valve type is chosen for each pipe section. Valves to choose from are open/close, valve with specified mass flow, back pressure control valve, P/V valve, valve which control volume flow as a function of time, valve which control volume flow as a function of upstream pressure, pressure valve with higher opening pressure than closing pressure and vacuum valve with lower opening pressure than closing pressure. A regular pipe with no valve in real life would be designated with an open/close valve being set to fully open. The last point before initiating the simulation is to choose how the valves are to be operated. Different valve types have different inputs, but the most important is timing, number of behaviour changes, degree of valve opening and opening/closing details. The degree of valve opening, Kv, are a part of equation 27 which can be transformed into a flow equation as a function of pressure data.

$$DP = Kv * Rho * Vel^2/2[Pa] \tag{27}$$

Where DP is the pressure difference, Kv is the valve opening factor, Rho is the density of the fluid and Vel is the velocity.

7.5.7 Running VOCSim

All inputs are now defined and the program is ready for its initial run. After first run it is necessary to read through the results for any miscalculations or typos. Regarding the diffusion coefficients, it is important to match the timing of the loaded percentage levels of each tank with the timing where the diffusion coefficients change. To analyse the emission results one should have experience with what levels to expect with the current setup to determine if the simulation works as it should. The program also has built in error messages to help the operator. If results fulfil the given requirements, the simulation is done.

7.6 Expected results

As Norway have regulated VOC-emissions since the 1990s, there have been retrieved a lot of emissions data from the Norwegian continental shelf. From a typical North Sea installation, each crude oil loading on to a shuttle tanker will be on average 850 000 bbls. During such a loading, around 110 tonnes of VOC will be emitted from the shuttle tanker's tanks [28]. Knowing this and the fact that Arosa loaded around 2 017 000 bbls of crude oil, the expected results from this project would be around 260 tonnes of VOC emissions given linear approximation and loading same oil type. In this approximation, it is assumed that the Arabian oil will act similar to the North Sea oil during loading, which typically is not the case.

8 Results

8.1 Segregation groups loaded

The loading terminal have the final say on how and where the crude is loaded. Just before loading, the segregation groups are decided and is shown in table 5 together with tank volumes in correct loading order, AMCO, AXLCO and AHCO. The loading segregations have an API of 31,3, 39,4 and 27,2 for AMCO, AXLCO and AHCO respectively and are retrieved from the terminal loading documents at Ras Tanura.

Table 5: Tank segregation group volumes

Segregation 1	100% m^3	Segregation 2	100% m^3	Segregation 3	100% m^3
1P	16224,9	1C	24459,9	2P	20720,7
1S	16224,9	2C	32233,9	2S	20720,7
3P	20909,6	4C	32233,9	3C	32233,9
3S	20909,6	5P	14752,1	5C	27017,2
4P	20818,6	5S	14752,1		
4S	20818,6	SLOPP P	4784,4		
SLOP S	4784,4				
Total	**120 690,6**	**Total**	**123 216,3**	**Total**	**100 692,5**

8.2 Sampling data

The first data which was reported was the tank, cargo and ambient conditions. These data sets were essential for structuring the samplings, measure volume difference in tanks between samplings and to help estimate the density of the gas. Table 6 shows details related to the samplings before loading. Samples were only taken from 1 tank per segregation from previous voyage (2 segregations) in the same period before first loading and assumed the same for rest of the tanks in same segregation group.

Table 6: Details for samples taken before loading

Segregation: AXLCO

Sample ident	Tank	Level (Sounding)	Status of COW	Previous crude loaded
1	5S	Bottom 5m	Done in China 3 weeks before loading	AXLCO
2	5S	Middle 15m	Done in China 3 weeks before loading	AXLCO
3	5S	Top 25m	Done in China 3 weeks before loading	AXLCO

Segregation: AMCO and AHCO

Sample ident	Tank	Level (Sounding)	Status of COW	Previous crude loaded
4	4S	Bottom 5m	Done in China 3 weeks before loading	AMCO
5	4S	Middle 15m	Done in China 3 weeks before loading	AMCO
6	4S	Top 25m	Done in China 3 weeks before loading	AMCO

Table 7, 8 and 9 shows data points related to every sampling taken during loading of all three segregations. The sounding levels are used to calculate displaced cargo volume using the ullage/volume tables for the ship and thereby find remaining gas volume in the tanks. Loading rate illustrates how volatile the flow rate of crude oil was. Temperature readings were only available for the slop tanks and are therefore not reliable for all of the tanks. No temperature readings were available for segregation 3, but note that cargo temperatures are given and weather was clear blue skies and 36°C during the day. This is helpful as assumptions are made. Gas temperature is assumed with slop tank temperature as base point. Ambient and tank gauge pressures are needed to calculate normalised density of the vapour volume released. Tank gauge pressure also shows the variations of tank pressure conditions throughout the loading procedures.

Table 7: Data points for Arabian medium crude oil

6.8.19 Time UTC: +0300	Samp. Id.	Gas temp	Atm & gauge pressure [mbar| mmH_2O]	C.O.T nr. Levels (sounding) [m]							Loading rate [bbls/h]
	Nr.	[C]		1 PORT	1 STRB	3 PORT	3STRB	4 PORT	4 STRB	SLOP STRB	
17:00	7	35	1006|600	4	4	4,2	4,1	4,6	4,5	0	53 000
17:30	8	35	1003|560	5,8	5,8	5,9	5,8	6,2	6,2	0	54 000
18:35	9	35	1003|530	7,9	7,9	8,04	8	8,35	8,35	0	53 000
19:55	10	35	1003|540	10,4	10,4	10,5	10,5	10,8	10,8	0	54 000
21:35	11	35-45	1003|540	13,2	13,3	13,4	13,45	13,8	13,9	0	55 000
23:45	12	36-45	1003|490	16,2	16,2	16,4	16,4	16,55	16,6	0	30 000
01:35	13	36-45	1003|600	19,8	19,8	18,1	18,1	19,9	19,7	0	53 000
02:35	14	39,7	1002|590	22,4	22,45	19,9	20	21,95	22	20,1	58 000
04:20	15	39,7	1002|570	24,83	25	22,52	22,53	24	24	20,92	30 000
06:40	16	39,7	1002|540	26,42	26,4	25,4	25,45	26,5	26,5	20,92	Finished
Note: Cargo temp after loading = 42°C.											

Table 8: Data points for Arabian extra light crude oil

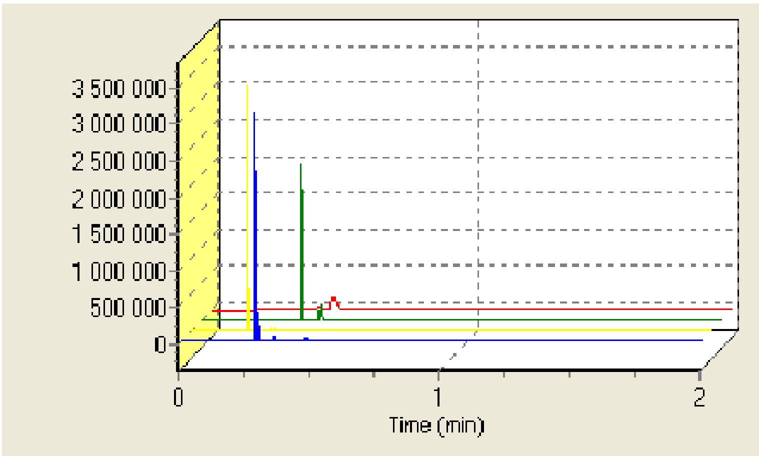
7.8.19 Time UTC: +0300	Samp. Id.	Gas temp (slop tank temp)	Atm & gauge pressure [mbar| mmH_2O]	C.O.T nr. Levels (sounding) [m]						Loading rate [bbls/h]
	Nr.	[C]		1 CENTER	2 CENTER	4 CENTER	5 PORT	5 STRB	SLOPP PORT	
08:50	17	36,4	1003|600	1,17	3,53	3,8	4,2	4,3	0	50 000
10:25	20	36,6	1003|625	3,68	6,53	7,2	7,1	7,1	0	45 000
11:55	23	42,8	1003|580	6,93	9,34	9,89	9,45	9,36	8,55	65 000
13:05	24	42,8	1003|580	8,65	12	12,55	11,9	11,63	11,82	62 000
14:15	27	41,9	1003|610	10	15,74	15,45	14,6	14,6	14,65	60 000
15:30	28	42,7	1003|550	12,75	17,37	18,1	17,3	17,15	17,16	62 000
16:40	31	42,7	1003|605	14,89	19,76	20,45	19,6	19,5	18,73	62 000
17:55	34	42,8	1003|650	17,58	22,66	23,25	22,2	22,25	18,7	60 000
19:30	35	43	1003|500	21,1	24,1	24,7	24,55	24,5	18,88	30 000
22:55	38	43	1003|500	27,155	27,087	27,108	26,575	26,588	20,93	Finished
Note: Cargo temp after loading = 40,8°C.										

Table 9: Data points for Arabian heavy crude oil

8.8.19 Time UTC: +0300	Samp. Id.	Gas temp	Atm & gauge pressure [mbar| mmH_2O]	C.O.T nr. Levels (sounding) [m]				Loading rate [bbls/h]
	Nr.	[C]		2 PORT	2 STRB	3 CENTER	5 CENTER	
00:55	39	N/A	1003|630	2,83	2,95	2,96	3,02	65 000
01:55	40	N/A	1003|680	5,48	5,41	5,67	5,9	60 000
02:55	41	N/A	1003|640	7,54	7,6	8,1	8,3	56 000
03:55	42	N/A	1003|530	9,95	9,9	10,5	10,8	58 000
04:50	43	N/A	1003|635	12,25	12,25	13	13,35	60 000
05:50	44	N/A	1003|720	14,72	24,76	15,56	15,9	58 000
06:45	45	N/A	1003|580	17,1	17,1	18	18,25	70 000
07:35	46	N/A	1003|580	19,72	19,5	20,55	20,8	71 000
08:35	47	N/A	1003|510	22,3	22,2	23	23	30 000
10:40	48	N/A	1003|690	24,55	24,26	24,55	27,14	Finished
	Note: Cargo temp after loading = 48,7°C							

8.3 Measurement data

In between taking samples, measurements of previous samples are done. Six to eight measurement runs of 3 minutes each is done on the GC for every sample to obtain consistent measurement readings. For every measurement run, chromatograms for each channel are obtained in the galaxy program. From these, the program made a multi-channel report to illustrate the results in a single data sheet as depicted in figure 19.



Galaxie Chromatography Software - Multi-Channel Report

Data File : C:\Galaxie\data\2019 VOC Sample results - Jakob\Sample1 6.8.2019 12_44_16_6.DATA
Method File : VOC method
Sample ID : Sample1 6.8.2019 12_44_16_6

Injection Date: 6.8.2019 12:44:35
Recalc Date : 10.8.2019 13:46:29

Operator : EmisLab
Workstation : VARIAN
Instrument : Varian 4900 GC

Run Mode : Analysis
Peak Measurement : Peak Areas
Calculation Type : External Standard
Normalized? Yes

#	Peak Name	Channel	RT (min.)	Result (mol-	Norm. %	Area (uV/Sec.)
1	Oxygen	Channel 1 - CP	0.4090	5.1446	5.5409	15909
2	Nitrogen	Channel 1 - CP	0.4627	74.6096	80.3573	198757
3	Methane	Channel 1 - CP	0.6627	0.0383	0.0413	282
4	Carbon Dioxide	Channel 2 - CP	0.4512	9.5253	10.2591	79311
5	Ethane	Channel 2 - CP	0.5050	0.1518	0.1635	1350
6	Propane	Channel 3 - CP	0.2412	1.2695	1.3673	10183
7	i-Butane	Channel 3 - CP	0.3040	0.4352	0.4687	4193
8	n-Butane	Channel 3 - CP	0.3153	1.0925	1.1767	10724
9	i-Pentane	Channel 4 - CO	0.6583	0.2979	0.3208	5904
10	n-Pentane	Channel 4 - CO	0.7483	0.2582	0.2780	5278
11	n-Hexane	Channel 4 - CO	1.3660	0.0245	0.0264	533
	Totals			92.8474	100.0000	332423

Fig. 19: Multi-channel report from sample 1 measurement nr.6

The measurement is considered as good the closer the total number under "Result (mol-" is to 100. Deviations from 100 indicates less optimal reading relative to the calibration measurement. The data is then normalised so that the total number equals 100 as if the components represents

100% of the gas. The normalised data is used further to define the α-value and molar mass of the hydrocarbon part of the gas. Normalised data from the most optimal measurement per sample is collected into tables for further analysis. As loadings proceeded and α-value increased, the "Result (mol-" number for measurements approached and stayed around 100. Table 10a and 10b shows the measured gas composition in tank 5S and 4S before loading where the α-value is measured by equation 18 and the average α-value is given on the right side of each table. The results show that the hydrocarbon fraction is higher in the upper layer than the lower levels of the tanks.

Table 10: Gas composition tables before loading for (a) C.O.T 5S representing AXLCO segregation and (b) C.O.T 4S representing AMCO and AHCO segregation

(a)

C.O.T 5 starboard AXLCO	Empty Tank lower	Empty Tank middle	Empty Tank upper	
Sample ident	1	2	3	
Tank no:	5s	5s	5s	
Methane	0,0413 %	0,0402 %	0,0316 %	
Ethane	0,1635 %	0,1628 %	0,1593 %	
Propane	1,3673 %	1,3879 %	1,3781 %	
i-Butane	0,4687 %	0,4937 %	0,4994 %	
n-Butane	1,1767 %	1,3102 %	1,3333 %	
i-Pentane	0,3208 %	0,4048 %	0,4298 %	
n-Pentane	0,2780 %	0,4042 %	0,4375 %	
n-Hexane	0,0264 %	0,0758 %	0,0939 %	
Nitrogen	80,3573 %	79,8589 %	79,3824 %	
Oxygen	5,5409 %	5,6842 %	6,3028 %	
CO_2	10,2591 %	10,2160 %	9,9520 %	
Alfa value	**3,8427 %**	**4,2796 %**	**4,3629 %**	**4,1617 %**

(b)

COT 4 starboard AMCO	Empty Tank lower	Empty Tank middle	Empty Tank upper	
Sample ident	4	5	6	
Tank no:	4s	4s	4s	
Methane	0,0610 %	0,0555 %	0,0580 %	
Ethane	0,2715 %	0,2787 %	0,2747 %	
Propane	2,1181 %	2,1439 %	2,1701 %	
i-Butane	0,8135 %	0,7928 %	0,8226 %	
n-Butane	2,2911 %	2,5032 %	2,7561 %	
i-Pentane	0,7165 %	0,8476 %	1,0301 %	
n-Pentane	0,7396 %	0,9275 %	1,2879 %	
n-Hexane	0,1478 %	0,1957 %	0,4247 %	
Nitrogen	77,7449 %	77,3537 %	76,2258 %	
Oxygen	4,6777 %	4,4465 %	4,6570 %	
CO_2	10,4183 %	10,4549 %	10,2930 %	
Alfa value	**7,1591 %**	**7,7449 %**	**8,8242 %**	**7,9094 %**

Each segregation is, based on the model, isolated as a loading by itself and therefore there are three tables containing measurement data for all three segregations loaded. The data are shown in Table 11, 12 and 13. The molar mass is calculated for the hydrocarbon part of the gas using equation 19. Cargo tanks gas space volume are measured from subtracting the displaced cargo volume from the total volume of tanks related to the given segregation.

Table 11: Normalised measurement table for AMCO

06.08.2019	1 (10% loaded)	2	3	4	5	6	7	8	9	10 (Finish Loading)
Sample ident	7	8	9	10	11	12	13	14	15	16
Time	16:30	17:30	18:35	19:55	21:35	23:45	01:35	02:35	04:20	06:40
Analysis										
Mole/Vol%										
Methane	0,0336 %	0,0281 %	0,0299 %	0,0495 %	0,0490 %	0,0440 %	0,0456 %	0,0420 %	0,0377 %	0,0554 %
Ethane	0,2762 %	0,2822 %	0,2830 %	0,2837 %	0,2945 %	0,3130 %	0,3539 %	0,3654 %	0,3662 %	0,4271 %
Propane	1,8924 %	2,0656 %	1,9660 %	2,1007 %	2,3252 %	2,4535 %	2,8621 %	2,9271 %	2,9868 %	3,3924 %
i-Butane	0,6463 %	0,7406 %	0,6824 %	0,7014 %	0,7920 %	0,8384 %	0,9504 %	0,9946 %	0,9774 %	1,0776 %
n-Butane	1,7670 %	2,0656 %	1,9732 %	2,0093 %	2,5151 %	2,6650 %	3,0205 %	3,1961 %	2,8574 %	2,9797 %
i-Pentane	0,5676 %	0,8242 %	0,6563 %	0,6479 %	0,9134 %	0,9614 %	1,0585 %	1,1365 %	0,9331 %	0,8757 %
n-Pentane	0,5406 %	0,9805 %	0,6762 %	0,6383 %	1,1325 %	1,1987 %	1,2800 %	1,4229 %	0,9945 %	0,7747 %
n-Hexane	0,1161 %	0,3235 %	0,1539 %	0,0935 %	0,3971 %	0,4219 %	0,4066 %	0,4983 %	0,2663 %	0,1014 %
Nitrogen	79,2670 %	77,5510 %	78,7851 %	78,8044 %	76,8915 %	76,2769 %	75,5581 %	74,8854 %	76,1695 %	76,2125 %
Oxygen	4,6456 %	4,3512 %	4,4334 %	4,3138 %	4,0908 %	4,5952 %	4,1791 %	4,7524 %	4,7324 %	4,4901 %
CO_2	10,2477 %	10,5489 %	10,3605 %	10,3575 %	10,6088 %	10,2320 %	10,2850 %	9,7793 %	9,6788 %	9,6134 %
HC molar mass [kg/kmole]	55,2283027	57,6192656	55,9791392	55,2348532	57,7547049	57,7957469	57,3428558	57,8210184	56,0798853	54,4157002
Alfa	**5,8398 %**	**7,3103 %**	**6,4209 %**	**6,5243 %**	**8,4188 %**	**8,8959 %**	**9,9776 %**	**10,5829 %**	**9,4194 %**	**9,6840 %**
Cargo tanks gas space volume [m3]*)	106202,1	98949,5	89396,9	78390,4	65201,8	52429,8	40049,6	27228,7	14492	4689,6

Table 12: Normalised measurement table for AXLCO

07.08.2019	1 (10% loaded)	2	3	4	5	6	7	8	9	10 (Finish Loading)
Sample ident	17	20	23	24	27	28	31	34	35	38
Time	08:50	10:25	11:55	13:05	14:15	15:30	16:40	17:55	19:30	22:55
Analysis										
mole %/Vol%										
Methane	0,0235 %	0,0216 %	0,0352 %	0,0244 %	0,0297 %	0,0268 %	0,0264 %	0,0238 %	0,0224 %	0,0730 %
Ethane	0,3369 %	0,2681 %	0,3132 %	0,2780 %	0,3738 %	0,3796 %	0,3640 %	0,4561 %	0,3694 %	0,8471 %
Propane	2,9653 %	2,5413 %	3,1042 %	2,6450 %	3,8099 %	3,8583 %	4,4050 %	4,5039 %	3,3270 %	7,4311 %
i-Butane	0,9839 %	0,8160 %	1,0097 %	0,8637 %	1,2766 %	1,3097 %	1,7422 %	1,5488 %	1,0636 %	2,9019 %
n-Butane	3,0353 %	2,5044 %	2,8103 %	2,6145 %	3,3547 %	3,5371 %	4,5050 %	3,9934 %	3,0212 %	7,0703 %
i-Pentane	1,0685 %	1,0089 %	0,9615 %	0,9450 %	1,0919 %	1,1865 %	1,4718 %	1,3505 %	1,0652 %	2,2079 %
n-Pentane	1,2791 %	1,2514 %	1,0764 %	1,1395 %	1,1490 %	1,2481 %	1,2624 %	1,3895 %	1,2259 %	2,1178 %
n-Hexane	0,4410 %	0,4814 %	0,3497 %	0,4062 %	0,3305 %	0,3224 %	0,1770 %	0,3692 %	0,4050 %	0,5146 %
Nitrogen	75,3253 %	76,3242 %	75,8296 %	76,9411 %	74,5355 %	74,1336 %	72,7133 %	72,8166 %	75,2812 %	64,6797 %
Oxygen	4,3991 %	4,2763 %	4,2443 %	4,4356 %	4,4525 %	4,2786 %	4,1303 %	4,0467 %	4,5809 %	4,2405 %
CO_2	10,1421 %	10,5065 %	10,2660 %	9,7069 %	9,5960 %	9,7194 %	9,2026 %	9,5017 %	9,6381 %	7,4311 %
HC molar mass [kg/kmole]	57,4587139	58,2506557	56,5275857	57,5296155	55,9795136	56,2103309	55,9878377	56,0563827	56,7446875	55,7072693
Alfa	**10,1335 %**	**8,8931 %**	**9,6602 %**	**8,9163 %**	**11,4161 %**	**11,8685 %**	**13,9538 %**	**13,6352 %**	**10,4997 %**	**23,1637 %**
Cargo tanks gas space volume [m3]*)	111416,9	99441,8	86505,1	75359,1	63369,5	50647	39894,6	27428,1	17922,8	3078,4

Table 13: Normalised measurement table for AHCO

08.08.2019	1 (10% loaded)	2	3	4	5	6	7	8	9	10 (Finish Loading)
Sample ident	39	40	41	42	43	44	45	46	47	48
Time	00:55	01:55	02:55	03:55	04:50	05:50	06:45	07:35	08:35	10:40
Analysis										
mole %/Vol%										
Methane	0,0319 %	0,0343 %	0,0312 %	0,0389 %	0,0498 %	0,0617 %	0,0607 %	0,0736 %	0,0891 %	0,1330 %
Ethane	0,5039 %	0,4830 %	0,4945 %	0,5595 %	0,5853 %	0,6711 %	0,7012 %	0,7814 %	0,9864 %	1,4728 %
Propane	4,6538 %	4,0825 %	4,0623 %	4,4386 %	4,4776 %	5,0582 %	5,1059 %	5,3500 %	6,2521 %	8,6511 %
i-Butane	1,6762 %	1,3881 %	1,3372 %	1,4024 %	1,4048 %	1,5910 %	1,5763 %	1,6322 %	1,8546 %	2,4890 %
n-Butane	4,5624 %	3,9105 %	3,8624 %	4,0128 %	4,0261 %	4,7325 %	4,6037 %	4,6304 %	4,9809 %	6,2571 %
i-Pentane	1,5937 %	1,4170 %	1,3799 %	1,3793 %	1,3494 %	1,5812 %	1,5526 %	1,4165 %	1,4724 %	1,6590 %
n-Pentane	1,6650 %	1,5623 %	1,6048 %	1,5906 %	1,5627 %	1,8791 %	1,8731 %	1,4969 %	1,5154 %	1,5573 %
n-Hexane	0,4609 %	0,4771 %	0,5380 %	0,4624 %	0,5008 %	0,5995 %	0,6182 %	0,3569 %	0,3585 %	0,3035 %
Nitrogen	71,5094 %	73,1564 %	72,8421 %	72,5578 %	72,8828 %	71,0109 %	71,0654 %	71,7329 %	70,5148 %	66,8124 %
Oxygen	4,4337 %	4,5179 %	5,3443 %	4,8039 %	4,3394 %	3,8550 %	4,5687 %	3,8949 %	3,9552 %	3,8264 %
CO_2	8,9094 %	8,9710 %	8,5032 %	8,7048 %	8,8213 %	8,9597 %	8,2741 %	8,6341 %	8,0205 %	6,8383 %
HC molar mass [kg/kmole]	56,6629826	56,843969	56,9806233	56,3253788	56,229842	56,4527454	56,3552162	54,9980624	54,2881185	53,0337672
Alfa	**15,1478 %**	**13,3548 %**	**13,3103 %**	**13,8845 %**	**13,9565 %**	**16,1743 %**	**16,0917 %**	**15,7379 %**	**17,5094 %**	**22,5228 %**
Cargo tanks gas space volume [m3]*)	90910,2	81281,9	72779,3	63817,2	54728,6	45335,5	36478,8	27054	18863,6	8661,6

Before loading, ship officers must always check oxygen and hydrocarbon content in tanks to verify that values are within limits for safety reasons. For this loading, a small measuring device which is regularly calibrated was brought out to take sample measurements directly from random tanks vapour control valve. Results from this device indicated a oxygen content of around 2%. This deviates from the measurements done by the gas chromatograph. Device type and brand is unknown.

8.4 VOCSim simulation inputs

Since VOCSim needs detailed information about the loading its going to simulate, parameter inputs are chosen in hindsight of the measurement results done on Arosa. Since the loading included 3 segregations, the tank and piping setup are set to be the same as illustrated in figure 18 with 1 tank per segregation.

8.4.1 General input parameters

Max limit parameter values are not listed, as specific values are used. These appear natural in the layout of the following tables. Table 14 shows the core parameters of the simulation program.

Table 14: Core parameters of VOCSim

Name	**Symbol**	**Value**
Time start	T_{start}	0 [s]
Time end	T_{end}	250 000 [s]
Time step	DT_{input}	500 [s]
No. of molecule components	NOC	15
No. of tanks	No_of_tanks	3
No. of gas pipes	$NoGasP$	4
No. of junctures	$NoGasPJunc$	1
No. of environment tanks	$NoGasEnv$	1

The time end is set to 250 000 seconds, or approximately 69,5 hours, even though the loading operation only lasts for 153 500 seconds, or 42,5 hours. This is done to observe what happens after loading completion. Time steps are set to 500 seconds. Number of molecules are set to 15 and includes C1 to C10+ of the hydrocarbons and oxygen, nitrogen and carbon dioxide as inert gasses. VOCSim includes more hydrocarbon components in its simulations than earlier measurements done in this project, where hydrocarbons up to C6 are included. The characteristics of hydrocarbon and inert components are given in table 15.

Table 15: Fluid composition parameters

No.	**Name**	**Molecular weight [kg/kmol]**	**Acentric factor**	**Crit. pressure [bar]**	**Crit. temp. [K]**	**Liq. dens. [kg/m^3]**
1	C1	16,04	0,0115[1]	46,04[1]	225[2]	299,39
2	C2	30,07	0,0908[1]	48,80[1]	311[2]	355,68
3	C3	44,09	0,1454[1]	42,49[1]	377[2]	506,68
4	iC4	58,12	0,1756[1]	36,48[1]	416[2]	561,97
5	nC4	58,12	0,1928[1]	37,97[1]	434[2]	583,22
6	iC5	72,15	0,2273[1]	33,81[1]	460,4[1]	623,44
7	nC5	72,15	0,2510[1]	33,69[1]	469,7[1]	629,73
8	C6	82,03	0,2957[1]	30,12[1]	512	684,63
9	C7	89,88	0,3506[1]	27,36[1]	560	701,28
10	C8	102,26	0,3978[1]	24,86[1]	640	734,98
11	C9	115,75	0,4437[1]	22,89[1]	680	750,46
12	C10+	290,53	0,9070[1]	10,971[1]	775,3[1]	861,95
13	N2	28,02[1]	0,0450[1]	33,99[1]	126,3[1]	469,50[1]
14	CO2	44,01[1]	0,2310[1]	73,82[1]	304,2[1]	499,50[1]
15	O2	32,00[1]	0,0250[1]	50,47[1]	154,4[1]	499,50[1]

[1] Default values in program are used. [2] Suggested values are used [27].

As mentioned in section 7.5.3, some fluid composition parameters are gathered from the "Aspen HYSIS" oil database and are chosen based on name of origin of the crude oil and API value that is closest to the segregations measured on board Arosa. Data sets gathered are named "AMCO 2012 - API 30,992", "AXLCO 2011 - API 41,6984" and "AHCO 1983 - API 27,7555". Parameters which are not gathered from this database due to lack of information are marked as default values in table 15. Since 3 segregations are loaded, it is necessary to mix the parameter values by weighted volume fractions of the segregations. Here AMCO counts for 35,35%, AXLCO counts for 36,6% and AHCO counts for 28,05% of total loaded volume on board Arosa. Suggestion for critical temperature for the lighter hydrocarbons (C1 to nC4) was also provided by Oldervik [27]. As these values come from an earlier project with a mix of AMCO and AXLCO, and that lower critical temperature is needed due to reasons discussed in 7.5.3, they are used in this project and also marked in table 15.

8.4.2 Parameters for tanks

The tanks are each given sets of parameters with most of them similar. Table 16 shows structural and initial state parameters.

Table 16

	Tank 1	**Tank 2**	**Tank3**
NOK	100	100	80
Length	85 [m]	86,8 [m]	70,91 [m]
Width	50 [m]	50 [m]	50 [m]
Height	28,4 [m]	28,4 [m]	28,4 [m]
Pipe area crude	0,4 [m^2]	0,4 [m^2]	0,4 [m^2]
Pipe area gas	0,4 [m^2]	0,4 [m^2]	0,4 [m^2]
Initial pressure	1.047 [bar]	1.045 [bar]	1.045 [bar]
Initial temperature	308,15 [K]	308,15 [K]	308,15 [K]
Initial ZSurf	0 [m]	0 [m]	0 [m]

Number of computational points are set to 100 as default but tank 3 is set to 80 because of the program struggling with running 100 computational points in tank 3. This is a result of fast loading rate and do not cause a problem if loading rate of tank 3 is reduced, but this would contradict the efforts of comparison to the loading of Arosa. Width and height of the tanks are identical to represent alignment in a virtual ship. The lengths are defined by dividing the segregation volumes given in table 5 with the product of the height and width of the tanks. Pipe areas are set by eye measuring. However, the pipe areas does not yield a big impact on emissions. Initial pressure are set to similar values of what Arosa had, but tank 1 have to have a slightly higher pressure to initiate movement in the simulation. Errors occur if all pressures are equal. Initial temperature is set as the same as first measurement in table 7. Tanks are initially empty, which is why initial ZSurf is 0 for all tanks.

Table 17 shows the initial mole fractions of gas in the different tanks. It is apparent that hydrocarbons C7 to C10+ are not included as the initial mole fraction of components are gathered from measurement data before loading in table 10a and 10b.

Table 17: Initial mole fractions of gas at different height levels in tanks prior loading start with a) representing AMCO and AHCO tanks, and b) representing AXLCO

(a)

Distance from bottom	**5 [m]**	**15 [m]**	**25 [m]**
C1	0,0610 %	0,0555 %	0,0580 %
C2	0,2715 %	0,2787 %	0,2747 %
C3	2,1181 %	2,1439 %	2,1747 %
iC4	0,8135 %	0,7928 %	0,8226 %
nC4	2,2911 %	2,5032 %	2,7561 %
iC5	0,7165 %	0,8476 %	1,0301 %
nC5	0,7396 %	0,9275 %	1,2879 %
C6	0,1478 %	0,1957 %	0,4247 %
C7	0 %	0 %	0 %
C8	0 %	0 %	0 %
C9	0 %	0 %	0 %
C10+	0 %	0 %	0 %
N2	77,7449 %	77,3537 %	76,2258 %
CO2	10,4183 %	10,4549 %	10,2930 %
O2	4,6777 %	4,4465 %	4,6570 %

(b)

Distance from bottom	**5 [m]**	**15 [m]**	**25 [m]**
C1	0,0413 %	0,0402 %	0,0316 %
C2	0,1635 %	0,1628 %	0,1593 %
C3	1,3673 %	1,3879 %	1,3781 %
iC4	0,4787 %	0,4937 %	0,4994 %
nC4	1,1767 %	1,3102 %	1,3333 %
iC5	0,3208 %	0,4048 %	0,4298 %
nC5	0,2780 %	0,4042 %	0,4375 %
C6	0,0264 %	0,0758 %	0,0939 %
C7	0 %	0 %	0 %
C8	0 %	0 %	0 %
C9	0 %	0 %	0 %
C10+	0 %	0 %	0 %
N2	80,3573 %	79,8589 %	79,3824 %
CO2	10,2591 %	10,2160 %	9,9520 %
O2	5,5409 %	5,6842 %	6,3028 %

Additional diffusion coefficients for the liquid phase are given as function of time as a table, and are represented in table 18. For simulation times in between the times in the table, linear interpolation is used. The same value applies to all computational points in the vertical direction. Highest additional diffusion coefficient representing the most fluid movement happens when a tank is filled to 20%. The same values are applied for every tank with only time changing to match time with filling level of tank.

Table 18: Additional diffusion coefficient development for liquid phase in a) tank 1, b) tank 2 and c) tank 3

(a)

Tank 1		
Time [s]	**D_{liq}**	**Filled %**
0	$1 \cdot 10^{-5}$	0%
2500	$6 \cdot 10^{-5}$	3%
6500	$15 \cdot 10^{-5}$	10%
12000	$20 \cdot 10^{-5}$	20%
23500	$15 \cdot 10^{-5}$	40%
46500	$10 \cdot 10^{-5}$	80%
56500	$9{,}5 \cdot 10^{-5}$	96,1%

(b)

Tank 2		
Time [s]	**D_{liq}**	**Filled %**
56500	$1 \cdot 10^{-5}$	0%
59000	$6 \cdot 10^{-5}$	3%
63000	$15 \cdot 10^{-5}$	10%
69000	$20 \cdot 10^{-5}$	20%
80500	$15 \cdot 10^{-5}$	40%
103000	$10 \cdot 10^{-5}$	80%
114000	$9{,}5 \cdot 10^{-5}$	97,5%

(c)

Tank 3		
Time [s]	**D_{liq}**	**Filled %**
114000	$1 \cdot 10^{-5}$	0%
116500	$6 \cdot 10^{-5}$	3%
119000	$15 \cdot 10^{-5}$	10%
123000	$20 \cdot 10^{-5}$	20%
131500	$15 \cdot 10^{-5}$	40%
148000	$10 \cdot 10^{-5}$	80%
153500	$9{,}5 \cdot 10^{-5}$	91,4%

Additional diffusion coefficients for the gas phase are also given as function of time and are represented for tank 1 in table 19. The additional diffusion coefficient for each specified time is the sum of a constant value and a value being a function of the density gradient in the gas phase. The latter is because it is experienced that if the gas released from the cargo is light, it mixes faster with the existing gas than if it is heavy. For simulation times in between the times in the table, linear interpolation is used. Same values apply for tank 2 and 3 which are given in appendix A.2.

Table 19: Artificial diffusion coefficients for the gas phase as a function of density gradient in tank 1

Tank 1								
Time [s]	**Constant artificial diffucivity** [m^2/s]	**Density gradient 1** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Density gradient 2** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Density gradient 3** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Tank filling state** [%]
0	$1 \cdot 10^{-4}$	-0,2	0	-0,02	0	0	0	0 %
2500	$1 \cdot 10^{-4}$	-0,2	0	-0,02	0	0	0	3 %
4000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	6 %
56500	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	96,1 %
250000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	96,1 %

Table 20 below shows the temperature development in all the tanks throughout the simulation. Temperature for all tanks start with initial temperature as stated in table 14. Efforts are made so that the temperature development of tank 1 and 2 are replicating the development of temperatures shown in measurement tables 7 and 8 by interpolation from start temperature to ending temperature, remembering that the original temperature readings were not perfectly representable. Tank 3 have a temperature development which is based on interpolation of start temperature to the AMCO crude oil temperature.

Table 20: Gas temperature development throughout simulation in a) tank 1, b) tank 2 and c) tank 3

(a)

Tank 1	
Time [s]	**Temp [K]**
-	-
0	308,15
12000	309,15
23500	310,15
35000	311,15
46500	312,15
56500	313,15
250000	313,15

(b)

Tank 2	
Time [s]	**Temp [K]**
0	308,15
56500	309,55
69000	310,87
80500	312,19
92000	313,51
103000	314,83
114000	316,15
250000	316,15

(c)

Tank 3	
Time [s]	**Temp [K]**
0	308,15
114000	309,55
123000	312,01
131500	314,47
140000	316,93
148000	319,85
153500	321,85
250000	321,85

The temperature of the liquid is set to a constant value throughout the loading of each tank as liquid temperature was not measured before loading was finished on board Arosa. Temperatures used are the same as shown in figure 7, 8 and 9, which are 315,15 K, 313,95 K and 321,85 K respectively. Table 21 shows these temperatures with the timing and magnitude of volume flow into tanks. For simulation times in between the times in the table, linear interpolation is used.

Table 21: Temperature and flow of different crude oils into a) tank 1, b) tank 2 and c) tank 3

(a)

Tank 1 - AMCO		
Time [s]	**Temp.** [K]	**Flow** [m^3/s]
0	315,15	0
1500	315,15	2,12
54650	315,15	2,12
56500	315,15	0

(b)

Tank 2 - AXLCO		
Time [s]	**Temp.** [K]	**Flow** [m^3/s]
56500	313,95	0
58500	315,95	2,165
112000	315,95	2,165
114000	315,95	0

(c)

Tank 3 - AHCO		
Time [s]	**Temp.** [K]	**Flow** [m^3/s]
114000	321,85	0
116000	321,85	2,455
151500	321,85	2,455
153500	321,85	0

The composition of these volume flows are given in table 22 which are retrieved from the "Aspen HYSIS" oil database. The values are rounded up to 1 decimal except for methane and ethane due to low fractions. AMCO and AXLCO have almost no methane and ethane, while AHCO have some. AHCO have more of the lighter hydrocarbons and the heavier hydrocarbons than AXLCO and AMCO have. The higher levels of light hydrocarbons points to possibly higher volatile evaporation.

Table 22: Crude oil composition which are pumped into simulation tanks

	C1	**C2**	**C3**	**iC4**	**nC4**	**iC5**	**nC5**	**C6**	**C7**	**C8**	**C9**	**C10+**
AMCO	0,00%	0,01%	0,9%	1,1%	5,3%	3,5%	2,5%	1,0%	6,4%	6,5%	7,7%	65,2%
AXLCO	0,00%	0,00%	0,5%	1,3%	5,9%	5,0%	3,0%	1,2%	9,1%	8,9%	9,4%	55,8%
AHCO	0,16%	1,00%	2,1%	2,5%	1,4%	1,0%	0,6%	1,5%	7,0%	6,9%	7,4%	68,3%

The environment tank have a constant temperature of 310 K and a pressure of 100,3 kPa, or 1,003 bar, to match ambient air during measurements. The composition of the environment tank is set to 83% N2, 12% CO2 and 5% O2. Composition values represents typical inert gas values if the program simulates emptying of the tanks and have no impact on emission results.

8.4.3 Parameters for piping and valves

Pipe setup are the same as illustrated in figure 18. Table 23 shows the dimensioning and operation of the pipe and valve system. Pipe number 1, 2 and 3 merges from each respective tank to a junction where pipe 4 goes to the environment "tank".

Table 23: Pipe and valve dimensioning and operation

Pipe no.	**Length [m]**	**Diameter [m]**	**DW friction factor**	**Valve type**	**Kv**
1	50	0,65	0,02	Open/Close	1
2	50	0,65	0,02	Open/Close	1
3	50	0,65	0,02	Open/Close	1
4	20	0,75	0,02	P/V	130

Pipe 1, 2 and 3 have basic open/close valves which are constantly set to open. Pipe 4 has a pressure valve that is active from start. P/V, or the pressure valve, has an opening pressure at 1,075 bar and a closing pressure at 1,045 bar. This results in a pressure interval between those values for all tanks. DW factor represents the Darcy Weisback friction factor for the pipes. The P/V valve has Kv opening factor of 130 as the valve on board Arosa was set between 10-20% opening during loadings. This gave similar pressure dynamics.

8.5 VOCSim simulation results

The results of the simulation program have high level of detail where pressure, gas flow rate, gas composition, α-value and molecular weight of the gas can be obtained for every time step, whether looking at individual tanks, junction, pipes or combined gas flow into the environment "tank". Even the composition of liquid phase and gas phase in the tanks at the end of loading can be obtained. To display all of these individual results would end up being several pages long. Results are therefore presented in 10 evenly distributed measurement steps per segregation, just like the results from Arosa were presented above. Detailed results are, however, available in appendix A.3.

8.5.1 Key simulation results

After several simulation attempts and tuning of inputs, the main result components are given in table 24, 25 and 26. Focus is given to key values regarding VOC emissions, such as α-value, vapour flow, emitted mass of VOC, among others.

Table 24: Key simulation results for AMCO loading

"Sample" number	Time [h]	Temp [K]	Pressure [kPa]	Flow [Nm^3/s]	Accum Flow [Nm^3]	Emitted mass of VOC [kg]	Emitted mass of IG [kg]	Released from cargo Total [kg]	Released from cargo VOC [kg]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
1	1,5	308,5	107,2	3,28	3324	698	4034	2770	3154	0,082	57,89	32,31
2	3,2	309	105,8	2,63	20656	4163	25137	4359	5087	0,078	57,23	32,15
3	4,7	309,6	105,5	2,49	34445	6947	41900	7369	8383	0,083	57,04	32,25
4	6,4	310,1	105,7	2,55	49627	10322	60186	12107	13388	0,095	57,20	32,57
5	7,9	310,6	105,7	2,52	63569	13972	76689	15761	17232	0,112	57,49	33,07
6	9,4	311,1	105,7	2,45	77236	18338	92454	18812	20439	0,139	57,84	33,84
7	11,1	311,6	105,7	2,36	91670	24433	108337	21627	23396	0,194	58,29	35,40
8	12,6	312,1	105,8	2,23	104256	32136	120957	23800	25679	0,277	58,70	37,82
9	14,3	312,6	105,8	2,11	117241	43088	132439	25665	27647	0,364	58,98	40,37
10	15,8	309,6	104,4	1,93	128710	52280	142830	26951	29004	0,095	57,93	32,63

Table 25: Key simulation results for AXLCO loading

"Sample" number	Time	Temp	Pressure	Flow	Accum Flow	Emitted mass of VOC	IG	Released from cargo Total	VOC	Alfa value	MW for HC	MW Total
	[h]	[K]	[kPa]	[Nm^3/s]	[Nm^3]	[kg]	[kg]	[kg]	[kg]		[kg/kmol]	[kg/kmol]
1	18,2	310,4	107,7	2,68	16522	2250	20595	4516	5223	0,05	55,81	31,25
2	19,7	311	105,8	2,36	30113	3851	37660	5938	6968	0,045	55,49	31,12
3	21,1	311,7	105,1	2,35	41678	5305	52135	8013	9296	0,049	55,93	31,22
4	22,6	312,3	105,1	2,58	55416	7240	69222	12578	14140	0,059	56,89	31,53
5	24,2	312,9	105,6	2,63	69864	9908	86874	16989	18786	0,089	58,19	32,42
6	25,7	313,6	105,8	2,62	84303	13484	104065	20725	22722	0,111	59,24	33,13
7	27,2	314,2	105,9	2,49	98320	18695	119898	23831	26002	0,173	60,37	35,11
8	28,6	314,8	106,0	2,33	110339	26020	132074	26275	28585	0,27	61,12	38,22
9	30,1	315,4	106,1	2,16	122668	36914	142924	28242	30687	0,368	61,58	41,39
10	31,7	311,7	106,1	1,71	134032	47972	152422	29601	32122	0,199	60,15	35,92

Table 26: Key simulation results for AHCO loading

"Sample" number	Time	Temp	Pressure	Flow	Accum Flow	Emitted mass of VOC	IG	Released from cargo Total	VOC	Alfa value	MW for HC	MW Total
	[h]	[K]	[kPa]	[Nm^3/s]	[Nm^3]	[kg]	[kg]	[kg]	[kg]		[kg/kmol]	[kg/kmol]
1	33,3	311,2	107,6	3,48	13516	3427	16110	6871	7121	0,077	58,39	32,19
2	34,4	312,3	107,6	3,46	27608	6562	33109	13263	13738	0,081	56,77	32,18
3	35,4	313,3	107,5	3,22	39264	9255	47064	17341	17968	0,102	54,75	32,54
4	36,4	314,3	107,1	3,03	50237	12178	59922	20622	21376	0,118	52,01	32,61
5	37,5	315,5	106,7	2,89	62154	16036	73404	23757	24640	0,155	49,70	33,05
6	38,5	316,5	106,5	2,84	72201	20068	84213	26178	27164	0,203	48,12	33,66
7	39,4	317,6	106,5	2,79	81898	25051	93872	28380	29464	0,281	47,19	34,81
8	40,4	318,8	106,6	2,78	91551	31762	102253	30825	32022	0,393	46,22	36,31
9	41,5	320,4	106,9	2,53	102188	42042	109558	33006	34312	0,544	45,91	38,57
10	42,5	320,4	106,6	1,48	110063	51036	114088	34774	36138	0,561	47,42	39,62

The tables show collected values from all tanks simultaneously and is separated only by the timing of each segregation loading. That means the flow shown in for example sample 6 in table 26 is the total flow from all 3 tanks in the given moment while AHCO segregation is loaded at 25,7 hours into loading process. Accumulated flow shows the total flow of gas emitted from vent riser during the given segregation and starts over when the next segregation starts. The same counts for emitted mass of VOC and IG, and gasses released from cargo. Notice that the total released amount of gas from cargo is less than VOCs released from cargo. This is because the program also simulates absorption of the inert gasses into the crude oil, trying to reach an equilibrium. The α-value is given in the above tables, but a more detailed look into the accumulated composition fractions for each segregation and the average of all segregations are given in table 27.

Table 27: Accumulated composition fractions of each segregation and average of all segregations

Segregation	C1	C2	C3	iC4	nC4	iC5	nC5	C6	C7	C8	C9	C10+
AMCO	0,3267 %	1,6578 %	23,5806 %	11,0833 %	38,0207 %	12,8480 %	9,4656 %	1,7836 %	1,0608 %	0,1228 %	0,0396 %	0,0106 %
AXLCO	0,2555 %	1,1008 %	16,8234 %	12,6737 %	40,7607 %	16,3367 %	8,8336 %	1,3042 %	1,6551 %	0,1830 %	0,0524 %	0,0210 %
AHCO	2,2488 %	11,5957 %	26,6911 %	13,9465 %	26,4332 %	9,0690 %	6,9653 %	1,7462 %	1,1245 %	0,1319 %	0,0419 %	0,0060 %
Average	1,6659 %	8,5264 %	23,8052 %	13,5743 %	30,6234 %	11,1945 %	7,5117 %	1,6169 %	1,2797 %	0,1468 %	0,0449 %	0,0104 %

8.5.2 VOCSim wide open valve test

After running measurements on board Arosa and multiple VOCSim simulations, deviations between α-values occurred between measurements and simulations. Since the vent riser valve of Arosa needed to open 100%, a hypothesis where this greatly affected measured α-values is developed. The hypothesis is based on when the vent riser is opened to 100%, it causes pressure drop in all tanks which results in a surge in gas flow from all tanks, loaded and unloaded. To test this hypothesis, changes are made to the P/V valve in the simulation where its Kv value is changed to 30 instead of 130 during a time step interval and then back to 130 after the interval. This results in a close to 100% open valve and is done in only one time step of an entire simulation looking at one segregation around "sample" number 9. This means that 3 separate simulations are done to look at the affect on all segregations. The results are given in table 28, 29 and 30. Time steps where wide open valve is active are marked with bold numbers. The most crucial parameters are included to best illustrate the affect on the results.

Table 28: Open valve simulation test comparison for AMCO segregation

(a) Wide open valve test active from 14,2h to 14,3h

Time [h]	Pressure [kPa]	Flow [Nm^3/s]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
14,0	105,8	2,13	0,351	58,95	39,99
14,2	105,8	2,12	0,357	58,97	40,18
14,3	**104,4**	**7,69**	**0,166**	**58,56**	**34,67**
14,4	105,2	0,00	0	0,00	0,00
14,6	105,9	0,00	0	0,00	0,00
14,7	106,5	0,00	0	0,00	0,00
14,9	107,2	0,00	0	0,00	0,00
15,0	107,8	0,00	0	0,00	0,00
15,1	107,5	2,72	0,379	58,88	40,75

(b) Reference simulation results without 100% open

Time [h]	Pressure [kPa]	Flow [Nm^3/s]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
14,0	105,8	2,13	0,351	58,95	39,99
14,2	105,8	2,12	0,357	58,97	40,18
14,3	**105,8**	**2,11**	**0,364**	**58,98**	**40,37**
14,4	105,9	2,11	0,371	58,98	40,57
14,6	105,9	2,10	0,379	58,98	40,79
14,7	105,9	2,10	0,386	58,99	41,01
14,9	105,9	2,10	0,393	58,99	41,19
15,0	105,9	2,10	0,394	58,97	41,21
15,1	105,9	2,10	0,387	58,92	41,01

Table 29: Open valve simulation test comparison for AXLCO segregation

(a) Wide open valve test active from 30,6h to 30,7h

Time [h]	Pressure [kPa]	Flow [Nm^3/s]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
30,3	106,1	2,15	0,378	61,59	41,69
30,4	106,1	2,15	0,385	61,56	41,92
30,6	106,2	2,15	0,393	61,53	42,15
30,7	**103,9**	**6,37**	**0,228**	**60,64**	**36,87**
30,8	105,7	0,00	0	0,00	0,00
31,0	107,1	0,00	0	0,00	0,00
31,1	108,3	0,00	0	0,00	0,00
31,3	107,4	2,57	0,411	61,41	42,65

(b) Reference simulation results without 100% open

Time [h]	Pressure [kPa]	Flow [Nm^3/s]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
30,3	106,1	2,15	0,378	61,59	41,69
30,4	106,1	2,15	0,385	61,56	41,92
30,6	106,2	2,15	0,393	61,53	42,15
30,7	**106,2**	**2,15**	**0,401**	**61,52**	**42,39**
30,8	106,2	2,14	0,407	61,52	42,59
31,0	106,2	2,13	0,405	61,48	42,51
31,1	106,1	2,12	0,402	61,43	42,40
31,3	105,9	2,10	0,367	61,30	41,27

Table 30: Open valve simulation test comparison for AHCO segregation

(a) Wide open valve test active from 40,8h to 41,0h

Time [h]	Pressure [kPa]	Flow [Nm^3/s]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
40,6	107,0	2,80	0,412	46,36	36,66
40,7	107,0	2,79	0,429	46,14	36,86
40,8	106,9	2,74	0,449	45,88	37,07
41,0	**102,9**	**4,57**	**0,465**	**47,19**	**37,89**
41,1	109,0	0,00	0	0,00	0,00
41,3	107,9	3,04	0,511	46,24	38,22
41,4	106,8	2,59	0,531	45,88	38,34
41,5	106,8	2,58	0,544	45,91	38,56

(b) Reference simulation results without 100% open

Time [h]	Pressure [kPa]	Flow [Nm^3/s]	Alfa value	MW for HC [kg/kmol]	MW Total [kg/kmol]
40,6	107,0	2,80	0,412	46,36	36,66
40,7	107,0	2,79	0,429	46,14	36,86
40,8	106,9	2,74	0,449	45,88	37,07
41,0	**106,8**	**2,69**	**0,47**	**45,81**	**37,36**
41,1	106,7	2,62	0,49	45,82	37,68
41,3	106,6	2,57	0,511	45,85	38,02
41,4	106,6	2,54	0,53	45,88	38,34
41,5	106,6	2,53	0,544	45,91	38,57

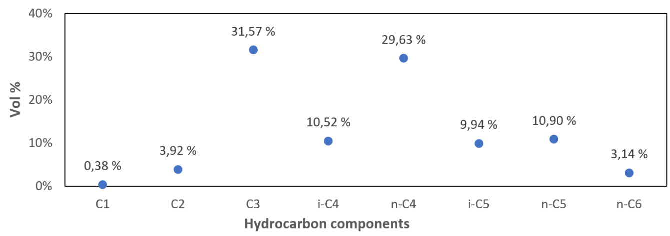
From the above tables it is observed that flow out of the vent riser increases significantly for all segregations as the pressure drops. The α-value on the other hand decreases significantly in the same period for AMCO and AXLCO, but not for AHCO. Total molecular weight also decreases compared to reference tables for the two first segregations.

9 Analysis & Discussion

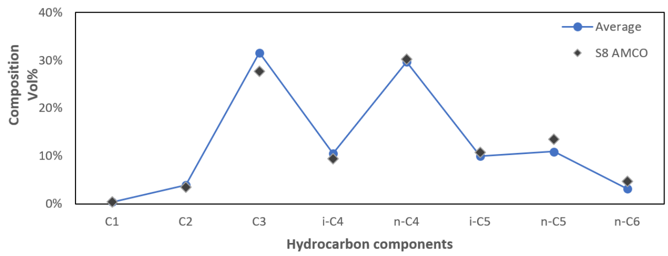
Results are analysed and discussed to become easier to illustrate. Figures are made to picture how the VOC emissions develop throughout the loading process.

9.1 HC gas composition

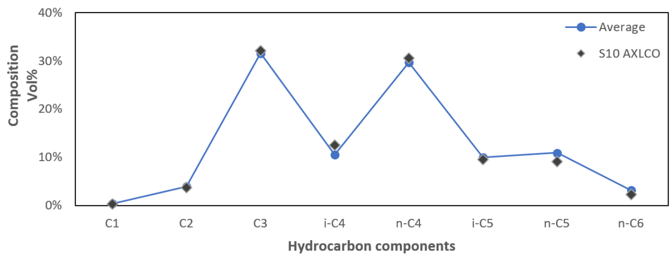
From table 11, 12 and 13 it is estimated that just over 12% of emitted gases are hydrocarbons and the average hydrocarbon composition for all three segregations is given in figure 20a.



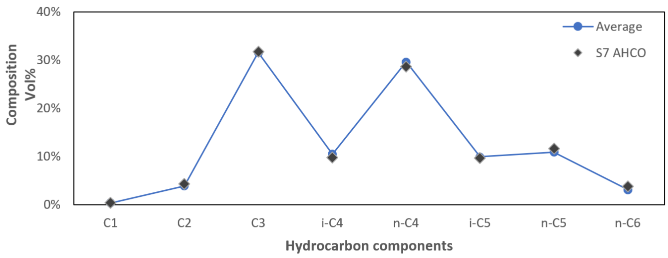
(a) Average HC composition from measurements done on Arosa



(b) HC composition of sample nr.8 from AMCO segregation



(c) HC composition of sample nr.10 from AXLCO segregation



(d) HC composition of sample nr.7 from AHCO segregation

Fig. 20: Hydrocarbon composition for average and specific samples

The average hydrocarbon gas is comprised of almost 72% propane and butane (C3 and C4), 24% pentane and hexane, and 4% of methane and ethane. Methane is only found in trace amounts for all samples, at less than 0.133% with regards to vapour gas and 0.59% for hydrocarbon part of vapour gas. When comparing individual sample compositions with the average hydrocarbon composition in figure 20b, 20c and 20d, it appears that the composition of hydrocarbon vapour gas is fairly consistent. The composition of sample number 8 from the first segregation in figure 20b deviates the most from the average. Many factors can play into this reading, and one reason can be that hydrocarbon gas from previous load and crude oil wash still had its presence in the tanks atmosphere. This gas may have had different hydrocarbon composition than the VOCs from the loading segregation. Sampling error may have also played a role.

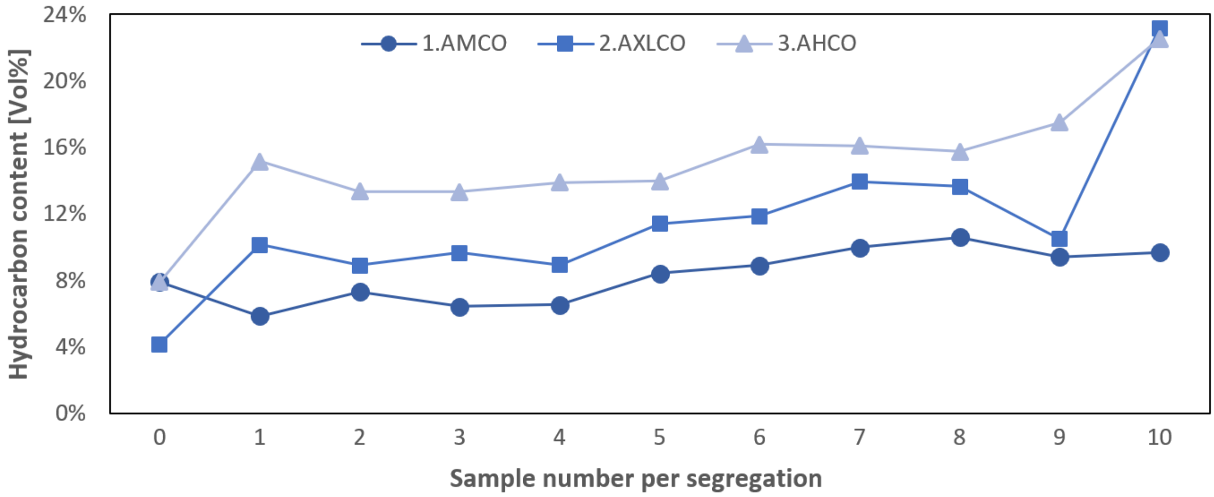


Fig. 21: α-value development throughout loading of segregations

Figure 21 shows the development of α-value for the gas samples. It is indicated that the first segregation had a higher α-value at sample number 0 (before loading) than the following sample. This may have its root cause in different sampling methods. α-values for sample 0 of all segregations are obtained from samples taken through vapour control valve, illustrated in figure 7b, which is from one tank representing the whole segregation group. This imposes high uncertainty to whether the α-values are representable or not compared to α-values from samples 1 to 10.

Development of the α-value has an upward trend for every segregation, mostly for 2^{nd} and 3^{rd} segregation, yet it is not consistently increasing. It is also shown that for every passing segregation, the α-value of first sample after segregation loading start (sample number 1) is considerably increased. This is also generally the case for the rest of the samples, excluding samples taken before loading. Sudden increase towards the end of loading for 2^{nd} and 3^{rd} segregation happened as VOCs developed at the surface of the loading crude oil and approached the ceiling of the tank and inert gas system. This may have lead to strong increase in α-values at end of loadings. However, this is not the case for segregation 1 as other factors may have played a bigger role. A hypothesis is that during the need for opening the vent riser valve to 100% to take samples, it caused a pressure drop in all tanks and thereby gas from all tanks were flowing into the inert gas system and out the vent riser. This is later reflected upon in the simulation analysis. In addition, during periods of increasing pressure in all tanks, gas from loading tanks flowed both out the vent riser and into tanks which were not loading. Hydrocarbon gasses are mostly heavier than inert gasses with propane and butane having molar mass of 44,1 and 58,12 g/mole compared to carbon dioxide of 44,1 g/mole which is the heaviest of the inert gasses. This means that a lot of the hydrocarbon gasses, given a stable environment, would sink to the bottom of the tanks or act as a layer on top of the crude oil. Based on this, as loadings proceeded more hydrocarbons flowed into passive unloaded tanks, and when these tanks started to load, the hydrocarbon concentration in the tanks gas was higher than for the previous segregations. For segregation 1, this hypothesis means that when vent riser valve was opened to 100%, more gas from empty tanks flowed out into the inert gas system than from the loading tanks. This lead to constant low hydrocarbon concentration in the vapour gas exiting the vent riser, which is the case looking at figure 21. For segregation 3, a high fraction of gas from fully loaded tanks flowed into the inert gas system together with the loading tanks when vent riser was opened to 100%. As the loading tanks of segregation 3 had already been receiving hydrocarbon gas during loading of previous segregation, the hydrocarbon content was already higher. This would result in higher hydrocarbon concentration in the vapour gas emissions, which also is the case seen in figure 21. This hypothesis correlate well with the results and indicates that the samples taken before loading may not be seen as representable for segregation 2 and 3. This could explain the rapid increase from sample 0 to 1 in figure 21 for AXLCO and AHCO. It also indicates that tank groups of loaded or non-loaded segregations interfered with the loading segregation and impacted the results.

9.2 Emission volume and mass development

Estimation of VOC emissions for each segregation are done in table 31, 32 and 33 where all data and necessary equations are used. Gas volume in tanks, α-values and hydrocarbon molar mass are retrieved from normalised measurement tables 11, 12 and 13. Tank pressure, temperature and ambient pressure are retrieved from table 7, 8 and 9. Temperatures for segregation 1 and 2 are used as data from slop tank were available. For segregation 3, gas temperature is assumed constant at 43°C on the basis of temperature from previous segregations, weather and cargo temp as no tank data is available. The $\Delta\alpha$-values, or "Delta alfa", are calculated as the difference between current and previous α-value. The STP density of the hydrocarbon gas, ρ_{HC}, are calculated from equation 25. This counts as "normalised" density rather than normalising the total vented volume. The end result would be the same if volume was normalised insted of the density. HC_g, HC_d and HC_t are calculated from equations 20, 21 and 22. Estimating the weight is the final calculation and is done by equation 26.

Table 31: Analysis table for AMCO segregation 1

Segregation 1: AMCO

Gas Sample	Alfa	Alfa value from sample analysis Vol%	Delta Alfa dA=Afax-Alfa(x-1) Vol%	Gas volume in tanks TV [m³] *)	Displaced cargo volume [m³]	Barometric pressure [mbar]	IG gauge pressure [mbar]	Tank temp [C]	HC molar mass [kg/kmole]	STP density of HC gas kg/m3(HC gas)	HC growth in tanks HCg [m³]	HC emitted due to tanks displacement HCd [m3]	Total vented HC HCt= HCg+HCd [m3]	Total vented HC [kg]
0	Alfa0	7,91 %	0,00 %	120690,6	0	1006					0	0	0	
1	Alfa1	5,84 %	-2,07 %	106202,1	14488,5	1003	58,8	35	55,23	2,29	-1173,94	996,03	-177,92	-407,2
2	Alfa2	7,31 %	1,47 %	98949,5	21741,1	1003	54,9	35	57,62	2,38	754,19	476,86	1231,05	2928,8
3	Alfa3	6,42 %	-0,89 %	89396,9	31293,7	1003	52	36	55,98	2,30	-418,79	655,84	237,06	544,7
4	Alfa4	6,52 %	0,10 %	78390,4	42300,2	1003	53	36	55,23	2,27	43,37	712,41	755,78	1715,0
5	Alfa5	8,42 %	1,89 %	65201,8	55488,8	1003	53	37	57,75	2,37	680,09	985,39	1665,48	3939,0
6	Alfa6	8,90 %	0,48 %	52429,8	68260,8	1003	48	37	57,80	2,36	140,31	1105,72	1246,02	2935,1
7	Alfa7	9,98 %	1,08 %	40049,6	80641,0	1003	58,8	38	57,34	2,35	250,09	1168,29	1418,38	3338,2
8	Alfa8	10,58 %	0,61 %	27228,7	93461,9	1002	57,9	40	57,82	2,35	101,81	1318,02	1419,83	3341,9
9	Alfa9	9,42 %	-1,16 %	14492	106198,6	1002	55,9	40	56,08	2,28	-121,36	1273,82	1152,46	2626,0
10	Alfa10	9,68 %	0,26 %	4689,6	116001,0	1002	53	40	54,42	2,20	12,69	936,30	948,98	2092,4
Total/ avg:										**2,31**			**9897,1**	**23053,8**

*) To be taken from Cargo tanks ullage/volume tables, at each sample point

As previously mentioned, the α-value difference from sample 0 before loading and sample 1 in table 31 indicates a decrease of alpha development which, because of the model, leads to negative emissions for given period. This in itself is not possible and it increases suspicion of uncertainty for measurements taken before loading.

Table 32: Analysis table for AXLCO segregation 2

Segregation 2: AXLCO

Gas Sample	Alfa	Alfa value from sample analysis Vol%	Delta Alfa dA=Afax-Alfa(x-1) Vol%	Gas volume in tanks TV [m^3] *)	Displaced cargo volume [m^3]	Barometric pressure [mbar]	IG gauge pressure [mbar]	Tank temp [C]	HC molar mass [kg/kmole]	**STP** density of HC gas kg/m3(HC gas)	HC growth in tanks HCg [m^3]	HC emitted due to tanks displacement HCd [m3]	Total vented HC HCt= HCg+HCd [m3]	Total vented HC [kg]
0	Alfa0	4,16 %	0,00 %	123216,3	0	1006					0	0	0	
1	Alfa1	10,13 %	5,97 %	111416,9	11799,4	1003	59	36	57,46	2,37	3502,94	843,38	4346,31	10318,0
2	Alfa2	8,89 %	-1,24 %	99441,8	23774,5	1003	61	37	58,25	2,40	-653,87	1139,23	485,35	1166,5
3	Alfa3	9,66 %	0,77 %	86505,1	36711,2	1003	57	43	56,53	2,28	356,60	1200,09	1556,69	3548,5
4	Alfa4	8,92 %	-0,74 %	75359,1	47857,2	1003	57	43	57,53	2,32	-301,03	1035,27	734,24	1703,4
5	Alfa5	11,42 %	2,50 %	63369,5	59846,8	1003	60	42	55,98	2,27	866,98	1218,89	2085,87	4736,9
6	Alfa6	11,87 %	0,45 %	50647	72569,3	1003	54	43	56,21	2,26	128,95	1481,19	1610,14	3639,4
7	Alfa7	13,95 %	2,09 %	39894,6	83321,7	1003	59	43	55,99	2,26	472,02	1388,26	1860,27	4207,9
8	Alfa8	13,64 %	-0,32 %	27428,1	95788,2	1003	64	43	56,06	2,28	-53,62	1719,69	1666,07	3791,0
9	Alfa9	10,50 %	-3,14 %	17922,8	105293,5	1003	49	43	56,74	2,27	-355,49	1147,05	791,55	1797,6
10	Alfa10	23,16 %	12,66 %	3078,4	120137,9	1003	49	43	55,71	2,23	664,90	2498,56	3163,46	7052,8
Total/ avg:										**2,29**			**18300,0**	**41962,0**

*) To be taken from Cargo tanks ullage/volume tables, at each sample point

The large $\Delta\alpha$-value for sample 1 has a large effect on all segregations because of the large gas volume in the tanks. Unlike segregation 1, segregation 2 in table 32 have a very large positive contribution from HC_g in sample 1, counting for about 20% of the total hydrocarbon volume for that segregation. Sample 10 have twice the $\Delta\alpha$-value as sample 1, and yet its HC_g is just a fifth of what sample 1's contribution was because of the low volume left in the segregations tanks.

Table 33: Analysis table for AHCO segregation 3

Segregation 3: AHCO

Gas Sample	Alfa	Alfa value from sample analysis Vol%	Delta Alfa dA=Afax-Alfa(x-1) Vol%	Gas volume in tanks TV [m^3] *)	Displaced cargo volume [m^3]	Barometric pressure [mbar]	IG gauge pressure [mbar]	Tank temp [C]	HC molar mass [kg/kmole]	**STP** density of HC gas kg/m3(HC gas)	HC growth in tanks HCg [m^3]	HC emitted due to tanks displacement HCd [m3]	Total vented HC HCt= HCg+HCd [m3]	Total vented HC [kg]
0	Alfa0	7,91 %	0,00 %	100692,5	0	1006					0	0	0	
1	Alfa1	15,15 %	7,24 %	90910,2	9782,3	1003	62	43	56,66	2,30	3467,24	1127,76	4595,00	10548,9
2	Alfa2	13,35 %	-1,79 %	81281,9	19410,6	1003	67	43	56,84	2,31	-771,85	1372,16	600,31	1389,0
3	Alfa3	13,31 %	-0,04 %	72779,3	27913,2	1003	63	43	56,98	2,31	-17,14	1133,61	1116,47	2579,9
4	Alfa4	13,88 %	0,57 %	63817,2	36875,3	1003	52	43	56,33	2,26	196,08	1218,61	1414,70	3198,1
5	Alfa5	13,96 %	0,07 %	54728,6	45963,9	1003	62	43	56,23	2,28	21,34	1265,18	1286,52	2930,9
6	Alfa6	16,17 %	2,22 %	45335,5	55357,0	1003	71	43	56,45	2,31	554,81	1415,11	1969,91	4543,7
7	Alfa7	16,09 %	-0,08 %	36478,8	64213,7	1003	57	43	56,36	2,27	-16,89	1428,85	1411,96	3208,7
8	Alfa8	15,74 %	-0,35 %	27054	73638,5	1003	57	43	55,00	2,22	-56,19	1499,94	1443,74	3202,0
9	Alfa9	17,51 %	1,77 %	18863,6	81828,9	1003	50	43	54,29	2,17	203,36	1361,54	1564,90	3403,2
10	Alfa10	22,52 %	5,01 %	8661,6	92030,9	1003	68	43	53,03	2,16	344,99	2042,04	2387,03	5157,9
Total/ avg:										**2,26**			**17790,5**	**40162,3**

*) To be taken from Cargo tanks ullage/volume tables, at each sample point

The most stable segregation measurement series was also the last one as possibly the other segregation tanks had less effect during loading of this segregation.

Fluctuations in α-values directly impact the HC_g estimations in a great manner and thereby the total HC_t. Because of the problems of measuring correct α-values for the loading tanks discussed in section 9.1, the performance of the model is limited as it is based on a stable and isolated system for each segregation with well mixed gas. As these assumptions are in question by the fact that all three segregations are connected to the same inert gas system, periodic loading sequences with varying loading intensity and the risk of heterogeneous mixture of gasses in the tanks, the performance of the model is challenged.

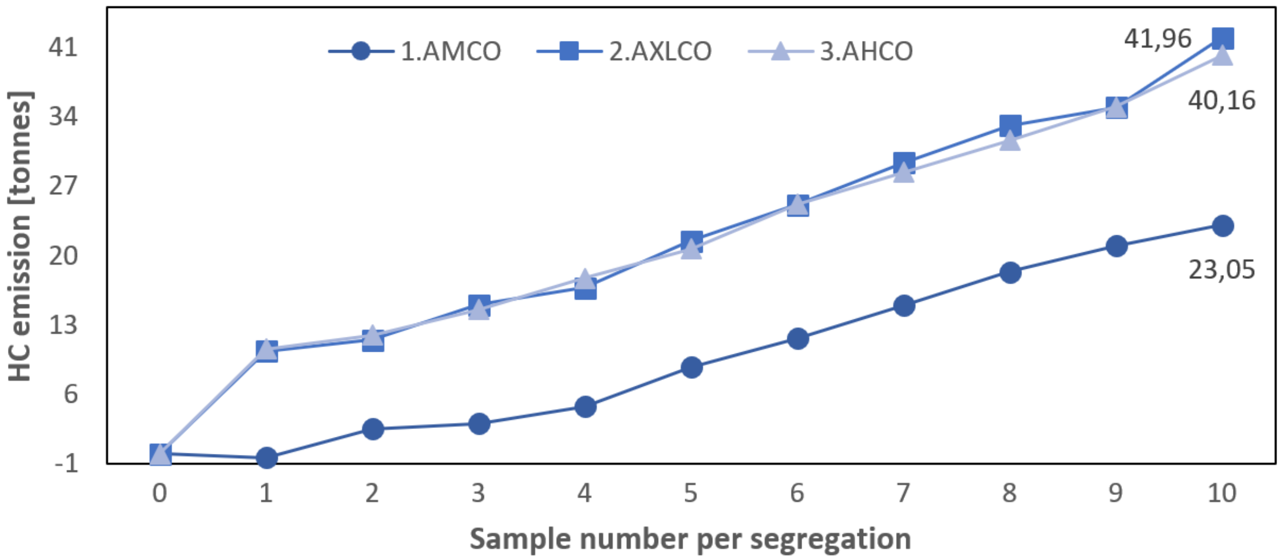


Fig. 22: Figure of estimated hydrocarbon emission mass

Figure 22 illustrates the final estimations of the emissions from Arosa with a total of 105,18 tonnes of hydrocarbons emitted to the atmosphere. This is less than half of the expected result of 260 tonnes which was assumed with north sea crude oil from experiences in the North Sea.

Given that the different segregations have similar volatility of light hydrocarbon gasses and that the segregations were isolated from each other, AHCO would have the lowest amount of hydrocarbon emissions and AMCO and AXLCO would have similar emissions based on tank volumes given in section 8.1. The end results tells a different story because of the development of α-values throughout the loading processes and the influence segregations had on each other. Simulation analysis can help find out to what degree the 100% opening of the vent riser influenced α-value readings.

9.3 Emissions during sailing

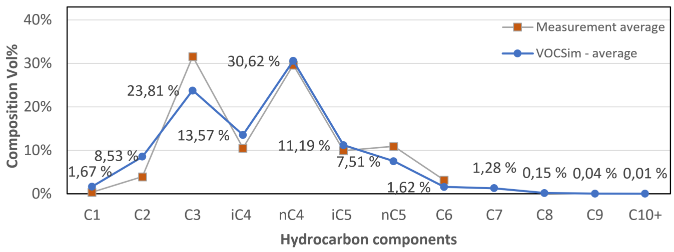
Before the project started it was anticipated that there would be vapour release during voyage. This did not occur. One possible reason is the temperature difference between Ras Tanura and the area south of Asia. During the sailing, the cargo temp decreased in temperature. From loading, with reported cargo temperature around 46°C, to one week after (14.8.19) with temperature of 41°C. Because of this temperature decrease, a vacuum was developing in the tanks, even with moderate ship rolling of up to 10° during sailing outside the southwest coast of India. Negative gauge vacuum of around negative 250 mmH_2O were observed. To increase the pressure in the cargo tanks, an IG-fan with a capacity of 20 600m3/h was turned on for 10-12 minutes. Pressure after filling with IG was 200-250 mmH_2O. After sailing past Sri Lanka there were calm seas and steady pressure build-up on hot, sunny days. These values continued to increase as the ship approached the port in China where Arosa discharged. During the hottest days the pressure varied from 300-500 mmH_2O during the night to around 1600 mmH_2O during the middle of the day. Still no vapour release. If the sailing were to last a week or so longer, vapour release would likely be necessary as the limit for vapour release is around 1700-1900mmH_2O. Maintenance was also done on the tanks P/V valves during loaded sailing. As these were lifted off the tanks, some vapour was released for brief moments before a lid was put back on where the P/V valves are normally placed. This may have had some impact on the need to release vapour through the vent riser during sailing.

9.4 Simulation comparison

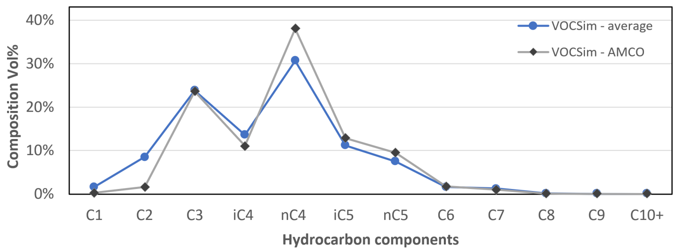
Large quantities of information are produced by VOCSim. This section highlights the most important aspects of the results to give a clear view into the amount of simulated emissions, composition differences of gas produced by different segregations and the average composition of emitted gas.

9.4.1 HC gas composition

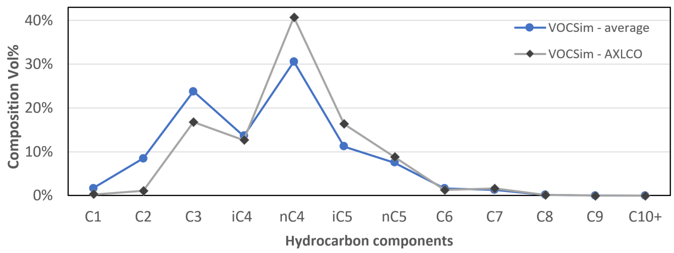
From table 24, 25 and 26 it is estimated that around 27% of simulated emitted gases are hydrocarbons. That is about 3 times higher than the estimated hydrocarbon fraction of total emitted gasses measured on board Arosa, which were 12%. The average hydrocarbon compositions for all three segregations are given in figure 23a compared with the average compositions from measurements on board Arosa. Average measurement compositions are marked with orange indicators to separate it from other indicators which represents simulation results. Figure 23b, 23c and 23d shows how each composition in a segregation deviates from the simulation average.



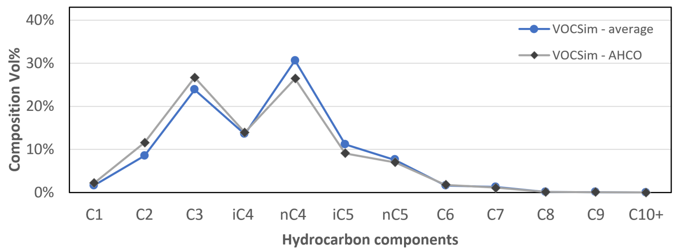
(a) Average HC composition in VOCSim simulation vs average measured on Arosa



(b) Accumulated HC composition fraction of AMCO vs Average in VOCSim



(c) Accumulated HC composition fraction of AXLCO vs Average in VOCSim



(d) Accumulated HC composition fraction of AHCO vs Average in VOCSim

Fig. 23: Accumulated hydrocarbon composition for average and specific segregations in VOCSim

In the simulation, the average hydrocarbon gas is comprised of mostly propane and butane at 68%, similar to the measurements. However, much higher propane levels are seen from the measurements. On the other hand, the simulation composition have much higher concentration of the two lightest hydrocarbons, which amounts to 10,2%. An important detail is that the simulation presents 4 more hydrocarbon components, even if it amounts to a small percentage of 1,48% of total hydrocarbon gas. Compared to the measurements average composition, the composition of the simulated segregations deviates significantly more from its total average. This may originate from the fact that a constant flow of vapour from the respective segregation tank flows out of the vent riser rather than a mix of flows as when the vent riser opens at 100% during measurements. Other factors like how the oil has been stored before loading and that the loaded crude oil composition not necessarily have the same composition as in the simulated, does also play a significant role in the resulting figures. It is observed that AHCO emissions have higher fractions of lighter hydrocarbons and lower fractions of median range compared to the other segregations. Reflecting back to table 22, it can be observed that the segregation with the highest fraction of a certain component also have the highest fraction of the given component in its hydrocarbon emission gas seen in the above figures. Looking at for example n-butane (nC4) in figure 23c, which clearly states that AXLCO emissions have the highest fraction of n-butane of all segregations, the crude oil composition in table 22 states the same fact.

Figure 24 shows the α-value developments from all segregations throughout the simulation. The α-value is given for each time step and gives a more detailed illustration of the development than figure 21 representing the measurements.

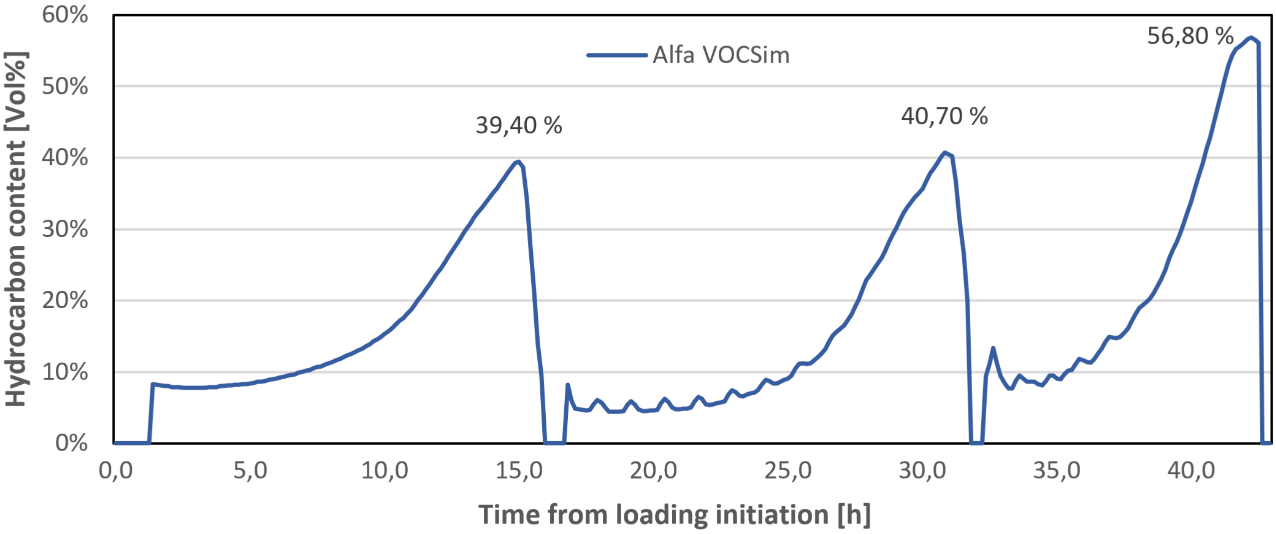


Fig. 24: Figure of α-value throughout simulation

In the simulation, where the vent riser valve is maximum opened to a small percentage of max capacity, the α-value gradually increases in a smooth curve for the first segregation. In the 2^{nd} and 3^{rd} segregation, the α-value fluctuates in the beginning. This indicates that the flow from both finished loaded tanks with high α and unloaded tanks with lower α are intermittently mixing in the emission pipe system as VOCs continue to emit from the cargo of loaded tanks. Individual pipe data also confirms this by showing small fluctuating mass flow in both positive and negative direction from tank 1 during 2^{nd} and 3^{rd} segregation loadings. Increase of α towards the end of loading for all the segregation happens as VOCs develop at the surface of the loading crude oil approaching the ceiling of the tank and inert gas system. This most likely is the reason to the strong increase in α-values at end of loadings. This was not the case for segregation 1 during measurements which further suggest that another factor influenced those readings. Another fascinating discovery is that the α-value increase significantly more during the AHCO segregation compared to the others. An α-value peak of around 40% higher compared to AMCO and AXLCO happens as AHCO have significantly more fractions of the lighter hydrocarbons (C1 to iC4) in its crude oil, which can be seen in table 22 and figure 23d. The lighter hydrocarbons are more volatile and releases more easily from the crude oil due to higher vapour pressure and lower boiling point. AMCO and AHCO also have higher initial α-value due to the fact that initial conditions before loading in those tanks have higher hydrocarbon fraction, similar to what was measured on board Arosa. Even with AXLCO having lower initial α-value, the α-value peaked higher for every segregation, likely due to impact from finished loaded segregations or because segregations were loaded in an order depending on crude oil volatility.

9.4.2 Mass development of VOC emissions

The VOC emission mass development from table 24, 25 and 26, and are illustrated in figure 25. To easily compare with emission estimation from Arosa, figure 22 is recreated with a longer y-axis in figure 26 below.

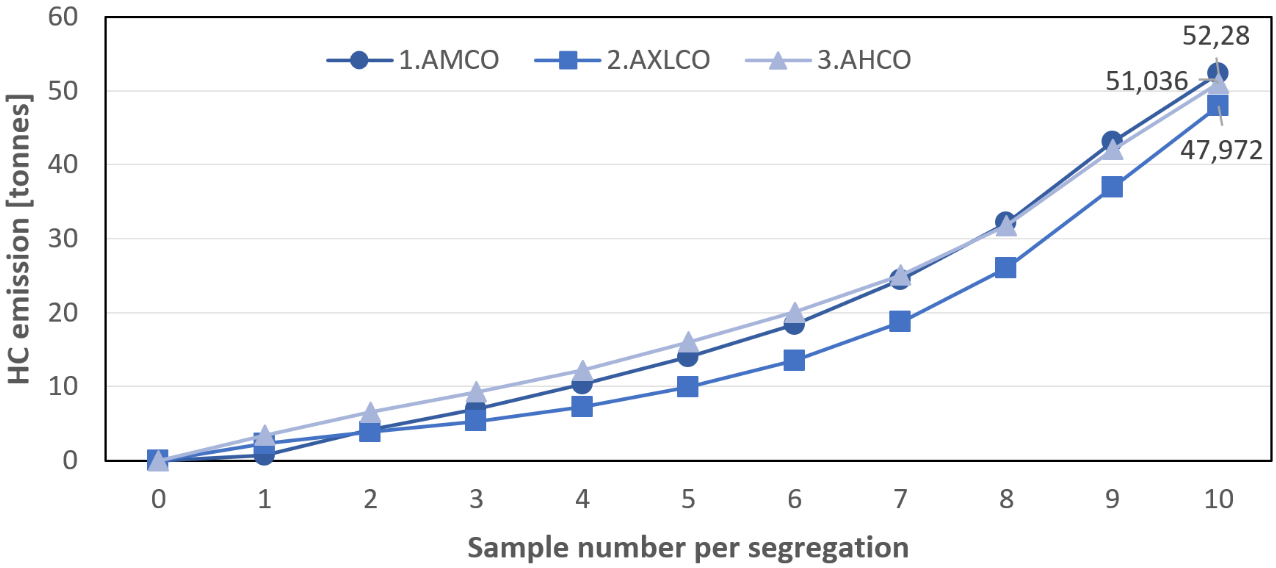


Fig. 25: Figure of simulated hydrocarbon emission mass

Figure 25 shows a smooth increase of VOC emissions during simulation of each segregation. The emissions released during loading of the AMCO segregation have the highest amount of VOCs emitted, followed by AHCO and AXLCO. Even as the AXLCO tank has the largest amount of crude loaded and percentage of tank volume filled, it ends up emitting the lowest amount of VOCs in terms of mass. The opposite is the case during measurements, which can be seen below in figure 26, where emissions during AXLCO loading are estimated to be the largest of all segregation. There are several factors playing in to this difference.

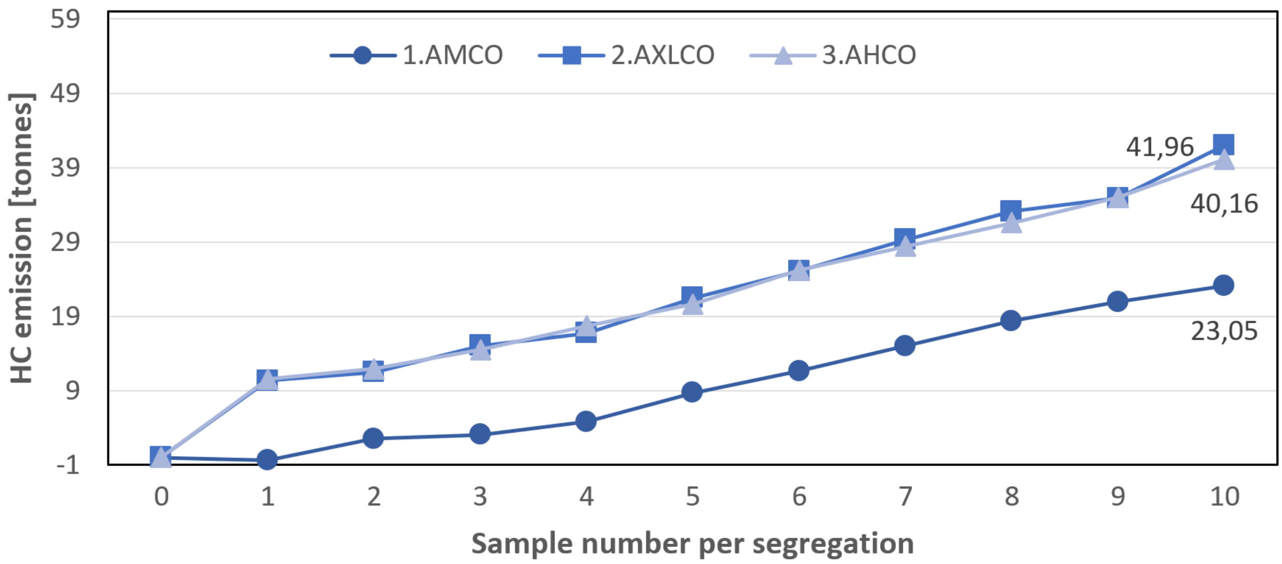


Fig. 26: Figure of estimated hydrocarbon emission mass from measurements on board Arosa

As a result of higher and more stable α-values during the simulation, the stated emissions are seen as higher than from the measurement model. The reason that AXLCO segregation have the lowest amount of VOCs emitted has its roots in that it has the lowest average α-value throughout the simulated loading of AXLCO due to set initial conditions earlier discussed. In regards to the measurement results, AXLCO is the segregation to have the highest amount of VOCs emitted due to a higher measured average of α-value, where it comes in second behind AHCO, and has the largest tank group volume and amount of crude loaded. With high tank volume, amount of cargo loaded and second highest average of α-value, the highest simulated VOC emissions happens during the AMCO segregation. If AHCO had similar tank volumes and amount of crude loaded as the other segregations, it would dominate in terms of emitting hydrocarbon emissions in the simulation.

9.4.3 VOCSim wide open valve test analysis

Deviations between α-values in simulation results and from measurements done on Arosa causes concern and is thought to be a consequence of the need to open the vent riser valve to 100% in short periods of time to properly take samples. As a way to prove this hypothesis, an open valve test is done and is described in section 8.5.2. Information are gathered from table 28, 29 and 30, and shown in figure 27, 28 and 29.

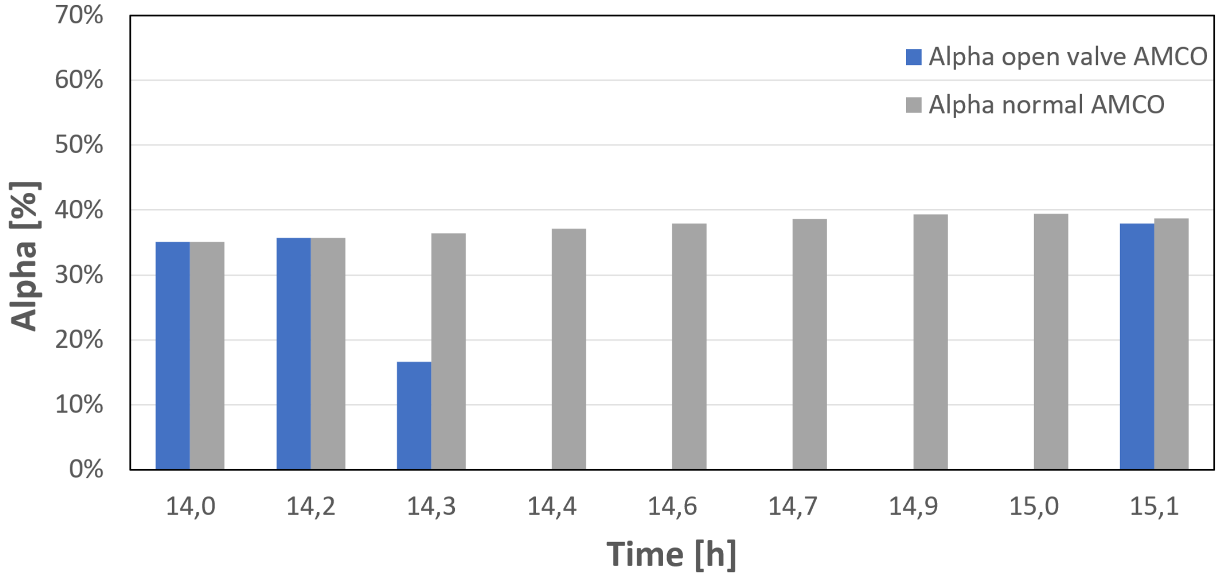


Fig. 27: Figure of alpha values during open valve simulation test for AMCO segregation

Figure 27 shows the α-value results after the Kv value is sett to 30 instead of 130 in the interval between 14,2h and 14,3h for AMCO segregation. Time steps where α percentage is 0 means that there is no flow exitting the valve due to the fact that the valve closes when tank pressure is below 104,5 kPa and reopens when pressure have passed over 107,5 kPa. As a result, a massive increase in gas volume flow rate, which is about 3,5 times higher than normal, and a significant drop in α, hydrocarbon molecular weight and pressure are seen compared to the initial simulation run. The α-value is reduced by almost 55% in the test interval compared to the same interval in the initial simulation run for AMCO, and is close to 7% points higher than the α-value in sample 9 related to Arosa measurements. It is important to remember that the cargo loading rate is continuously the same during loading of each segregation except at start up period and ending period of segregation loading and does not impact the change in gas flow rate.

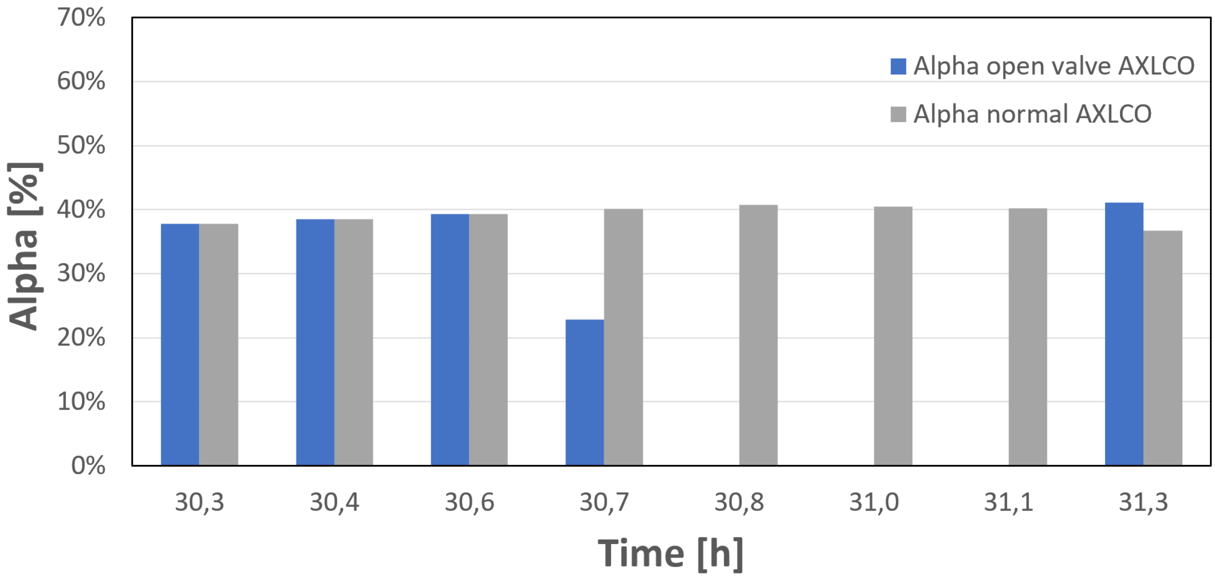


Fig. 28: Figure of alpha values during open valve simulation test for AXLCO segregation

A new simulation test is conducted for a time step interval during loading of the second segregation, AXLCO, and the α-value impact are shown in figure 28. Kv value is reduced in the interval between 30,6h and 30,7h. The results are the same as for AMCO segregation, but to a smaller degree. The gas flow rate increases with just under 3 times the normal and the α-value drops by 43%. Still, the α-value is twice as high as what was measured in sample 9 related to Arosa measurements.

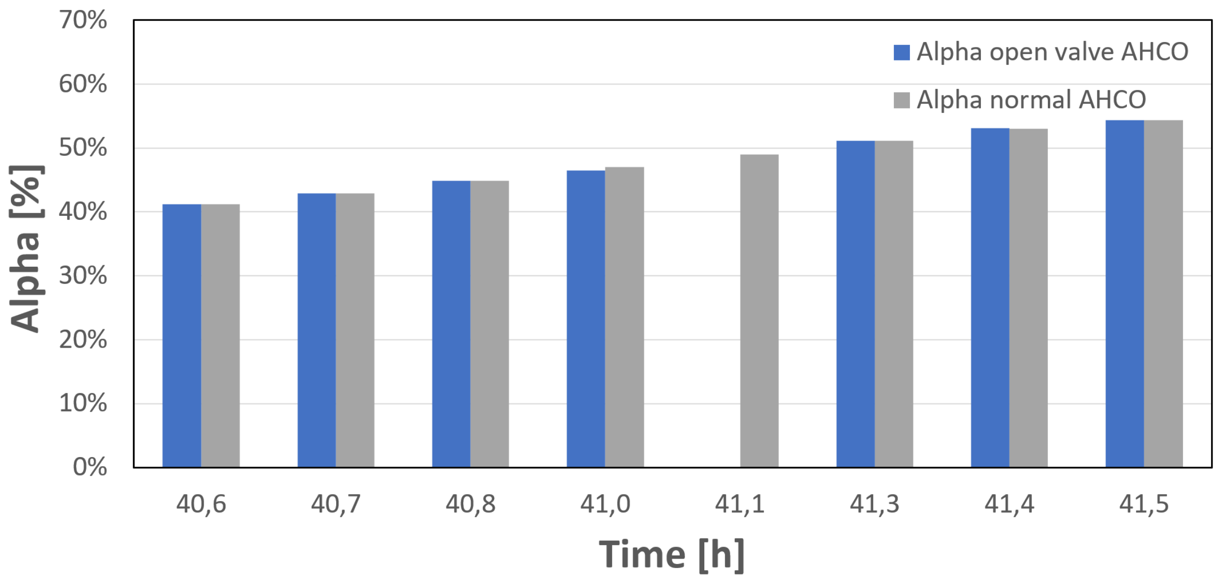


Fig. 29: Figure of alpha values during open valve simulation test for AHCO segregation

The final simulation test is conducted for the time step interval between 40,8h and 41h during loading of the third segregation, AHCO, and the α-value impact are shown in figure 29. As expected from the hypothesis, almost no decrease in α-value can be seen even as the gas flow rate ended up 70% higher than normal during the interval. The reason for this is that when the valve opens significantly during this last segregation, vapour flows only from filled or filling tanks with elevated α-values. The molecular weight did not change during the test of AHCO segregation but it significantly dropped for the first two segregation while the hydrocarbon molecular weight stayed at the same level, indicating a large amount of gas flow from the unfilled tanks which have higher fraction of lighter inert gasses.

The wide open valve test showed promising signs as to why α-values in simulation deviates from the measurement results. When the first segregation tank group for example is half full, the two other tank groups have more amounts of gas within them and thereby have more gas flow capacity if pressure should drop. In the event where the vent riser valve is opened to 100%, this pressure drop would be a fact and the gas from the unloaded groups would represent the highest fraction of the gasses exiting the vent riser due to the higher gas flow capacity. Given that the last segregation is half full after the previous segregations are finished loading, the situation would be the opposite. Now the half full tank group of the last segregation has the largest gas flow capacity and would represent the highest fraction of the gasses exiting the vent riser during a pressure drop lead by 100% opening the valve. This means that during sampling on board Arosa, the gas with the lowest hydrocarbon fraction of all the cargo groups always took a large part in the gas samples taken.

10 Sources of error

Challenges did arise during the measurement program and several sources of error emerged. A recap of sources of error is helpful to come to a conclusion.

10.1 Sampling from vent riser

When starting to take samples from vent riser after the vent valve, it was noticed that there was no flow coming out from the sampling pipe. The problem turned out to be vacuum in the sampling pipe when trying to take samples. A reason for this may have been because of the partially opened valve of the vent riser, turbulence was produced and the pressure at steel pipe inlet was lower than in the inert gas system. A chimney effect may also be responsible for the creation of vacuum. Vent riser was set on 10-20% to keep a balanced pressure in the tanks. A solution was to increase vent riser valve opening. When vent riser valve was increased to 100%, there was a flow of vapour coming out of the sampling pipe, and it was now possible to take samples. This led to pressure decreasing in all tanks, filled and not filled with crude, and thereby mixing the gas flow. An effort was made to take samples as soon as the valve opened to minimise the mixing effect.

10.2 Influence of other segragations

When vent riser valve was operated between 10-20%, the pressure in the tanks varied between 500-700mmH2O. Based on this, as loadings proceeded more hydrocarbons flowed into passive tanks, and when these tanks started to load, the hydrocarbon concentration in the tanks gas was higher than for the previous segregations. This supports the hypothesis of mixing VOCs from loading tanks with the inert gas in empty tanks when pressure increases. Such a source of error disrupts the symmetry of the different segregations results and effects the final result.

10.3 Uneven filling of tanks

Some tanks were prioritised to load up more quickly to affect the trim of the vessel such that the ballast water pumps were less stressed. This meant that valves of slowly filling tanks were half way open. This could cause more turbulent flow which again could lead to more VOC development.

10.4 Gas chromatograph inaccuracy

The gas chromatograph did not continuously produce ideal results. A parameter which decides this is how many moles of gas the machine detects in total compared to 100%. Ideal results are 99-101. When results deviated from 100, it could be normalized to 100. These are the results that were used. Contamination with air during sampling have also been a risk but have received a lot of attention to be minimised. Lack of proper calibration was also a factor that have played in, but can be sorted in hindsight if needed. Certain peaks in the chromatograms of the tests showed that there were some unknown gasses which was not calibrated for, but in small amounts. There is also reason to believe that the oxygen content in the samples was too high. The reason of this suspicion is because the equipment on board, which is designed for measuring oxygen to HC content, measured a lower oxygen-content than the GC. Calibration of oxygen were done with ambient air, which is not ideal, and this may have had an impact on the oxygen results and thereby the fraction of other gasses.

10.5 Sources of error in VOCSim

VOCSim is made up of several variables and parameters which all play a role in the final result. Additional diffusion coefficients is one of them and play a huge role in the mixing of fluids and thereby the evaporation of VOCs. Depending on the sea state, different sets of diffusion coefficients are used to match simulation results with real life measurements. Deciding these coefficients demand experience to choose which diffusion sets to use. A set of lower diffusion coefficients designed for calm sea state was used in the simulation late in the writing process, which resulted in significant decrease of VOC emissions compared to the original simulation. The result was around two thirds of what the estimated emissions from Arosa and was considered very low. It is not further evaluated.

The composition of crude oil used in the simulation is not identical to the cargo loaded on board Arosa as no testing of such detail took place. API of the crude oil segregations was measured, among other parameters, and is used to find matching crude oil data. The fact that segregations loaded on Arosa and segregations simulated in VOCSim are not identical also counts as a source of error. In the simulation, since 3 segregations are loaded, it is necessary to mix the fluid composition parameter values by weighted volume fractions of the segregations as this is a general input for the whole simulation. This means that the parameters do not exactly match either of the segregations, but acts as an average. Critical temperature of the lighter hydrocarbons are reduced in the simulation compared to information listed in "Aspen Hysis" oil database due to reasons discussed in section 7.5.3. These uncertainties also challenges the confidence in the results. Lack of detailed temperature development data is one of the issues experienced during measurements on Arosa and the temperatures used in this project are therefor also questionable for both the measurement modeling and simulation.

11 Conclusion and future work

In the presented work, experimental investigations were performed on vapour gasses emitted from vent riser on board a very large crude carrier (VLCC) during loading of three segregations, voyage and discharging. The ship loaded in Ras Tanura, outside Saudi Arabia, and dicharged at Quanzhou in China. Estimation of emissions was done by the development and use of a model with gas sample measurements and tank data as inputs. It was found that emitted vapour contained volatile organic compounds and other inert gasses. These volatile organic compounds included mostly propane and butane, but also methane, ethane, pentane, hexane and small amounts of heavier components. It was found that the average hydrocarbon content of the vapour gas was just over 12% hydrocarbons. Higher hydrocarbon concentration in the vapour gas was observed over time as loading proceeded. As three segregations were loaded separately, these interfered with each other as all tanks were connected to the same inert gas system. Doubts regarding sample measurements accuracy before loading initiation are discussed together with its affect on final results. It was found that the estimated VOC emissions during loading of all segregations were 23,05, 41,96 and 40,16 tonnes for segregation AMCO, AXLCO and AHCO respectively in given loading order, which equals an estimated 105,17 tonnes of hydrocarbons emitted during loading.

A simulation program called VOCSim was used to validate the estimated emissions and to test the effect of opening vent riser valve to 100% during loading. Given similar input data as the measurements done on board the VLCC, VOCSim stated an emission of 52,28, 47,97 and 51,04 tonnes of VOC from segregation AMCO, AXLCO and AHCO respectively, totaling 151,29 tonnes. It was found that when opening the vent riser valve to 100%, the α-value at vent riser reduced by around 50% during the first two segregation loadings. This revealed that the sample method done on board the VLCC was insufficient to estimate accurate emission levels as it was needed to have the valve 100% open to take samples. On board the VLCC, it was also observed that no vapour release happened during voyage or discharging due to temperature decrease in tanks. It is therefore concluded that expected VOC emissions from given loaded segregations are higher than what was estimated from the measurements done in this project and most likely would be around the values stated from the simulation. Moderate margin of error is expected for future loadings as ship movement, temperature, crude composition and other factors will change compared to the loading procedure measured and simulated in this thesis. The results of this study are used as part of Wärtsilä Gas Solutions' and NEDA Maritime's vision to explore if liquefying the VOC emissions from a VLCC to fuel is viable in the middle east region.

For future measurement projects it is recommended to look closely into sources of error. A new way of measuring common vapour gas from vent riser should be implemented, possibly to move sampling point ahead of vent riser valve to have stable pressure difference between sample pipe inlet and outlet. If a similar model as in this paper is to be used, the most promising loading scenario would be to load one segregation at close to constant tank pressure. Better results would be possible if more focus is on keeping the pressure in tanks close to constant, as this may limit the interference between segregations. A new estimation model which takes into account the heterogeneous mixture of gas is also recommended to develop.

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A Appendix

A.1 Sample sheet during voyage - Vent riser

Sample ident	Sampling Time [Date: time] UTC:___________	IG Pressure **at vent start** [mbar]/WC	IG Pressure **at vent stop** [mbar]/WC	Barometric pressure [mbar]	Upper tank temp [C] Sailing condition →

A.2 Artificial diffusion coefficients for the gas phase

Table 34: Artificial diffusion coefficients for the gas phase as a function of density gradient in tank 2

Tank 2								
Time [s]	**Constant artificial diffucivity** [m^2/s]	**Density gradient 1** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Density gradient 2** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Density gradient 3** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Tank filling state** [%]
0	$1 \cdot 10^{-4}$	-0,2	0	-0,02	0	0	0	0 %
59000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	0	0	0	3 %
61000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	6 %
114000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	96,1 %
250000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	96,1 %

Table 35: Artificial diffusion coefficients for the gas phase as a function of density gradient in tank 3

Tank 3								
Time [s]	**Constant artificial diffucivity** [m^2/s]	**Density gradient 1** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Density gradient 2** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Density gradient 3** [$\frac{kg/m^3}{m}$]	**Added artificial diffusivity** [m^2/s]	**Tank filling state** [%]
0	$1 \cdot 10^{-4}$	-0,2	0	-0,02	0	0	0	0 %
116500	$1 \cdot 10^{-4}$	-0,2	0	-0,02	0	0	0	3 %
117500	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	6 %
153500	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	96,1 %
250000	$1 \cdot 10^{-4}$	-0,2	0	-0,02	$1 \cdot 10^{-3}$	0	$1 \cdot 10^{-3}$	96,1 %

A.3 VOCSim main data output

Time	Time	Pressure	Temp	Flow	Flow	Accum	Emitted mass of			Released from cargo		Alfa	MWHC	MW
						Flow	VOC	IG	C1	Total	VOC			
[s]	[h]	[Pa]	[K]	[Nm^3/s]	[Nm^3/h]	[Nm^3]	kg	kg	kg	kg	kg		[g/mol]	[g/mol]
0.	0,0	-	0.0	0.0000	0.	0.	0.	0.	0.	0.	0.	0.000	0.00	0.00
500.	0,1	104625.	0.0	0.0000	0.	0.	0.	0.	0.	170.	188.	0.000	0.00	0.00
1000.	0,3	104827.	0.0	0.0000	0.	0.	0.	0.	0.	580.	638.	0.000	0.00	0.00
1500.	0,4	105196.	0.0	0.0000	0.	0.	0.	0.	0.	1010.	1109.	0.000	0.00	0.00
2000.	0,6	105629.	0.0	0.0000	0.	0.	0.	0.	0.	1354.	1489.	0.000	0.00	0.00
2500.	0,7	106045.	0.0	0.0000	0.	0.	0.	0.	0.	1637.	1807.	0.000	0.00	0.00
3000.	0,8	106449.	0.0	0.0000	0.	0.	0.	0.	0.	1878.	2083.	0.000	0.00	0.00
3500.	1,0	106846.	0.0	0.0000	0.	0.	0.	0.	0.	2089.	2329.	0.000	0.00	0.00
4000.	1,1	107238.	0.0	0.0000	0.	0.	0.	0.	0.	2277.	2554.	0.000	0.00	0.00
4500.	1,3	107627.	0.0	0.0000	0.	0.	0.	0.	0.	2449.	2762.	0.000	0.00	0.00
5000.	1,4	107378.	308.5	3.3641	12111.	1682.	355.	2040.	1.	2612.	2961.	0.083	57.99	32.34
5500.	1,5	107202.	308.5	3.2846	11824.	3324.	698.	4034.	1.	2770.	3154.	0.082	57.89	32.31
6000.	1,7	107038.	308.6	3.2097	11555.	4929.	1028.	5984.	2.	2923.	3339.	0.081	57.80	32.27
6500.	1,8	106884.	308.6	3.1387	11299.	6499.	1348.	7892.	3.	3068.	3518.	0.080	57.72	32.25
7000.	1,9	106740.	308.7	3.0722	11060.	8035.	1659.	9761.	3.	3210.	3691.	0.080	57.65	32.23
7500.	2,1	106604.	308.7	3.0088	10832.	9539.	1961.	11593.	4.	3348.	3860.	0.079	57.58	32.21
8000.	2,2	106478.	308.7	2.9503	10621.	11014.	2256.	13389.	4.	3483.	4024.	0.079	57.52	32.19
8500.	2,4	106360.	308.8	2.8949	10422.	12462.	2544.	15152.	5.	3615.	4185.	0.079	57.47	32.18
9000.	2,5	106249.	308.8	2.8439	10238.	13884.	2826.	16885.	6.	3744.	4342.	0.078	57.42	32.17
9500.	2,6	106147.	308.9	2.7947	10061.	15281.	3102.	18587.	6.	3872.	4497.	0.078	57.37	32.16
10000.	2,8	106051.	308.9	2.7490	9896.	16655.	3374.	20262.	7.	3996.	4648.	0.078	57.33	32.16
10500.	2,9	105961.	308.9	2.7063	9743.	18009.	3641.	21911.	7.	4119.	4797.	0.078	57.29	32.15
11000.	3,1	105878.	309.0	2.6661	9598.	19342.	3903.	23535.	8.	4240.	4943.	0.078	57.26	32.15
11500.	3,2	105800.	309.0	2.6295	9466.	20656.	4163.	25137.	8.	4359.	5087.	0.078	57.23	32.15
12000.	3,3	105728.	309.1	2.5947	9341.	21954.	4419.	26718.	9.	4476.	5229.	0.078	57.20	32.15
12500.	3,5	105660.	309.1	2.5619	9223.	23235.	4673.	28278.	9.	4598.	5375.	0.079	57.18	32.16
13000.	3,6	105599.	309.2	2.5327	9118.	24501.	4924.	29820.	10.	4746.	5547.	0.079	57.16	32.16
13500.	3,8	105548.	309.2	2.5074	9027.	25755.	5174.	31346.	10.	4942.	5769.	0.079	57.14	32.17
14000.	3,9	105513.	309.3	2.4905	8966.	27000.	5424.	32861.	11.	5192.	6046.	0.080	57.11	32.18
14500.	4,0	105493.	309.3	2.4796	8926.	28240.	5673.	34368.	11.	5492.	6373.	0.080	57.08	32.19
15000.	4,2	105486.	309.4	2.4766	8916.	29478.	5924.	35873.	12.	5829.	6737.	0.081	57.06	32.20
15500.	4,3	105490.	309.5	2.4761	8914.	30716.	6177.	37376.	12.	6191.	7125.	0.081	57.05	32.21
16000.	4,4	105499.	309.5	2.4799	8928.	31956.	6431.	38881.	13.	6572.	7533.	0.082	57.05	32.22
16500.	4,6	105513.	309.5	2.4859	8949.	33199.	6688.	40389.	13.	6966.	7954.	0.082	57.04	32.24
17000.	4,7	105529.	309.6	2.4925	8973.	34445.	6947.	41900.	14.	7369.	8383.	0.083	57.04	32.25
17500.	4,9	105547.	309.6	2.5008	9003.	35696.	7209.	43415.	14.	7779.	8817.	0.083	57.05	32.27
18000.	5,0	105566.	309.7	2.5069	9025.	36949.	7473.	44932.	15.	8190.	9253.	0.084	57.05	32.28
18500.	5,1	105584.	309.7	2.5146	9052.	38206.	7741.	46453.	15.	8601.	9688.	0.085	57.06	32.30
19000.	5,3	105602.	309.8	2.5212	9076.	39467.	8012.	47976.	16.	9009.	10120.	0.086	57.07	32.33
19500.	5,4	105619.	309.8	2.5282	9102.	40731.	8287.	49502.	16.	9414.	10548.	0.086	57.08	32.35
20000.	5,6	105634.	309.8	2.5324	9117.	41997.	8565.	51029.	17.	9815.	10971.	0.087	57.09	32.38
20500.	5,7	105648.	309.9	2.5374	9135.	43266.	8848.	52557.	17.	10211.	11389.	0.089	57.11	32.41
21000.	5,8	105660.	309.9	2.5407	9147.	44536.	9134.	54085.	18.	10601.	11802.	0.090	57.12	32.44
21500.	6,0	105671.	310.0	2.5425	9153.	45808.	9424.	55612.	18.	10987.	12208.	0.091	57.14	32.47
22000.	6,1	105681.	310.0	2.5450	9162.	47080.	9719.	57138.	19.	11366.	12608.	0.092	57.16	32.50
22500.	6,3	105689.	310.1	2.5466	9168.	48353.	10018.	58663.	19.	11739.	13001.	0.093	57.18	32.54
23000.	6,4	105696.	310.1	2.5463	9167.	49627.	10322.	60186.	20.	12107.	13388.	0.095	57.20	32.57
23500.	6,5	105702.	310.1	2.5461	9166.	50900.	10630.	61706.	21.	12468.	13768.	0.096	57.23	32.61
24000.	6,7	105706.	310.2	2.5454	9163.	52172.	10942.	63223.	21.	12823.	14142.	0.097	57.25	32.65
24500.	6,8	105710.	310.2	2.5442	9159.	53444.	11259.	64737.	22.	13172.	14509.	0.099	57.27	32.69
25000.	6,9	105713.	310.3	2.5418	9151.	54715.	11581.	66247.	22.	13516.	14870.	0.100	57.30	32.73
25500.	7,1	105715.	310.3	2.5399	9144.	55985.	11907.	67754.	23.	13853.	15225.	0.102	57.32	32.77
26000.	7,2	105716.	310.4	2.5371	9133.	57254.	12238.	69256.	23.	14185.	15574.	0.103	57.35	32.82
26500.	7,4	105717.	310.4	2.5338	9122.	58521.	12575.	70753.	24.	14511.	15917.	0.105	57.38	32.86
27000.	7,5	105717.	310.5	2.5307	9111.	59786.	12916.	72245.	24.	14831.	16254.	0.107	57.40	32.91
27500.	7,6	105717.	310.5	2.5272	9098.	61050.	13263.	73732.	25.	15146.	16585.	0.108	57.43	32.96
28000.	7,8	105716.	310.5	2.5219	9079.	62311.	13614.	75214.	25.	15456.	16911.	0.110	57.46	33.01
28500.	7,9	105715.	310.6	2.5173	9062.	63569.	13972.	76689.	26.	15761.	17232.	0.112	57.49	33.07
29000.	8,1	105714.	310.6	2.5124	9045.	64826.	14335.	78158.	26.	16061.	17547.	0.114	57.52	33.12
29500.	8,2	105713.	310.7	2.5080	9029.	66080.	14704.	79621.	27.	16355.	17856.	0.116	57.55	33.18
30000.	8,3	105711.	310.7	2.5018	9006.	67330.	15080.	81076.	27.	16645.	18161.	0.118	57.58	33.24

30500.	8,5	105710.	310.8	2.4968	8988.	68579.	15461.	82525.	27.	16931.	18462.	0.121	57.61	33.30
31000.	8,6	105708.	310.8	2.4916	8970.	69825.	15850.	83967.	28.	17212.	18757.	0.123	57.64	33.37
31500.	8,8	105707.	310.8	2.4860	8949.	71068.	16245.	85402.	28.	17489.	19048.	0.125	57.67	33.44
32000.	8,9	105706.	310.9	2.4798	8927.	72308.	16648.	86829.	29.	17761.	19335.	0.128	57.70	33.51
32500.	9,0	105705.	310.9	2.4739	8906.	73544.	17058.	88248.	29.	18030.	19617.	0.130	57.73	33.59
33000.	9,2	105704.	311.0	2.4672	8882.	74778.	17476.	89659.	30.	18294.	19895.	0.133	57.77	33.67
33500.	9,3	105703.	311.0	2.4616	8862.	76009.	17902.	91061.	30.	18555.	20169.	0.136	57.80	33.75
34000.	9,4	105703.	311.1	2.4542	8835.	77236.	18338.	92454.	31.	18812.	20439.	0.139	57.84	33.84
34500.	9,6	105703.	311.1	2.4474	8811.	78460.	18782.	93838.	31.	19065.	20705.	0.143	57.87	33.93
35000.	9,7	105703.	311.1	2.4413	8789.	79680.	19237.	95213.	32.	19315.	20967.	0.146	57.90	34.03
35500.	9,9	105704.	311.2	2.4339	8762.	80897.	19701.	96578.	32.	19561.	21226.	0.149	57.94	34.13
36000.	10,0	105705.	311.2	2.4275	8739.	82111.	20175.	97933.	33.	19804.	21481.	0.153	57.97	34.24
36500.	10,1	105706.	311.3	2.4193	8710.	83321.	20660.	99277.	33.	20043.	21732.	0.157	58.01	34.35
37000.	10,3	105708.	311.3	2.4124	8685.	84527.	21157.	100611.	34.	20279.	21980.	0.161	58.05	34.46
37500.	10,4	105710.	311.4	2.4043	8655.	85729.	21666.	101933.	34.	20512.	22225.	0.166	58.08	34.59
38000.	10,6	105713.	311.4	2.3957	8625.	86927.	22189.	103242.	34.	20741.	22466.	0.171	58.12	34.74
38500.	10,7	105716.	311.5	2.3865	8592.	88120.	22727.	104538.	35.	20967.	22703.	0.176	58.16	34.89
39000.	10,8	105719.	311.5	2.3768	8556.	89309.	23279.	105819.	35.	21190.	22937.	0.182	58.21	35.05
39500.	11,0	105723.	311.5	2.3672	8522.	90492.	23848.	107086.	36.	21410.	23168.	0.187	58.25	35.22
40000.	11,1	105727.	311.6	2.3564	8483.	91670.	24433.	108337.	36.	21627.	23396.	0.194	58.29	35.40
40500.	11,3	105731.	311.6	2.3454	8443.	92843.	25037.	109572.	36.	21840.	23620.	0.201	58.33	35.60
41000.	11,4	105736.	311.7	2.3342	8403.	94010.	25659.	110789.	37.	22051.	23841.	0.207	58.37	35.79
41500.	11,5	105741.	311.7	2.3231	8363.	95172.	26300.	111990.	37.	22258.	24059.	0.215	58.41	36.01
42000.	11,7	105746.	311.8	2.3120	8323.	96328.	26960.	113173.	38.	22462.	24273.	0.222	58.45	36.22
42500.	11,8	105752.	311.8	2.3000	8280.	97478.	27640.	114339.	38.	22663.	24484.	0.230	58.49	36.44
43000.	11,9	105758.	311.8	2.2877	8236.	98622.	28340.	115486.	38.	22860.	24692.	0.237	58.53	36.67
43500.	12,1	105764.	311.9	2.2766	8196.	99760.	29059.	116616.	39.	23055.	24896.	0.245	58.56	36.89
44000.	12,2	105770.	311.9	2.2656	8156.	100893.	29799.	117728.	39.	23246.	25097.	0.253	58.60	37.12
44500.	12,4	105776.	312.0	2.2535	8113.	102020.	30558.	118822.	40.	23434.	25295.	0.261	58.63	37.36
45000.	12,5	105782.	312.0	2.2418	8070.	103140.	31337.	119898.	40.	23619.	25489.	0.269	58.67	37.59
45500.	12,6	105789.	312.1	2.2308	8031.	104256.	32136.	120957.	40.	23800.	25679.	0.277	58.70	37.82
46000.	12,8	105795.	312.1	2.2191	7989.	105365.	32953.	121998.	41.	23977.	25865.	0.285	58.73	38.05
46500.	12,9	105801.	312.2	2.2094	7954.	106470.	33790.	123024.	41.	24151.	26048.	0.293	58.76	38.28
47000.	13,1	105807.	312.2	2.1981	7913.	107569.	34645.	124032.	41.	24320.	26227.	0.301	58.79	38.51
47500.	13,2	105813.	312.3	2.1882	7877.	108663.	35518.	125025.	42.	24486.	26401.	0.308	58.82	38.73
48000.	13,3	105819.	312.3	2.1778	7840.	109752.	36409.	126002.	42.	24647.	26571.	0.316	58.84	38.95
48500.	13,5	105825.	312.4	2.1677	7804.	110836.	37316.	126964.	42.	24803.	26735.	0.323	58.87	39.17
49000.	13,6	105829.	312.4	2.1589	7772.	111915.	38241.	127912.	42.	24954.	26895.	0.330	58.89	39.38
49500.	13,8	105834.	312.4	2.1485	7734.	112990.	39180.	128844.	43.	25099.	27048.	0.337	58.92	39.59
50000.	13,9	105837.	312.5	2.1389	7700.	114059.	40136.	129763.	43.	25238.	27195.	0.344	58.94	39.79
50500.	14,0	105840.	312.6	2.1303	7669.	115124.	41106.	130668.	43.	25373.	27338.	0.351	58.95	39.99
51000.	14,2	105843.	312.6	2.1206	7634.	116184.	42090.	131560.	44.	25508.	27482.	0.357	58.97	40.18
51500.	14,3	105848.	312.6	2.1127	7606.	117241.	43088.	132439.	44.	25665.	27647.	0.364	58.98	40.37
52000.	14,4	105860.	312.7	2.1067	7584.	118294.	44103.	133306.	44.	25857.	27847.	0.371	58.98	40.57
52500.	14,6	105884.	312.8	2.1045	7576.	119346.	45138.	134161.	45.	26055.	28053.	0.379	58.98	40.79
53000.	14,7	105910.	312.8	2.1029	7570.	120398.	46194.	135004.	45.	26214.	28219.	0.386	58.99	41.01
53500.	14,9	105922.	312.8	2.0988	7556.	121447.	47264.	135837.	45.	26312.	28323.	0.393	58.99	41.19
54000.	15,0	105915.	312.9	2.0950	7542.	122495.	48334.	136667.	45.	26358.	28375.	0.394	58.97	41.21
54500.	15,1	105892.	312.8	2.0966	7548.	123543.	49388.	137507.	46.	26377.	28400.	0.387	58.92	41.01
55000.	15,3	105789.	312.5	2.1221	7640.	124604.	50335.	138418.	46.	26431.	28459.	0.344	58.84	39.76
55500.	15,4	105561.	311.8	2.1388	7700.	125673.	51099.	139434.	46.	26528.	28559.	0.276	58.74	37.81
56000.	15,6	105232.	311.1	2.1058	7581.	126726.	51679.	140524.	46.	26628.	28662.	0.213	58.63	36.02
56500.	15,7	104798.	310.2	2.0384	7338.	127746.	52046.	141679.	47.	26717.	28751.	0.140	58.35	33.92
57000.	15,8	104395.	309.6	1.9284	6942.	128710.	52280.	142830.	47.	26951.	29004.	0.095	57.93	32.63
57500.	16,0	104705.	0.0	0.0000	0.	128710.	52280.	142830.	47.	27372.	29466.	0.000	0.00	0.00
58000.	16,1	105154.	0.0	0.0000	0.	128710.	52280.	142830.	47.	27764.	29906.	0.000	0.00	0.00
58500.	16,3	105723.	0.0	0.0000	0.	128710.	52280.	142830.	47.	28084.	30274.	0.000	0.00	0.00
59000.	16,4	106338.	0.0	0.0000	0.	128710.	52280.	142830.	47.	28404.	30643.	0.000	0.00	0.00
59500.	16,5	106961.	0.0	0.0000	0.	128710.	52280.	142830.	47.	28907.	31195.	0.000	0.00	0.00
60000.	16,7	107659.	0.0	0.0000	0.	128710.	52280.	142830.	47.	29410.	31746.	0.000	0.00	0.00
60500.	16,8	107399.	310.3	3.3912	12208.	130405.	52630.	144883.	47.	29701.	32080.	0.082	57.37	32.18
61000.	16,9	107168.	310.0	3.3457	12045.	132078.	52882.	146956.	48.	29895.	32315.	0.060	56.60	31.56
61500.	17,1	106934.	309.9	3.2652	11755.	133711.	53079.	149004.	48.	30032.	32492.	0.049	55.96	31.23
62000.	17,2	106706.	310.0	3.1573	11366.	135289.	53264.	150987.	49.	30151.	32652.	0.048	55.84	31.19

62500.	17,4	106497.	310.0	3.0565	11003.	136818.	53440.	152909.	49.	30277.	32821.	0.047	55.77	31.17
63000.	17,5	106313.	310.1	2.9678	10684.	138302.	53608.	154776.	50.	30443.	33028.	0.046	55.69	31.15
63500.	17,6	106161.	310.2	2.8906	10406.	139747.	53775.	156593.	50.	30670.	33294.	0.047	55.71	31.17
64000.	17,8	106047.	310.3	2.8126	10126.	141153.	53967.	158345.	50.	30932.	33592.	0.055	56.18	31.40
64500.	17,9	105955.	310.5	2.7551	9918.	142531.	54174.	160052.	51.	31159.	33854.	0.061	56.44	31.56
65000.	18,1	105860.	310.5	2.7182	9785.	143890.	54365.	161743.	51.	31333.	34061.	0.057	56.24	31.44
65500.	18,2	105757.	310.4	2.6845	9664.	145232.	54530.	163425.	51.	31467.	34227.	0.050	55.81	31.25
66000.	18,3	105651.	310.4	2.6460	9525.	146555.	54673.	165093.	52.	31565.	34356.	0.044	55.40	31.09
66500.	18,5	105545.	310.5	2.5933	9336.	147852.	54813.	166728.	52.	31647.	34471.	0.044	55.40	31.09
67000.	18,6	105446.	310.5	2.5447	9161.	149124.	54951.	168332.	52.	31752.	34608.	0.044	55.39	31.09
67500.	18,8	105366.	310.6	2.5058	9021.	150377.	55086.	169912.	53.	31890.	34778.	0.044	55.35	31.08
68000.	18,9	105307.	310.7	2.4739	8906.	151614.	55223.	171469.	53.	32083.	35002.	0.045	55.43	31.11
68500.	19,0	105274.	310.9	2.4386	8779.	152833.	55385.	172991.	53.	32305.	35253.	0.054	56.00	31.36
69000.	19,2	105254.	311.0	2.4170	8701.	154042.	55563.	174490.	54.	32495.	35471.	0.059	56.29	31.51
69500.	19,3	105224.	311.0	2.4108	8679.	155247.	55727.	175992.	54.	32638.	35641.	0.055	56.09	31.39
70000.	19,4	105181.	311.0	2.4048	8657.	156450.	55870.	177501.	54.	32747.	35776.	0.048	55.68	31.20
70500.	19,6	105131.	311.0	2.3873	8594.	157643.	56000.	179005.	55.	32824.	35880.	0.045	55.43	31.10
71000.	19,7	105076.	311.0	2.3590	8492.	158823.	56131.	180490.	55.	32889.	35972.	0.045	55.49	31.12
71500.	19,9	105023.	311.1	2.3326	8397.	159989.	56261.	181958.	55.	32980.	36089.	0.046	55.54	31.13
72000.	20,0	104987.	311.1	2.3147	8333.	161146.	56391.	183415.	56.	33107.	36242.	0.046	55.55	31.13
72500.	20,1	104968.	311.2	2.3025	8289.	162298.	56524.	184862.	56.	33289.	36449.	0.047	55.66	31.17
73000.	20,3	104972.	311.4	2.2850	8226.	163440.	56684.	186283.	56.	33505.	36688.	0.056	56.22	31.43
73500.	20,4	104987.	311.5	2.2802	8209.	164580.	56861.	187693.	57.	33712.	36919.	0.062	56.52	31.60
74000.	20,6	104997.	311.5	2.2933	8256.	165727.	57026.	189117.	57.	33919.	37149.	0.058	56.34	31.48
74500.	20,7	105005.	311.5	2.3135	8329.	166884.	57170.	190565.	57.	34145.	37400.	0.050	55.96	31.26
75000.	20,8	105020.	311.6	2.3273	8378.	168047.	57306.	192027.	58.	34386.	37667.	0.048	55.80	31.18
75500.	21,0	105040.	311.6	2.3347	8405.	169215.	57444.	193492.	58.	34647.	37955.	0.048	55.86	31.20
76000.	21,1	105066.	311.7	2.3473	8450.	170388.	57585.	194965.	58.	34964.	38300.	0.049	55.93	31.22
76500.	21,3	105112.	311.7	2.3685	8527.	171572.	57729.	196449.	59.	35342.	38706.	0.049	56.00	31.23
77000.	21,4	105177.	311.8	2.3975	8631.	172771.	57878.	197950.	59.	35790.	39181.	0.050	56.10	31.27
77500.	21,5	105261.	311.9	2.4191	8709.	173981.	58057.	199450.	59.	36279.	39697.	0.059	56.57	31.52
78000.	21,7	105352.	312.0	2.4513	8825.	175206.	58257.	200960.	60.	36747.	40189.	0.065	56.81	31.68
78500.	21,8	105423.	312.0	2.4931	8975.	176453.	58449.	202502.	60.	37170.	40637.	0.062	56.72	31.59
79000.	21,9	105471.	312.0	2.5306	9110.	177718.	58623.	204078.	60.	37561.	41052.	0.055	56.50	31.41
79500.	22,1	105502.	312.1	2.5491	9177.	178993.	58794.	205668.	61.	37920.	41436.	0.054	56.47	31.37
80000.	22,2	105519.	312.1	2.5548	9197.	180270.	58968.	207260.	61.	38270.	41811.	0.055	56.56	31.40
80500.	22,4	105533.	312.2	2.5594	9214.	181550.	59146.	208853.	61.	38649.	42215.	0.056	56.65	31.43
81000.	22,5	105559.	312.2	2.5700	9252.	182835.	59329.	210450.	62.	39063.	42654.	0.057	56.75	31.46
81500.	22,6	105597.	312.3	2.5818	9294.	184126.	59520.	212052.	62.	39529.	43144.	0.059	56.89	31.53
82000.	22,8	105652.	312.4	2.5886	9319.	185420.	59742.	213641.	62.	40020.	43658.	0.068	57.21	31.78
82500.	22,9	105712.	312.5	2.6036	9373.	186722.	59984.	215230.	63.	40479.	44138.	0.074	57.40	31.95
83000.	23,1	105751.	312.5	2.6284	9462.	188036.	60222.	216838.	63.	40887.	44567.	0.072	57.42	31.89
83500.	23,2	105768.	312.5	2.6465	9528.	189359.	60446.	218465.	63.	41257.	44958.	0.067	57.39	31.76
84000.	23,3	105769.	312.6	2.6498	9539.	190684.	60666.	220096.	64.	41593.	45316.	0.066	57.45	31.74
84500.	23,5	105760.	312.6	2.6392	9501.	192004.	60893.	221717.	64.	41917.	45663.	0.068	57.56	31.80
85000.	23,6	105749.	312.7	2.6292	9465.	193318.	61125.	223329.	64.	42265.	46032.	0.070	57.68	31.86
85500.	23,8	105752.	312.8	2.6258	9453.	194631.	61363.	224936.	65.	42644.	46433.	0.071	57.79	31.91
86000.	23,9	105769.	312.8	2.6281	9461.	195945.	61611.	226539.	65.	43071.	46882.	0.074	57.91	31.99
86500.	24,0	105805.	312.9	2.6252	9451.	197258.	61888.	228125.	65.	43522.	47353.	0.083	58.07	32.24
87000.	24,2	105849.	312.9	2.6315	9474.	198574.	62188.	229704.	66.	43940.	47790.	0.089	58.19	32.42
87500.	24,3	105875.	313.0	2.6453	9523.	199896.	62485.	231293.	66.	44311.	48179.	0.087	58.26	32.39
88000.	24,4	105879.	313.1	2.6559	9561.	201224.	62771.	232896.	66.	44646.	48533.	0.084	58.32	32.30
88500.	24,6	105871.	313.1	2.6524	9548.	202551.	63056.	234496.	67.	44949.	48855.	0.084	58.41	32.30
89000.	24,7	105854.	313.1	2.6371	9493.	203869.	63349.	236083.	67.	45238.	49163.	0.086	58.51	32.37
89500.	24,9	105835.	313.2	2.6225	9441.	205180.	63649.	237657.	68.	45548.	49492.	0.089	58.61	32.45
90000.	25,0	105832.	313.3	2.6131	9407.	206487.	63958.	239220.	68.	45885.	49849.	0.091	58.72	32.54
90500.	25,1	105843.	313.3	2.6107	9399.	207792.	64278.	240776.	68.	46268.	50251.	0.095	58.83	32.64
91000.	25,3	105875.	313.4	2.6036	9373.	209094.	64630.	242311.	69.	46675.	50675.	0.104	58.91	32.92
91500.	25,4	105915.	313.4	2.6060	9382.	210397.	65007.	243835.	69.	47049.	51066.	0.111	58.99	33.13
92000.	25,6	105938.	313.5	2.6146	9413.	211704.	65387.	245363.	69.	47379.	51413.	0.112	59.11	33.15
92500.	25,7	105941.	313.6	2.6168	9421.	213013.	65764.	246895.	70.	47676.	51726.	0.111	59.24	33.13
93000.	25,8	105933.	313.6	2.6084	9390.	214317.	66147.	248419.	70.	47942.	52008.	0.112	59.36	33.20
93500.	26,0	105915.	313.6	2.5901	9324.	215612.	66542.	249924.	70.	48193.	52276.	0.116	59.46	33.33
94000.	26,1	105898.	313.7	2.5706	9254.	216897.	66950.	251411.	70.	48463.	52563.	0.121	59.56	33.47

94500.	26,3	105894.	313.8	2.5569	9205.	218176.	67374.	252880.	71.	48757.	52875.	0.126	59.67	33.64
95000.	26,4	105906.	313.9	2.5486	9175.	219450.	67817.	254335.	71.	49087.	53222.	0.132	59.78	33.81
95500.	26,5	105935.	313.9	2.5404	9145.	220720.	68291.	255769.	71.	49439.	53590.	0.142	59.82	34.11
96000.	26,7	105974.	314.0	2.5366	9132.	221989.	68795.	257184.	72.	49774.	53939.	0.151	59.87	34.38
96500.	26,8	106002.	314.0	2.5371	9133.	223257.	69317.	258592.	72.	50071.	54251.	0.156	59.99	34.55
97000.	26,9	106012.	314.1	2.5322	9116.	224523.	69852.	259990.	72.	50337.	54531.	0.160	60.14	34.68
97500.	27,1	106010.	314.2	2.5184	9066.	225782.	70403.	261372.	73.	50568.	54777.	0.165	60.28	34.86
98000.	27,2	105997.	314.2	2.4947	8981.	227030.	70975.	262728.	73.	50782.	55006.	0.173	60.37	35.11
98500.	27,4	105982.	314.2	2.4681	8885.	228264.	71571.	264055.	73.	51010.	55249.	0.181	60.46	35.39
99000.	27,5	105980.	314.3	2.4453	8803.	229487.	72196.	265353.	73.	51258.	55513.	0.192	60.56	35.71
99500.	27,6	105992.	314.4	2.4278	8740.	230700.	72849.	266625.	74.	51570.	55840.	0.202	60.65	36.03
100000.	27,8	106036.	314.4	2.4177	8704.	231909.	73547.	267868.	74.	51908.	56192.	0.216	60.63	36.46
100500.	27,9	106090.	314.5	2.4150	8694.	233117.	74286.	269089.	74.	52202.	56499.	0.229	60.66	36.85
101000.	28,1	106116.	314.6	2.4102	8677.	234322.	75047.	270296.	75.	52456.	56766.	0.236	60.79	37.10
101500.	28,2	106123.	314.6	2.3968	8628.	235520.	75829.	271485.	75.	52676.	56999.	0.243	60.92	37.35
102000.	28,3	106118.	314.7	2.3765	8556.	236709.	76632.	272651.	75.	52865.	57201.	0.251	61.01	37.62
102500.	28,5	106101.	314.7	2.3535	8473.	237885.	77455.	273791.	75.	53039.	57388.	0.260	61.07	37.91
103000.	28,6	106084.	314.8	2.3269	8377.	239049.	78300.	274904.	75.	53226.	57589.	0.270	61.12	38.22
103500.	28,8	106081.	314.9	2.3027	8290.	240200.	79174.	275987.	76.	53431.	57808.	0.282	61.19	38.59
104000.	28,9	106091.	314.9	2.2868	8233.	241344.	80074.	277047.	76.	53645.	58036.	0.292	61.24	38.93
104500.	29,0	106108.	315.0	2.2747	8189.	242481.	81001.	278086.	76.	53881.	58284.	0.302	61.29	39.24
105000.	29,2	106136.	315.0	2.2668	8161.	243614.	81957.	279104.	76.	54127.	58543.	0.313	61.29	39.58
105500.	29,3	106169.	315.1	2.2623	8144.	244745.	82942.	280106.	77.	54347.	58774.	0.323	61.30	39.89
106000.	29,4	106186.	315.2	2.2532	8112.	245872.	83949.	281091.	77.	54536.	58974.	0.331	61.37	40.16
106500.	29,6	106188.	315.2	2.2389	8060.	246992.	84974.	282059.	77.	54698.	59148.	0.338	61.45	40.43
107000.	29,7	106179.	315.3	2.2226	8002.	248103.	86013.	283010.	77.	54824.	59286.	0.345	61.50	40.65
107500.	29,9	106156.	315.3	2.2054	7939.	249206.	87060.	283945.	77.	54929.	59404.	0.350	61.52	40.83
108000.	30,0	106130.	315.3	2.1834	7860.	250297.	88116.	284862.	78.	55051.	59537.	0.357	61.55	41.04
108500.	30,1	106121.	315.4	2.1619	7783.	251378.	89194.	285754.	78.	55193.	59691.	0.368	61.58	41.39
109000.	30,3	106127.	315.5	2.1487	7735.	252453.	90294.	286626.	78.	55358.	59868.	0.378	61.59	41.69
109500.	30,4	106149.	315.6	2.1453	7723.	253525.	91414.	287486.	78.	55551.	60072.	0.385	61.56	41.92
110000.	30,6	106186.	315.6	2.1465	7727.	254598.	92557.	288335.	78.	55747.	60277.	0.393	61.53	42.15
110500.	30,7	106221.	315.7	2.1477	7732.	255672.	93723.	289173.	78.	55897.	60437.	0.401	61.52	42.39
111000.	30,8	106228.	315.8	2.1392	7701.	256742.	94903.	289999.	79.	55980.	60529.	0.407	61.52	42.59
111500.	31,0	106198.	315.7	2.1328	7678.	257808.	96073.	290825.	79.	56014.	60570.	0.405	61.48	42.51
112000.	31,1	106147.	315.7	2.1199	7632.	258868.	97226.	291651.	79.	56019.	60583.	0.402	61.43	42.40
112500.	31,3	105947.	315.1	2.1037	7573.	259920.	98269.	292520.	79.	56077.	60647.	0.367	61.30	41.27
113000.	31,4	105539.	314.1	2.0373	7334.	260939.	99125.	293437.	79.	56222.	60796.	0.313	61.06	39.54
113500.	31,5	104994.	313.2	1.8967	6828.	261887.	99801.	294351.	80.	56394.	60969.	0.266	60.78	38.05
114000.	31,7	104299.	311.7	1.7110	6160.	262742.	100252.	295252.	80.	56552.	61126.	0.199	60.15	35.92
114500.	31,8	104626.	0.0	0.0000	0.	262742.	100252.	295252.	80.	56764.	61350.	0.000	0.00	0.00
115000.	31,9	105205.	0.0	0.0000	0.	262742.	100252.	295252.	80.	57170.	61782.	0.000	0.00	0.00
115500.	32,1	106223.	0.0	0.0000	0.	262742.	100252.	295252.	80.	57667.	62308.	0.000	0.00	0.00
116000.	32,2	107642.	0.0	0.0000	0.	262742.	100252.	295252.	80.	58125.	62800.	0.000	0.00	0.00
116500.	32,4	107303.	310.2	3.2881	11837.	264387.	100655.	297220.	80.	58905.	63616.	0.094	59.13	32.74
117000.	32,5	107354.	310.9	3.2589	11732.	266016.	101130.	299131.	81.	59961.	64701.	0.111	59.65	33.27
117500.	32,6	107562.	311.4	3.2875	11835.	267660.	101710.	301009.	81.	60867.	65627.	0.134	59.75	33.95
118000.	32,8	107616.	311.0	3.3853	12187.	269352.	102202.	302993.	81.	61660.	66442.	0.112	58.93	33.22
118500.	32,9	107589.	310.9	3.4275	12339.	271066.	102619.	305043.	82.	62426.	67238.	0.094	58.65	32.70
119000.	33,1	107558.	311.0	3.4425	12393.	272787.	102992.	307127.	82.	63209.	68057.	0.084	58.58	32.41
119500.	33,2	107550.	311.1	3.4597	12455.	274517.	103336.	309237.	82.	64057.	68944.	0.077	58.49	32.22
120000.	33,3	107592.	311.2	3.4822	12536.	276258.	103679.	311362.	83.	64996.	69921.	0.077	58.39	32.19
120500.	33,5	107686.	311.6	3.4886	12559.	278003.	104076.	313464.	83.	65991.	70950.	0.088	58.79	32.55
121000.	33,6	107799.	311.8	3.5186	12667.	279762.	104512.	315566.	84.	66938.	71926.	0.095	58.95	32.77
121500.	33,8	107855.	311.8	3.5623	12824.	281543.	104930.	317706.	84.	67806.	72822.	0.091	58.64	32.61
122000.	33,9	107850.	311.8	3.5801	12888.	283333.	105323.	319868.	85.	68609.	73651.	0.086	58.03	32.42
122500.	34,0	107805.	311.9	3.5603	12817.	285113.	105714.	322017.	85.	69336.	74404.	0.086	57.69	32.40
123000.	34,2	107721.	312.0	3.5234	12684.	286875.	106099.	324144.	86.	70012.	75108.	0.086	57.46	32.38
123500.	34,3	107624.	312.2	3.4879	12556.	288619.	106465.	326257.	87.	70685.	75808.	0.083	57.15	32.28
124000.	34,4	107548.	312.3	3.4627	12466.	290350.	106814.	328361.	88.	71388.	76538.	0.081	56.77	32.18
124500.	34,6	107512.	312.5	3.4257	12333.	292063.	107189.	330427.	89.	72094.	77269.	0.087	56.87	32.36
125000.	34,7	107488.	312.8	3.3933	12216.	293760.	107593.	332456.	90.	72747.	77945.	0.095	56.94	32.56
125500.	34,9	107431.	312.9	3.3697	12131.	295445.	107992.	334470.	91.	73338.	78557.	0.095	56.53	32.53
126000.	35,0	107345.	312.9	3.3454	12043.	297117.	108367.	336478.	92.	73882.	79121.	0.091	55.78	32.37

126500.	35,1	107247.	313.0	3.3088	11912.	298772.	108729.	338468.	94.	74414.	79674.	0.090	55.09	32.28
127000.	35,3	107165.	313.2	3.2544	11716.	300399.	109111.	340410.	96.	74944.	80225.	0.097	54.96	32.43
127500.	35,4	107103.	313.3	3.2150	11574.	302006.	109507.	342316.	98.	75466.	80768.	0.102	54.75	32.54
128000.	35,6	107051.	313.4	3.1931	11495.	303603.	109899.	344209.	100	76055.	81377.	0.103	54.30	32.51
128500.	35,7	107065.	313.7	3.1810	11452.	305194.	110319.	346079.	102	76657.	81998.	0.110	54.48	32.69
129000.	35,8	107087.	313.9	3.1717	11418.	306779.	110768.	347927.	105	77165.	82523.	0.118	54.61	32.89
129500.	36,0	107030.	314.0	3.1571	11366.	308358.	111203.	349771.	108	77595.	82970.	0.116	53.87	32.77
130000.	36,1	106931.	314.1	3.1243	11247.	309920.	111618.	351600.	111	77982.	83374.	0.114	53.01	32.63
130500.	36,3	106826.	314.2	3.0835	11101.	311462.	112020.	353406.	114	78351.	83761.	0.113	52.25	32.53
131000.	36,4	106737.	314.3	3.0338	10922.	312979.	112430.	355174.	118	78747.	84176.	0.118	52.01	32.61
131500.	36,5	106693.	314.4	2.9980	10793.	314478.	112864.	356904.	121	79188.	84635.	0.126	52.02	32.78
132000.	36,7	106700.	314.6	2.9898	10763.	315973.	113317.	358616.	125	79706.	85171.	0.133	51.89	32.90
132500.	36,8	106771.	314.8	3.0018	10806.	317474.	113806.	360317.	130	80235.	85716.	0.142	52.17	33.13
133000.	36,9	106834.	315.0	3.0171	10862.	318982.	114322.	362013.	134	80673.	86169.	0.149	52.24	33.30
133500.	37,1	106806.	315.1	3.0162	10858.	320490.	114827.	363710.	139	81026.	86536.	0.148	51.44	33.16
134000.	37,2	106717.	315.2	2.9854	10747.	321983.	115317.	365392.	144	81316.	86841.	0.147	50.62	33.04
134500.	37,4	106601.	315.3	2.9379	10576.	323452.	115799.	367043.	150	81591.	87132.	0.149	49.96	32.98
135000.	37,5	106509.	315.5	2.8884	10398.	324896.	116288.	368656.	156	81882.	87440.	0.155	49.70	33.05
135500.	37,6	106459.	315.6	2.8566	10284.	326324.	116791.	370238.	162	82236.	87811.	0.161	49.52	33.15
136000.	37,8	106484.	315.7	2.8515	10265.	327750.	117323.	371799.	169	82658.	88249.	0.171	49.55	33.33
136500.	37,9	106566.	315.8	2.8727	10342.	329186.	117890.	373353.	175	83093.	88700.	0.181	49.66	33.54
137000.	38,1	106640.	316.0	2.8911	10408.	330632.	118489.	374900.	183	83485.	89106.	0.189	49.71	33.71
137500.	38,2	106657.	316.2	2.8980	10433.	332081.	119098.	376442.	191	83815.	89448.	0.194	49.28	33.72
138000.	38,3	106614.	316.3	2.8810	10372.	333522.	119709.	377968.	199	84081.	89728.	0.198	48.70	33.69
138500.	38,5	106528.	316.5	2.8436	10237.	334943.	120320.	379465.	208	84303.	89964.	0.203	48.12	33.66
139000.	38,6	106429.	316.6	2.7897	10043.	336338.	120941.	380918.	217	84527.	90202.	0.211	47.92	33.77
139500.	38,8	106367.	316.8	2.7520	9907.	337714.	121577.	382335.	227	84787.	90478.	0.220	47.72	33.89
140000.	38,9	106367.	316.9	2.7422	9872.	339085.	122236.	383729.	237	85107.	90813.	0.230	47.54	34.01
140500.	39,0	106432.	317.1	2.7518	9906.	340461.	122937.	385103.	248	85479.	91200.	0.243	47.55	34.25
141000.	39,2	106535.	317.2	2.7739	9986.	341848.	123692.	386459.	259	85851.	91585.	0.259	47.71	34.56
141500.	39,3	106609.	317.4	2.7910	10048.	343244.	124486.	387800.	271	86187.	91934.	0.271	47.62	34.75
142000.	39,4	106625.	317.6	2.7934	10056.	344640.	125303.	389124.	284	86505.	92264.	0.281	47.19	34.81
142500.	39,6	106622.	317.8	2.7860	10030.	346033.	126145.	390421.	298	86811.	92584.	0.294	46.72	34.88
143000.	39,7	106614.	318.0	2.7703	9973.	347419.	127019.	391684.	314	87097.	92887.	0.309	46.44	35.04
143500.	39,9	106595.	318.2	2.7455	9884.	348791.	127926.	392908.	329	87394.	93200.	0.324	46.30	35.25
144000.	40,0	106602.	318.4	2.7327	9838.	350158.	128869.	394098.	346	87727.	93551.	0.339	46.18	35.45
144500.	40,1	106658.	318.6	2.7382	9857.	351527.	129860.	395258.	364	88090.	93931.	0.357	46.07	35.69
145000.	40,3	106737.	318.8	2.7541	9915.	352904.	130904.	396394.	382	88510.	94367.	0.374	45.99	35.94
145500.	40,4	106863.	318.8	2.7790	10004.	354293.	132014.	397505.	402	88950.	94822.	0.393	46.22	36.31
146000.	40,6	106976.	319.0	2.7991	10077.	355693.	133189.	398589.	422	89332.	95218.	0.412	46.36	36.66
146500.	40,7	106979.	319.2	2.7859	10029.	357086.	134404.	399635.	443	89655.	95553.	0.429	46.14	36.86
147000.	40,8	106913.	319.5	2.7420	9871.	358457.	135648.	400629.	465	89938.	95849.	0.449	45.88	37.07
147500.	41,0	106829.	319.7	2.6869	9673.	359800.	136921.	401566.	488	90180.	96104.	0.470	45.81	37.36
148000.	41,1	106732.	319.9	2.6243	9448.	361112.	138219.	402445.	511	90397.	96337.	0.490	45.82	37.68
148500.	41,3	106648.	320.0	2.5671	9242.	362396.	139542.	403270.	534	90633.	96587.	0.511	45.85	38.02
149000.	41,4	106632.	320.2	2.5390	9141.	363665.	140902.	404053.	558	90883.	96851.	0.530	45.88	38.34
149500.	41,5	106649.	320.4	2.5298	9107.	364930.	142294.	404810.	582	91131.	97112.	0.544	45.91	38.57
150000.	41,7	106657.	320.6	2.5255	9092.	366193.	143703.	405553.	606	91380.	97373.	0.552	45.93	38.70
150500.	41,8	106668.	320.7	2.5211	9076.	367454.	145124.	406287.	631	91617.	97621.	0.556	46.03	38.82
151000.	41,9	106659.	320.9	2.5118	9042.	368710.	146552.	407010.	655	91817.	97831.	0.561	46.07	38.92
151500.	42,1	106596.	321.1	2.4842	8943.	369952.	147976.	407717.	679	92001.	98024.	0.566	45.97	38.95
152000.	42,2	106146.	321.1	2.3013	8285.	371102.	149304.	408368.	701	92229.	98260.	0.568	46.14	39.06
152500.	42,4	105211.	320.8	1.9216	6918.	372063.	150420.	408915.	719	92535.	98571.	0.565	46.65	39.29
153000.	42,5	104123.	320.4	1.4832	5340.	372805.	151288.	409340.	732	92899.	98938.	0.561	47.42	39.62
153500.	42,6		0.0	0.0000	0.	372805.	151288.	409340.	732	92990.	99036.	0.000	0.00	0.00
154000.	42,8		0.0	0.0000	0.	372805.	151288.	409340.	732	92811.	98869.	0.000	0.00	0.00
154500.	42,9		0.0	0.0000	0.	372805.	151288.	409340.	732	92751.	98819.	0.000	0.00	0.00
155000.	43,1		0.0	0.0000	0.	372805.	151288.	409340.	732	92829.	98907.	0.000	0.00	0.00
155500.	43,2		0.0	0.0000	0.	372805.	151288.	409340.	732	92939.	99026.	0.000	0.00	0.00
156000.	43,3		0.0	0.0000	0.	372805.	151288.	409340.	732	93011.	99107.	0.000	0.00	0.00
156500.	43,5		0.0	0.0000	0.	372805.	151288.	409340.	732	93046.	99151.	0.000	0.00	0.00
157000.	43,6		0.0	0.0000	0.	372805.	151288.	409340.	732	93070.	99184.	0.000	0.00	0.00
157500.	43,8		0.0	0.0000	0.	372805.	151288.	409340.	732	93100.	99223.	0.000	0.00	0.00
158000.	43,9		0.0	0.0000	0.	372805.	151288.	409340.	732	93137.	99270.	0.000	0.00	0.00

158500.	44,0	0.0	0.0000	0.	372805.	151288.	409340.	732	93177.	99319.	0.000	0.00	0.00
159000.	44,2	0.0	0.0000	0.	372805.	151288.	409340.	732	93215.	99365.	0.000	0.00	0.00

Time	Time	Accumulated Moles [kmol]														
		C1	C2	C3	iC4	nC4	iC5	nC5	C6	C7	C8	C9	C10+	N2	CO2	O2
[s]	[h]															
0.	0,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
500.	0,1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1000.	0,3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
1500.	0,4	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2000.	0,6	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2500.	0,7	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3000.	0,8	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
3500.	1,0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4000.	1,1	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
4500.	1,3	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
5000.	1,4	0,04	0,20	1,56	0,58	1,90	0,70	0,87	0,27	4,1E-06	3,2E-07	9,1E-09	2,5E-09	56,81	7,67	3,46
5500.	1,5	0,08	0,40	3,07	1,15	3,75	1,37	1,70	0,53	1,7E-05	1,4E-06	4,2E-08	1,0E-08	112,30	15,17	6,83
6000.	1,7	0,12	0,59	4,55	1,70	5,53	2,02	2,49	0,77	4,8E-05	4,0E-06	1,4E-07	2,8E-08	166,70	22,50	10,13
6500.	1,8	0,16	0,78	5,98	2,23	7,26	2,64	3,25	0,99	1,1E-04	9,3E-06	3,7E-07	6,5E-08	219,80	29,66	13,36
7000.	1,9	0,20	0,96	7,39	2,75	8,95	3,25	3,99	1,21	2,2E-04	1,9E-05	8,7E-07	1,3E-07	271,90	36,68	16,53
7500.	2,1	0,24	1,14	8,77	3,27	10,59	3,83	4,70	1,41	4,1E-04	3,5E-05	1,8E-06	2,3E-07	322,90	43,56	19,62
8000.	2,2	0,27	1,32	10,12	3,77	12,20	4,40	5,38	1,61	6,8E-04	6,0E-05	3,5E-06	3,8E-07	373,00	50,30	22,66
8500.	2,4	0,31	1,49	11,44	4,26	13,77	4,96	6,05	1,80	1,1E-03	9,7E-05	6,4E-06	6,0E-07	422,10	56,92	25,64
9000.	2,5	0,35	1,66	12,74	4,75	15,31	5,51	6,69	1,98	1,6E-03	1,5E-04	1,1E-05	8,9E-07	470,40	63,42	28,57
9500.	2,6	0,38	1,82	14,03	5,23	16,83	6,04	7,32	2,15	2,3E-03	2,2E-04	1,8E-05	1,3E-06	517,80	69,81	31,44
10000.	2,8	0,41	1,99	15,29	5,70	18,32	6,56	7,94	2,32	3,3E-03	3,0E-04	2,7E-05	1,8E-06	564,50	76,09	34,26
10500.	2,9	0,45	2,15	16,54	6,17	19,79	7,08	8,54	2,49	4,4E-03	4,2E-04	4,1E-05	2,4E-06	610,40	82,28	37,04
11000.	3,1	0,48	2,31	17,77	6,63	21,24	7,58	9,13	2,64	0,01	5,6E-04	5,9E-05	3,1E-06	655,70	88,37	39,78
11500.	3,2	0,51	2,46	18,99	7,09	22,68	8,08	9,70	2,80	0,01	7,3E-04	8,3E-05	4,0E-06	700,40	94,38	42,47
12000.	3,3	0,55	2,62	20,19	7,54	24,10	8,58	10,27	2,95	0,01	9,3E-04	1,1E-04	5,0E-06	744,40	100,30	45,13
12500.	3,5	0,58	2,77	21,39	8,00	25,51	9,06	10,83	3,09	0,01	1,2E-03	1,5E-04	6,2E-06	787,90	106,20	47,75
13000.	3,6	0,61	2,92	22,57	8,44	26,92	9,55	11,38	3,24	0,01	1,4E-03	2,0E-04	7,6E-06	830,90	111,90	50,34
13500.	3,8	0,64	3,07	23,76	8,89	28,31	10,03	11,92	3,38	0,02	1,8E-03	2,5E-04	9,3E-06	873,50	117,70	52,89
14000.	3,9	0,67	3,22	24,94	9,34	29,71	10,51	12,45	3,51	0,02	2,1E-03	3,2E-04	1,1E-05	915,70	123,30	55,42
14500.	4,0	0,71	3,37	26,12	9,79	31,12	10,99	12,99	3,65	0,03	2,6E-03	4,0E-04	1,3E-05	957,80	129,00	57,93
15000.	4,2	0,74	3,52	27,31	10,24	32,53	11,47	13,52	3,78	0,03	3,0E-03	5,0E-04	1,6E-05	999,80	134,60	60,43
15500.	4,3	0,77	3,67	28,52	10,70	33,96	11,96	14,05	3,91	0,03	3,6E-03	6,1E-04	1,9E-05	1042,00	140,30	62,92
16000.	4,4	0,80	3,82	29,73	11,16	35,41	12,45	14,59	4,04	0,04	4,2E-03	7,3E-04	2,2E-05	1084,00	145,90	65,41
16500.	4,6	0,83	3,97	30,95	11,63	36,87	12,94	15,12	4,18	0,05	4,9E-03	8,8E-04	2,5E-05	1126,00	151,60	67,91
17000.	4,7	0,86	4,12	32,18	12,11	38,34	13,44	15,66	4,31	0,05	0,01	1,0E-03	2,9E-05	1168,00	157,20	70,41
17500.	4,9	0,89	4,27	33,42	12,59	39,84	13,95	16,20	4,44	0,06	0,01	1,2E-03	3,3E-05	1210,00	162,90	72,92
18000.	5,0	0,93	4,42	34,68	13,07	41,35	14,46	16,74	4,57	0,07	0,01	1,4E-03	3,8E-05	1253,00	168,60	75,44
18500.	5,1	0,96	4,58	35,95	13,56	42,89	14,98	17,29	4,70	0,08	0,01	1,6E-03	4,3E-05	1295,00	174,30	77,96
19000.	5,3	0,99	4,73	37,23	14,06	44,46	15,51	17,84	4,83	0,09	0,01	1,9E-03	4,9E-05	1338,00	180,00	80,48
19500.	5,4	1,02	4,88	38,53	14,57	46,05	16,04	18,39	4,96	0,10	0,01	2,2E-03	5,6E-05	1380,00	185,70	83,01
20000.	5,6	1,05	5,03	39,85	15,08	47,66	16,59	18,95	5,09	0,11	0,01	2,5E-03	6,3E-05	1423,00	191,40	85,55
20500.	5,7	1,09	5,19	41,18	15,60	49,31	17,14	19,51	5,22	0,13	0,01	2,8E-03	7,1E-05	1466,00	197,00	88,08
21000.	5,8	1,12	5,34	42,52	16,13	50,98	17,70	20,08	5,36	0,14	0,01	3,3E-03	8,0E-05	1508,00	202,70	90,61
21500.	6,0	1,15	5,50	43,89	16,67	52,68	18,27	20,65	5,49	0,16	0,02	3,7E-03	9,0E-05	1551,00	208,40	93,15
22000.	6,1	1,18	5,65	45,27	17,22	54,42	18,86	21,23	5,62	0,17	0,02	4,2E-03	1,0E-04	1594,00	214,10	95,68
22500.	6,3	1,21	5,80	46,66	17,78	56,18	19,45	21,81	5,75	0,19	0,02	4,7E-03	1,1E-04	1636,00	219,80	98,21
23000.	6,4	1,25	5,96	48,07	18,34	57,98	20,05	22,39	5,88	0,21	0,02	0,01	1,3E-04	1679,00	225,40	100,70
23500.	6,5	1,28	6,11	49,50	18,92	59,81	20,67	22,98	6,02	0,23	0,03	0,01	1,4E-04	1721,00	231,10	103,30
24000.	6,7	1,31	6,26	50,95	19,50	61,68	21,29	23,58	6,15	0,26	0,03	0,01	1,6E-04	1764,00	236,70	105,80
24500.	6,8	1,34	6,42	52,41	20,09	63,58	21,93	24,17	6,28	0,28	0,03	0,01	1,8E-04	1806,00	242,30	108,30
25000.	6,9	1,37	6,57	53,89	20,70	65,51	22,57	24,78	6,42	0,31	0,03	0,01	2,0E-04	1848,00	247,90	110,80
25500.	7,1	1,41	6,72	55,38	21,31	67,48	23,23	25,39	6,55	0,33	0,04	0,01	2,2E-04	1891,00	253,40	113,30
26000.	7,2	1,44	6,88	56,89	21,93	69,49	23,90	26,00	6,69	0,36	0,04	0,01	2,4E-04	1933,00	259,00	115,80
26500.	7,4	1,47	7,03	58,42	22,56	71,53	24,59	26,62	6,82	0,39	0,04	0,01	2,7E-04	1975,00	264,50	118,30
27000.	7,5	1,50	7,18	59,97	23,20	73,61	25,28	27,24	6,95	0,43	0,05	0,01	3,0E-04	2016,00	270,00	120,80
27500.	7,6	1,53	7,33	61,53	23,86	75,73	25,99	27,87	7,09	0,46	0,05	0,01	3,3E-04	2058,00	275,50	123,20
28000.	7,8	1,56	7,48	63,12	24,52	77,89	26,71	28,51	7,22	0,50	0,06	0,01	3,7E-04	2099,00	280,90	125,70
28500.	7,9	1,59	7,63	64,72	25,20	80,10	27,45	29,15	7,36	0,54	0,06	0,02	4,1E-04	2141,00	286,40	128,10
29000.	8,1	1,62	7,78	66,34	25,88	82,34	28,20	29,80	7,50	0,58	0,06	0,02	4,6E-04	2182,00	291,80	130,60
29500.	8,2	1,65	7,93	67,98	26,58	84,63	28,97	30,45	7,63	0,62	0,07	0,02	5,1E-04	2223,00	297,10	133,00
30000.	8,3	1,68	8,08	69,64	27,29	86,97	29,75	31,11	7,77	0,67	0,07	0,02	5,7E-04	2264,00	302,50	135,40
30500.	8,5	1,71	8,23	71,32	28,02	89,36	30,54	31,78	7,90	0,71	0,08	0,02	6,3E-04	2304,00	307,80	137,90
31000.	8,6	1,74	8,38	73,03	28,75	91,80	31,36	32,45	8,04	0,76	0,09	0,02	7,0E-04	2345,00	313,00	140,30
31500.	8,8	1,77	8,53	74,75	29,50	94,28	32,19	33,13	8,18	0,82	0,09	0,03	7,8E-04	2385,00	318,30	142,60
32000.	8,9	1,80	8,68	76,50	30,27	96,83	33,04	33,82	8,31	0,87	0,10	0,03	8,7E-04	2425,00	323,50	145,00
32500.	9,0	1,83	8,83	78,28	31,05	99,43	33,91	34,51	8,45	0,93	0,11	0,03	9,6E-04	2465,00	328,60	147,40
33000.	9,2	1,86	8,97	80,08	31,85	102,10	34,80	35,22	8,59	0,99	0,11	0,03	1,1E-03	2505,00	333,80	149,70
33500.	9,3	1,89	9,12	81,91	32,66	104,80	35,71	35,93	8,73	1,06	0,12	0,04	1,2E-03	2544,00	338,90	152,10
34000.	9,4	1,92	9,26	83,77	33,50	107,60	36,64	36,66	8,87	1,12	0,13	0,04	1,3E-03	2583,00	343,90	154,40
34500.	9,6	1,95	9,41	85,65	34,35	110,50	37,60	37,39	9,01	1,19	0,14	0,04	1,5E-03	2622,00	348,90	156,70
35000.	9,7	1,98	9,55	87,57	35,22	113,40	38,58	38,13	9,15	1,27	0,14	0,04	1,7E-03	2661,00	353,90	159,00
35500.	9,9	2,01	9,70	89,52	36,11	116,40	39,58	38,89	9,29	1,35	0,15	0,05	1,9E-03	2699,00	358,80	161,30
36000.	10,0	2,03	9,84	91,50	37,02	119,50	40,61	39,65	9,43	1,43	0,16	0,05	2,1E-03	2737,00	363,70	163,50

36500. 10,1	2,06	9,98	93,52	37,95	122,70	41,67	40,43	9,57	1,52	0,17	0,05	2,4E-03	2775,00	368,50	165,80
37000. 10,3	2,09	10,12	95,58	38,90	125,90	42,76	41,21	9,71	1,61	0,18	0,06	2,7E-03	2812,00	373,30	168,00
37500. 10,4	2,12	10,26	97,67	39,88	129,30	43,88	42,02	9,85	1,70	0,19	0,06	3,0E-03	2850,00	378,00	170,20
38000. 10,6	2,14	10,40	99,81	40,89	132,70	45,04	42,83	10,00	1,80	0,21	0,06	3,4E-03	2887,00	382,70	172,40
38500. 10,7	2,17	10,54	102,00	41,93	136,30	46,23	43,67	10,14	1,91	0,22	0,07	3,8E-03	2923,00	387,30	174,60
39000. 10,8	2,20	10,68	104,20	43,00	140,00	47,46	44,52	10,28	2,02	0,23	0,07	4,3E-03	2959,00	391,90	176,70
39500. 11,0	2,22	10,82	106,50	44,09	143,80	48,73	45,38	10,43	2,13	0,24	0,08	4,9E-03	2995,00	396,40	178,80
40000. 11,1	2,25	10,95	108,80	45,23	147,70	50,05	46,27	10,58	2,26	0,26	0,08	0,01	3030,00	400,80	180,90
40500. 11,3	2,27	11,09	111,20	46,40	151,80	51,41	47,17	10,72	2,39	0,27	0,09	0,01	3065,00	405,10	183,00
41000. 11,4	2,30	11,22	113,70	47,60	156,00	52,81	48,10	10,87	2,52	0,29	0,09	0,01	3100,00	409,40	185,00
41500. 11,5	2,32	11,35	116,20	48,85	160,30	54,27	49,04	11,02	2,67	0,31	0,10	0,01	3134,00	413,60	187,00
42000. 11,7	2,35	11,48	118,80	50,13	164,80	55,78	50,01	11,17	2,82	0,32	0,10	0,01	3167,00	417,70	189,00
42500. 11,8	2,37	11,61	121,40	51,45	169,40	57,33	51,00	11,33	2,98	0,34	0,11	0,01	3200,00	421,70	191,00
43000. 11,9	2,40	11,74	124,10	52,81	174,20	58,94	52,01	11,48	3,14	0,36	0,11	0,01	3233,00	425,60	192,90
43500. 12,1	2,42	11,87	126,80	54,21	179,10	60,60	53,04	11,63	3,32	0,38	0,12	0,01	3265,00	429,50	194,80
44000. 12,2	2,44	11,99	129,60	55,65	184,20	62,31	54,09	11,79	3,50	0,40	0,13	0,02	3296,00	433,30	196,70
44500. 12,4	2,46	12,12	132,50	57,13	189,50	64,07	55,17	11,95	3,69	0,43	0,14	0,02	3327,00	437,00	198,50
45000. 12,5	2,49	12,24	135,50	58,65	194,90	65,88	56,26	12,11	3,88	0,45	0,14	0,02	3358,00	440,60	200,30
45500. 12,6	2,51	12,36	138,40	60,21	200,40	67,74	57,38	12,26	4,09	0,47	0,15	0,02	3388,00	444,20	202,10
46000. 12,8	2,53	12,49	141,50	61,80	206,10	69,65	58,52	12,42	4,30	0,50	0,16	0,03	3418,00	447,70	203,90
46500. 12,9	2,55	12,60	144,60	63,44	211,90	71,61	59,68	12,59	4,52	0,52	0,17	0,03	3447,00	451,10	205,60
47000. 13,1	2,57	12,72	147,80	65,11	217,90	73,62	60,87	12,75	4,74	0,55	0,18	0,03	3476,00	454,40	207,30
47500. 13,2	2,59	12,84	151,00	66,81	224,00	75,67	62,07	12,91	4,97	0,58	0,18	0,04	3504,00	457,70	209,00
48000. 13,3	2,61	12,96	154,20	68,55	230,20	77,77	63,29	13,08	5,21	0,60	0,19	0,04	3532,00	460,90	210,70
48500. 13,5	2,63	13,07	157,50	70,33	236,50	79,91	64,53	13,24	5,46	0,63	0,20	0,05	3560,00	464,00	212,30
49000. 13,6	2,65	13,19	160,90	72,13	243,00	82,10	65,79	13,41	5,71	0,66	0,21	0,05	3587,00	467,10	213,90
49500. 13,8	2,67	13,30	164,30	73,97	249,60	84,32	67,06	13,58	5,97	0,69	0,22	0,06	3614,00	470,10	215,50
50000. 13,9	2,69	13,41	167,80	75,84	256,40	86,59	68,35	13,74	6,23	0,72	0,23	0,06	3640,00	473,00	217,00
50500. 14,0	2,70	13,52	171,30	77,74	263,20	88,90	69,66	13,91	6,50	0,75	0,24	0,07	3666,00	475,90	218,60
51000. 14,2	2,72	13,63	174,80	79,66	270,10	91,24	70,99	14,08	6,77	0,78	0,25	0,07	3692,00	478,80	220,10
51500. 14,3	2,74	13,74	178,40	81,61	277,20	93,62	72,33	14,25	7,05	0,82	0,26	0,08	3717,00	481,50	221,60
52000. 14,4	2,76	13,85	182,00	83,60	284,30	96,04	73,69	14,43	7,34	0,85	0,27	0,09	3742,00	484,20	223,10
52500. 14,6	2,77	13,96	185,70	85,63	291,70	98,51	75,07	14,60	7,63	0,88	0,29	0,09	3767,00	486,90	224,50
53000. 14,7	2,79	14,06	189,50	87,70	299,10	101,00	76,48	14,78	7,93	0,92	0,30	0,09	3791,00	489,50	226,00
53500. 14,9	2,81	14,17	193,30	89,79	306,70	103,60	77,91	14,95	8,24	0,95	0,31	0,09	3815,00	492,10	227,40
54000. 15,0	2,82	14,28	197,10	91,89	314,30	106,20	79,34	15,13	8,55	0,99	0,32	0,09	3839,00	494,60	228,80
54500. 15,1	2,84	14,38	200,90	93,96	321,80	108,70	80,74	15,31	8,85	1,02	0,33	0,09	3864,00	497,20	230,30
55000. 15,3	2,86	14,49	204,30	95,82	328,50	110,90	82,02	15,48	9,10	1,05	0,34	0,09	3890,00	500,10	231,90
55500. 15,4	2,88	14,60	207,10	97,31	333,80	112,70	83,10	15,64	9,30	1,08	0,35	0,09	3919,00	503,50	233,70
56000. 15,6	2,90	14,70	209,30	98,43	337,70	114,10	83,96	15,79	9,44	1,09	0,35	0,09	3949,00	507,20	235,70
56500. 15,7	2,92	14,80	210,80	99,12	340,10	114,90	84,58	15,92	9,50	1,10	0,35	0,09	3982,00	511,30	237,90
57000. 15,8	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
57500. 16,0	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
58000. 16,1	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
58500. 16,3	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
59000. 16,4	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
59500. 16,5	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
60000. 16,7	2,93	14,89	211,80	99,55	341,50	115,40	85,02	16,02	9,53	1,10	0,36	0,09	4014,00	515,40	240,20
60500. 16,8	2,96	15,03	213,40	100,20	343,70	116,10	85,59	16,14	9,58	1,11	0,36	0,09	4071,00	522,60	244,50
61000. 16,9	2,99	15,16	214,70	100,70	345,20	116,60	86,03	16,23	9,60	1,11	0,36	0,09	4128,00	529,90	248,80
61500. 17,1	3,01	15,28	215,80	101,10	346,30	116,90	86,40	16,31	9,60	1,11	0,36	0,09	4185,00	537,10	253,10
62000. 17,2	3,04	15,40	216,80	101,50	347,30	117,20	86,75	16,40	9,61	1,11	0,36	0,10	4240,00	544,10	257,20
62500. 17,4	3,06	15,52	217,80	101,80	348,30	117,60	87,08	16,47	9,61	1,11	0,36	0,10	4294,00	550,90	261,20
63000. 17,5	3,09	15,63	218,80	102,20	349,20	117,80	87,39	16,54	9,61	1,11	0,36	0,10	4345,00	557,50	265,10
63500. 17,6	3,11	15,74	219,70	102,50	350,10	118,10	87,70	16,61	9,61	1,11	0,36	0,10	4396,00	563,90	268,80
64000. 17,8	3,14	15,85	220,70	102,90	351,20	118,50	88,03	16,68	9,62	1,11	0,36	0,10	4445,00	570,10	272,40
64500. 17,9	3,16	15,95	221,80	103,30	352,40	118,90	88,37	16,75	9,64	1,12	0,36	0,10	4492,00	576,10	275,90
65000. 18,1	3,18	16,05	222,80	103,70	353,60	119,20	88,69	16,81	9,66	1,12	0,36	0,10	4539,00	582,10	279,30
65500. 18,2	3,20	16,16	223,70	104,00	354,50	119,50	88,98	16,87	9,67	1,12	0,36	0,10	4586,00	588,00	282,70
66000. 18,3	3,23	16,25	224,60	104,30	355,30	119,80	89,24	16,92	9,67	1,12	0,36	0,10	4632,00	593,90	286,10
66500. 18,5	3,25	16,35	225,40	104,60	356,00	120,00	89,49	16,98	9,67	1,12	0,36	0,10	4678,00	599,70	289,50
67000. 18,6	3,27	16,45	226,20	104,90	356,80	120,30	89,73	17,03	9,67	1,12	0,36	0,10	4722,00	605,40	292,70
67500. 18,8	3,29	16,54	227,00	105,10	357,50	120,50	89,97	17,07	9,67	1,12	0,36	0,10	4766,00	611,00	295,90
68000. 18,9	3,31	16,63	227,70	105,40	358,30	120,70	90,20	17,12	9,68	1,12	0,36	0,10	4810,00	616,60	299,00
68500. 19,0	3,33	16,72	228,60	105,80	359,30	121,00	90,46	17,17	9,69	1,12	0,36	0,10	4852,00	621,90	302,10
69000. 19,2	3,35	16,81	229,50	106,10	360,30	121,40	90,74	17,22	9,71	1,12	0,36	0,10	4894,00	627,20	305,10
69500. 19,3	3,37	16,90	230,40	106,50	361,30	121,70	91,00	17,26	9,72	1,12	0,36	0,10	4936,00	632,50	308,20
70000. 19,4	3,39	16,99	231,20	106,80	362,10	121,90	91,24	17,31	9,73	1,13	0,36	0,10	4978,00	637,80	311,20
70500. 19,6	3,42	17,08	232,00	107,00	362,90	122,20	91,46	17,35	9,73	1,13	0,36	0,10	5019,00	643,20	314,20
71000. 19,7	3,44	17,16	232,70	107,30	363,60	122,40	91,68	17,39	9,74	1,13	0,36	0,10	5061,00	648,40	317,20
71500. 19,9	3,46	17,25	233,40	107,60	364,30	122,60	91,90	17,43	9,74	1,13	0,36	0,10	5102,00	653,60	320,20
72000. 20,0	3,48	17,33	234,20	107,80	365,10	122,90	92,12	17,47	9,75	1,13	0,36	0,10	5142,00	658,80	323,10
72500. 20,1	3,50	17,42	234,90	108,10	365,80	123,10	92,33	17,51	9,75	1,13	0,36	0,10	5182,00	663,90	326,00
73000. 20,3	3,51	17,50	235,70	108,50	366,80	123,40	92,58	17,55	9,77	1,13	0,36	0,10	5222,00	668,90	328,90
73500. 20,4	3,53	17,58	236,60	108,80	367,90	123,80	92,85	17,59	9,79	1,13	0,36	0,10	5261,00	673,90	331,70
74000. 20,6	3,55	17,67	237,50	109,20	368,90	124,10	93,10	17,64	9,81	1,13	0,36	0,10	5301,00	678,90	334,50

74500.	20,7	3,57	17,75	238,20	109,50	369,70	124,40	93,33	17,67	9,82	1,14	0,36	0,10	5341,00	684,00	337,40
75000.	20,8	3,59	17,83	239,00	109,80	370,50	124,60	93,54	17,71	9,83	1,14	0,36	0,10	5382,00	689,20	340,40
75500.	21,0	3,61	17,92	239,70	110,10	371,30	124,90	93,76	17,75	9,84	1,14	0,36	0,10	5423,00	694,30	343,30
76000.	21,1	3,63	18,00	240,50	110,40	372,10	125,10	93,99	17,78	9,85	1,14	0,36	0,10	5464,00	699,50	346,30
76500.	21,3	3,65	18,08	241,20	110,70	373,00	125,40	94,21	17,82	9,86	1,14	0,36	0,10	5505,00	704,80	349,30
77000.	21,4	3,67	18,17	242,00	111,00	373,90	125,70	94,45	17,86	9,87	1,14	0,37	0,10	5547,00	710,10	352,30
77500.	21,5	3,69	18,26	242,90	111,40	375,00	126,10	94,72	17,91	9,90	1,14	0,37	0,10	5589,00	715,30	355,30
78000.	21,7	3,71	18,35	243,80	111,80	376,20	126,50	95,02	17,95	9,92	1,15	0,37	0,10	5631,00	720,60	358,30
78500.	21,8	3,73	18,44	244,80	112,20	377,40	126,90	95,31	18,00	9,95	1,15	0,37	0,10	5674,00	726,00	361,40
79000.	21,9	3,76	18,53	245,60	112,60	378,40	127,20	95,58	18,04	9,97	1,15	0,37	0,10	5718,00	731,60	364,50
79500.	22,1	3,78	18,62	246,50	112,90	379,50	127,60	95,84	18,08	9,98	1,15	0,37	0,10	5762,00	737,20	367,70
80000.	22,2	3,80	18,71	247,30	113,30	380,50	127,90	96,11	18,13	10,00	1,15	0,37	0,10	5807,00	742,80	370,90
80500.	22,4	3,82	18,80	248,20	113,70	381,60	128,30	96,39	18,17	10,02	1,16	0,37	0,10	5851,00	748,40	374,10
81000.	22,5	3,84	18,89	249,00	114,10	382,70	128,70	96,67	18,22	10,05	1,16	0,37	0,10	5896,00	754,00	377,30
81500.	22,6	3,86	18,98	249,90	114,50	383,90	129,10	96,96	18,26	10,07	1,16	0,37	0,10	5940,00	759,60	380,50
82000.	22,8	3,88	19,07	250,90	114,90	385,30	129,60	97,29	18,32	10,10	1,17	0,37	0,10	5985,00	765,10	383,70
82500.	22,9	3,91	19,17	252,00	115,50	386,80	130,10	97,65	18,37	10,14	1,17	0,37	0,10	6029,00	770,70	386,90
83000.	23,1	3,93	19,26	253,00	116,00	388,30	130,70	98,01	18,42	10,18	1,17	0,37	0,10	6074,00	776,30	390,10
83500.	23,2	3,95	19,35	254,00	116,40	389,70	131,10	98,34	18,48	10,22	1,18	0,37	0,10	6119,00	781,90	393,40
84000.	23,3	3,97	19,44	255,00	116,90	391,10	131,60	98,68	18,53	10,25	1,18	0,37	0,10	6165,00	787,60	396,60
84500.	23,5	3,99	19,54	255,90	117,40	392,50	132,20	99,02	18,58	10,29	1,19	0,38	0,10	6210,00	793,30	399,90
85000.	23,6	4,02	19,63	256,90	117,90	394,00	132,70	99,37	18,64	10,33	1,19	0,38	0,10	6255,00	798,90	403,10
85500.	23,8	4,04	19,72	257,80	118,40	395,50	133,20	99,73	18,69	10,37	1,19	0,38	0,10	6300,00	804,50	406,30
86000.	23,9	4,06	19,81	258,80	118,90	397,10	133,80	100,10	18,75	10,41	1,20	0,38	0,10	6345,00	810,10	409,60
86500.	24,0	4,08	19,90	259,90	119,50	398,90	134,50	100,50	18,81	10,47	1,20	0,38	0,10	6389,00	815,60	412,70
87000.	24,2	4,10	19,99	261,10	120,20	400,90	135,20	100,90	18,87	10,53	1,21	0,38	0,10	6433,00	821,00	415,90
87500.	24,3	4,12	20,09	262,20	120,80	402,80	135,90	101,40	18,94	10,59	1,22	0,38	0,10	6478,00	826,50	419,10
88000.	24,4	4,15	20,18	263,30	121,40	404,70	136,60	101,80	19,00	10,65	1,22	0,39	0,10	6523,00	832,00	422,30
88500.	24,6	4,17	20,27	264,30	122,00	406,50	137,30	102,20	19,07	10,71	1,23	0,39	0,10	6567,00	837,60	425,50
89000.	24,7	4,19	20,36	265,40	122,60	408,40	138,00	102,70	19,13	10,77	1,24	0,39	0,10	6612,00	843,00	428,70
89500.	24,9	4,21	20,45	266,40	123,30	410,40	138,80	103,10	19,20	10,83	1,24	0,39	0,10	6656,00	848,50	431,80
90000.	25,0	4,23	20,53	267,50	124,00	412,40	139,60	103,60	19,27	10,90	1,25	0,39	0,10	6700,00	853,90	435,00
90500.	25,1	4,25	20,62	268,60	124,60	414,60	140,40	104,00	19,34	10,98	1,26	0,40	0,10	6743,00	859,20	438,10
91000.	25,3	4,27	20,71	269,80	125,40	416,90	141,30	104,60	19,41	11,06	1,27	0,40	0,10	6786,00	864,50	441,20
91500.	25,4	4,29	20,80	271,00	126,20	419,40	142,20	105,10	19,49	11,15	1,28	0,40	0,10	6829,00	869,60	444,20
92000.	25,6	4,31	20,89	272,30	127,00	422,00	143,20	105,60	19,57	11,24	1,29	0,40	0,10	6872,00	874,80	447,30
92500.	25,7	4,33	20,97	273,50	127,80	424,50	144,20	106,20	19,65	11,34	1,30	0,41	0,10	6915,00	880,10	450,40
93000.	25,8	4,35	21,06	274,60	128,60	427,10	145,20	106,80	19,73	11,44	1,31	0,41	0,10	6957,00	885,30	453,40
93500.	26,0	4,37	21,14	275,80	129,50	429,80	146,30	107,30	19,81	11,54	1,32	0,41	0,10	7000,00	890,40	456,50
94000.	26,1	4,39	21,23	277,00	130,40	432,50	147,40	107,90	19,90	11,65	1,33	0,42	0,10	7041,00	895,40	459,50
94500.	26,3	4,41	21,31	278,30	131,30	435,40	148,50	108,50	19,99	11,76	1,35	0,42	0,10	7083,00	900,40	462,40
95000.	26,4	4,43	21,39	279,50	132,20	438,40	149,70	109,20	20,08	11,88	1,36	0,42	0,10	7124,00	905,30	465,30
95500.	26,5	4,45	21,47	280,90	133,20	441,70	151,00	109,90	20,17	12,01	1,37	0,43	0,10	7164,00	910,10	468,20
96000.	26,7	4,47	21,56	282,30	134,30	445,10	152,40	110,60	20,27	12,16	1,39	0,43	0,10	7204,00	914,90	471,10
96500.	26,8	4,49	21,64	283,70	135,40	448,80	153,80	111,30	20,38	12,31	1,41	0,44	0,10	7243,00	919,50	473,90
97000.	26,9	4,51	21,71	285,10	136,60	452,50	155,30	112,10	20,49	12,47	1,42	0,44	0,10	7283,00	924,20	476,70
97500.	27,1	4,53	21,79	286,50	137,80	456,30	156,90	112,90	20,60	12,63	1,44	0,45	0,10	7322,00	928,80	479,50
98000.	27,2	4,55	21,87	287,90	139,00	460,20	158,50	113,70	20,71	12,80	1,46	0,45	0,10	7360,00	933,30	482,20
98500.	27,4	4,56	21,94	289,30	140,30	464,40	160,20	114,60	20,83	12,99	1,48	0,46	0,10	7397,00	937,60	484,90
99000.	27,5	4,58	22,01	290,80	141,60	468,80	162,00	115,50	20,95	13,18	1,50	0,47	0,10	7434,00	941,90	487,50
99500.	27,6	4,60	22,08	292,30	143,00	473,30	163,90	116,40	21,08	13,39	1,53	0,47	0,11	7470,00	946,00	490,10
10000(	27,8	4,61	22,15	293,90	144,50	478,20	165,90	117,40	21,22	13,61	1,55	0,48	0,11	7505,00	950,00	492,60
10050(	27,9	4,63	22,22	295,70	146,00	483,40	168,10	118,50	21,36	13,85	1,58	0,49	0,11	7540,00	953,90	495,10
10100(	28,1	4,65	22,29	297,40	147,70	488,80	170,30	119,60	21,51	14,10	1,61	0,50	0,11	7574,00	957,80	497,50
10150(	28,2	4,66	22,36	299,10	149,30	494,30	172,60	120,70	21,66	14,35	1,63	0,50	0,11	7608,00	961,50	499,90
10200(	28,3	4,68	22,42	300,80	151,00	500,00	175,00	121,80	21,82	14,62	1,66	0,51	0,12	7641,00	965,20	502,30
10250(	28,5	4,69	22,48	302,50	152,80	505,80	177,40	123,00	21,98	14,90	1,70	0,52	0,12	7673,00	968,80	504,60
10300(	28,6	4,71	22,54	304,20	154,60	511,80	180,00	124,20	22,14	15,18	1,73	0,53	0,12	7705,00	972,30	506,90
10350(	28,8	4,72	22,60	306,00	156,50	518,00	182,60	125,50	22,31	15,48	1,76	0,54	0,13	7736,00	975,70	509,10
10400(	28,9	4,73	22,66	307,80	158,40	524,40	185,30	126,80	22,48	15,79	1,79	0,55	0,13	7766,00	978,90	511,20
10450(	29,0	4,75	22,72	309,60	160,30	531,00	188,10	128,10	22,66	16,11	1,83	0,56	0,14	7796,00	982,10	513,30
10500(	29,2	4,76	22,77	311,50	162,40	537,80	191,00	129,50	22,84	16,44	1,87	0,57	0,15	7825,00	985,20	515,40
10550(	29,3	4,77	22,83	313,50	164,50	544,80	193,90	130,90	23,03	16,78	1,90	0,58	0,15	7854,00	988,20	517,50
10600(	29,4	4,79	22,88	315,40	166,60	552,00	197,00	132,30	23,22	17,13	1,94	0,59	0,16	7882,00	991,20	519,50
10650(	29,6	4,80	22,93	317,40	168,80	559,30	200,10	133,80	23,42	17,49	1,98	0,61	0,17	7910,00	994,00	521,40
10700(	29,7	4,81	22,98	319,30	171,00	566,70	203,20	135,20	23,62	17,85	2,02	0,62	0,18	7937,00	996,90	523,40
10750(	29,9	4,82	23,03	321,30	173,20	574,10	206,40	136,70	23,82	18,22	2,06	0,63	0,20	7964,00	999,60	525,30
10800(	30,0	4,84	23,08	323,30	175,40	581,60	209,60	138,20	24,02	18,59	2,11	0,64	0,21	7990,00	1002,00	527,20
10850(	30,1	4,85	23,13	325,30	177,70	589,30	212,90	139,80	24,23	18,97	2,15	0,65	0,22	8016,00	1005,00	529,00
10900(	30,3	4,86	23,18	327,30	180,00	597,20	216,30	141,40	24,43	19,36	2,19	0,67	0,23	8041,00	1007,00	530,80
10950(	30,4	4,87	23,22	329,40	182,40	605,20	219,70	142,90	24,65	19,76	2,24	0,68	0,25	8066,00	1010,00	532,60
11000(	30,6	4,88	23,27	331,50	184,80	613,40	223,20	144,60	24,86	20,17	2,28	0,69	0,25	8090,00	1012,00	534,30
11050(	30,7	4,89	23,31	333,60	187,30	621,70	226,70	146,20	25,08	20,58	2,33	0,71	0,26	8114,00	1015,00	536,00
11100(	30,8	4,90	23,35	335,70	189,80	630,20	230,40	147,90	25,31	21,01	2,37	0,72	0,26	8138,00	1017,00	537,70
11150(	31,0	4,91	23,40	337,90	192,30	638,60	234,00	149,60	25,53	21,43	2,42	0,73	0,26	8162,00	1019,00	539,40
11200(	31,1	4,92	23,44	340,00	194,80	646,90	237,50	151,20	25,75	21,83	2,46	0,74	0,26	8186,00	1022,00	541,10

11250(	31,3	4,94	23,49	342,00	197,00	654,30	240,60	152,80	25,96	22,19	2,50	0,76	0,26	8211,00	1024,00	542,80
11300(	31,4	4,95	23,56	343,80	198,80	660,30	243,20	154,00	26,16	22,47	2,53	0,76	0,26	8237,00	1027,00	544,60
11350(	31,5	4,97	23,63	345,30	200,20	665,00	245,10	155,10	26,33	22,68	2,56	0,77	0,26	8263,00	1030,00	546,40
11400(	31,7	4,98	23,71	346,60	201,10	668,10	246,30	155,80	26,47	22,79	2,57	0,77	0,26	8289,00	1033,00	548,00
11450(	31,8	4,98	23,71	346,60	201,10	668,10	246,30	155,80	26,47	22,79	2,57	0,77	0,26	8289,00	1033,00	548,00
11500(	31,9	4,98	23,71	346,60	201,10	668,10	246,30	155,80	26,47	22,79	2,57	0,77	0,26	8289,00	1033,00	548,00
11550(	32,1	4,98	23,71	346,60	201,10	668,10	246,30	155,80	26,47	22,79	2,57	0,77	0,26	8289,00	1033,00	548,00
11600(	32,2	4,98	23,71	346,60	201,10	668,10	246,30	155,80	26,47	22,79	2,57	0,77	0,26	8289,00	1033,00	548,00
11650(	32,4	5,00	23,81	348,10	201,80	670,50	247,30	156,70	26,71	22,81	2,57	0,78	0,26	8343,00	1040,00	551,50
11700(	32,5	5,02	23,90	349,60	202,60	673,50	248,40	157,70	26,95	22,86	2,57	0,78	0,26	8397,00	1047,00	554,90
11750(	32,6	5,04	24,00	351,50	203,60	677,30	249,90	158,80	27,20	22,95	2,58	0,78	0,26	8450,00	1054,00	558,20
11800(	32,8	5,06	24,11	353,40	204,50	680,30	251,00	159,80	27,45	23,01	2,59	0,79	0,26	8505,00	1061,00	561,60
11850(	32,9	5,09	24,22	355,10	205,20	682,90	251,90	160,70	27,69	23,03	2,59	0,79	0,26	8562,00	1069,00	565,10
11900(	33,1	5,11	24,33	356,70	205,80	685,10	252,70	161,50	27,92	23,04	2,59	0,79	0,26	8620,00	1077,00	568,70
11950(	33,2	5,13	24,43	358,20	206,30	687,00	253,40	162,30	28,14	23,04	2,59	0,79	0,26	8679,00	1085,00	572,20
12000(	33,3	5,15	24,55	359,70	206,80	689,00	254,10	163,20	28,36	23,05	2,59	0,79	0,26	8738,00	1093,00	575,80
12050(	33,5	5,18	24,67	361,20	207,50	691,40	255,00	164,00	28,58	23,07	2,59	0,79	0,26	8797,00	1100,00	579,30
12100(	33,6	5,21	24,79	362,80	208,20	694,10	256,00	164,90	28,80	23,11	2,60	0,79	0,26	8856,00	1108,00	582,90
12150(	33,8	5,24	24,93	364,50	209,00	696,60	256,90	165,80	29,01	23,15	2,60	0,79	0,26	8916,00	1116,00	586,50
12200(	33,9	5,27	25,10	366,20	209,60	699,00	257,70	166,70	29,22	23,16	2,60	0,79	0,26	8976,00	1124,00	590,10
12250(	34,0	5,31	25,28	367,90	210,30	701,30	258,50	167,50	29,42	23,18	2,60	0,79	0,26	9036,00	1132,00	593,70
12300(	34,2	5,35	25,49	369,60	211,00	703,50	259,30	168,30	29,62	23,20	2,61	0,79	0,26	9095,00	1140,00	597,20
12350(	34,3	5,40	25,72	371,30	211,60	705,60	260,00	169,10	29,81	23,21	2,61	0,79	0,26	9154,00	1148,00	600,70
12400(	34,4	5,46	26,00	373,00	212,30	707,50	260,60	169,80	30,00	23,22	2,61	0,79	0,26	9213,00	1156,00	604,20
12450(	34,6	5,52	26,30	374,60	213,00	709,70	261,40	170,60	30,18	23,24	2,61	0,79	0,26	9271,00	1164,00	607,70
12500(	34,7	5,59	26,64	376,40	213,70	712,00	262,20	171,40	30,37	23,28	2,61	0,80	0,26	9327,00	1171,00	611,10
12550(	34,9	5,67	27,03	378,10	214,50	714,20	263,00	172,20	30,55	23,31	2,62	0,80	0,26	9384,00	1179,00	614,40
12600(	35,0	5,76	27,47	379,90	215,30	716,20	263,70	172,90	30,73	23,34	2,62	0,80	0,26	9440,00	1186,00	617,80
12650(	35,1	5,86	27,97	381,70	216,00	718,10	264,40	173,60	30,91	23,36	2,62	0,80	0,26	9495,00	1194,00	621,10
12700(	35,3	5,98	28,52	383,60	216,80	720,10	265,10	174,30	31,08	23,38	2,63	0,80	0,26	9549,00	1201,00	624,30
12750(	35,4	6,10	29,11	385,60	217,70	722,20	265,80	175,00	31,26	23,42	2,63	0,80	0,26	9603,00	1208,00	627,50
12800(	35,6	6,23	29,78	387,60	218,50	724,20	266,40	175,70	31,43	23,45	2,63	0,80	0,26	9656,00	1215,00	630,70
12850(	35,7	6,38	30,50	389,60	219,50	726,40	267,20	176,40	31,61	23,50	2,64	0,80	0,26	9708,00	1222,00	633,80
12900(	35,8	6,54	31,27	391,70	220,50	728,70	268,00	177,10	31,79	23,56	2,65	0,80	0,26	9759,00	1229,00	636,90
12950(	36,0	6,71	32,13	393,80	221,50	730,90	268,80	177,80	31,97	23,62	2,65	0,81	0,26	9811,00	1236,00	639,90
13000(	36,1	6,90	33,08	396,00	222,60	732,80	269,50	178,50	32,15	23,66	2,66	0,81	0,26	9862,00	1243,00	643,00
13050(	36,3	7,11	34,10	398,20	223,60	734,60	270,10	179,10	32,32	23,71	2,66	0,81	0,26	9912,00	1249,00	646,00
13100(	36,4	7,33	35,19	400,50	224,60	736,40	270,70	179,80	32,49	23,75	2,67	0,81	0,26	9962,00	1256,00	648,90
13150(	36,5	7,57	36,34	402,80	225,70	738,30	271,40	180,40	32,66	23,81	2,68	0,81	0,26	10010,00	1262,00	651,80
13200(	36,7	7,82	37,57	405,30	226,90	740,30	272,00	181,00	32,84	23,87	2,68	0,82	0,26	10060,00	1269,00	654,70
13250(	36,8	8,08	38,88	407,90	228,20	742,60	272,80	181,70	33,02	23,95	2,69	0,82	0,26	10110,00	1275,00	657,50
13300(	36,9	8,36	40,27	410,50	229,60	744,90	273,70	182,40	33,21	24,04	2,71	0,82	0,27	10150,00	1281,00	660,30
13350(	37,1	8,67	41,79	413,20	231,00	747,10	274,40	183,10	33,40	24,13	2,72	0,83	0,27	10200,00	1288,00	663,20
13400(	37,2	9,00	43,43	416,00	232,40	749,00	275,10	183,70	33,58	24,21	2,73	0,83	0,27	10250,00	1294,00	666,00
13450(	37,4	9,35	45,17	418,80	233,80	750,80	275,70	184,30	33,77	24,29	2,73	0,83	0,27	10290,00	1300,00	668,70
13500(	37,5	9,71	47,00	421,70	235,20	752,60	276,30	184,90	33,95	24,37	2,74	0,83	0,27	10340,00	1306,00	671,40
13550(	37,6	10,10	48,92	424,70	236,80	754,50	277,00	185,50	34,14	24,46	2,76	0,84	0,27	10380,00	1312,00	674,00
13600(	37,8	10,51	50,95	427,90	238,40	756,40	277,60	186,10	34,33	24,56	2,77	0,84	0,27	10430,00	1318,00	676,60
13650(	37,9	10,94	53,09	431,20	240,10	758,50	278,30	186,80	34,52	24,67	2,78	0,85	0,27	10470,00	1323,00	679,20
13700(	38,1	11,39	55,37	434,60	241,90	760,80	279,10	187,40	34,72	24,80	2,80	0,85	0,27	10510,00	1329,00	681,80
13750(	38,2	11,88	57,81	438,20	243,90	763,00	279,90	188,10	34,93	24,93	2,81	0,86	0,27	10560,00	1335,00	684,40
13800(	38,3	12,40	60,42	441,90	245,80	765,00	280,60	188,70	35,14	25,06	2,83	0,86	0,27	10600,00	1340,00	686,90
13850(	38,5	12,95	63,20	445,70	247,90	766,90	281,30	189,30	35,34	25,19	2,84	0,87	0,27	10640,00	1346,00	689,40
13900(	38,6	13,53	66,08	449,60	250,00	768,80	281,90	189,80	35,55	25,32	2,86	0,87	0,27	10680,00	1351,00	691,90
13950(	38,8	14,13	69,10	453,60	252,10	770,80	282,60	190,40	35,76	25,47	2,88	0,88	0,27	10720,00	1356,00	694,20
14000(	38,9	14,76	72,30	457,80	254,40	772,70	283,20	191,00	35,98	25,62	2,90	0,88	0,27	10760,00	1362,00	696,50
14050(	39,0	15,44	75,70	462,30	256,90	774,80	284,00	191,50	36,20	25,79	2,92	0,89	0,27	10800,00	1367,00	698,80
14100(	39,2	16,15	79,30	467,00	259,50	777,00	284,70	192,20	36,43	25,98	2,94	0,90	0,27	10840,00	1372,00	701,10
14150(	39,3	16,91	83,15	472,00	262,30	779,40	285,60	192,80	36,67	26,19	2,96	0,91	0,27	10880,00	1376,00	703,30
14200(	39,4	17,73	87,29	477,20	265,20	781,70	286,40	193,40	36,92	26,40	2,99	0,91	0,27	10910,00	1381,00	705,60
14250(	39,6	18,61	91,76	482,70	268,30	783,90	287,20	194,00	37,18	26,63	3,02	0,92	0,27	10950,00	1386,00	707,70
14300(	39,7	19,55	96,53	488,40	271,60	786,10	287,90	194,60	37,44	26,86	3,05	0,93	0,27	10980,00	1390,00	709,80
14350(	39,9	20,53	101,50	494,50	275,00	788,30	288,70	195,10	37,71	27,11	3,08	0,94	0,27	11020,00	1395,00	711,90
14400(	40,0	21,57	106,80	500,80	278,60	790,60	289,50	195,70	37,98	27,38	3,11	0,95	0,27	11050,00	1399,00	713,90
14450(	40,1	22,66	112,40	507,40	282,50	792,90	290,30	196,30	38,27	27,67	3,14	0,96	0,27	11080,00	1403,00	715,80
14500(	40,3	23,83	118,40	514,40	286,60	795,30	291,10	196,90	38,57	27,98	3,18	0,97	0,27	11120,00	1407,00	717,70
14550(	40,4	25,03	124,60	521,80	290,90	798,00	292,00	197,50	38,88	28,31	3,22	0,99	0,27	11150,00	1411,00	719,60
14600(	40,6	26,29	131,10	529,60	295,50	800,80	293,00	198,10	39,21	28,68	3,26	1,00	0,27	11180,00	1415,00	721,40
14650(	40,7	27,62	138,00	537,70	300,30	803,60	294,00	198,70	39,55	29,06	3,31	1,02	0,28	11210,00	1419,00	723,20
14700(	40,8	29,00	145,10	546,10	305,40	806,30	295,00	199,30	39,91	29,47	3,36	1,03	0,28	11240,00	1422,00	724,80
14750(	41,0	30,42	152,50	554,80	310,70	808,90	295,90	199,90	40,27	29,89	3,41	1,05	0,28	11260,00	1425,00	726,40
14800(	41,1	31,85	160,10	563,60	316,10	811,60	296,90	200,50	40,63	30,34	3,46	1,06	0,28	11290,00	1428,00	727,90
14850(	41,3	33,30	167,70	572,70	321,70	814,30	297,80	201,00	41,01	30,80	3,52	1,08	0,28	11310,00	1431,00	729,30
14900(	41,4	34,78	175,60	582,00	327,50	817,00	298,80	201,50	41,40	31,29	3,58	1,10	0,28	11330,00	1434,00	730,60
14950(	41,5	36,28	183,60	591,50	333,50	819,80	299,80	202,10	41,80	31,80	3,64	1,11	0,28	11360,00	1436,00	731,90
15000(	41,7	37,80	191,60	601,20	339,60	822,60	300,80	202,60	42,20	32,32	3,70	1,13	0,28	11380,00	1439,00	733,20

15050(	41,8	39,31	199,70	610,90	345,80	825,50	301,80	203,20	42,60	32,84	3,76	1,15	0,28	11400,00	1441,00	734,40
15100(	41,9	40,82	207,80	620,60	351,90	828,40	302,90	203,80	43,01	33,36	3,82	1,17	0,28	11420,00	1444,00	735,60
15150(	42,1	42,34	215,90	630,30	358,10	831,30	303,90	204,30	43,41	33,88	3,88	1,19	0,28	11440,00	1446,00	736,80
15200(	42,2	43,73	223,30	639,30	363,80	834,10	304,90	204,90	43,77	34,36	3,94	1,21	0,28	11460,00	1448,00	737,90
15250(	42,4	44,84	229,30	646,70	368,40	836,70	305,80	205,40	44,08	34,75	3,99	1,22	0,28	11470,00	1450,00	738,90
15300(	42,5	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15350(	42,6	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15400(	42,8	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15450(	42,9	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15500(	43,1	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15550(	43,2	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15600(	43,3	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15650(	43,5	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15700(	43,6	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15750(	43,8	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15800(	43,9	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15850(	44,0	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60
15900(	44,2	45,64	233,60	652,20	371,90	839,00	306,70	205,80	44,30	35,06	4,02	1,23	0,28	11490,00	1451,00	739,60

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