Air under the Surface
– Particulate Concentrations in a Submarine Work Environment

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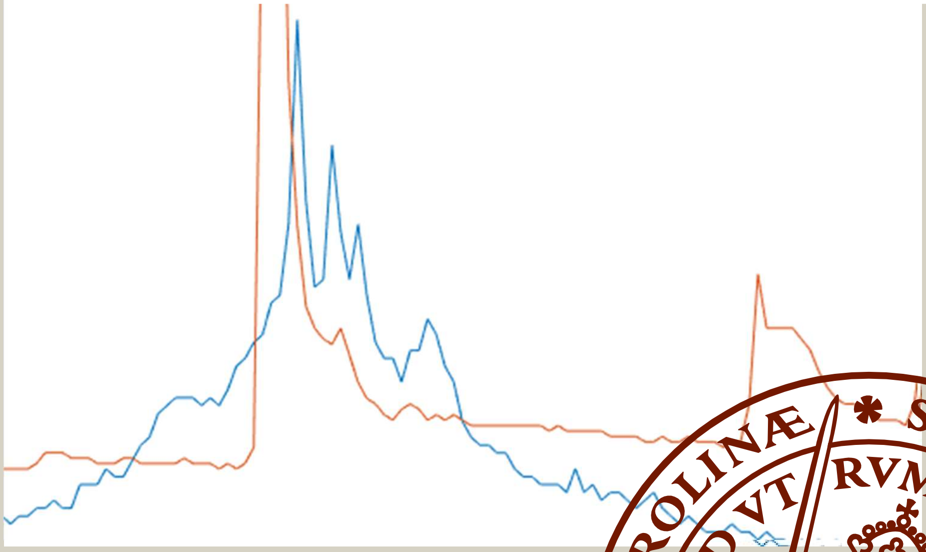

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Abstract

On board a submarine the crew is exposed to the same air environment for a long time. In this thesis typical indoor air quality parameters were analysed in a field measurement on board a submarine in the Swedish Navy. The submarine air quality was evaluated by highly time-resolved measurements of ultrafine particles (UFPs), black carbon (BC), $PM_{2.5}$ (mass concentration for particles below 2.5 μm in diameter), volatile organic compounds (VOC), carbon dioxide (CO_2), pressure, temperature, relative humidity and polycyclic aromatic hydrocarbons (PAHs). The measurements lasted for four days in total and were divided in three measurement periods over an 11 day sailing. Measurements were conducted in the accommodation space of the submarine and in the machinery room. In the analysis of the parameters in the accommodation space, concentrations of $PM_{2.5}$ reached 210 μg/m^3 during frying in the kitchen of the submarine. High concentrations of VOC were found during use of the oven, the VOC concentration reached a maximum of 2.83 ppm. During surface mode and when the hatches to the atmosphere were open, BC from the diesel exhaust was found infiltrating the submarine indoor air. The mean CO_2 level was 1700 ppm which was over the recommended level of 1000 ppm, but below the allowed of 5000 ppm. The analysis of the machinery room showed elevated mean concentration of $PM_{2.5}$ compared to the accommodation space. The average $PM_{2.5}$ concentration was 15 μg/m^3 in the machinery room whilst 4 μg/m^3 in the accommodation space. During starting and stopping of the diesel engines the $PM_{2.5}$ peaked in the machinery room. Increases in UFP concentrations could be seen after the stopping of diesel engines. The machinery room had a mean total PAH concentration of 579 ng/m^3 and the accommodation space had correspondingly a concentration of 152 ng/m^3. Although further assessments are required to assess the worker exposure levels, this study shows that the machinery room can be an area of the submarine where the occupation should be as low as possible when the diesel engines are operating.

Keywords: Indoor air quality, Submarine, Field measurement, Ultrafine particles, Black carbon, Underwater work environments

Sammanfattning

Besättningen ombord på en ubåt spenderar lång tid i ett slutet utrymme. I det här examensarbetet analyserades typiska luftkvalitetsparametrar för inomhusluft ombord en ubåt i det svenska försvaret. Ubåtens luftkvalitet blev utvärderad med tidsupplösta mätningar av ultrafina partiklar (UFP), black carbon (BC), $PM_{2.5}$ (masskoncentrationen av partiklar under 2.5 μm i diameter), lättflyktiga organiska föreningar (VOC), CO_2, tryck, temperatur, relativ luftfuktighet och polycykliska aromatiska kolväten (PAH). Mätningen utfördes på en segling som varade i 11 dagar och utfördes i mässen (besättningens matsal) och i maskinrummet. Mätningen i sig varade i sammanlagt fyra dagar och var indelad i tre mätperioder över den 11 dagar långa seglingen.

Luften i mässen visade höga partikelkoncentrationer vid matlagning. Den högsta koncentrationen av $PM_{2.5}$ uppmättes vid stekning och nådde då en maximal koncentration på 210 μg/m^3. Även koncentrationerna för VOC ökade under matlagning, främst då ugnen användes och då uppnåddes en koncentration på 2.83 ppm. Vid ytläge och öppna manluckor detekterades BC partiklar från avgaser i mässen. Analysen av maskinrummet visade på förhöjda koncentrationer av $PM_{2.5}$ jämfört med i mässen. Medelkoncentrationen var 15 μg/m^3 i maskinrummet medan den bara var 4 μg/m^3 i mässen. CO_2 nivån var 1700 ppm vilket överskrider den rekommenderade nivån på 1000 ppm, men är under den tillåtna på 5000 ppm. $PM_{2.5}$ pikade vid start och stopp av dieselmotorerna. Ökning av UFP detekterades vid stopp av dieselmotorerna. Maskinrummet visade en total PAH medelkoncentration på 579 ng/m^3 och mässen uppmätte motsvarande en koncentration på 152 ng/m^3. Fler utvärderingar av luften ombord bör utföras men maskinrummet kan vara en del av ubåten man bör vistas i endast då det är nödvändigt när dieslarna körs.

Nyckelord: Luftkvalitet i inomhusmiljö, ubåt, mätning ombord, ultrafina partiklar, black carbon, arbetsmiljö under vatten

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List of acronyms and abbreviations

ACC	accomodation space
AFS	Arbetsmiljöverkets författningssamling (Rules from the Swedish Work Environmental Authority)
B(a)Peq	equivalents of benzo(a)pyrene
BC	black carbon
CO_2	carbon dioxide
IARC	International Agency for Research on Cancer
IKDC	Ingvar Kamprad Designcentrum
MAR	machinery room
NaCl	sodium chloride
OEL	occupational exposure limit
PAH	polycyclic aromatic hydrocarbon
PUF	polyurethane foam
RH	relative humidity
SMPS	scanning mobility particle sizer
TEF	toxic equivalency factor
UFP	ultrafine particle
US EPA	U.S. Environmental Protection Agency
VOC	volatile organic compound
WHO	World Health Organization

1 Introduction

1.1 Background and Aim of the Project

The World Health Organization (WHO) has concluded that air pollution is a major environmental risk to health [1]. Air pollution is estimated to cause 4.2 million premature deaths per year all around the globe [1]. Especially $PM_{2.5}$ (particulate matter of 2.5 μm or less in aerodynamic diameter) is associated with cardiovascular and respiratory diseases and it can also cause lung cancer [1]. In Sweden and other countries alike the majority of time is spent indoors, approximately 90% [2]. Normally, the indoor particle composition is a mixture of both particles infiltrated from outdoors and particles generated from indoor activities [2]. But what happens when we have an entirely closed system as in a submarine? The studies made public in this environment are few. The air quality on board of submarines need to be studied and evaluated because the crew is exposed to a closed indoor environment for a long time. The particles and gases that may accumulate in the submarine environment could have a negative health effect on the crew. The aim with this project was to analyse particle concentrations and gas contaminants of relevance for occupational exposure assessments in submarine air. In this project, the submarine air quality was evaluated by highly time-resolved measurements of ultrafine particles (UFPs), black carbon (BC), $PM_{2.5}$ (mass concentration for particles below 2.5 μm in diameter), volatile organic compounds (VOCs), carbon dioxide (CO_2), pressure, temperature, relative humidity and polycyclic aromatic hydrocarbons (PAHs).

Measurement of the submarine air contaminants was previously conducted by Persson et al. [3]. They measured oxygen, carbon dioxide, hydrogen, VOC, formal dehyde, nitrogen dioxide and ozone [3]. In addition, particulate matter and microbiological contamination were measured [3]. These measurements did not show any concentrations exceeding the Swedish Occupational Exposure Limits (OEL) [3]. In the measurement conducted by Persson et al. an optical particle counter for coarse particles in a size range of 1-10 μm was used [3]. The air in indoor environments has been studied by Omelekhina et al. [4] where they found that especially cooking can emit high particle mass concentrations [4].

In addition to coarse particles in the size range 1-10 μm, this project will characterize UFP concentrations. UFP are particles in the size range of 100 nm in diameter or less. The small particle sizes, the high number concentration and the large surface area make UFP a health risk. The characteristics of UFP enable a high deposition efficiency in the lungs and can cause inflammation in the pulmonary region. [5]

Another novelty in this thesis is the analysis of Black carbon (BC). BC is a major component of soot and soot from combustion is a big contributor to atmospheric particulate matter [7]. It is known that BC has health effects on humans; inhalation of BC can lead to cardiovascular diseases and premature deaths [7]. It is relevant to measure BC due to that combustion occur on board and unfiltered ambient air can infiltrate the submarine through the mast or through the hatches.

PAHs are emitted from cooking and incomplete combustion and are also considered in this study.

1.2 Aerosol Technology

William C. Hinds describes in his book *Aerosol Technology* (1999) the properties, behavior and measurement of airborne particles. Basic facts about aerosol technology are presented in this section. The definition of an aerosol is a collection of solid or liquid particles suspended in a carrier gas, usually air. The air that we breathe contains microscopic particles. These particles are created by human activities, from so called antropogenic sources such as smoke from power generation, cooking and cleaning spray. There are also natural sources of aerosols, for instance wildfires, ocean spray and resuspended soil. Aerosol technology has grown from 1970 until today especially due to the increasing environmental awareness and of the health effects caused from air pollution in our communities. Aerosols are commonly measured in mass concentration i.e. the mass of particulate matter in a unit volume of aerosol. Particle size is commonly described with the aerodynamic particle diameter. The aerodynamic particle diameter is the equivalent diameter to the one of a spherical particle with a density of 1000 kg/m^3 with the same settling velocity as the investigated particle. The number concentration is also a property commonly used for describing an aerosol and is the number of particles per unit volume commonly expressed in particles/cm^3. [8]

1.3 Submarine Air Quality and OELs

A submarine forms a confined indoor environment where the crew is onboard for sometimes several weeks without resurfacing. The air quality onboard is due to this full-time occupation central for the well being and performance of the crew. A submariner is normally onboard 60-70 days per year and is on his or her freetime between shifts still exposed to the same enclosed habitat. The Swedish Work Environmental Authority (AFS) has stated occupational exposure limits (OELs) for workplaces and they are calculated for eight hour workdays. There are also short time exposure limits which are calculated for 15 minute exposure. The OELs consider substances and aerosols which can lead to illness for the person being exposed to it [9]. This report consists of an analysis of the parameters $PM_{2.5}$, black carbon (BC) and CO_2 which have stated OELs. 32 individual Polycyclic Aromatic Hydrocarbons (PAHs) were also analysed and there are stated OELs for two PAHs; benzo(a)pyrene and naphtalene. The previously mentioned PAHs have short-time OELs, this is the hygienic limit for 15 minute exposure [9].

The submarine is equipped with a CO_2 purification system where a soda-lime filter is used for removing the CO_2 from the air.

1.3.1 $PM_{2.5}$

The mass concentration of particles below 2.5 μm in aerodynamic diameter are referred to as $PM_{2.5}$. The U.S. Environmental Protection Agency (USEPA) established this particle standard due to a minimum of the ambient particle size distribution at 2.5 micrometers and that combustion products have aerodynamic particle diameters smaller than this. WHO presented thereafter $PM_{2.5}$ as a hazard for respiratory health. [10]

The Swedish OEL for an eight hour work day is 5 mg/m^3 for respirable inorganic dust [9]. There is no maximum short time exposure level for respriable dust stated by AFS. [9]. The World Health Organization (WHO) has stated air quality guidelines for $PM_{2.5}$ for prolonged exposure; 10 μg/m^3 (annual mean) and 25 μg/m^3 (24-hour mean) [1]. Note that the guidelines from WHO are expressed in μg/m^3 and the Swedish OEL in mg/m^3.

For a comparison to other indoor environments, a study by Omelekhina et al. [4] found an average of particle mass concentration of 15.6 μg/m^3 in a residential home in Sweden. The mass concentration peaks reached 15.7 mg/m^3 during the use of E-cigarettes indoors. Cooking contributed with a 9 μg/m^3 increase of the average particulate concentration. [4]

Other studies on indoor PM$_{2.5}$ have been conducted in Helsinki, Finland where the mean PM$_{2.5}$ of 102 homes was 9.2 μg/m^3 from personal sampling [11]. In Agria, India the mean PM$_{2.5}$ was as high as 156.4 μg/m^3 in five urban homes [12]. Measurements in 212 non-smoking homes in Houston, TX, Los Angeles, CA and Elisabeth, NJ, U.S.A. found an average of 17.6 μg/m^3 [13].

A study by Zhang et al. [14] found the PM$_{2.5}$ mass concentration being highly affected by residential indoor cooking and the average concentration ranged from 10.0 μg/m^3 to 230.9 μg/m^3 [14].

1.3.2 Ultrafine Particles

Ultrafine Particles (UFP) are particles that are smaller than 100 nm. Indoor UFP is important to study in a health perspective, the high concentration and surface area lead to a high deposition efficiency in the pulmonary region. Once the UFPs are deposited in the pulmonary region they can cause inflammation and also be transferred to the blood system. In a clean environment the daily mean number concentration of the UFP is expected to be less than 1000 particles/cm^3 and in an urban background it is expected to be less than 10,000 particles/cm^3. UFP air concentrations tend to vary largely in a spatial and temporal way and an hourly mean concentration in an urban background typically is less than 20,000 particles/cm^3. [5]

The main sources to the generation of UFP are combustion processes and chemical processes of gaseous precursors in the atmosphere [15]. Cooking is also a contributor to UFP generation, a study by Zhang et al. [14] found an average concentration emissions ranging from $1.34 \cdot 10^4$ particles/cm^3 to $6.04 \cdot 10^5$ particles/cm^3 [14]. These were 550 times higher concentrations than under no cooking conditions [14]. The UFP concentrations could be decreased by decreasing the stove temperature and turning on the kitchen fan [14]. A study by Dennekamp, Howarth, Dick et al. [16] found high UFP concentrations during indoor cooking mainly during frying and cooking of fatty foods [16]. High concentrations were also obtained during combustion of the gas from the gas stove [16]. Frying bacon could cause UFP number concentration of $5.9 \cdot 10^5$ UFPs/cm^3 [16].

1.3.3 Black Carbon

Soot is the product of the incomplete combustion processes of carbonaceous fuels. When measuring the light-absorbing properties one refers to soot as black carbon (BC) due to that the substances that absorb the light are carbonaceous. A major source to the soot emissions are diesel-driven vehicles including road vehicles and ships [7]. Besides contributing to the global warming, BC has shown negative health impact on humans [17]. The International Agency for Research on Cancer (IARC) stated BC as being possibly carcinogenic to humans [7]. Due to that the submarine is propelled with diesel engines when it is operating on the surface the measurement of BC is relevant for the air quality on board. During surface operation the hatches are for the most part open, hence the diesel engine exhaust may enter the otherwise confined inside of the submarine.

BC have been monitored in outdoor and indoor environment for studying the BC infiltrated from outdoors. A study by Omelekhina et al. (2019) found an average BC concentration of 900 ng/m^3 in a residential indoor environment in Sweden [2]. The BC contributed to 6 % of the total airborne particle mass and the BC was infiltrated from outdoor particle mass and also from candle burning [2]. The OEL for respirable coal dust which contains BC is 3 mg/m^3 [9].

The BC concentration generated by cooking have been studied by Zhang et al. [14]. They found an average BC mass concentration of 100-800 ng/m^3 in residential kitchen air by different stove cooking activities such as frying [14]. The concentration was found increasing even after the stove was switched off [14].

1.3.4 Pressure, CO_2, Humidity and Temperature

CO_2 is a gas that occurs naturally in the air and it can not be sensed by smell or sight [18]. The normal CO_2 concentration in the air is 0.04% (400 ppm) and the Swedish OEL is set to 0.5% (5000 ppm) [9]. In indoor environments the human metabolism is the major contributor to increased CO_2 and this is called bioeffluent

CO_2 [19]. The exhaled air contains a CO_2 concentration that is hundred times higher than the one inhaled, approximately 40,000 - 55,000 ppm [19].

CO_2 is a product of the metabolism in our cells. It is carried by the blood from the parts of our body to the lungs. In the lungs, the CO_2 is released from the alveolar system to the ambient air. Due to that the CO_2 lowers the pH level in the blood the body releases CO_2 for preserving the acid-base balance in the blood. A CO_2 level of 10,000 ppm during 30 minutes in the inhaled air will lead to respiratory acidosis which is a condition when the pH level decreases in the blood and causes headaches, anxiety and drowsiness. [18]

Studies have shown that a CO_2 concentration level over 500 ppm can affect the human body physically by increasing blood pressure and heart rate. Already at a CO_2 level of 1000 ppm there are effects on the performance in decision making and problem resolution. However, the typical indoor CO_2 concentration is 800-1000 ppm. [18]

Persson et al. found in an earlier study on the Gotland Class submarines relatively high average carbon dioxide concentrations of 0.5% during a long submersion period [3]. The Swedish Defence Materiel Administration has stated requirements and recommendations for CO_2. The CO_2 concentration is not recommended to exceed 1000 ppm for a 30 day exposure [20]. The CO_2 is measured continuously on board the Gotland class submarines.

The CO_2 concentration can be used combined with the BC concentration as a trace gas for determining whether diesel or stirling exhausts are present in the submarine air because of both CO_2 and BC are products of combustion.

The temperature is recommended by the Swedish Defence Materiel Administration to be 18-23°C for a long term exposure. There are no recommendations for the relative humidity. [20]

1.3.5 Volatile Organic Compounds

Volatile Organic Compounds (VOCs) include organic substances with boiling points between 50-260°C. Total Volatile Organic Compounds (TVOC) designates the collective VOC concentration. VOCs are common air contaminants but usually at much lower concentrations than those specified by the OELs. The concentrations are found higher in indoor environments. VOC can be infiltrated from outdoors to indoors, other different sources to VOC in indoor environments are other forms of combustion, building materials and furnishing, activities and people. There are no guidelines for which the VOC concentrations should not exceed when a mixture of VOCs is measured. VOC can cause an apprehension of bad air quality in the cause of smell, eye and also throat irritation. Additionally, VOC can cause difficulties in thinking, headaches, weariness and nausea. [21]

An earlier study by Persson et al. [3] the VOC concentration on board a Gotland Class submarine was measured in the Stirling engine section. The VOC concentration exceeded 1 ppm once and they found no increase of VOC during longer submersion time [3]. They found no difference in VOC concentration during diesel operation and Stirling engine operation [3].

1.3.6 Polycyclic Aromatic Hydrocarbons

A study by Strandberg et al. [23] claimed that the fuel can affect the air quality onboard ships due to its Polycyclic Aromatic Hydrocarbon (PAH) content [23]. PAHs are a class of chemicals that are of interest to monitor due to the carcinogenic nature of some of them [23]. The Swedish OELs for benzo(a)pyrene and naphtalene are 0.002 mg/m^3 and 50 mg/m^3 respectively [9]. Benzo(a)pyrene is classified by the IARC as being carcinogenic and naphtalene is classified as possible carcinogenic [24]. Other PAHs indicates an impact on the likelihood to develop cancer due to exposure and are therefore also of importance to measure [24].

PAHs can be formed by combustion processes and additionally high temperature cooking can generate PAHs in the food [25]. The PAHs can stick to small particles in the air which is called the particulate phase. The sampling of PAH can be conducted by using Polyurethane Foam (PUF) passive air samplers which are small cylindrical shaped samplers which will take up individual PAH in both the particulate phase and the gaseous phase [24]. The samplers are then analyzed in a laboratory and the mean concentrations can be obtained. In this study 32 individual PAHs will be analyzed including the 16 PAHs prioritized by the United States Environmental Protection Agency (US EPA).

Benzo(a)pyrene is classified by IARC as being carcinogenic and the carcinogenic risk of PAH mixtures in an environment can be compared to others by calculating the equivalents of benzo(a)pyrene (B(a)Peq). This is accomplished by multiplying each concentration of the individual PAHs with a toxic equivalency factor (TEF) [26]. The alkylated PAHs do not yet have confirmed TEFs.

2 Methodology

Measurements on the indoor air quality were conducted on a sailing of 11 days onboard of the Gotland submarine in March 2020. In total, three measurement periods were recorded the following days of the sailing: 1-2, 6-7 and 9-11. Measurements were performed in the mess (the dining area) which is a part of the accommodation space (ACC) and in the machinery room (MAR) of the submarine. The position of the measurement can be seen in Figure 1. The handling of the instruments were delegated to an employee of SAAB Kockums who was onboard during the first measurement period. The starting and stopping of the two other measurement periods were delegated to a crew member. Machinery systems were tested onboard during the sailing, hence, the instruments were not allowed to be running during the whole sailing period. This type of sailing is called a sea trial and the operation in submerged condition was 16 h at its longest.

MAR - Machinery Room
MCR - Machinery Control Room
EC - Electronic Central
SS - Stirling Section
CR - Control Room
AMS - Auxiliary Machinery Space
ACC - Accommodation Space
TR - Torpedo Room

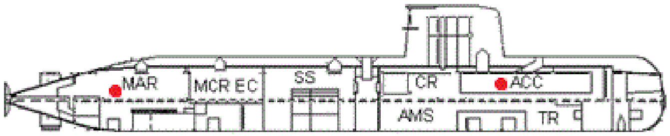


Figure 1: The spots of the two measurement sites in a cross-sectional view of the Gotland Submarine [27].

Time-resolved measurements were performed for carbon dioxide (CO_2), VOC, temperature, relative humidity, pressure, $PM_{2.5}$, ultrafine particles (UFPs) and black carbon (BC). Additionally, the concentration of polycyclic aromatic hydrocarbons (PAH) was measured with polyurethane foam passive air samplers (PUF) for the whole sailing period. The duration of the measurement periods can be seen in Table 1 together with the hours of submersion. The duration differed for the instruments, the durations given in Table 1 are therefore approximated for the instruments in ACC and in MAR. The duration differed due to different starting and stopping times, it was not possible to start and stop all of the instruments at the same time.

Table 1: The days of the sailing that measurement was conducted in the accomodation space (ACC) and in the machinery room (MAR). The hours of submersion for the measurement periods are also shown.

Days of the sailing	*Hours in ACC*	*Hours in MAR*	*Hours of Submersion*
1-2	30 h	32 h	0 h
6-7	26 h	30 h	10 h
9-11	40 h	40 h	16 h

2.1 Measurements in the Accommodation Space

The accommodation space (ACC) is adjacent to the galley (the kitchen). The instruments were placed on a cabinet and the instruments were located close to the ceiling and in the corner of ACC. The set-up is depicted in Figure 2. The instruments included in the set-up were DustTrak, VelociCalc and microAeth. The picture is taken in the aerosol laboratory in Ingvar Kamprad Designcentrum (IKDC).

Figure 2: The set-up in the accommodation space (ACC).

PUF-samplers were placed on the side of the box during the whole sailing of 11 days that accumulate PAHs in the submarine air. They were stored in a freezer (-20 °C) before and after the sailing. The PAH concentration was analyzed by Bo Strandberg, Associate professor at Division of Occupational and Environmental Medicine, Lund University.

2.1.1 Measuring $PM_{2.5}$ with DustTrak

Time-resolved mass concentration reading with gravimetric sampling was achieved with a DustTrak (DustTrak DRX Aerosol Monitor Model 8533, TSI inc, Minnesota, USA). This is a light-scattering laser photometer with a separator that lets the particles with an aerodynamic particle diameter of 2.5 μm or less ($PM_{2.5}$) pass through and be measured [28]. Hence it will measure $PM_{2.5}$ in the air.

Before the measurements the flow rate was set to 3 liters/min with an external flow meter. The DustTrak was set on a program logging mode for extended periods of time and for conducting multiple samples. The logging interval was set to 20 seconds and the measuring range of this instrument is 0.001-150 mg/m^3.

2.1.2 Calibration and Accuracy of DustTraks

One DustTrak was placed in ACC and one in MAR. Simultaneously as the DustTraks were measuring optically a gravimetric sampling was conducted and the data read by the DustTraks was corrected by the gravimetric sampling. The correction procedure is described in the following text.

The DustTraks were equipped with filter holders for 37 mm filters. The mean concentrations for the whole sailing readings were calculated for ACC and MAR which gave the optic mean concentration. The gravimetric mean mass concentration was calculated by dividing the total collected mass with the total air volume passing the filter.

$$C_{gravimetric} = \frac{m_{particles}}{Q \cdot T} \tag{1}$$

Where Q is the flow rate (m$^3/s$), T is the total sample time (seconds) and $m_{particles}$ is the total collected particle mass (μg). The collected masses in ACC (38.3 μg) and MAR (155 μg) were divided with the flow rate Q = 2 liters/min = $3.33 \cdot 10^{-5}$ m$^3/s$ and the total sample times T = 305 800 s (MAR) and T = 301 100 s (ACC). For gravimetric analysis only 2/3 of the total flow is used since the sheath flow is 1/3 of the total flow.

Calibration factors were calculated in order to correct the data using the obtained mean concentration from the gravimetric sampling. The calibration factors were obtained by dividing the gravimetric mean concentrations with the optic mean concentrations. The data was then corrected by multiplying the calibration factors with the particle mass concentrations. The gravimetric mean concentrations, the optic mean concentrations and the calibration factors can be seen in Table 2.

Table 2: The table shows the optic and gravimetric mean mass concentrations expressed in μg/m^3 for the whole sailing in the locations ACC and MAR. The calibration factors for each instrument are also depicted.

Location	C_{optic} ***[μg/m^3]***	$C_{gravimetric}$ ***[μg/m^3]***	***Calibration factor*** ($\frac{C_{gravimetric}}{C_{optic}}$)
ACC	3.8	3.8	1
MAR	10.1	15.4	1.5248

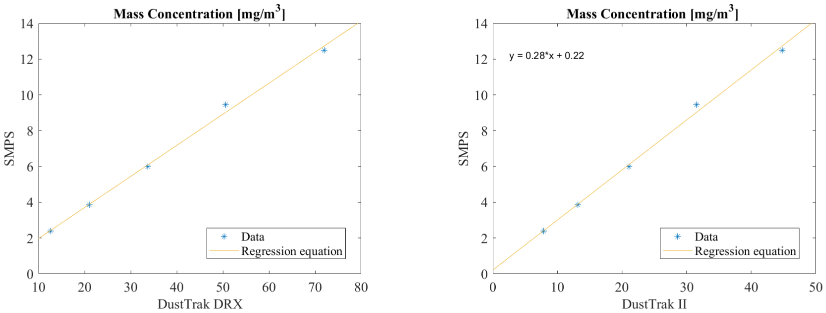
In addition to the filters in the DustTraks, three reference filters of the same kind were also weighed and brought on board. In order to weigh the particle mass the moisture has to be taken in consideration. Therefore, the filters were weighed several times before and after the onboard measurements. The reference filters will show an average of collected moisture mass. The moisture mass was then subtracted from the mass of the filters in the DustTraks and the collected particle mass was calculated. The weighing procedure was conducted with the following steps:

1. Deionization of the filters with a deionization fan (2020 Ionised Air Blower).

2. Weighing with a microgram scale.

3. Putting the filters in containers.

In order to investigate the accuracy of the DustTraks their performances were compared to a scanning mobility particle sizer (SMPS) system during soot generation in the Aerosol Laboratory Chamber at IKDC. A SMPS system is an aerosol measurement system for measuring size distributions of particles below 1 μm. The soot was generated from biomass burning in an African stove. The DustTraks had a log interval of 20 seconds and the measured values of mass concentration of soot particles in the chamber was compared to the ones measured by the SMPS. When calculating the mass concentration from the SMPS data the density of the particles were approximated to 1 g/m^3. The comparison of the mass concentration readings can be seen in Figure 3. The names of the DustTraks are *DustTrak DRX* and *DustTrak II*.



(a) DustTrak DRX **(b) DustTrak II**

Figure 3: A comparison between soot mass concentration readings by the DustTrak DRX and the DustTrak II with the SMPS system.

The linear regression equations for the mass concentrations obtained by the data fitting were:

$$C_{SMPS} = 0.17 \cdot C_{DustTrakDRX} + 0.24 \cdot 10^5 \tag{2}$$

$$C_{SMPS} = 0.28 \cdot C_{DustTrakII} + 0.22 \cdot 10^5 \tag{3}$$

These regression equations were not used to correct the data, the data was corrected using offline paticle measurements as described earlier in the report. The linear relationship between the readings by the SMPS and the DustTrak DRX and DustTrak II supports the reliability of the DustTrak readings.

2.1.3 VelociCalc

A VelociCalc (VelociCalc Air Velocity Meter Model 9565 Series, TSI inc, Minnesota, USA [29]), equipped with a probe (VOC Indoor Air Quality Probe Model 986, TSI inc, Minnesota, USA) was used for measuring carbon dioxide, VOC, temperature, relative humidity and pressure. This instrument uses photo-ionization detection (PID) technology for measuring VOC [30]. The VOCs are ionized in positive and negative ions by ultra violet light and are then detected by the charge [30]. The charge is then representative to the concentration of the VOC [30]. Each VOC has a characteristic potential energy which is required for the VOC to ionize [30]. The krypton lamp can detect VOC with an ionization energy up to 10.6 electron-volts (eV) [30].

The VelociCalc had its annual recalibration in July 2019 with isobutylene as calibration gas. In this study different kinds of VOCs will be present in the air of the submarine. The concentration will only represent one VOC at a time and by multiplying with a response factor a specific VOC can be depicted. In order to compare the measurements with an earlier study by Persson et al. [3] the VOC concentration was depicted in toluene (C_7H_8) equivalents [3]. During the measurements the logging interval was set to 20 seconds. The measuring range of the different parameters can be seen in Table 3.

2.1.4 microAeth

The microAeth (microAeth AE51, AethLabs, San Francisco, California [32]) is a portable instrument used for measuring black carbon (BC) concentrations in both indoor and outdoor environment. The working principle of the microAeth is measuring the absorption of transmitted light. BC absorbs light at the wavelength of 880 nm and by measuring the rate of change in absorption of transmitted light on the filter the concentration can be determined. [32]

A timebase of 300 seconds and a flow rate of 150 ml/min was selected. These operational settings were suitable for area monitoring with low BC mass concentrations [32].

2.1.5 Overview of the set-up in ACC

The instruments included in the set-up in the accomodation space (ACC) together with the measured parameter, the logging interval, measuring range and the resolution/accuracy are shown in Table 3.

Table 3: Overview of the instruments in the accommodation space.

Instrument	***Parameter***	***Logging interval***	***Range***	***Resolution/ Accuracy***
DustTrak DRX	PM 2.5	20 s	0.001-150 mg/m^3	+/- 0.001 mg/m^3
microAeth	BC	5 min	0-1 mg/m^3	1 ng/m^3
VelociCalc	CO_2	20 s	0 - 5,000 ppm	+/- 50 ppm
	VOC	20 s	10 - 20,000 ppb	10 ppb
	P_{atm}	20 s	0.7-1.2 bar	+/- 3%
	RH	20 s	5 to 95%	+/- 3%
	Temp	20 s	-10 - 60°C	+/- 0.5°C

The galley, in other words the kitchen of the submarine, is close to the accommodation space. The chef cooks breakfast, lunch, dinner and midnight snack every day. Which type of cooking (boiling, frying, use of oven) was determined by studying the menu. The particle mass concentration and VOC concentration could then be correlated to the type of cooking. The submarine was operating in surface mode during the sailing and hence the hatch was open to get fresh air into the submarine. The outdoor air is then mixed with the air in the confined space which can lower the concentrations of aerosols and gases accumulated inside of the submarine.

In submerged mode, the CO_2 concentration in the air is limited by CO_2 purification. The CO_2 purification consists of a soda-lime filter that reacts with the CO_2 and lower the concentration in the air. Due to saturation of the filter it has to be changed every day. It was kept logs of the soda-lime exchange in order to see the effects of the CO_2 purification.

2.2 Measurements in the Machinery Room

The Machinery Room (MAR) is located in the stern of the submarine and it is were the diesel engines are placed. The measurement equipment was placed in a box on the starboard side. The set-up can be seen in Figure 4. The set-up included a NanoTracer, a DustTrak and two PAH-samplers included. The PUF-samplers were placed on the side of the box during the whole sailing of 11 days alike in ACC. They were stored in a freezer (-20 °C) before and after the sailing. The PAH concentration was then analyzed in the laboratory.

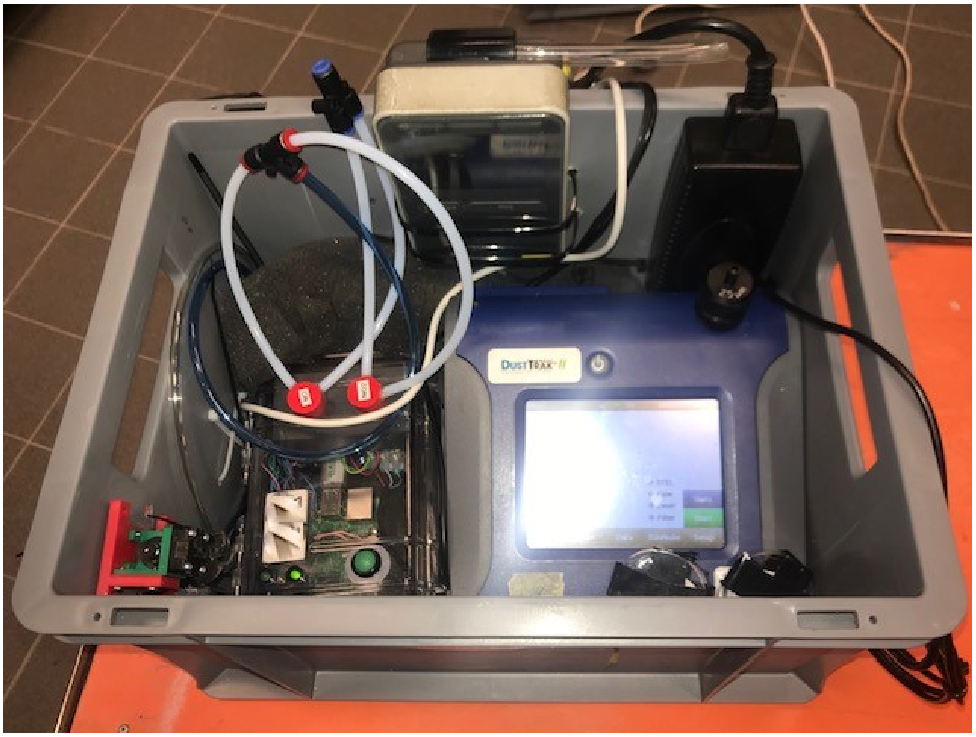


Figure 4: The set-up in the machinery room (MAR).

2.2.1 Overview of the set-up in MAR

The instruments included in the set-up in MAR together with the measured parameter, the logging interval, measuring range and the resolution/accuracy are shown in Table .

Table 4: An overview of the instruments placed in the machinery room (MAR).

Instrument	***Parameter***	***Logging interval***	***Range***	***Resolution***
DustTrak II	PM 2.5	20 s	0.001-400 mg/m^3	+/- 0.001 mg/m^3
NanoTracer	UFP Concentration	10 s	0-10^6 UFP/cm3	+/- 1500 UFP/cm3
	UFP Diameter	10 s	20-120 nm	+/- 10 nm

The staff on board made logs for the diesel engines and stirling engines in order to see variations of particle mass concentration and UFP number concentration in the air. Hydraulic oils are also sources to aerosols in this section of the submarine and may be detectable by the NanoTracer.

2.2.2 DustTrak

A DustTrak (DustTrak II Aerosol Monitor 8530, TSI inc, Minnesota, USA [28]) was included in the set-up in MAR. It is a similar model to the DustTrak in ACC but has another measuring range of 0.001-400 mg/m^3. For the rest this model of DustTrak uses the same light scattering technology for measuring PM$_{2.5}$. A flow calibration was conducted before the field measurements in order to set the flow to 3 liters/min. Due to the longer duration of the measurements a program logging mode for extend periods of time and for conducting multiple samples was chosen.

2.2.3 NanoTracer

For detecting ultrafine particles (UFPs) a NanoTracer (Philips Aerasense Nanotracer, Oxility, Netherlands) was used. The NanoTracer measures the average particle diameter and number concentration of UFPs in the size interval of 10-

300 nm. The NanoTracer measures the electrical charging of the particles in the sampled airflow. The measured sensor signal is proportional to the total number concentration and the number-averaged particle diameter.

2.2.4 Corrections for NanoTracer

The number concentration and the average particle diameter measured by the NanoTracer was compared to a scanning mobility particle sizer (SMPS) system. The set-up for aerosol generation, conditioning and readings is depicted in Figure 5.

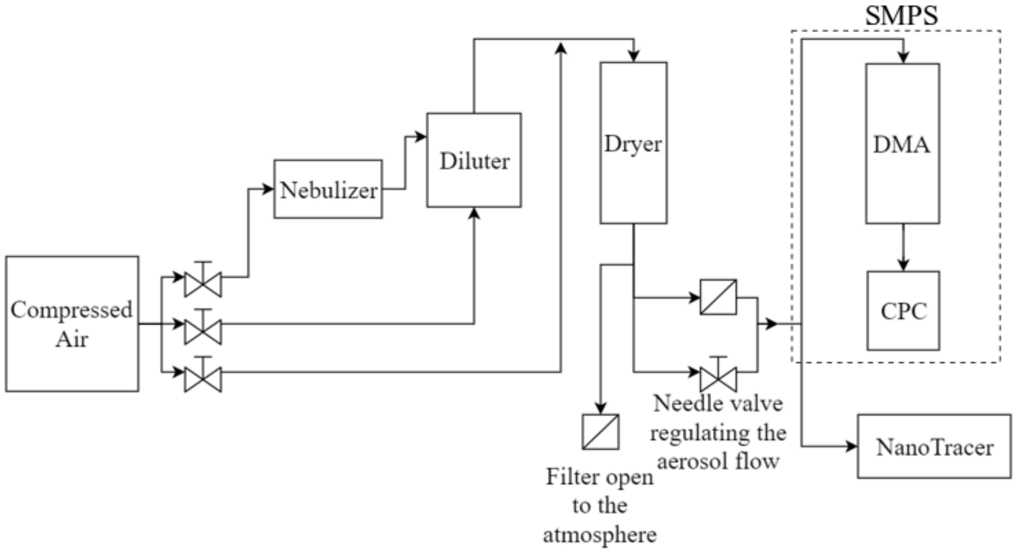


Figure 5: The set-up for aerosol generation, conditioning and readings.

A nebulizer was used to generate NaCl particles from a 1 % NaCl solution in water and then dried with a diffusion dryer (model 3062, TSI). This generates a polydisperse aerosol which is an aerosol with different sized particles [8]. The polydisperse aerosol consisted of submicrometer sized particles which then entered a differential mobility analyzer (DMA) of model Electrostatic Classifier 3082 TSI which uses radioactive source to neutralize the aerosol and then selects particles by electrical mobility. The electrical mobility is dependent on the particle size.

The aerosol was then led to the condensation particle counter (CPC) of model 3772, TSI. The CPC controlled the aerosol flow of 1 liter per minute. The CPC and the DMA makes the SMPS system. The concentration of the aerosol was regulated by the needle valve that adjusted the ratio of particle containing and particle free air in the final aerosol. During the sampling event the concentration was low, then increased and then lowered again.

The size distribution of the NaCl particles measured by the SMPS system can be seen in Figure 6. The geometric mean diameter for the different normalized concentrations forms a normally distributed curve.

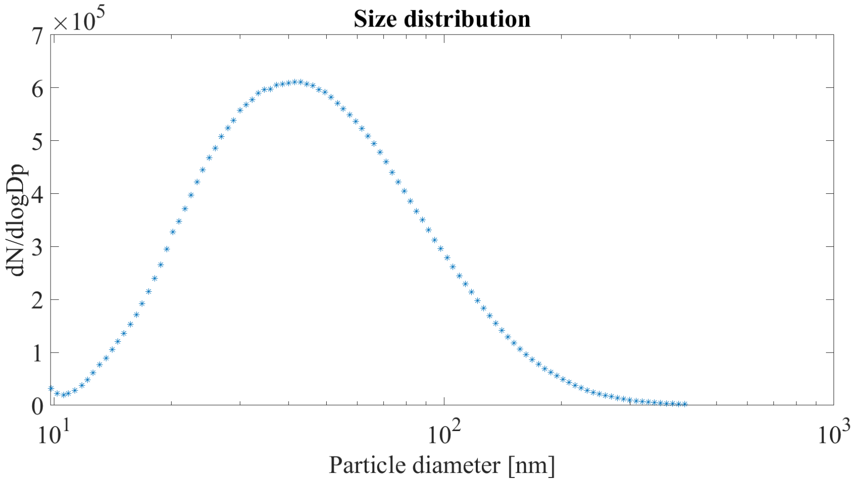


Figure 6: Size distribution of NaCl particles with the particle diameter in nanometer on the x-axis and the normalized number concentration.

The ultra-fine particle number concentration readings by the SMPS system and the NanoTracer can be seen in Figure 7.

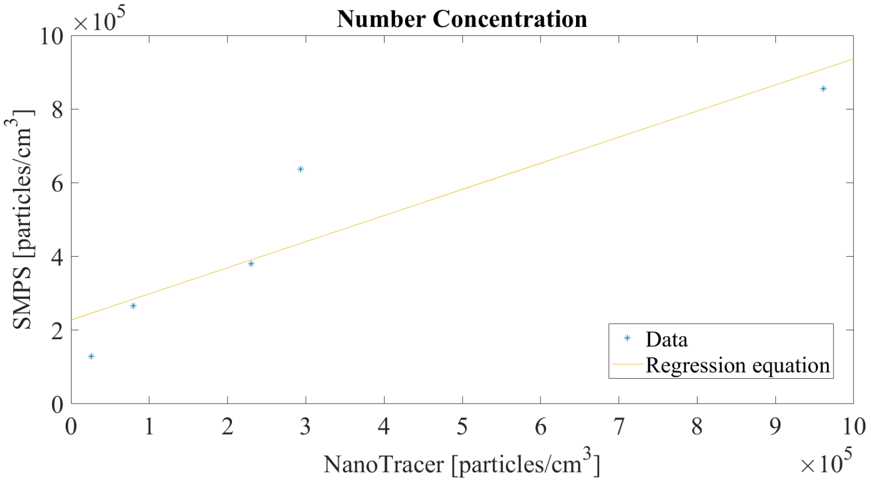


Figure 7: A comparison between NaCl aerosol number concentration readings by the NanoTracer and the SMPS system.

The linear regression equation for the number concentration obtained by the data fitting was:

$$C_{SMPS} = 0.71 C_{NanoTracer} + 2.3 \cdot 10^5 \tag{4}$$

Figure 8 depicts the average particle diameter readings done by the NanoTracer compared to the SMPS system.

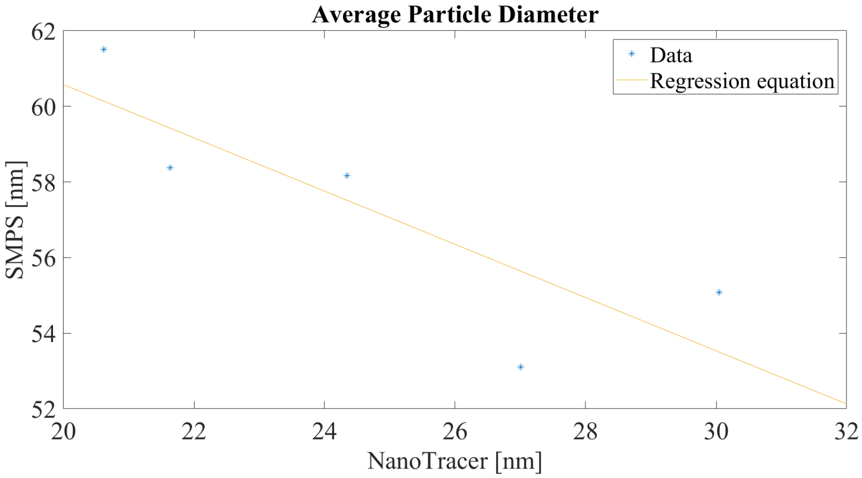


Figure 8: A comparison between NaCl aerosol average particle diameter readings by the NanoTracer and the SMPS system.

The linear regression equation for the number concentration obtained by the data fitting was:

$$d_{SMPS} = -0.7 d_{NanoTracer} + 75 \qquad (5)$$

3 Results and Analysis

3.1 Overview of Results

During the sailing measurements were conducted in three periods; day 1-2, day 6-7 and day 9-11. The submarine was submerged the first 8 hours of measurement period day 6-7 and the first 14 hours of measurement period day 9-11. Short time 10 minute average concentrations and the average for the total measurement time were calculated. Table 5 shows an overview of the average and the 10 minute average maximum and minimum for the different parameters measured in ACC. The OELs stated by the Swedish Work Envrionmental Authority (AFS) are given for $PM_{2.5}$ (respirable dust), for soot which contains BC and for CO_2. The guideline by WHO are included as well as the recommendations by the Swedish Materiel Administration (UKR).

Table 5: The table shows an overview of the average and the 10 minute average maximum and minimum for the different parameters in measured in ACC and MAR. Occupational exposure limits (OELs) by the Swedish Work Environmental Authority (AFS) are included. Also the guideline by WHO are included as well as the recommendations by the Swedish Materiel Administration (UKR).

Parameter	***Average***	***10 Minute Avg Max***	***10 Minute Avg Min***	***AFS***	***WHO***	***UKR***
ACC						
$PM_{2.5}$	4 μg/m^3	210 μg/m^3	1 μg/m^3	5000 μg/m^3 (8-h) [9]	25 μg/m^3 (24-h) [1]	
BC	200 ng/m^3	7800 ng/m^3	0 ng/m^3	3000 μg/m^3 [9]		
CO_2	1700 ppm	4400 ppm	700 ppm	5000 ppm [9]		1000 ppm [20]
VOC	0.54 ppm	2.83 ppm	0.02 ppm			
P_{atm}	1.02 bar	1.04 bar	0.96 bar			
RH	37%	50%	30%			
Temperature	24°C	26°C	21°C			18-23°C [20]
MAR						
$PM_{2.5}$	15 μg/m^3	55 μg/m^3	3 μg/m^3	5000 μg/m^3 (8-h) [9]	25 μg/m^3 (24-h) [1]	
UFP Number Concentration	$1 \cdot 10^4$ particles/cm^3	$3.2 \cdot 10^5$ particles/cm^3	575 particles/cm^3			
UFP Average Particle Diameter	60 nm	140 nm	20 nm			

Different activities including cooking, diesel propulsion, submersion and CO_2 purification were identified in the time resolved measurement. Chapter 3.2 contains an air quality assessment of the accommodation space and chapter 3.3 contains an air quality assessment of the machinery room. An analysis of the passive PAH measurements in the accommodation space (ACC) and the machinery room (MAR) resulted in mean concentrations for 32 individual PAHs for the sailing of 11 days and the result of this is presented in chapter 3.4.

3.2 Air Quality Assessment of the Accommodation Space

3.2.1 Pressure, CO_2, Humidity and Temperature

Figure 9 shows an overview of the pressure and CO_2 concentration for the three measurement periods. The times of submersion are marked with arrows during day 6-7 and 9-11. During submersion, an increase of CO_2 can be seen but does not reach the Swedish OEL. The Swedish OEL for CO_2 is 5000 ppm which was not exceeded during these measurements. The average CO_2 concentration for all of the sailing periods however was 1700 ppm. This exceeds the recommendation by the Swedish Defence Materiel Administration of 1000 ppm for a 30 day exposure [20]. A CO_2 level over 1000 ppm can can have a negative influence on decision making [18].

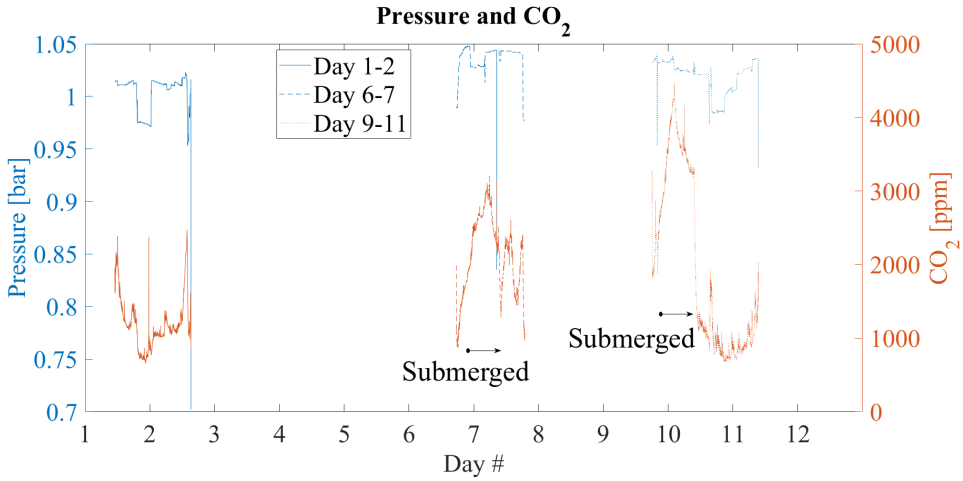


Figure 9: The pressure in bar and CO_2 concentration in ppm for the three measurement periods.

The CO_2 had a 10 minute average maximum of 4400 ppm. However, the highest short time exposure maximum occurred during submersion and prolonged submersion can result in recurring short time exposures of high CO_2 concentrations. The lowest CO_2 10 minute average minimum was 700 ppm. The normal CO_2 concentration in the air is 0.04% (400 ppm) which implicate elevated concentrations on board despite open hatches to the atmosphere. This suggest CO_2 purification not just during submersion but also all the time during surface operation.

The mean pressure for all of the measurement periods was 1.02 bar. The 10 minute average maximum pressure was 1.04 bar and the minimum was 0.96 bar which are normal values aboard. There can be seen drastic decreases in pressure readings below 0.96 bar and they can be seen in the end of period day 1-2 and in the middle of period day 6-7. These sudden parameter drops are presumably misreadings by the VelociCalc when the pressure gradient aboard was too great. This lead to sudden misreadings for the other parameters CO_2, humidity, temperature and VOC at this moment as well.

Figure 10 shows an overview of the temperature and the relative humidity for the three measurement periods. The sudden decreases in temperature and humidity occur when there are drastic decreases of pressure. The Swedish Defence Materiel Administration recommends an air temperature of 18-25°C on board and the average temperature for all of the sailings was 24°C [20]. The 10 minute average maximum was 26°C and the minimum was 21°C which are acceptable temperatures. The relative humidity had an average of 37% during the sailing. The 10 minute average maximum was 50% in the beginning of the sailing and the minimum was 30%.

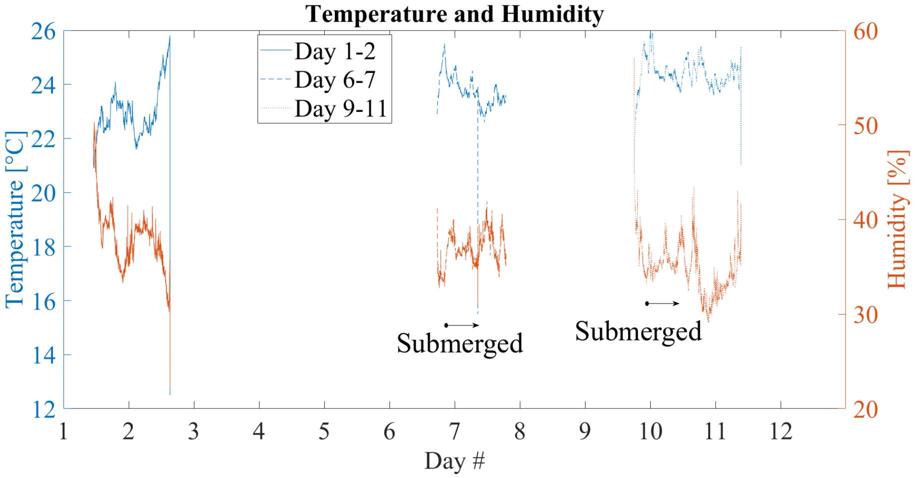


Figure 10: The temperature in °C and relative humidity in % for the three measurement periods.

3.2.2 $PM_{2.5}$ and VOC

Both $PM_{2.5}$ and VOC indicated increase of concentrations during the cooking activities in the accommodation space (ACC). Hence these parameters will be collaterally analyzed, first will overviews of the $PM_{2.5}$ and the VOC concentrations be presented separately.

Figure 11 shows the $PM_{2.5}$ mass concentration for the three measurement periods expressed in $\mu g/m^3$. It is also shown when the submarine was submerged. The highest short time exposure occurred day 10 with a mass concentration of 210 $\mu g/m^3$. This concentration can be coupled to frying in the galley during submersion. The average $PM_{2.5}$ concentration was 4 $\mu g/m^3$ for all of the sailing periods.

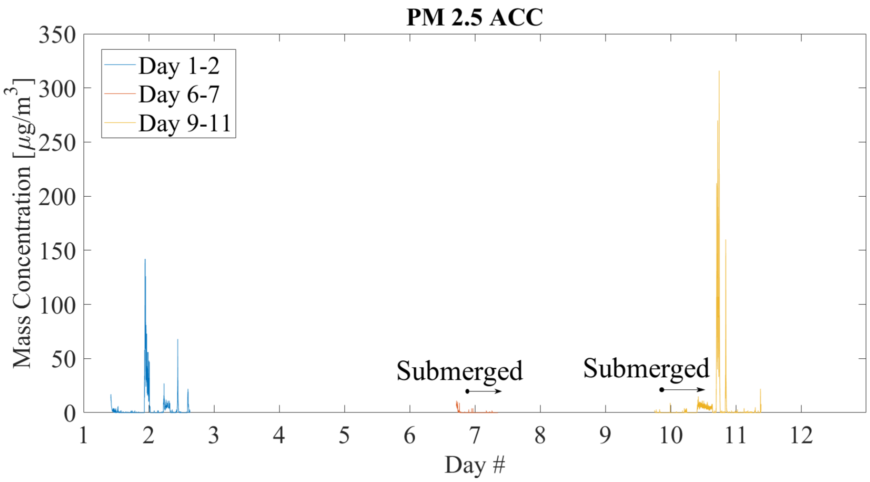


Figure 11: The $PM_{2.5}$ mass concentration for the three measurement periods expressed in $\mu g/m^3$.

Furthermore, the VOC concentration expressed in toluene equivalents can be seen in Figure 12. The peak values occur during the cooking events in the galley which is adjacent to the ACC. One can see that the concentrations do not peak above 10 ppm. The highest peak of 10 ppm during day 7 is not a reliable reading due to a drastic decrease in pressure. During measurement period day 6-7 the submarine was submerged 19:00-05:00. Submersion occurred also during 19:00-11:00 in the beginning of measurement period 9-11. It can be seen as small "hills" of increased VOC concentrations for day 6-7 and 9-11. In other words, the mean VOC concentration increased during submersion. During submersion the hatch to the atmosphere is closed and the air quality is reliable on the the air purification system and the fans in the galley during cooking. The average VOC concentration for all of the sailing periods was 0.54 ppm.

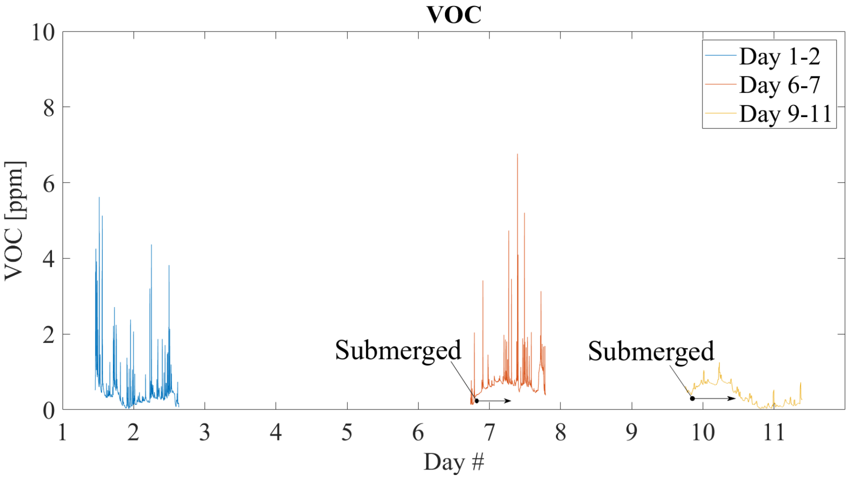


Figure 12: The VOC concentration for the three measurement periods expressed in toluene equivalents [ppm].

Figure 13 shows the VOC concentration and the $PM_{2.5}$ in ACC for the first measurement period, day 1-2. It is clear see that the VOC concentration increase during cooking in the galley. The different cooking activities are identified in the figure. The mean VOC concentration for this period was 0.5 ppm and the highest 10 minute average was 2.8 ppm. $PM_{2.5}$ was the parameter mostly affected by the frying, the short time exposure maximum was 102 $\mu g/m^3$ for this sailing period and this occurred during the cooking activity involving frying of hamburgers. From the logs it was noted that the oven emitted a lot of smoke. Cooking activities when the oven was used may have caused elevated VOC concentrations.

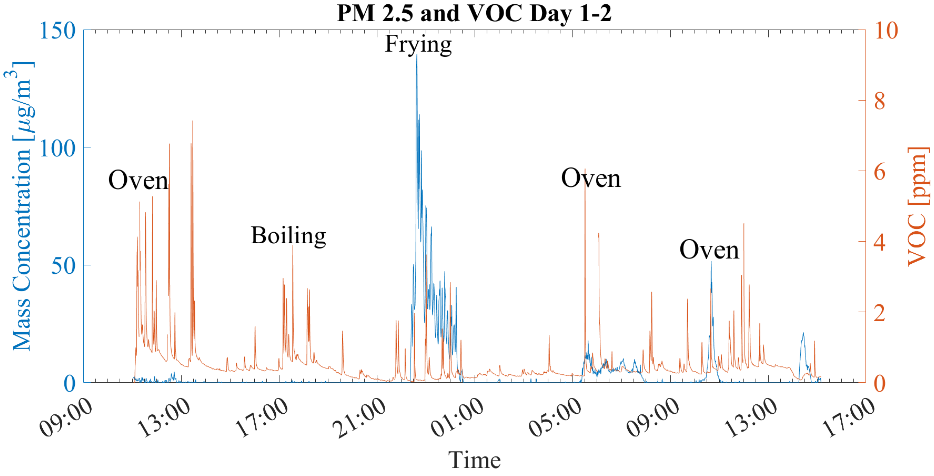


Figure 13: The left y-axis show the $PM_{2.5}$ mass concentration for day 1-2 expressed in $\mu g/m^3$. The right y-axis show the VOC concentration expressed in toluene equivalents [ppm]. Cooking activities are shown in the figure. The data is averaged in one minute intervals.

During the measurement period day 6-7 in Figure 14 the submarine was submerged between 19:00 and 05:00. This resulted in a small build up of VOC and the mean concentration for this period was 0.7 ppm. The mean concentration for this period was higher than the previous when the submarine was only operating on the surface. The VOC 10 minute average maximum was 2.25 ppm. Elevated $PM_{2.5}$ concentrations occured during frying in the galley. Otherwise the $PM_{2.5}$ was low, the mean concentration was 0.3 $\mu g/m^3$ and the short time exposure maximum was 8 $\mu g/m^3$.

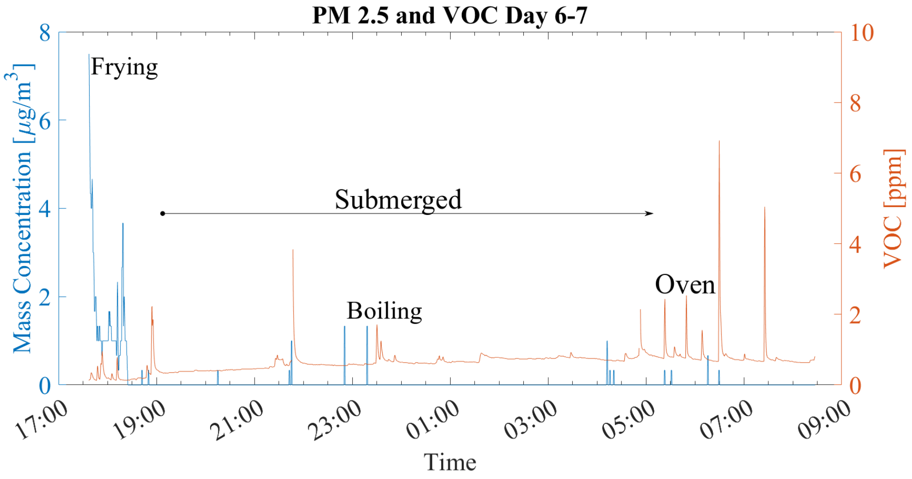


Figure 14: The left y-axis show the $PM_{2.5}$ mass concentration expressed in $\mu g/m^3$ for day 6-7. The VOC concentration for day 6-7 of the measurement period expressed in toluene equivalents [ppm]. Cooking activities are shown in the figure. The data is averaged in one minute intervals.

Figure 15 shows the VOC concentration and $PM_{2.5}$ mass concentration for day 9-11. The highest peak for $PM_{2.5}$ occurred during frying, this is also the highest peak for the whole sailing. The 10 minute average maximum was 210 $\mu g/m^3$, concentrations similar to this have been reached in studies about indoor cooking. Zhang et al. [14] measured concentrations reaching 230.9 $\mu g/m^3$ during frying. The minimum $PM_{2.5}$ was 1 $\mu g/m^3$. The 10 minute average maximum for VOC was 1.36 ppm, this was the lowest VOC short-time exposure of the sailing periods. The mean VOC concentration of 0.8 ppm was also the lowest of all of the sailing periods. The figure shows that the mean VOC concentration is higher during submersion. It should be noted that this measurement period had the longest submersion duration.

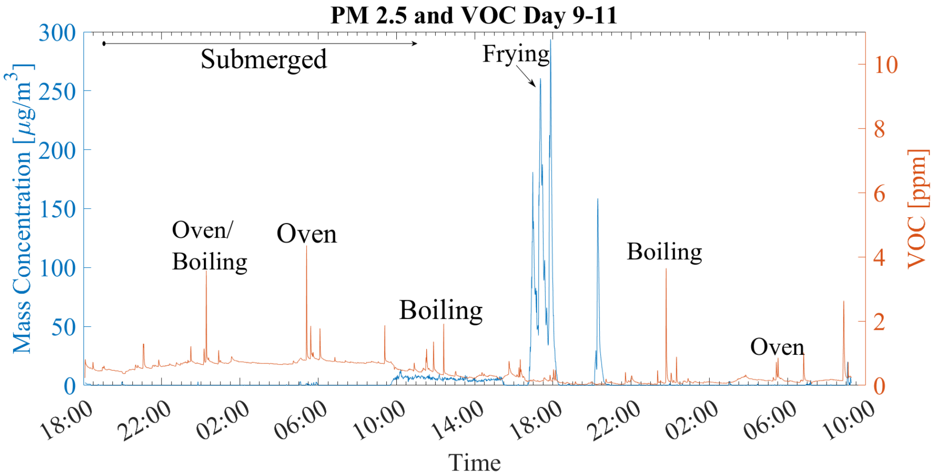


Figure 15: The left y-axis show the $PM_{2.5}$ mass concentration expressed in $\mu g/m^3$ for day 9-11. The VOC concentration is expressed in toluene equivalents [ppm] on the right y-axis. Cooking activities are shown in the figure. The data is averaged in one minute intervals.

3.2.3 BC and CO_2

The BC concentration measured in the ACC can be seen in Figure 16. The highest concentrations were obtained day 2 of the sailing, the highest short time exposure was 7800 ng/m^3. According to the log a diesel engine was operating and exhausts may have entered through the hatch. The average BC concentration for the whole period was 200 ng/m^3. The mean BC concentration is relatively low when comparing to a residential indoor environment (900 ng/m^3) [4].

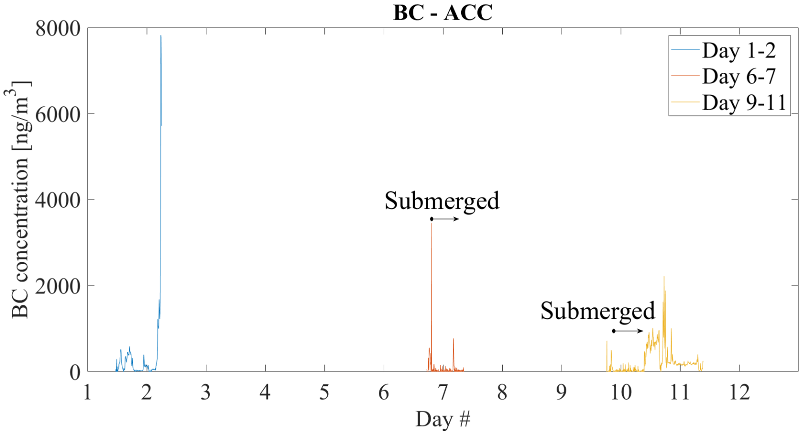


Figure 16: The BC mass concentration expressed in ng/m^3 for the three measurement periods.

Table 6 shows the average BC mass concentration and the standard deviation (std) expressed in ng/m^3 for the three measurement periods. Day 1-2 measured the highest BC mean concentration. The OEL for respirable coal dust which contains BC is 3 mg/m^3 for an eight hour working day [9].

Table 6: The mean BC mass concentration and the standard deviation (std) expressed in ng/m^3 for the three measurement campaigns.

Days	***Mean +/- std BC mass concentration [ng/m^3]***
1-2	320 +/- 1220
6-7	70 +/- 290
9-11	230 +/- 310

In order to determine if diesel exhausts entered the ACC when the submarine operated at the surface the BC and CO_2 were plotted together. During surface operation the diesel exhaust are let out to the atmosphere. The hatches to the atmosphere are usually open during surface operation. Figure 17 depicts the BC mass concentration expressed in ng/m^3 and CO_2 concentration expressed in ppm as a function of time for day 1-2. As can be seen in the figure there is an increase in CO_2 concentration at the moment when the BC peaks at 05:30. This supports the conclusion that diesel engine exhaust enter ACC through the hatch 05:30 day 2. This led to the highest short time exposure of BC during the sailing of 7800 ng/m^3. For the rest the BC concentration was low with a mean of 320 ng/m^3.

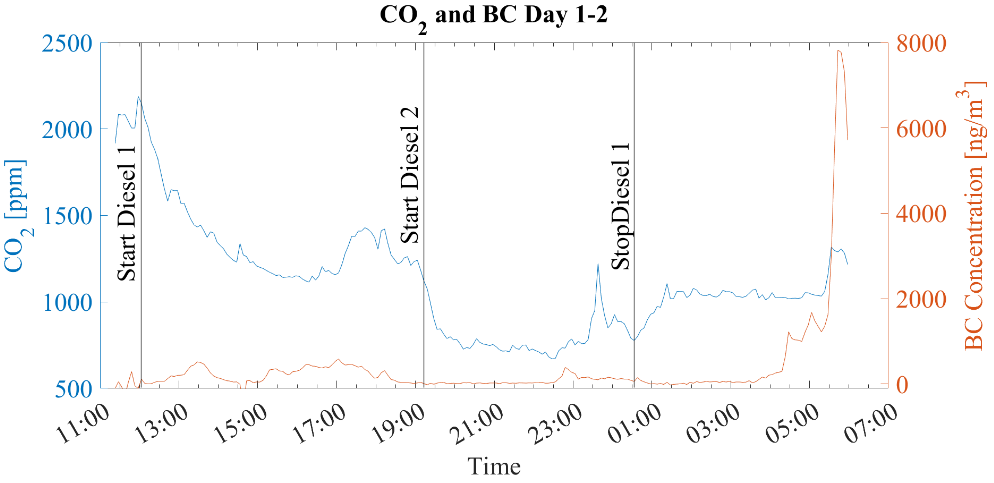


Figure 17: The BC mass concentration expressed in ng/m^3 and CO_2 concentration expressed in ppm as a function of time in five minute intervals.

Figure 18 shows the BC mass concentration expressed in ng/m^3 and CO$_2$ concentration expressed in ppm as a function of time for day 6-7. One can see an almost linear increase in CO$_2$ concentration during submersion and it peaks at 3000 ppm. As the submarine submerged the CO$_2$ purification system started but there is still an increase in CO$_2$. After resurfacing the CO$_2$ decreased again probably due to that the hatches to the atmosphere where opened. The BC concentration range from 0-600 ng/m^3 and occasionally below zero due to disturbances in the readings. One cannot see a correlation between the BC and CO$_2$ concentration during this period and no exhaust infiltration in the ACC can be seen.

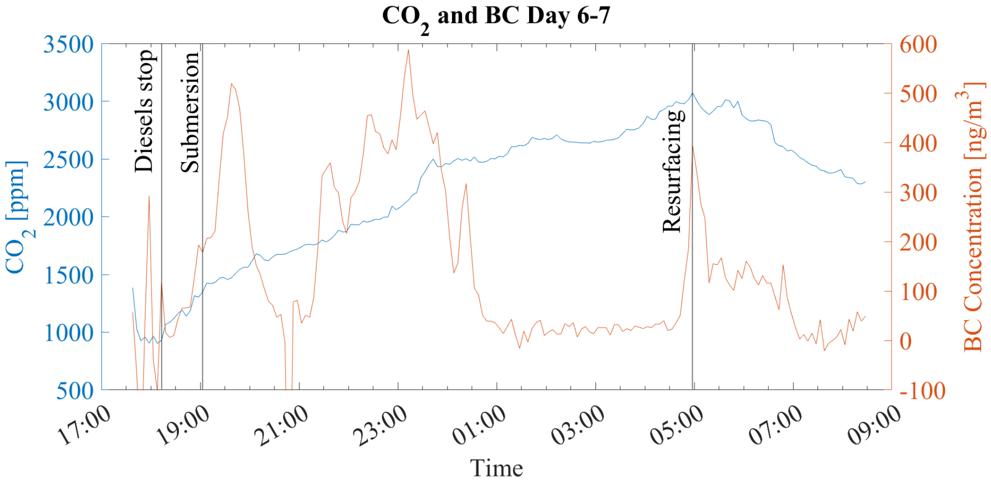


Figure 18: The BC mass concentration expressed in ng/m^3 and CO$_2$ concentration expressed in ppm as a function of time in five minute intervals.

Figure 19 shows the BC mass concentration expressed in ng/m^3 and CO_2 concentration expressed in ppm for day 9-11. After the submersion there is an increase of CO_2 until the start of the CO_2 purification. When the CO_2 purification starts there is a decrease until the resurfacing and a diesel engine starts. The BC concentration in the ACC increases as soon as the submarine resurfaces. The 10 minute average maximum was 1900 ng/m^3 which occurred 18:00 during surface operation and the chef was cooking dinner in the galley. The frying generated 10 minute average concentration of BC reaching 1900 ng/m^3 which is eight times higher than the mean concentration during this period. The BC increased in a similar way as $PM_{2.5}$ after the resurfacing at 09:30. However, the CO_2 decreased drastically after the resurfacing which indicates that the hatches to the atmosphere were opened up. This lowered the CO_2 concentration but forced the aerosol generation in the galley through the hatch instead through the ventilation in the galley.

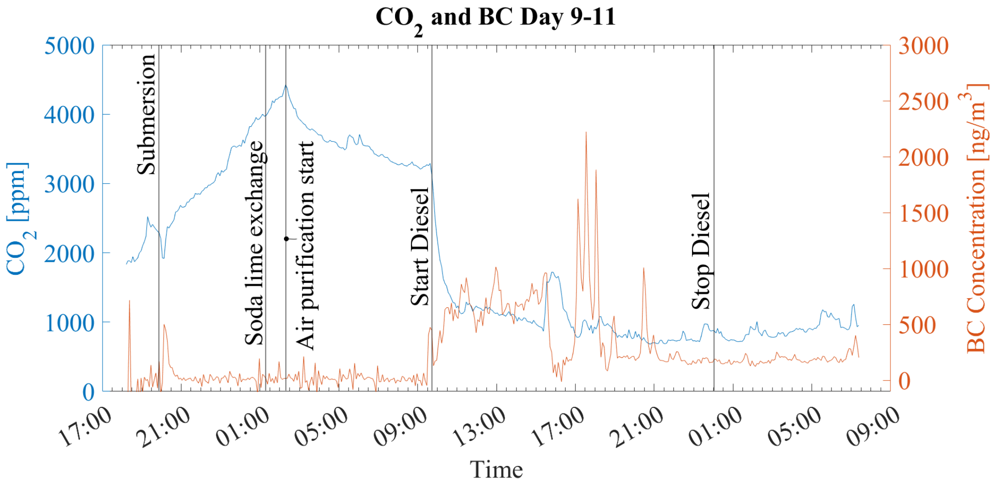


Figure 19: The BC mass concentration expressed in ng/m^3 and CO_2 concentration expressed in ppm as a function of time in five minute intervals.

3.3 Air Quality Assessment of the Machinery Room

MAR is where the diesel engines are and they are placed in the stern of the submarine. The activities logged in order to assess the air quality here were the diesel engine running and the running of the CO_2 purification system. Ultrafine particles (UFPs) and $PM_{2.5}$ were measured in MAR during the sailing.

3.3.1 UFP Concentration and Average Particle Diameter

Figure 20 shows the number concentration particles/cm^3 for the three measurement periods. The highest peaks occur when the submarine is not submerged, the peaks can be coupled to the running of the diesel engines. The highest short time exposure was $3.3 \cdot 10^5$ particles/cm^3 and the lowest short time exposure was 600 particles/cm^3.

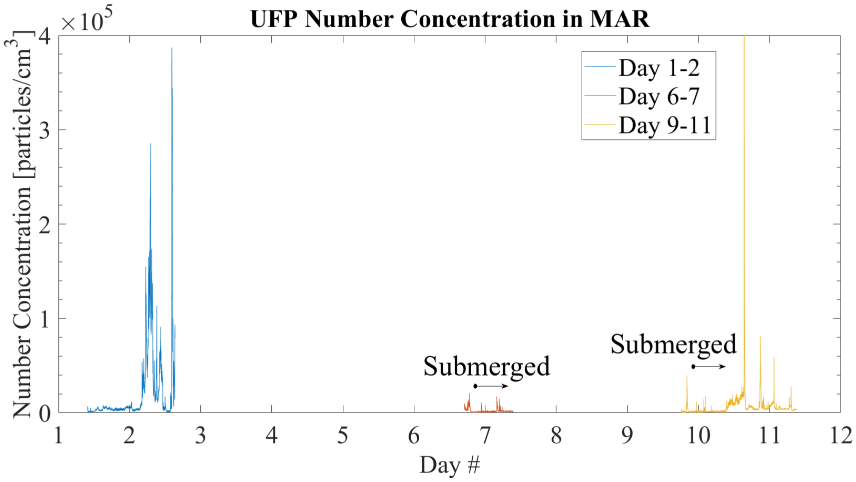


Figure 20: The UFP number concentration expressed in particles/cm^3 as a function of time.

Figure 21 shows the ultrafine particle (UFP) average particle diameter expressed in nanometer during the three measurement periods. The UFP average particle diameter was 60 nm for the three measurement periods. The short time exposure maximum was 140 nm and the minimum was 20 nm.

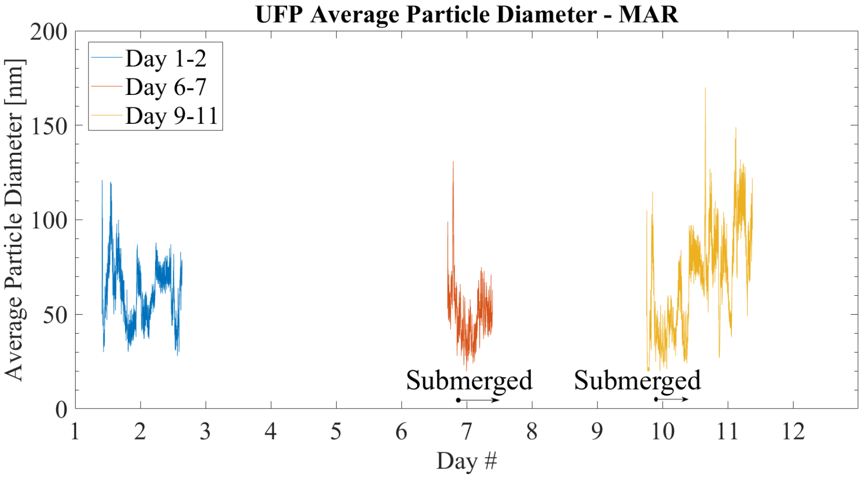


Figure 21: The UFP average particle diameter expressed in nanometer as a function of time.

Figure 22 shows the number concentration particles/cm^3 and the average particle diameter for day 1-2. One can see higher levels of particle number concentration between 04:00 and 11:00. There was no activity logged at this time but due to the long period of time and particles of fairly the same size there may have been an exhaust leakage. There is an increase in average particle diameter during the increase in number concentration. The increase in particle diameter can be explained by accumulation processes of the aerosol which lead to bigger particle diameters. Day 1-2 showed the highest mean concentration of $2.1 \cdot 10^4$ particles/cm^3. Urban air contains around $1 \cdot 10^4$ particles/cm^3 [5].

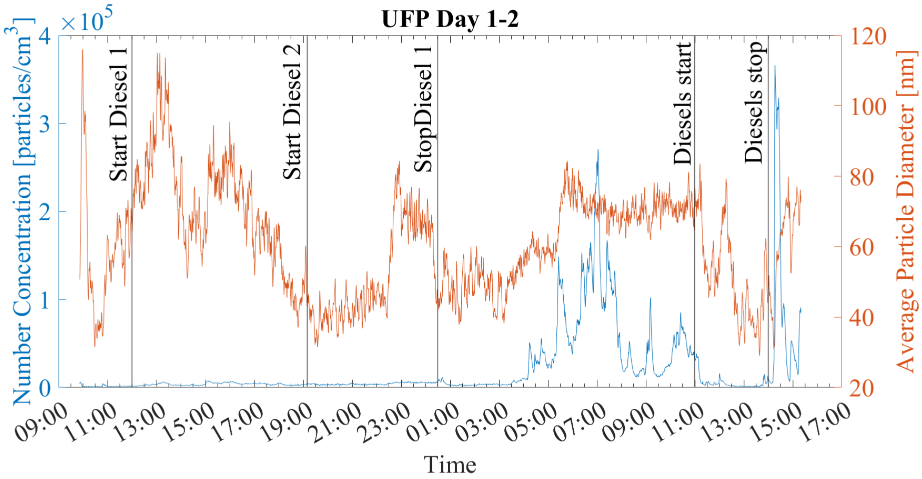


Figure 22: Number concentration of particles/cm^3 and the average particle diameter for day 1-2. The data is averaged in one minute intervals.

Figure 23 shows the number concentration of particles/cm^3 for day 6-7 and the average particle diameter. The mean concentration for this measurement period was 2000 particles/cm^3 and the mean average particle diameter is 50 nm. The air during this measurement period is fairly clean, a clean environment contains less than 1000 particles/cm^3. As seen in the figure the submersion and the resurfacing has an impact on the UFP number concentration in MAR. The UFP number concentration increases after the diesel engines stop and is then lowered after the submersion.

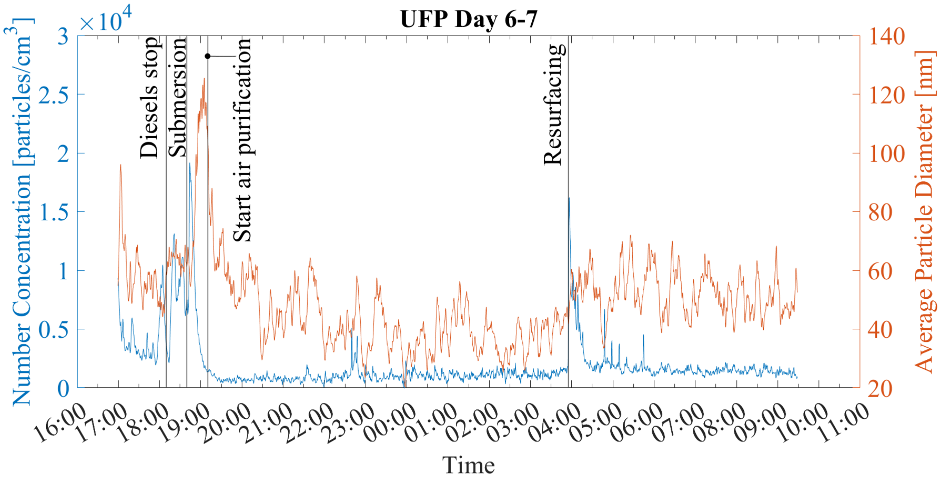


Figure 23: The number concentration particles/cm^3 and the average particle diameter for day 6-7. The data is averaged in one minute intervals.

Figure 24 shows the number concentration of particles/cm^3 and the average particle diameter for day 9-11. This measurement period measured the highest short time exposure of UFP number concentration $3.2 \cdot 10^5$ particles/cm^3. The reason to this high concentration is not known but happened during surface operation and diesel propulsion. Some sort of exhaust leakage in the machinery room may have happened. During the start/stop of one of the diesel engines there is an increase in UFP concentration.

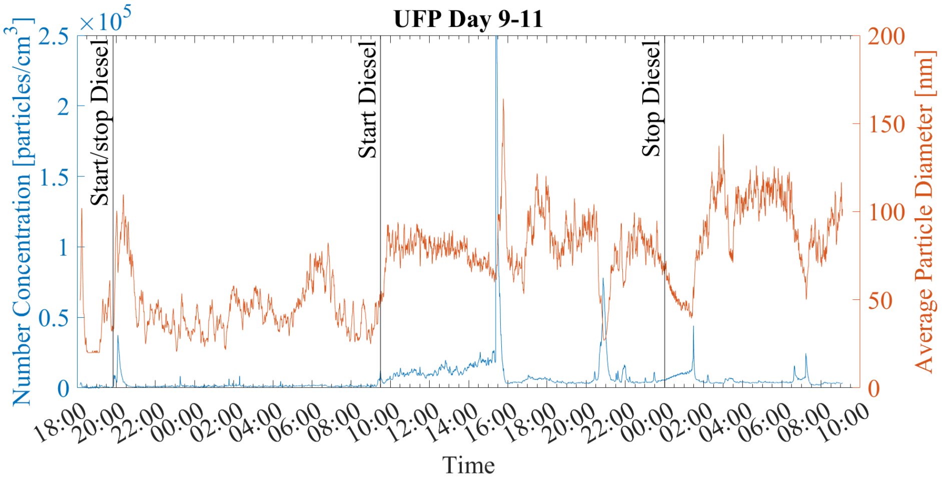


Figure 24: The number concentration particles/cm^3 and the average particle diameter for day 9-11. The data is averaged in one minute intervals.

3.3.2 $PM_{2.5}$ and UFP Number Concentration

In order to analyze the aerosols in MAR the $PM_{2.5}$ and UFP number concentration were plotted together for the measurement periods. Due to that the data was noisy it was smoothed, this lowered some peaks and the peaks for short time exposure maximum were thereby lowered in the plots. The time resolved data plots will show the correlations between parameters and the short time exposures will be mentioned in the text. Figure 25 shows an overview of the $PM_{2.5}$ mass concentration for the three measurement periods expressed in $\mu g/m^3$. It is also shown when the submarine is submerged. The average $PM_{2.5}$ mass concentration in MAR for the three measurement periods was 15 $\mu g/m^3$. This concentration is comparable to a study on the concentration of $PM_{2.5}$ in indoor air of 212 homes in the U.S.A. (17.6 $\mu g/m^3$) [13].

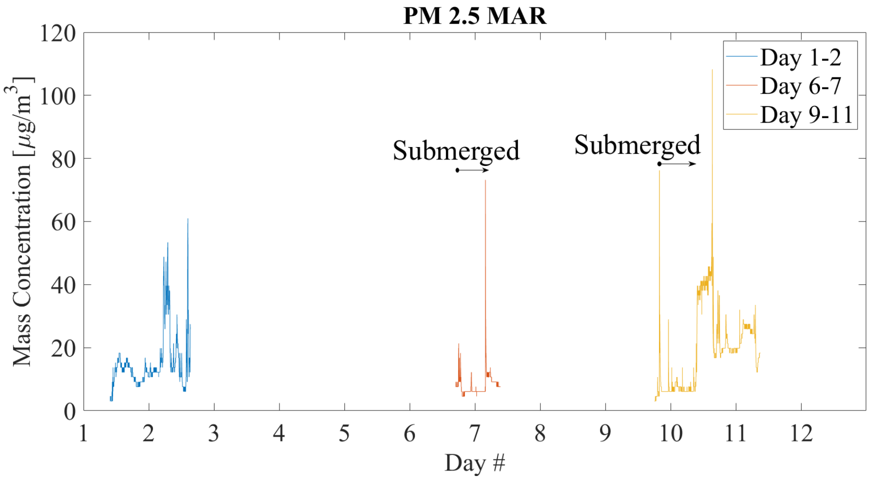
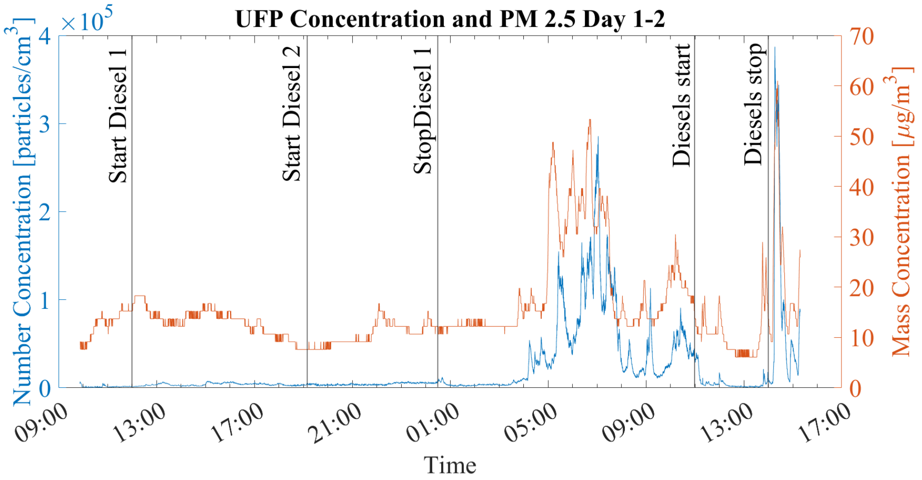


Figure 25: The $PM_{2.5}$ mass concentration for the three measurement periods expressed in $\mu g/m^3$.

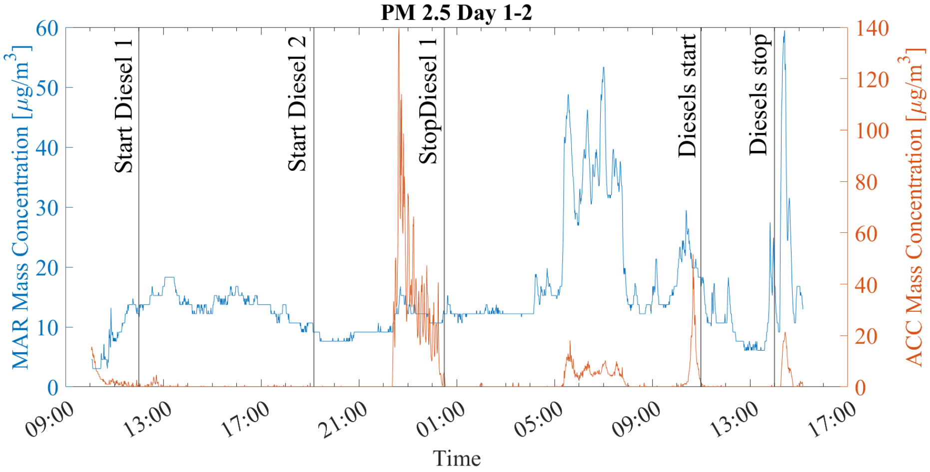
Figure 26 (a) on the next side shows the $PM_{2.5}$ mass concentration expressed in $\mu g/m^3$ and the UFP number concentration expressed in particles/cm^3 for day 1-2. The highest short time exposure concentration of $3.3 \cdot 10^5$ particles/cm^3 was measured for the UFP number concentration during this period. This occurred after the stopping of the diesel engines. Levels of UFP similar to this can be for example reached during cooking of fatty foods [16]. But in this case the UFPs consists of presumably diesel exhaust particles.

The maximum $PM_{2.5}$ short time exposure was one of the highest of the sailing in MAR, it was 55 $\mu g/m^3$. The activity causing this concentrations is unknown. It was more than three times higher compared to the mean $PM_{2.5}$ during the sailing. The mean of 15 $\mu g/m^3$ is above the annual mean limit of 10 $\mu g/m^3$ recommended by WHO [1]. On the other hand this is almost the same mean concentration as measured indoors in a Swedish apartment (15.6 $\mu g/m^3$) and in a study on American homes (17.6 $\mu g/m^3$) which makes the $PM_{2.5}$ concentration in MAR a normal indoor concentration [4] [13]. This means still that some activity in MAR generates high concentrations of particles in the micrometer and the submicrometer range. The toxicity is not just determined by the mass concentration of the particles but also by other characteristics such as chemical composition.

Figure 26 (b) on the next side shows the $PM_{2.5}$ mass concentration 1-2 expressed in $\mu g/m^3$ for both MAR and ACC. The average $PM_{2.5}$ mass concentration for the three measurement periods was 15 $\mu g/m^3$ in MAR. Compared to the ACC which measured an average of 5 $\mu g/m^3$ the $PM_{2.5}$ is significantly higher in MAR. MAR is an area of the submarine that is highly affected by aerosols in the small particle range (below 2.5 μm).



(a)

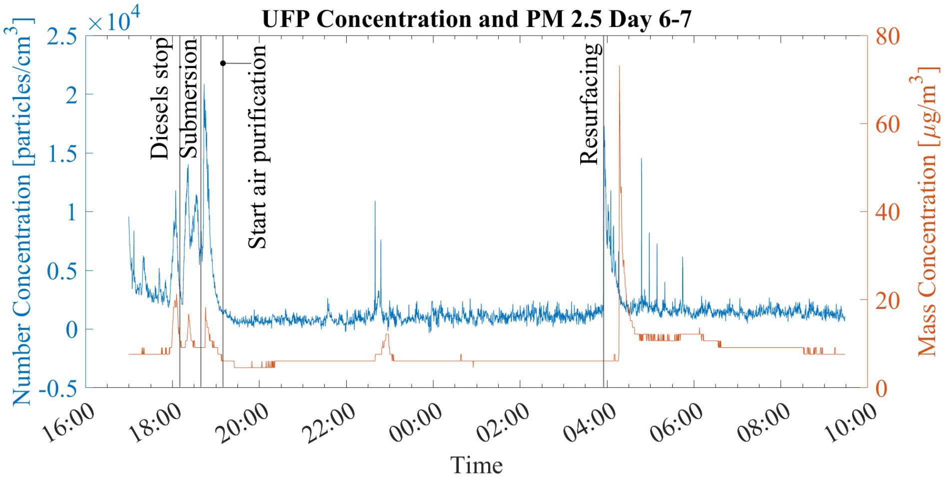


(b)

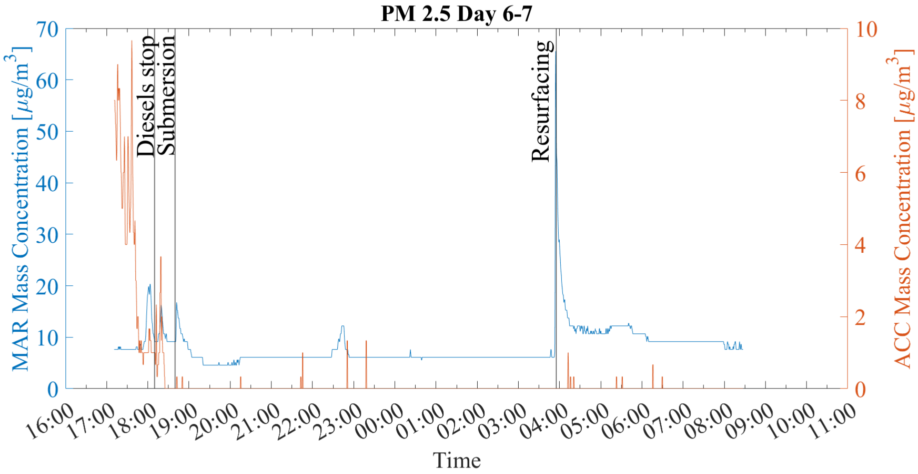
Figure 26: (a) The PM$_{2.5}$ mass concentration expressed in μg/m^3 and the UFP number concentration expressed in particles/cm^3 for day 1-2. (b) The PM$_{2.5}$ mass concentration for day 1-2 expressed in μg/m^3. The data is averaged in one minute intervals.

Figure 27 (a) on the next side shows the $PM_{2.5}$ mass concentration expressed in $\mu g/m^3$ and the UFP number concentration expressed in particles/cm^3 for day 6-7. One can see an increase in $PM_{2.5}$ when the diesels stop. Both $PM_{2.5}$ and UFP concentration increase after the submersion and is then decreased again. The CO_2 purification does not noticeably affect the UFP concentration levels. At the moment of the resurfacing the UFP number concentration increase drastically and then decreased again. The highest short time exposure of the UFP was $2.4 \cdot 10^5$ particles/cm^3 which may be originating from the diesel exhausts.

Figure 27 (b) on the next side shows the $PM_{2.5}$ mass concentration day 6-7 expressed in $\mu g/m^3$ for both the MAR and the ACC. ACC showed elevated concentrations and this was caused by frying. In MAR, $PM_{2.5}$ was increased by the diesels stopping and the submersion. MAR measured a mean concentration of 8 $\mu g/m^3$ which was the lowest of all of the measurement periods in MAR. The measurement period day 6-7 was dominated by a long submersion period and this may have lowered the generated particulate matter from the diesel engines. Also a high peak can be seen at the time of the resurfacing.



(a)

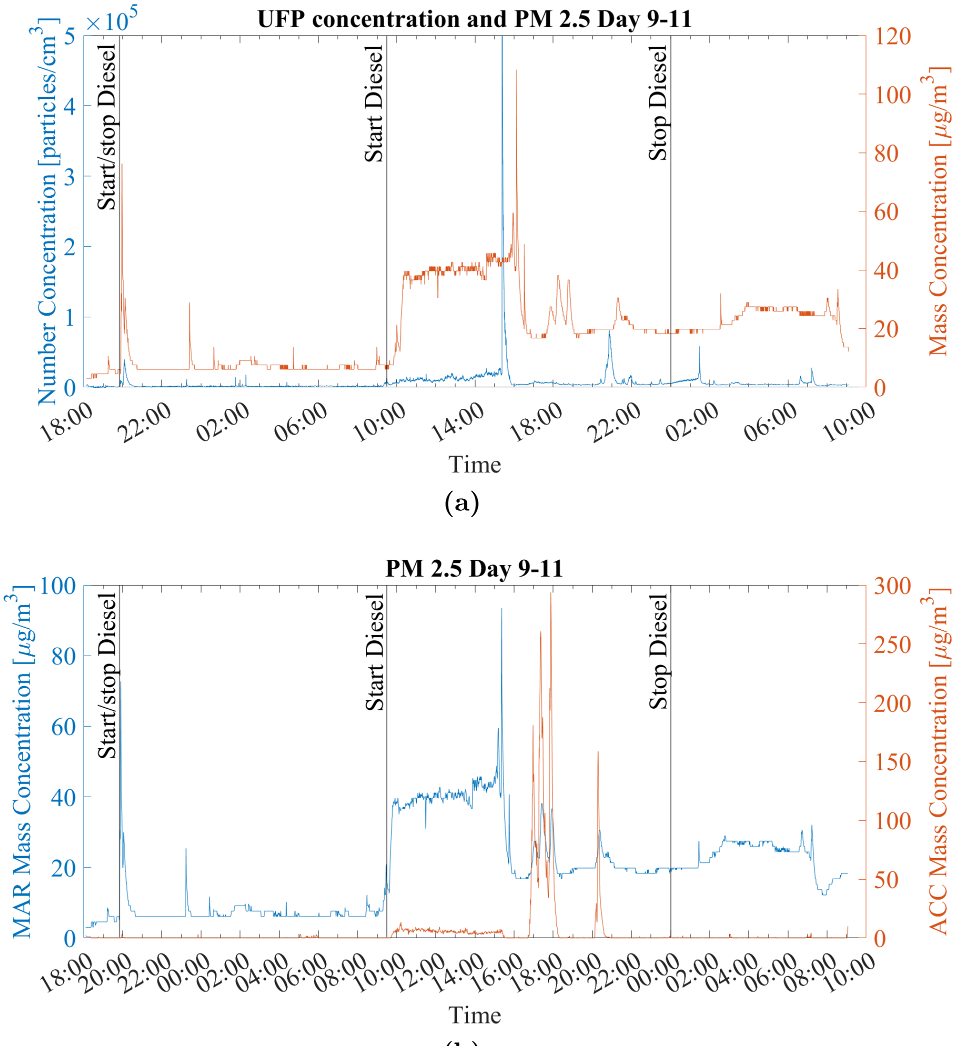


(b)

Figure 27: (a) PM$_{2.5}$ mass concentration day 6-7 expressed in μg/m^3 and the UFP number concentration expressed in particles/cm^3. (b) The PM$_{2.5}$ mass concentration for day 6-7 expressed in μg/m^3 for both MAR and ACC. The data is averaged in one minute intervals.

Figure 28 (a) on the next side shows the $PM_{2.5}$ mass concentration for day 9-11 expressed in $\mu g/m^3$ and the UFP number concentration expressed in particles/cm^3. The UFP concentration is clearly affected by the operating of the submarine, the high peaks are coupled to the starting and the stopping of the diesels. The $PM_{2.5}$ on the other hand increase at 10.00 when the diesel start and the submarine resurfaces. Higher mass concentrations where found when the submarine was operating in surface mode. The mean $PM_{2.5}$ in MAR for this sailing period was 19 $\mu g/m^3$ which is high and close to the outdoor 24 h limit recommended value stated by WHO that $PM_{2.5}$ should be under 25 $\mu g/m^3$ [1]. The mean concentration for this period is higher than the ones found indoors in homes in the U.S.A. (17.6 $\mu g/m^3$) and it is also higher than the mean concentration from a study in Helsinki, Finland (9.2 $\mu g/m^3$) [13] [11].

Figure 28 (b) on the next side shows the $PM_{2.5}$ mass concentration day 9-11 expressed in $\mu g/m^3$ for both MAR and ACC. Compared to MAR, ACC had a lower mean concentration of 5 $\mu g/m^3$. It was though characterized by the highest $PM_{2.5}$ in the ACC of all of the measurement periods. At 10:00 the concentration is elevated in the ACC as the diesel starts. The maximum short time exposure in ACC for this period was 210 $\mu g/m^3$ and was reached during frying. This concentration was 40 times higher than the mean concentration for this period (5 $\mu g/m^3$). MAR had a maximum short time exposure of 55 $\mu g/m^3$ which was only three times higher than the mean concentration for this sailing (19 $\mu g/m^3$). This implies high short time exposures occurring in ACC whilst in MAR there is a more constant high $PM_{2.5}$.



(a)

(b)

Figure 28: (a) The PM$_{2.5}$ mass concentration 9-11 expressed in μg/m^3 and the UFP number concentration expressed in particles/cm^3. (b) The PM$_{2.5}$ mass concentration for day 9-11 expressed in μg/m^3 for both MAR and ACC. The data is averaged in one minute intervals.

3.4 Polycyclic Aromatic Hydrocarbon Analysis

Table 7 shows the air concentration of 32 PAH components for the whole sailing period of 11 days expressed in ng/m^3. The OEL for naphthalene and benzo(a)pyrene are also given in the table, the remaining PAHs do not have any Swedish OELs. The results are presented for individual PAHs and the sum of the PAHs in ACC and MAR. There were duplicates of samplers in MAR, the uptake of PAHs were similar in the duplicates. Benzo(a)pyrene is classified by IARC as being carcinogenic and the carcinogenic risk of PAH mixtures in an environment can be compared to others by calculating the equivalents of benzo(a)pyrene (B(a)Peq). This is accomplished by multiplying each concentration of the individual PAHs with a toxic equivalency factor (TEF). The alkylated PAHs do not yet have confirmed TEFs. The toxic equivalency factors (TEFs) are given in Table 7 and also the equivalents of benzo(a)pyrene (B(a)Peq).

A Swedish urban background concentration for total PAH is 2-10 ng/m^3 and some elevated concentrations may occur and then reach 30 ng/m^3. Comparing with the total concentration measured in the ACC (152 ng/m^3) the concentration is approximately 10 times higher than in an urban background. The total PAH concentrations in MAR (579 ng/m^3 and 517 ng/m^3) are more than 15 times higher than in an urban background.

The yellow marked PAHs occur >90% in gas-phase, these are the PAHs that mainly contributed to the PAH sum concentrations in both MAR and ACC. The gas-phase PAHs accounted for 96% of total PAHs in ACC and 99% in MAR. The highest air concentration was phenanthrene which is a PAH formed by incomplete combustion of fuels. MAR measured twice as high concentrations of phenanthrene as in ACC. This implies some sort of exhaust leakage in MAR that have been spread from the front of the submarine where ACC is situated. A recent study by Strandberg et al. [24] pointed out that the fuel may impact the PAH concentration levels on the entire ship which seems to be the situation in this case as well. Another study of a submarine by Langer S et al. [22] showed high phenanthrene concentrations which accounted for 22% of the total PAHs in ACC and 7% in MAR [22]. The air concentration on phenanthrene was in that study also the highest in MAR with 127 ng/m^3 [22]. Naphthalene is a gas-phase PAH that have Swedish OEL for an eight hour working day ($50 \cdot 10^6$ ng/m^3) and for short time exposure ($80 \cdot 10^6$ ng/m^3). The mean concentration measured in ACC was 8.2

ng/m^3 and in MAR the mean concentrations were 20 ng/m^3 and 21 ng/m^3. These concentrations were far below the Swedish OEL.

The green marked PAHs occur in both gas-phase and particle-bound phase. These PAHs accounted for 3% of the total PAHs in ACC and 1% in MAR. The blue marked PAHs are mainly particle bound and the concentrations of these were below 0.010 ng/m^3. Benzo(a)pyrene is a particulate PAH. There is a Swedish OELs for benzo(a)pyrene for an eight hour working day of $2 \cdot 10^3$ ng/m^3 and the limit for short time exposure is $2 \cdot 10^4$ ng/m^3. The average concentrations on board the submarine are far below the OEL.

The limit recommended by the European Community for B(a)Peq is 1 ng/m^3. In ACC the B(a)Peq was 0.2 ng/m^3 and in MAR B(a)Peq was 0.3 ng/m^3. The B(a)Peq limit of 1 ng/m^3 is not exceeded, the toxicity in MAR can be compared other B(a)Peqs measured in the purifier room on ships (1.5-7 ng/m^3) [24]. The toxicity in ACC is lower compared to the one by Langer S et al. [22] where the B(a)Peq in the ACC of that submarine was 0.46 ng/m^3. There was a hydraulic fluid leakage during the sailing which may have resulted in higher PAH concentrations than under normal sailing conditions. Leakages occur occasionally and it is necessary to detect and seal these leakages so that the PAH concentration is preserved low.

Due to the elevated PAH concentrations on board compared to an urban background further assessments can be motivated. These results motivates additional studies that aim to determine the personal exposure, for example by means of personal PAH and particle sampling systems. This will give the mean concentration one individual is exposed to.

Table 7: The mean PAH concentrations for the whole sailing period of 11 days expressed in ng/m^3. The toxic equivalency factors (TEF) and the sum of the benzo(a)pyrene equivalents (B(a)Peq) are also shown. Additionally, the two occupational exposure limits (OELs) by the Swedish Work Environmental Authority (AFS) can be seen.

	ACC *[ng/m^3]*	***MAR 1*** *[ng/m^3]*	***MAR 2*** *[ng/m^3]*	***TEF [26]***	***Swedish OEL [ng/m^3] [9]***
naphthalene	8.2	20	21	0.001	$50 \cdot 10^6$
2-methylnaphthalene	6.6	71	54		
1-methylnaphthalene	4.2	56	42		
biphenyl	7.8	49	38		
2,3-dimethylnaphthalene	4.4	64	50		
acenaphthylene	1.3	5.2	4.0	0.001	
acenaphthene	33	59	57	0.001	
2,3,5-trimethylnaphthalene	3.6	48	48		
fluorene	23	61	58	0.001	
1-methylfluorene	1.9	27	27		
phenanthrene	41	81	82	0.001	
anthracene	5.7	5.5	5.7	0.01	
2-methylphenanthrene	1.4	7.0	6.6		
3-methylphenanthrene	1.5	7.0	6.7		
1-methylphenanthrene	1.2	7.7	7.4		
1-methylanthracene	0.5	4.4	4.5		
2-phenylnaphthalene	0.38	1.0	1.0		
fluoranthene	3.8	3.7	3.4	0.001	
pyrene	1.4	1.2	1.2	0.001	
1-methylfluoranthene	<0,010	<0,010	<0,010		
retene	<0,010	<0,010	<0,010		
1-methylpyrene	<0,10	<0,10	<0,10		
benzo(a)anthracene	0.060	<0,010	<0,010	0.1	
chrysene	0.30	0.084	0.085	0.01	
2-methylchrysene	<0,030	<0,030	<0,030		
benzo(b)fluoranthene	<0,030	<0,030	<0,030	0.1	
benzo(k)fluoranthene	<0,010	<0,010	<0,010		
benzo(a)pyrene	<0,010	<0,010	<0,010	1	2000
perylene	<0,020	<0,020	<0,020	0.001	
indeno(1,2,3-c,d)pyrene	<0,010	<0,010	<0,010		
dibenzo(a,h)anthracene	<0,010	<0,010	<0,010	1	
benzo(g,h,i)perylene	<0,010	<0,010	<0,010	0.01	
coronene	<0,011	<0,011	<0,011		
SUM PAHs	152	579	517		
B(a)Peq	0.2	0.3	0.3		

3.5 Sources of Error and Improvements

It should be taken in consideration that the DustTrak and microAeth were not flow calibrated between the measurement periods on board. This is a suggested improvement for measurements in the future. The re-calibration reduces the risk for flow error which will lead to more reliable measurements.

The instruments were not allowed to be running during the whole sailing period and the operation in submerged condition was 16 h at its longest. In a statistical point of view would a longer sailing be preferable. Then the 24 hour mean concentrations could be analysed and compared to one another. When conducting measurement on board in the future the methodology used in this study is applicable on sailings with longer submersion periods where the instruments can run nonstop. It is of importance to keep logs of events that may affect the air aboard for example, if a leakage of some sort occur.

A NanoTracer was also supposed to be measuring in the accommodation space but did not log the measurement data during the sailing. In future research the UFP is of interest to be studied in ACC as well due to the large UFP emissions from cooking [14].

A microAeth was supposed to be measuring black carbon in the machinery room (MAR) but was out of order. An improvement for further measurements would be to measure black carbon in MAR. The black carbon levels may be higher here than in the accommodation space due to soot from the engines.

4 Conclusion and Implications

An overview of concentrations measured on board and urban, residential, ship or submarine concentrations can be seen in Table 8. The comparison was made for significant values that could be compared to other environments.

Table 8: An overview of a comparison between measured values on board and urban/residential/ship/submarine values.

	This study	***Comparison***
ACC		
$PM_{2.5}$	4 $\mu g/m^3$ (mean of the sailing) 210 $\mu g/m^3$ (frying)	9.2 $\mu g/m^3$ (homes in Finland [11]) 230.9 $\mu g/m^3$ (frying [14])
BC	220 ng/m^3 (mean of the sailing)	900 ng/m^3 (Swedish home [4])
CO_2	1700 ppm (mean of the sailing)	800-1000 ppm (indoor air [18])
PAH (B(a)Peq)	0.2 ng/m^3 (mean of the sailing)	0.46 ng/m^3 (ACC another submarine [22])
MAR		
$PM_{2.5}$	19 $\mu g/m^3$ (mean day 9-11)	17.6 $\mu g/m^3$ (homes in the U.S.A. [13])
UFP conc.	10 824 particles/cm^3 (mean of the sailing)	10 000 particles/cm^3 (urban background [5])
PAH (B(a)Peq)	0.3 ng/m^3 (mean of the sailing)	1.5 ng/m^3 (purifier room on ship [24]

The machinery room (MAR) showed overall high $PM_{2.5}$ and high short time peaks in the concentration of $PM_{2.5}$. The concentration peaks could be linked to the operating of the diesel engines. The mean $PM_{2.5}$ for all of the sailing periods (15 μg) was very similar to an average of $PM_{2.5}$ in a Swedish occupied apartment (15.6 μg) [4]. The mean concentration in MAR was also slightly lower than the mean concentration from a study of homes in the U.S.A. (17.6 $\mu g/m^3$) [13]. The measurement period day 9-11 had an average of 19 $\mu g/m^3$ which is close to the 24 hour exposure limit of 25 $\mu g/m^3$ suggested in the WHO guidelines [1]. This makes MAR an area of the submarine that is of interest to further investigate the air quality in. In order to analyse more representative conditions the measurement should be conducted when the submarine is submerged the majority of the time. The contribution from the diesel engines might be reduced under such conditions when instead the stirling engines are mainly used.

The air in MAR contains higher $PM_{2.5}$ mean concentrations and the indoor air quality in MAR can be improved by detecting the sources. This study showed that the exhaust from the diesel engines had an impact on the elevated concentrations. But other sources may also exist for example leakage of hydraulic oils can contribute to elevated concentrations. When leakage occur of course it should be eliminated at the source by sealing. If exhaust enter MAR through the snork the wind is possibly blowing from where the exhaust exits to the snork and down in MAR again. This could be prevented by changing the course of the submarine. If this can not be prevented then it is possible to monitor particle number and mass concentration to inform the crew and reduce the risk of occupational diseases from poor indoor air quality. A recommendation is to not use this area of the submarine as a workout place when the diesel engines are used if that is the case.

The total PAH concentration was more than 15 times higher in MAR than in an urban background. However, the calculated equivalents of benzo(a)pyrene (B(a)Peq) (see Table 7) of the PAH was five times lower compared to another recent study onboard a submarine in the purifier room. The elevated PAH concentrations are probably the consequence of some sort of fuel leakage. Another reason to the elevated concentrations may be the hydraulic fluid leakage. It should be taken in consideration that the PAH can spread through the submarine and if a leakage occur the door to MAR should be closed.

The air contaminants in the accommodation space (ACC) were primarily linked to the cooking where frying was a big contributor to $PM_{2.5}$. The concentration varies over time and during time of no cooking the $PM_{2.5}$ concentrations were low. The same behavior was observed for the VOC concentrations. The $PM_{2.5}$ can be lowered with a higher fan power but the available power in the submarine is limited. A finer particle filter after the already existing can increase the air quality by reducing particulate matter and smokes. Lowering the temperature when frying can also decrease the particle generation. Additionally if the UFP concentration would be measured simultaneously it could be analysed which cooking activities that were contributing to the UFP concentration.

It should be taken in consideration that the VOC concentration is a reference value and represents only the total concentration of VOC present in the air and not any specific VOC concentrations. In order to find which VOC that the confined submarine air mainly consist of and the toxicity of these one can use passive VOC samplers for identifying specific VOC on board and compare the concentration of individual VOC to OELs stated by AFS. In future studies the rate of increase of mean VOC concentration after submersion could be investigated. This study found an increase in VOC mean concentration after submersion but could not be investigated further due to the relatively short submersion periods.

The CO_2 average level on board was higher than the one recommended by the Swedish Defence Materiel Administration. The level was 1700 ppm and the recommended level is 1000 ppm for a 30 day exposure. Elevated CO_2 concentrations is a known issue on board due to the closed environment condition. During this sailing the CO_2 mean level could have been lower if the air purification was on throughout the whole surface operation. The highest 10 minute average CO_2 level was detected during submersion and prolonged submersion periods can result in recurring high short time exposures of CO_2. The effect of this though needs further investigation.

Black carbon (BC) was low in ACC, but elevated concentrations could be linked to exhaust entering from an open hatch in surface mode. Further measurement of BC would not be prioritised in ACC but rather in MAR were exhaust may be present. The PAHs in ACC are possibly originating from MAR and closing of doors should be considered to minimize the spread to other areas of the submarine.

For further measurements, other highly occupied spaces may be of interest to analyse, for example the control room. Further studies would also benefit from having more activities logged on board, for example if the crew sense any type of smell that would indicate emission from the mechanical system. This would help in clarifying increases of airborne particulates.

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