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Summary

This report describes the characterization of the chemical, biological and radiological environment in a decommissioned coal mine (Mine 3) on Svalbard, where the Artic World Archive (AWA), established by Piql and Store Norske Spitsbergen Kullkompani (SNSK) is located. AWA is used for long-term storage of digital information on a digital photosensitive archival film (piqlFilm). With the combination of resilient long-term storage technology and the remote, safe and cold conditions found on Svalbard, AWA is designed to keep data preserved for >1000 years. Storage at low temperature will increase the lifespan of the piqlFilm, but little is known about how mine vault environments can affect the different components of a Piql system (piqlFilm, piqlBox and wrapping bag). The results from this environmental characterization will be used for accelerated life testing of the Piql system. This report is based on literature studies of the chemical, biological and radiation environment in coal mines, and data collected during two sampling campaigns (summer 2021 and winter 2022).

The measured concentrations of NH_3 in the AWA vault was six times higher than the 2018–2020 annual averages measured by Norwegian Institute for Air Research (NILU) at Norwegian mainland measurement sites and 16 times higher than concentrations measured at the Zeppelin observatory in Ny-Ålesund. The concentrations of the other gases measured (NO_2, SO_2, CO_2 and CH_4) were at natural atmospheric background levels.

The DNA concentration observed in air samples collected in the AWA vault were in the lower range of concentrations found in environmental outdoor environments, indicating fewer airborne microorganisms. The results suggest that there is no reason to customize the microbiological environment during accelerated life testing of the Piql system. Visible fungal growth was observed on the plywood floor in the storage container inside the AWA vault during the sampling campaigns. If left unchecked, the fungal growth would undoubtedly increase during long-term storage and exchanging the plywood floor with e.g. steel should be considered since this will limit problems associated with fungal and other kinds of microbial growth.

The effective radiation dose inside the mine tunnels and AWA vault was measured at levels equivalent to the lower range of the average background radiation in Norway and lower than the outdoor reference measurements near Mine 3. Therefore, these results indicate no increased risk of long-term storage effects on the Piql system from radiation in the AWA vault compared to other possible storage environments.

Sammendrag

Rapporten beskriver karakterisering av det kjemiske, biologiske og radioaktive miljøet i en nedlagt kullgruve (Gruve 3) på Svalbard, hvor Piql og Store Norske Spitsbergen Kullkompani (SNSK) i samarbeid har etablert Arctic World Archive (AWA) for langtidslagring av digital informasjon på fotosensitiv film (piqlFilm). Kombinasjonen av en fleksibel teknologi for langtidslagring og de stabile og kalde forholdene på Svalbard gjør AWA egnet for langtidslagring av piqlFilm i >1000 år. Lagring ved lav temperatur øker levetiden til piqlFilm, men det er ikke kjent hvordan gruvemiljøet vil påvirke de ulike komponentene i Piql systemet (piqlFilm, piqlBox og innpakningspose). Resultatene fra miljøkartleggingen benyttes som faktagrunnlag i forbindelse med akselerert levetidstesting av Piql systemet. Den endelige rapporten er basert på sammenstilling av litteraturstudier av det kjemiske og biologiske miljøet samt radioaktiv stråling i gruver og data fra miljøkartlegginger utført sommer 2021 og vinter 2022.

Målte konsentrasjoner av NH_3 i AWA var seks ganger høyere enn årlig gjennomsnitt målt ved bakgrunnsstasjoner i fastlands-Norge av Norsk institutt for luftforskning (NILU) i perioden 2018-2020 og 16 ganger høyere enn konsentrasjoner målt ved Zeppelinobservatoriet i Ny-Ålesund på Svalbard. Konsentrasjonen av NO_2, SO_2, CO_2 and CH_4 var ikke forhøyet i forhold til gjennomsnittsverdier ved norske bakgrunns stasjoner.

DNA konsentrasjoner i luftprøver fra AWA var lavere enn gjennomsnitt fra tilsvarende målinger utført i ulike utendørsmiljøer, noe som indikerte lavere konsentrasjon av luftbårne mikroorganismer. Resultatet gir ikke noe grunnlag for å tilpasse det mikrobiologiske miljøet ved akselerert levetidstesting av Piql systemet. Det ble observert vekst av muggsopp på tregulv i container benyttet i AWA. Vekst av muggsopp vil sannsynligvis øke ved langtidslagring hvis dette ikke håndteres. Det anbefales derfor å bytte ut tregulvet med et uorganisk materiale som for eksempel stål for å redusere problemer med muggvekst og andre mikroorganismer.

Effektiv stråledose målt inne i gruvegangene og i AWA tilsvarte lavere område av gjennomsnittlig bakgrunnsstråling i Norge og var lavere enn stråledose målt i utendørsmiljø like ved Gruve 3. Dette indikerer ingen økt risiko for negative effekter på de ulike komponentene i Piql systemet ved langtidslagring i AWA sammenlignet med andre lagringsmiljøer.

Contents

1 Introduction

Over several years, Piql have developed a unique solution for long-term storage of digital data. The system include hardware and software for reading and writing of data on the storage medium piqlFilm, a storage box (piqlBox) and an aluminium laminate wrapping bag. As a result of a lifetime study by Norner Research the piqlFilm and the piqlBox have a documented lifetime of >500 years. The Piql system has true long-term preserving abilities compared to today's dominating storage technologies (hard disks and magnetic tapes), which have a lifetime of 5-10 years when unattended, and additionally require continuous maintenance. The ambition of Piql is to establish its platform as the "gold standard"of safe long-term storage of digital information by increasing capacity, reducing cost and increasing the documented lifetime of the system for up to 2000 years!

Together with SNSK, Piql have established a unique archive for long-term storage of the Piql system in a rock vault: Arctic World Archive (AWA) inside Mine 3 in Svalbard. Mine 3 was operational in the period from 1971 – 1996 when coal mining was stopped. The main entrance to Mine 3, shown in Figure 1.1, is located in the hillside just above Longyearbyen airport approx. 175 m above sea level. Figure 1.2 shows a map of the tunnel system. The mine tunnels extends in the coal layer below Platåberget and exits in Bjørndalen approximately 3 km away from and 150 m lower than the main entrance. The eastern part of Mine 3 is home to the Svalbard Global Seed Vault.

Figure 1.1 Entrance to AWA and the storage container located inside the AWA vault.

The mine exit at Bjørndalen is open and results in a natural ventilation of the mine tunnel with direction of airflow dependent on the outside temperature and air pressure. The natural ventilation of Mine 3 reduces accumulation of gases released from the mine walls and bedrock. AWA is located relatively close to the main entrance and within the area where guided mine tours are frequently arranged, and in proximity of a mechanical ventilation system. The mechanical ventilation system is used during guided tours and contributes to aeration of the mine in this part of the tunnel system. However, the AWA vault is located in an appendix of the main tunnel and separated from the tunnel system with a retrofitted steel wall with limited air exchange.

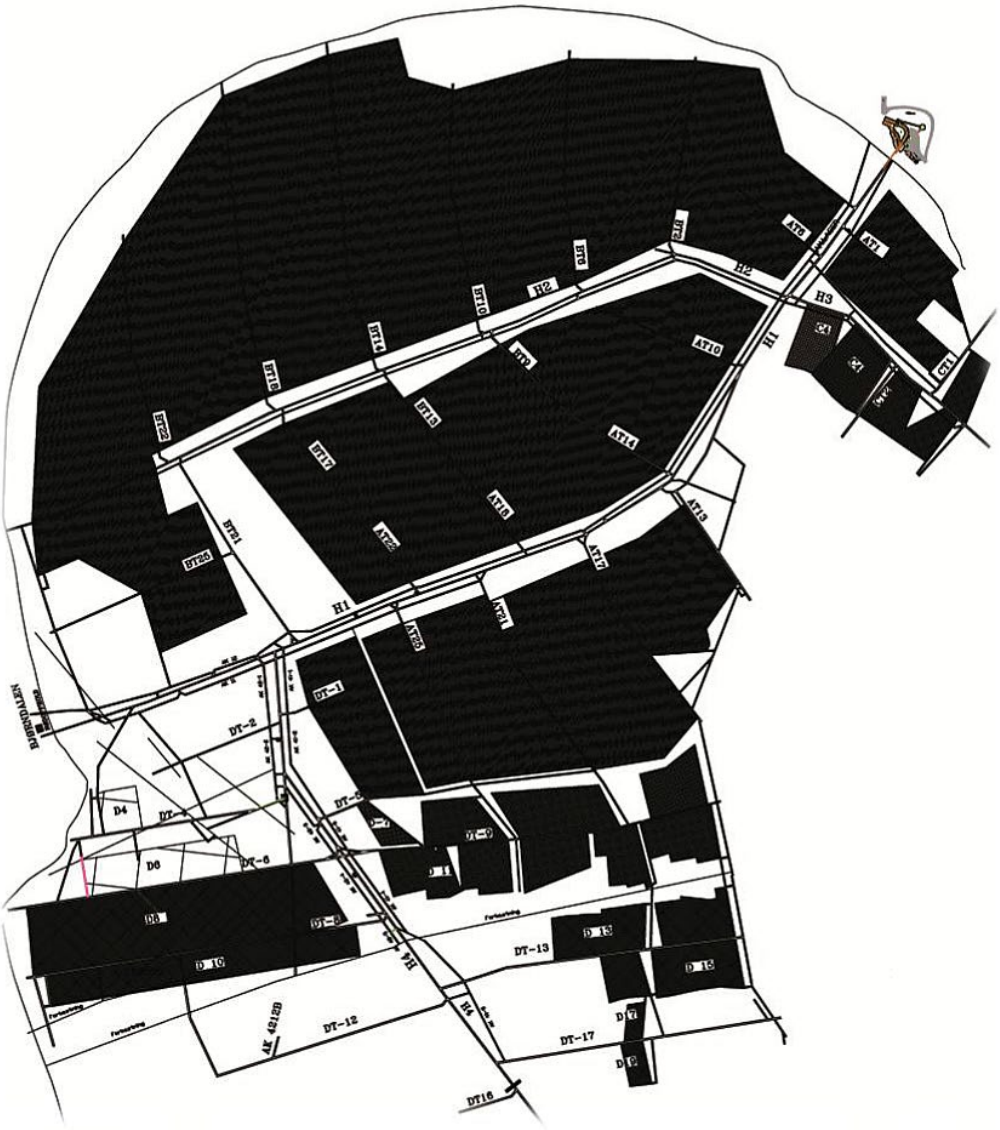

Figure 1.2   Map of Mine 3 tunnel system. AWA is located relatively close to the main entrance.

Due to permafrost on Svalbard, long-term storage in AWA takes place at low temperatures down to -5 °C. Storage at low temperature will increase lifespan of the piqlFilm, but little is known about how mine vault environments can affect the different components of a Piql system (film, storage box and aluminum laminate wrapping bag) over a long-term period.

The environmental characteristics of a mine are decided from both its geology and history. In an abandoned coal mine the oxygen concentration will be lower than the standard atmospheric condition, which is an advantage for long-term storage. However, concentration of CO_2 will be higher, and there will be detectable amounts of NOx, SOx and H_2S (Green Gas Ltd. Coal mine gas end uses. 2010). Mine environments may in addition contain a number of additional chemical, biological and radiological factors, which may have a negative impact on long-term storage of the Piql system. Thus, using mines and rock vaults for long-term storage may be challenging compared to a storage facility with control of the air quality by heating, ventilation and conditioning (HVAC).

In order to succeed in Piql's ambition of documented lifetime up to 2000 years an improved method for accelerated life testing of the Piql system had to be developed. An essential basis for this development is knowledge about environmental characteristics like temperature, humidity and the presence of chemical, biological and radiological factors in mines and rock vaults. Knowledge about the storage conditions in Mine 3 and AWA was collected through characterization of the environment during two sampling campaigns taking place at summer and winter conditions (August 30th – September 3rd 2021 and March 28th - 31st 2022).

2 Literature study - chemical, biological and radiation environment in coal mines

Literature studies of the chemical, biological and radiological background in mines, with emphasis on coal mines, were performed in order to gain an understanding of the instrumentation and analyses necessary for characterizing the environmental background in AWA. Little specific information about the chemical, biological and radiological environment inside abandoned coal mines were found. Most literature focused on health hazards to coal miners during operational phase and the impact coal mine waste has on the local environment. One must also bear in mind that coal mines differ much with aspect to their surrounding bedrock composition, depth and hence accumulation of water and natural ventilation.

A literature study dedicated to the particulate matter background is yet to be performed. Anyhow, particulate matter inside AWA and the coal mine tunnel was measured as a part of the environmental background characterization of this study. In order to put these measurements into context measurement data from the Norwegian Institute for Air Research (NILU) was used. The annual mean mass concentrations of PM_{10} and $PM_{2.5}$ measured during 2020 in the Norwegian rural background were respectively (2.9 – 5.2 $\mu g/m^3$) and (2.2 – 2.5 $\mu g/m^3$). For comparison, the annual PM_{10} mean mass concentration measured in an urban area like Oslo 2020 was 16 $\mu g/m^3$.
(https://www.oslo.kommune.no/statistikk/miljostatus/luftkvalitetsstatistikk/). The particles

belonging to the $PM_{10-2.5}$ fraction is typically attributed to natural sources such as sea salts, primary biological aerosol particles (PBAP), and mineral dust.

2.1 Chemical background in coal mines

There is little information to find about trace amounts of gases that could have significance for long-term storage. Most literature about measurements of gases in mines have emphasis on fire and explosion hazard, toxic gases or suffocation due to lack of air/elevated carbon dioxide levels. Traditionally the emphasis has been on five different types of gases: Blackdamp (gases causing suffocation), white damp (carbon monoxide (CO), toxic and combustible), firedamp (combustible gases, mostly methane (CH_4)), stink damp (hydrogen sulphide (H_2S), toxic and combustible) and afterdamp caused by explosions (CO and CO_2). Methane gas in coal mines as a lost resource is also discussed in several articles (Karacan et al., 2011 and Limbri et al., 2013).

Underground coal mine environment invariably contains more impurities in comparison to normal atmospheric air (Muduli, 2018). The impurities found in an underground coal mine environment (Misra, 1986) are non-toxic but explosive gases (methane (CH_4), acetylene, hydrogen and higher hydrocarbons), toxic gases (CO_2, radon and its daughter products) and acutely poisonous gases (sulphur dioxide (SO_2), nitrogen oxides (NO_X), CO, H_2S and sometimes arsenic and phosphine).

NILU operates the Norwegian measurement sites for long-range transport of pollution and monitors e.g. sulphur- and nitrogen-containing compounds in air and precipitation, inorganic compounds, tropospheric ozone, particulate matter (PM_{10} and $PM_{2.5}$) and particulate carbonaceous compounds. The annual average concentrations of sulphur- and nitrogen-containing compounds in air is of special interest for comparing with concentrations measured in AWA. Therefore, the concentrations measured during 2018, 2019 and 2020 are shown in Table 2.1. The measured background concentrations are variable and strongly affected by long-range transport as well as local road traffic and farming. Back trajectory analysis of air mass transport show examples of SO_4^{2-} transported from Great Britain and SO_2 transported from the Kola Peninsula.

The concentration of nitrogen-containing compounds in urban areas with traffic and industry is much higher. Air monitoring in Oslo showed a 2020 annual average of 23 µg N/m^3 (https://www.oslo.kommune.no/statistikk/miljostatus/luftkvalitetsstatistikk/).

Table 2.1 Annual averages of sulphur- and nitrogen-containing compounds in air at five Norwegian measurement sites. Values displayed are minimum and maximum averages measured at the measurement sites.

	NO_2 µg N/m^3	NH_3 µg N/m^3	Sum NO_3 µg N/m^3	SO_2 µg S/m^3	SO_4^{2-} µg S/m^3
Annual average concentration 2018	0.11 – 0.60	0.09 – 0.54	0.03 – 0.24	0.03 – 0.10	0.10 – 0.26
Annual average concentration 2019	0.14 – 0.50	0.09 – 0.40	0.05 – 0.15	0.03 – 0.08	0.10 – 0.20
Annual average concentration 2020	0.14 – 0.35	0.10 – 0.43	0.03 – 0.17	0.03 – 0.07	0.07 – 0.19

2.2 Biological background in coal mines

Most studies of the biological background in coal mines are performed on acid mine drainages with focus on characterization of its microbial community and the ecological role and impact of its microbiome. A number of microorganisms, such as, filamentous fungi, yeasts and bacteria are known to degrade coal by their enzymatic action and use it as their sole source of carbon. In addition, the indoor environments of coalmines possess bioaerosols, which may include living or dead allergens, pathogenic or non-pathogenic bacteria, fungi, viruses, mycotoxins, bacterial endotoxins, peptidoglycans, etc. that may cause skin, respiratory tract and other health problems (Sharma and Sumbali 2019).

Studies of drainage and biofilms from coalmines has shown an abundance of diverse microbiome communities. In a heavily polluted coalmine in Nigeria the microbiome was also found to be rich and diverse with microorganisms adapted to local environmental factors (Oyetibo et al. 2021). The Shannon diversity indexes for bacteria and eukaryota respectively were 5.86 and 3.51. Another study (Giddings et al. 2020) found that the microbial oxidation of metal sulfides plays a major role in the formation of acid rock drainage. Shannon diversity indices of taxa were similar for species of bacteria (6.8–7.0), archaea (4.0–4.9), and fungi (5.4–5.5) and confirm that microbial diversity in coalmine environments can be high.

The microbial diversity and abundance in bioaerosols of a coalmine in China were analysed based on 454 pyrosequencing and real-time polymerase chain reaction (PCR) (Wei et al. 2015). Results showed that microbial concentrations in the bioaerosols were significantly high, and there were abundant and diverse microorganisms in coalmine bioaerosols with Crenarchaeota (archaea), Proteobacteria (bacteria) and Ascomycota (fungi) as the dominant phyla. The concentrations of total archaea, bacteria and fungi were 1.44×10^8, 1.02×10^8 and 9.60×10^4 cells/m^3, respectively. The coal mine microbial community also included microorganisms associated with methane metabolism along with bacterial and fungal genera containing potential pathogens, several identified pathogens were observed in coal mine bioaerosols. The Shannon diversity index for archaea, bacteria and fungi was respectively 4.71, 6.29 and 3.86, indicating a high diversity in coal mine bioaerosols.

Mine 3 is a dry and cold mine with no rain or meltwater entering and accumulating in the tunnels. This may reduce the concentration of microorganisms present on surfaces and in biofilms. It is expected that both natural ventilation and human activity (e.g. guided coal mine tours) contribute to the microbiome community present as bioaerosols in the tunnel system and inside AWA.

2.3 Radiation background in coal mines

Almost anywhere on Earth there are natural radioactive materials, in soil, sub-soil and rock. There is no such thing as a natural space where radioactive isotopes and therefore a field of radiation, are not present. The most significant radioactive component of natural materials on Earth is potassium-40 (a component of natural potassium in anything organic, such as soil humus, vegetation, coal, peat, wood). Potassium-40 is a gamma ray emitter. As well as the potassium in organic components of the environment; In rocks and clays (and therefore soils that contain these minerals) there are usually trace elements such as uranium and thorium. The amounts depend on the types of minerals present (granite being an example with significant amounts) and of course, the location will determine this.

Uranium is the most significant of the radioactive isotopes occurring in rocks and minerals, because of its complex decay series. Wherever minerals hold uranium there is an array of the other isotopes present in the uranium decay series. Because each radioactive isotope created by a decay event will also decay away – both of these processes at a fixed and known rate; and because there is a cascade of daughter isotopes for uranium decay, then a large number of radioisotopes will be present all together – in a series of equilibrium amounts.

One of the isotopes to which uranium decays is radon-222. This, unlike its immediate parent isotope radium-226, is a gas, and so it escapes from the surface where it is born. This means that, unless the air in the internal space is ventilated, a significant amount of radon will build up in that space. Radon itself decays away to the daughter isotope, polonium-218, some of which will sediment as a solid, due to gravitational settling, diffusiophoresis, or thermophoresis. Over decades, this may be significant in building up an internal dose from Po-218 to the canister contents.

Any radioactive isotope present in the walls, floor and ceiling of a natural tunnel, a mined shaft or gallery as well as in masonry used in building structures will contribute to a standing radiation dose rate. This radiation will bathe the internal spaces of tunnels, shafts galleries and rooms. This radiation will consist mainly of gamma-rays (because alpha and beta radiation will not travel far enough to really contribute) and some neutrons. This ‘direct shine’ radiation can be measured with appropriate equipment.

In the case of storage spaces constructed of, or bored into, uranium-bearing rock the direct shine radiation dose will be only one component of the radiological threat to sensitive materials stored. The dose impinging on any container will be larger than the dose received inside the container, as the container material will offer some shielding effect. The other two components to consider are cosmic rays and radioactive particulate with the potential to become radioactive contamination inside containers and enclosures.

Reports and articles found on radiation background, in or from coal mines, emphasize the impact of coal mining on the environmental radioactivity and, if so, whether this has increased radioactive dose rates in the area. Coal contains radionuclides of the uranium and thorium series as well as potassium-40 and results from an in situ dosimetric survey within the settlement of Ny-Ålesund have shown that a small but significantly enhanced radiation rate can be determined at locations at which historic coal mining operations has resulted in severe degradation of the ground surface. Ex situ gamma spectrometric analyses of soil and substrate samples from within Ny-Ålesund and from several control sites outside of the settlement indicated enhanced activity concentrations of potassium-40 and the uranium-238 and thorium-232 series radionuclides within samples obtained in areas of Ny-Ålesund contaminated with coal wastes (Dowdall et al. 2004).

Even though the tunnels of Mine 3 do not contain coal waste, they do contain remains from the coal mining and some elevation of background radiation may be expected. Due to melting of permafrost, the dose from increased exhalation of radon-222 from the soil (the most stable isotope of radon, with a half-life of approximately 3.8 days) is predicted to increase in the order of a factor of 2 – 3 (McDonald et al., 2003).

3 Characterizing the environmental background

The environment of the AWA vault was considered representative for environmental conditions inside the storage container (figure 1.1), with the exception that the steel container used for storing the piqlBoxes could provide extra shielding from radiation. Therefore, emphasis was on characterizing the environmental conditions inside the AWA vault. There is little or no natural nor mechanical ventilation in the AWA vault, therefore the human activities inside the AWA vault may have larger impact on the environmental background compared to the ventilated mine tunnels. In order to address this, “baseline” measurements of microbiological background and particulate matter was performed in another enclosed appendix of the tunnel with very limited air exchange and no human activity. This vault was used as location for the Nordic Gene Bank for storing backup Nordic plant germplasm via frozen seeds from 1984 - 2008.

Instruments used for characterization were dependent on environmental conditions (e.g. low temperature, high relative humidity and the combination of these) and the availability of AC power inside Mine 3. A summary of data and samples collected at each of the locations described is shown in Table 3.1.

Due to COVID-19 travel restrictions, the environmental sampling campaign was postponed several times, ultimately resulting in a delay to the simulation of long-term storage effects. In order to reduce the delay it was decided to ship passive air samplers and a Dräger X-am 5600 gas detection instrument (Drägerwerk AG&Co. KGaA, Lübeck, DE) to Svalbard in the beginning of April 2021 to collect data on the chemical background inside AWA. These samplers were set up by personnel working in Mine 3 and did not require FFI personnel travelling to Longyearbyen.

Temperature and RH loggers running on batteries were left to continuously collect data inside the AWA vault, in the main tunnel outside the AWA vault and in the old seed vault between the summer and winter sampling campaigns (Sept 3rd 2021 – Mar 28th 2022).

Table 3.1 Measurements performed at each location.

Location	**Chemical**	**Biological**	**Radiation**	**Particulate matter**
Storage container	-	Swab samples	Automess dose rate monitor	-
AWA vault	NO_2, SO_2,CO_2, CH_4, NH_3, O_2	Air samples + swab samples	Radon measurement + Automess dose rate monitor	Alphasense OPC-N3
Tunnel outside AWA vault	-	-	Automess dose rate monitor	Alphasense OPC-N3
Old seed vault	-	Air samples + swab samples	Automess dose rate monitor	Alphasense OPC-N3

3.1 Chemical

Passive air samplers with an impregnated filter were used to collect nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and ammonia (NH_3) inside the AWA vault during the periods April 9th – May 5th 2021 and March 29th – May 11th 2022. The air samplers were supplied and analysed by NILU using spectrophotometry (NO_2 and NH_3) and ion chromatography (SO_2).

A Dräger X-am 5600 gas detection instrument was used to measure the concentration of carbon dioxide (CO_2), oxygen (O_2) and methane (CH_4). The instrument battery can only run for ~16 hours and not while charging. During both summer and winter sampling campaigns the instrument was charged during night and placed inside the AWA vault for periods of 5 – 15 hours.

3.2 Biological

SASS 3100 dry air samplers (Research international, Monroe, WA, USA), which efficiently capture particles of all sizes to electret filters, were used to collect aerosols from the AWA vault and the old seed vault (reference). The SASS 3100 operates at 300 lpm, is able to run on battery for >16 hours with a sampling efficiency documented through several reports and research articles (Skogan and Dybwad, 2021).

The SASS 3100 filters were transferred to a tube containing 10 ml NucliSENS lysis buffer immediately after sample collection and stored at -20 ℃ until DNA extraction using a custom DNA isolation method (Bøifot et al. 2020). Swab samples were collected from floors, walls and construction surfaces inside AWA, the storage container, the mine tunnel and in the old seed vault, transferred to tubes containing 1 ml NucliSENS lysis buffer and stored at -20 ℃ prior to DNA extraction. DNA yield from air and swab samples were determined using the Qubit dsDNA HS assay (Life Technologies, Carlsbad, CA, USA) on a Qubit 3.0 Fluorimeter (Life Technologies) and expressed as picograms per cubic meter of air.

Next Generation Sequencing (NGS) was performed in order to identify the dominant microorganisms present in a selection of the DNA samples. Focus was targeted at air samples collected inside the AWA vault because these samples will provide information about airborne microorganisms that may deposit on the piqlBox wrapping and cause damage. It was concluded that during long-term storage, microorganisms are transported into AWA and deposited on the piqlBox wrapping throughout the year. Therefore, DNA extracted from air samples collected during summer and winter were pooled before shotgun metagenomics sequencing with an Illumina MiniSeq (Illumina Inc., San Diego, CA, USA). DNA extracted from air samples directly outside the mine were additionally sequenced. Together, these results may provide some information about the AWA microbial community originating from outdoor air being ventilated into the mine tunnel environment itself. It must also be noted that human activity in the mine tunnel (guided tours) and AWA itself will influence the microbial community.

Microbial growth, of a presumed fungus, was observed at several locations on the plywood floor inside the AWA storage container. Swab samples were collected from three areas with fungi growth and brought to the laboratory for microbial growth, DNA isolation and identification by sequencing the DNA with the MinION nanopore sequencing technology (Oxford Nanopore Technologies plc., Oxford, UK).

Bioinformatics analysis of the sequenced metagenome was used to provide a taxonomical breakdown of the identified microorganisms. The amount of information from shotgun metagenome sequencing is large and the most detailed taxonomic levels are likely not suited for displaying an overview of the microbiome present in the AWA vault or evaluating the significance on long-term storage of the piqlBoxes. Therefore, the bioinformatics analysis in this report display the information on a higher microbiological taxonomic level (phylum and above). Limitations in sequencing depth, database representation as well as size are limiting factors in classification of reads to a low taxonomical level, e.g. species.

3.3 Radiation

One of the findings from the literature study was that radon-222 gas may accumulate in unventilated spaces. Therefore, a Corentium Plus radon monitor (Airthings, Oslo, NO) was placed inside AWA for a period of 33 days (April 9th – May 11th 2021) to measure radiation from radon gas.

An Automess 6150 AD 6/E dose rate meter was used during both sampling campaigns to measure effective radiation dose inside AWA, the storage container, in the old seed vault and in the tunnel system. The Automess dose rate meter measure only gamma radiation effectively, not alpha and beta radiation. Alpha and beta radiation are not considered to be a challenge for the piqlFilm because of their limited penetration power. Alpha radiation is absorbed by the skin or by a few centimetres of air, while beta radiation is absorbed by a few millimetres of aluminium. The material in the storage boxes is expected to efficiently stop beta and alpha radiation before it reaches the film itself.

3.4 Particulate matter

Alphasense OPC-N3 is a low-cost optical particle monitor with a particle measurement range of 0.35 – 40 μm in 24 particle size bins. The Alphasense has a very low power consumption and can run on a consumer power bank for several days and may be used in low temperatures and high RH (-10 °C, non-condensing). These properties were useful as the mine tunnel temperatures around 0 °C with high RH is outside the operational parameters for more sensitive and expensive particle counters. The Alphasense monitors collected aerosol data from a height of 1.5 meter above floor level at three locations: the AWA vault, in the tunnel outside AWA and in the old seed vault. After the summer 2021 sampling campaign the Alphasense monitors in the AWA vault and in the mine tunnel outside AWA were left monitoring the particle concentration for several weeks in order to collect more data from periods without human activity.

4 Results

The temperature and RH monitors collected data on an hourly basis in the period between the summer and winter sampling campaigns, with results shown in Figure 4.1. Unfortunately, the monitor placed in the tunnel outside AWA did not collect data in the period October 17th 2021 to January 8th 2022. Deposition of data in the period of September 21st – 23rd 2021 with increased human activity in AWA is visible on both temperature and RH.

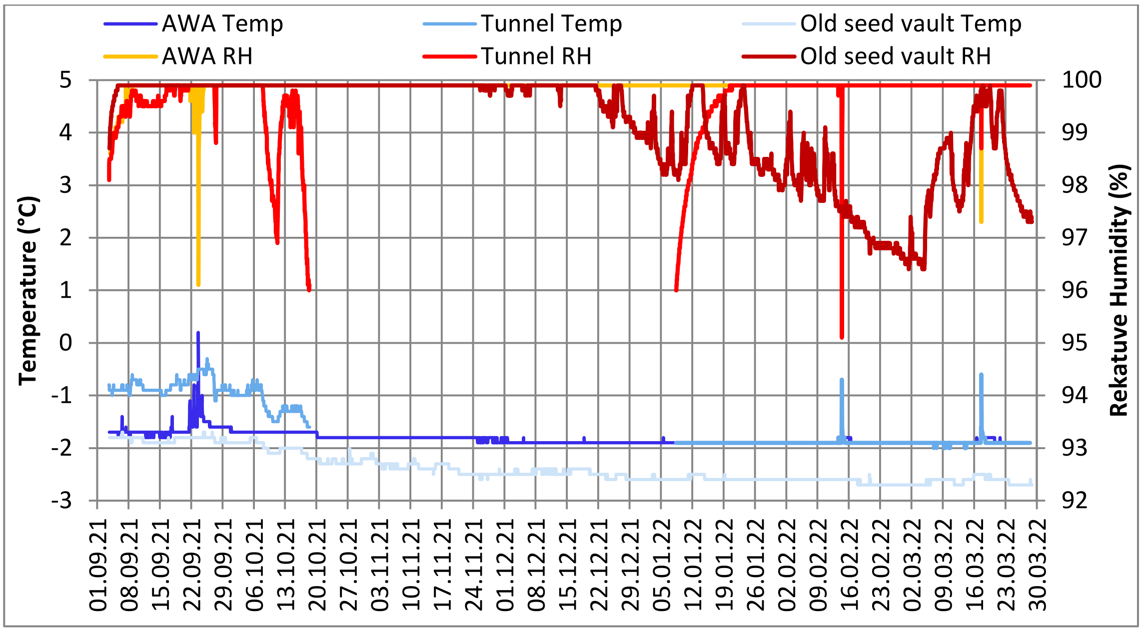

Figure 4.1 Temperature and relative humidity monitored in the period September 2021 – March 2022. Tunnel data are missing in the period Oct 18th 2021 – Jan 8th 2022.

4.1 Chemical

The concentrations of SO_2, NO_2 and NH_3 gas in the AWA vault are shown in Table 4.1. Two passive air samplers were used during both sampling periods to rule out statistical errors.

The SO_2 concentrations measured in the AWA vault during the period April 9th – May 5th 2021 were significantly higher than at the Norwegian background measurement sites and downtown Longyearbyen (by NILU) during the same period (0.02 µg/m^3 SO_2). The SO_2 concentration measured in AWA during the period March 29th – May 11th 2022 on the other hand was much lower than the 2021 measurements and in the same range as the SO_2 concentrations at Norwegian measurement sites. SO_2 measurements performed downtown Longyearbyen on weekly basis in March and April 2022 showed a concentration of 0.16 ± 0.15 µg/m^3 SO_2. NILU has later informed that the passive SO_2 samplers used in 2021 had very high baseline levels of SO_2, which is believed to have affected the results and the SO_2 measurements from 2021.

Results show that the NH_3 concentrations measured in the AWA vault were 6x higher than the 2018-2020 average concentrations measured at Norwegian mainland measurement sites (0.278 µg/m^3) and 16x higher than the 2018-2020 average concentration (0.107 µg/m^3) measured at the Zeppelin observatory at Ny-Ålesund (Svalbard). The NH_3 concentration measured downtown Longyearbyen by NILU in April 2021 was 0.04 µg/m^3 and confirm that the AWA vault concentration is higher than average outdoor background. Agriculture is regarded the principal NH_3 emission source and the Norwegian measurement sites may have lower concentrations than populated areas with agriculture and livestock. Ambient atmospheric ammonia in Ireland was measured at 25 sites in 2013 - 2014 (EPA research report 193) with a mean concentration of 1.72 µg/m^3, a result comparable with the AWA vault concentration.

The NO_2 concentration measured was within the range of concentrations measured at the Norwegian measurement sites (Table 2.1).

Table 4.1 Measured concentrations of SO_2, NO_2 and NH_3 gas inside AWA.

	NO_2-N µg N/m^3	**NO_2 µg/m^3**	**NH_3-N µg N/m^3**	**NH_3 µg/m^3**	**SO_2-S µg S/m^3**	**SO_2 µg/m^3**
April 9th – May 5th 2021 **#1**	0.11	0.37	1.67	2.03	2.48	4.96
April 9th – May 5th 2021 **#2**	0.11	0.37	1.54	1.86	3.62	7.23
March 29th – May 11th 2022 **#1**	0.07	0.23	1.83	1.33	0.00	0.01
March 29th – May 11th 2022 **#2**	0.07	0.23	1.94	1.46	0.04	0.07

A Dräger X-am 5600 instrument was used for measuring concentrations of O_2, CO_2 and CH_4 gases inside AWA. The results (Table 4.2) indicate that the concentration of O_2 was slightly reduced, while the CO_2 and CH_4 concentrations increased during the winter sampling campaign.

Table 4.2 Measured concentrations of O_2, CO_2 and CH_4 gases inside AWA.

Date	**Sampling time**	**O_2 (vol.-%)**	**CO_2 (vol.-%)**	**CH_4 (% LEL[1])**
12.07.2021	5 h 10 min	20.88 ± 0.06	0.040 ± 0.002	0
13.07.2021	5 h 07 min	20.89 ± 0.04	0.040 ± 0.002	0
14.07.2021	5 h 27 min	20.89 ± 0.04	0.039 ± 0.002	0
15.07.2021	4 h 35 min	20.84 ± 0.14	0.041 ± 0.004	0
16.07.2021	5 h 10 min	20.88 ± 0.07	0.039 ± 0.003	0
01.09.2021	15 h 10 min	20.50 ± 0.12	0.057 ± 0.005	0.91 ± 0.28
29.03.2022	7 h 09 min	20.20 ± 0.00	0.150 ± 0.002	1.71 ± 0.55
30.03.2022	15 h 24 min	20.20 ± 0.00	0.141 ± 0.002	1.90 ± 0.33
31.03.2022	7 h 46 min	20.20 ± 0.00	0.140 ± 0.000	1.87 ± 0.34

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[1] The minimum concentration of a combustible gas or vapor necessary to support its combustion in air is defined as the Lower Explosive Limit (LEL) for that gas. Below this level, the mixture is too "lean" to burn.

4.2 Biological

The DNA yield from environmental samples will follow the natural spatio-temporal variation of the microbial communities. In addition, the sampling method and efficiency of the DNA extraction method used may cause variations in DNA yields. The SASS 3100 air sampler and the DNA extraction method used here has also been used for extracting DNA from air samples collected in other background environments. DNA yields, expressed as picograms DNA per cubic meter air (pg /m^3), from air samples collected in the AWA vault, old seed vault and the outdoor environment close to Mine 3 is shown in Table 4.3.

Table 4.3 DNA yield from air samples collected.

Location	**pg /m^3 air (summer)**	**pg /m^3 air (winter)**
Outside air	26.5 ± 10.3	n.a.
AWA vault	67.7 ± 25.7	82.7 ± 23.6
Old seed vault	120.9 ± 3.9	7.5 ± 3.9

The results show that the DNA yield from air samples collected outside the entrance of Mine 3 were lower than in air samples collected inside the AWA vault, indicating that more airborne microorganisms are present in the AWA vault than the outdoor environment. An investigation of the microbial communities at nine different meteorological stations around the world (Tignat-Perrier, 2019) showed that the abundance of airborne microorganisms were significantly lower (>200x) at the polar station compared to the other meteorological stations. The number of bacterial gene copies found in the AWA vault were also significantly lower compared to the eight non-polar meteorological stations in this investigation. The DNA yield from samples collected in a semi–suburban environment (Kjeller) and in a subway station (Oslo) were measured to 69 ± 92 pg/m^3 and 255 ± 91 pg/m^3 respectively (Bøifot et al. 2020). Other, unpublished results have shown DNA yields in the range of 150 – 1500 pg/m^3 in outdoor and indoor subway stations around Europe, Asia and North America. Together, these results show that the biomass measured in the AWA vault is in the lower range of biomass measured in environmental backgrounds.

Bioinformatics analysis of the shotgun metagenome shows higher levels of bacteria in the AWA vault (53% of reads, Table 4.4) compared with the outside (19% reads). Conversely 18% and 28% of reads were classified to eukaryotes, respectively. Focusing on the phylum level, we see both Actinobacteria (33%) and Proteobacteria (11%) dominating in the AWA vault. The latter being comparable to outdoor measurements, however the first is highly inflated, with <5% of outdoor reads being assigned as Actinobacteria. The majority of Actinobacteria are saprophytes and may indicate decomposition of plant or animal debris within the vault. Levels of Fungi, and in particular Ascomycota, are comparable between the AWA vault (9%) and outdoors (10%). However, we observe a reduced level of Basidiomycota, going from 9% of classified reads outside to <5% of reads in the AWA vault.

Table 4.4 List of dominant bacteria and eukaryota at taxonomic levels with >5% relative abundance in the AWA vault and outdoor air.

	AWA vault			**Outdoor air**		
	%	**sequence**	**OTUs**	**%**	**sequences**	**OTUs**
unclassified	26.25	2943839	2943839	49.06	2740455	274045
root	73.75	8270525	11945	50.94	2845624	7998
cellular organisms	73.49	8241980	260887	50.57	2824694	181981
Bacteria	53.09	5953872	255271	18.67	1043104	82456
Terrabacteria group	35.93	4029844	39435	5.83	325470	8368
Actinobacteria	32.71	3667705	24675	-	-	-
Proteobacteria	11.30	1266721	86825	7.16	399688	19696
Eukaryota	17.82	1998422	47575	28.22	1576649	43592
Opisthokonta	15.91	1784746	31582	24.49	1368287	25886
Fungi	13.43	1506239	16948	20.13	1124484	11865
Dikarya	12.89	1445945	21528	19.31	1078868	15049
Ascomycota	8.52	955346	852	9.68	540643	819
Basidiomycota	-	-	-	9.37	523176	4572

The fungi collected from the plywood floor inside the AWA container and sequenced using Nanopore were identified as Aspergillus spp. and Penicillium spp (Ascomycota). Both species are ubiquitous, found in most environments, and capable of growing in cold and nutrient-depleted environments. There is no reason to assume that these are the only species of fungi able of growing on the plywood floor. An abundance of fungi species will be able to grow in the cold and humid environment in the presence of a carbon source like the plywood. It should be noted however, that Aspergillus sps. degrade plant tissue i.e. wooden floors. Further, they can cause infection, primarily lung, for people with lowered immunological response. From the air-sampling within AWA we find the level of Aspergillaceae fungi, the family harbouring both Aspergillus spp. and Penicillium spp., to be five times higher (1.65% of total) than that of the outdoor air sample (0.33% of total). The higher observed levels of Aspergillaceae fungi within AWA can been seen as both possible health and contamination risk. It is difficult to ascertain of the latter has any negative consequence for the Piql system.

4.3 Radiation

Average measured radiation level from radon gas inside the AWA vault during the 33 day measurement period equals to 30 ± 10 Bq/m^3. This is lower than the average radiation level of 56 Bq/m^3 measured in Norwegian households in 2001 (StrålevernRapport 2001:6), and well under the action limit of 100 Bq/m^3 established for health reasons by the Norwegian Radiation and Nuclear Safety Authority (DSA).

Effective dose measured with the Automess 6150 AD 6/E inside AWA, in the tunnel outside AWA and in the old seed vault is shown in Table 4.5. For comparison, the average background radiation in Norway varies from ca. 0.05 µSv/h to 0.20 µSv/h (Radnett).

Table 4.5 The effective radiation dose at different locations.

Location	**µSv/h**
Inside AWA	0.073 ± 0.057
Tunnel outside AWA	0.063 ± 0.042
Old seed vault	0.052 ± 0.042
Inside container	0.070 ± 0.037
Outdoor (outside Mine 3)	0.142 ± 0.049

4.4 Particulate matter

In the course of a 5-day period during summer sampling campaign, 2-3 people entered the AWA vault on a daily basis around 15:00 for filter exchange, surface sampling and general instrument maintenance. During the winter sampling campaign, instrument maintenance took place more often, at 07:00, 15:00 and 23:00. Particle data (Figure 4.2 and Figure 4.3) show that human activity in AWA caused a significant increase of suspended particulate matter and that the suspended particles settled within hours after these activities. Theoretical settling velocities for 1, 2.5 and 5 µm particles in still air are 11, 68 and 270 cm/hour respectively, explaining that even small particles sediment to the ground within 24 hours in the absence of activities re-suspending or transporting particles into AWA.

Suspended particulate matter in the mine tunnel show less variation compared to AWA (result not shown).

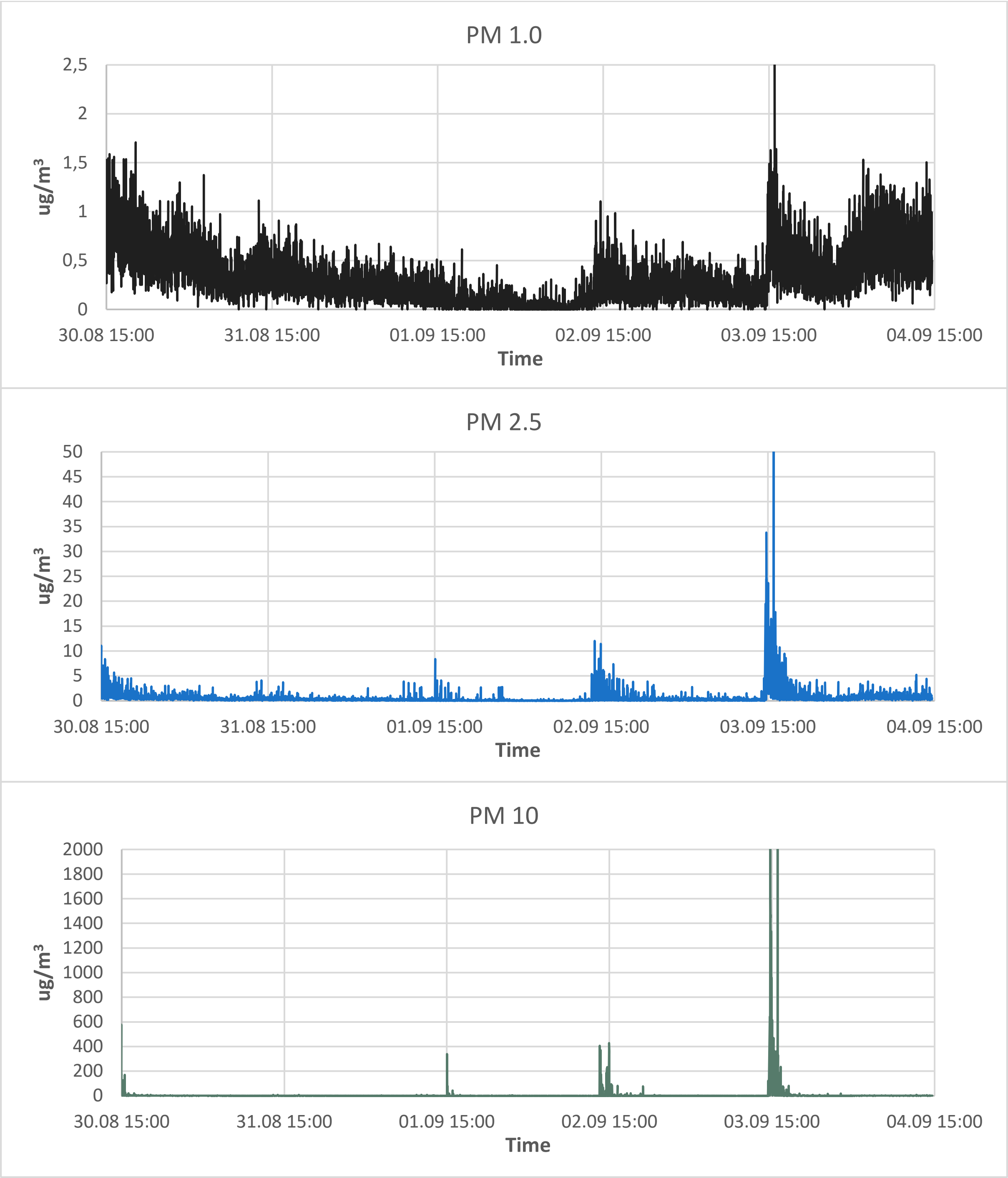

Figure 4.2 Results from the 2021 summer sampling campaign show increased suspended particulate matter around 15:00 when human activity in AWA took place.

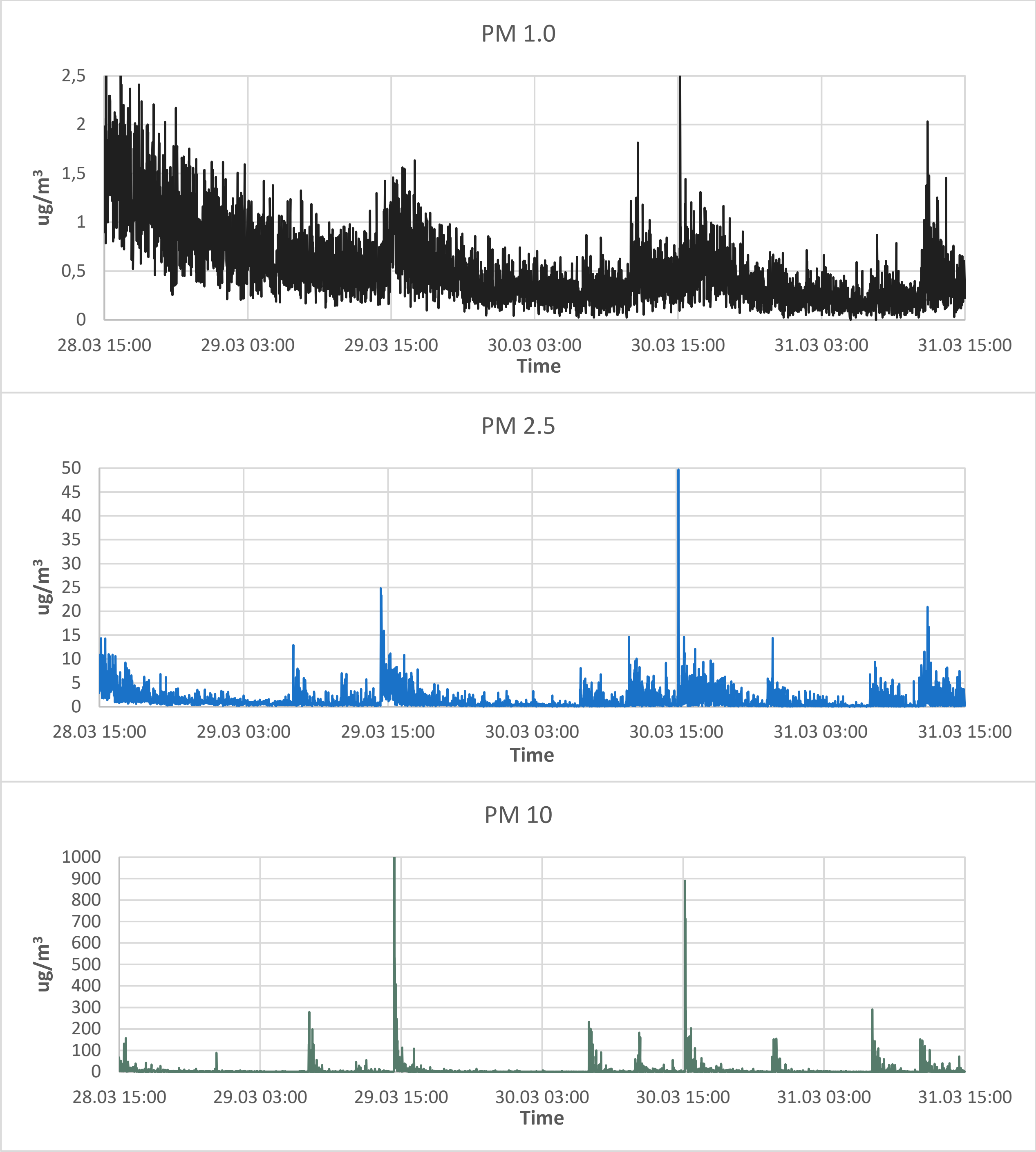

Figure 4.3 Results from the 2022 winter sampling campaign show increased suspended particulate matter around 07:00, 15:00 and 23:00 when human activity in AWA took place.

Table 4.6 displaying the average suspended particulate matter during a period with no human activity show less suspended particulate matter inside AWA and the old seed vault compared to the tunnel system. This result was as expected, as both natural and active ventilation continuously bring outside air containing suspended particulate matter into the mine tunnel. The average suspended particulate matter during periods without human activity was also significantly higher in the mine tunnel compared to AWA and the old seed vault (Table 4.6).

Table 4.6 Particulate matter suspended in air during a period with no human activity in each of the three locations monitored.

	Average (µg/m^3)		
Location	**PM$_{1.0}$**	**PM$_{2.5}$**	**PM$_{10}$**
Old seed vault	0.17	0.41	0.62
Tunnel outside AWA	1.30	3.10	10.15
AWA	0.07	0.10	0.14

Comparison with annual mean mass concentration of PM10 (2.9 – 5.2 µg/m^3) and PM2.5 (2.2 – 2.5 µg/m^3) at Norwegian rural background sites (NILU, 2020) show that suspended particulate matter inside AWA is low.

5 Conclusions

This report describes the characterization of the chemical, biological and radiological environment in AWA, which is located inside the decommissioned Mine 3 on Svalbard and used for long-term storage of digital information on the piqlFilm. Due to the permafrost on Svalbard, long-term storage in AWA takes place at low temperatures, which will increase the lifespan of the piqlFilm. Apart from this, little is known about how the chemical, biological and radiological conditions of the Mine 3 environment influence the lifetime of the Piql system. In order to develop methods for accelerated life testing of the Piql system detailed knowledge about the storage conditions is essential. In this study, we have characterized the Mine 3 environment during two sampling campaigns in summer 2021 and winter 2022. This report summarizes the results from a literature study on coal mine environments and from two sampling campaigns, taking place at summer and winter conditions.

The literature study did not reveal information about whether higher concentrations of NH_3 could be expected in coal mines, although the measured concentrations of NH_3 in the AWA vault were significantly higher than the annual averages measured at several Norwegian measurement sites (Table 2.1) and downtown Longyearbyen in the same period of time.

Measurements of ambient NH_3 in Ireland showed higher concentration than at the Norwegian measurement sites and indicate that the concentration measured in AWA may be at the ambient concentrations found in populated and agricultural areas. The measured concentrations of SO_2 during the 2021 sampling campaign were significantly higher than SO_2 measurements at Norwegian measurement sites. The 2022 SO_2 concentrations were significantly lower and at similar to the Norwegian measurement sites. According to NILU the SO_2 filters used during the 2021 sampling had a high baseline value, which has probably affected the measurements. The results are relevant to assess whether the NH_3 and SO_2 concentrations may cause long-term storage effects on the different components of the Piql system and as input for the simulation of long-term storage effects. The concentrations of NO_2, CO_2 and CH_4 were at natural atmospheric background levels and indicate that accelerated life testing of the Piql system can be performed at atmospheric concentrations. The concentration of these (and other gases) might increase if natural and active ventilation of the mine tunnel is reduced or prevented.

The DNA concentration from the air samples collected in the AWA vault were in the lower range of DNA concentrations found in environmental outdoor air samples. These results indicate that there is no reason to customize the microbiological environment during accelerated life testing of the Piql system.

The fungal growth found on the plywood floor in the storage container will undoubtedly increase during long-term storage, it is difficult to predict if this will have any effect on the piqlBox wrapping. Exchanging the plywood floor with e.g. steel should be considered and will reduce problems associated with fungal growth.

The effective radiation dose inside the Mine 3 tunnels and the AWA vault were measured at levels equivalent to the lower range of average background radiation in Norway and lower than outdoor measurement close to Mine 3. The measured radiation from radon gas was also lower than the average in Norwegian households. These results indicate no special risk of long-term storage effects on the different components of the Piql system from radiation in the AWA vault and mine environment compared to other random storage environments.

In the absence of human activity inside the AWA vault particulate matter will sediment within 24 hours. Left unattended for long-term storage, it can be assumed that only small amounts of particulate matter will enter the AWA vault and ultimately sediment on the piqlBox. Particulate matter that sediments on the piqlBox wrapping has its origin both from environmental air ventilated into the mine tunnels and re-suspended dust from the mine tunnel. Chemical or biological analysis of the particulate matter sedimenting on surfaces inside AWA were not included in the characterization of the Mine 3 environment. Thus, whether the sedimented particulate matter has the potential to damage the piqlBox wrapping during long-term storage cannot be ascertained.

These results will be used as input for the accelerated life testing of the Piql system during long-term storage in AWA. The results indicate that the accelerated life testing of the Piql system can be performed at atmospheric concentrations of gases, with the ambient microbiological community and at average background radiation levels measured in Norway.

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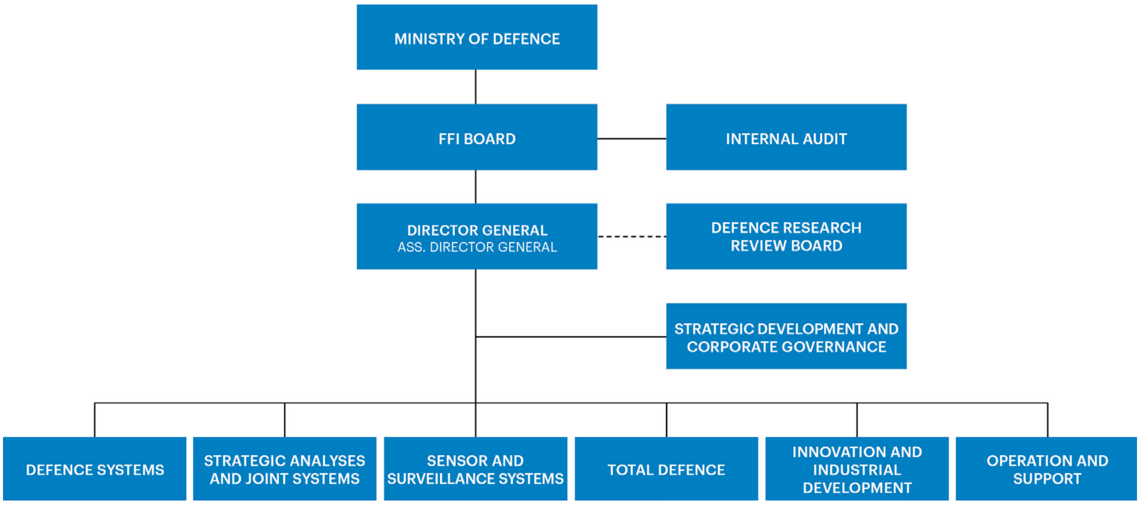

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