Leibniz University Hannover

Faculty of Mathematics and Physics

Institute of Radioecology and Radiation Protection

Environmental Forensic Measurements Related to the 2019 Explosion at the Nenoksa Test Site

Bachelor Thesis

October 2020

Author:
Imke Spykman
(10005669)

Supervisor:
Tobias Blenke

Examiner:
Prof. Dr. Georg Steinhauser

Eigenständigkeitserklärung[1]

Hiermit erkläre ich, dass ich die folgende Bachelorarbeit selbstständig verfasst habe und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet wurden.
Alle Stellen der Arbeit, die wörtlich oder sinngemäß aus anderen Quellen übernommen wurden, sind als solche kenntlich gemacht worden.

Diese Bachelorarbeit wurde in dieser oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegt.

Ort, Datum, Unterschrift

[1] Fakultät für Mathematik und Physik der Leibniz Universität Hannover, 2020

Table of contents

1. Abstract

On August 8, 2019, an explosion of a military missile occurred at the Nenoksa (also transcribed as Nyonoksa) Missile Test Center (Russian Federation). Russian authorities confirmed a release of radioactive material in the course of this incident, which fueled rumors that it could have involved a nuclear-propelled missile of the Burevestnik/Skyfall type. In this study, our radioanalytical efforts are summarized searching for the "smoking gun" of the incident. These included the gamma-measurements of air filters from two vessels that were in some proximity to the event as well as one Greek high-volume air filter. In addition, the hypothesis was tested that radioactive ^{42}Ar may have been used to operate a radiothermal generator. If the incident had released ^{42}Ar, it may have become detectable by measuring characteristic gamma radiation emitted from a liquefied argon tank. In no instance were any traces found that could provide clues about the release. It is possible that only radioactive fission noble gases were released.

2. Introduction

Following the end of atmospheric nuclear testing and especially after the 1986 Chernobyl nuclear accident, a powerful monitoring network for anthropogenic radionuclides was established in Europe (and worldwide). Many European monitoring stations are connected through an informal network called "Ring of Five" (Ro5) that allows rapid exchange of data and discussions. Most of these monitoring stations employ high-volume samplers and low-level radiation detectors that allow detecting trace or ultra-trace levels of radionuclides. Today, the Ro5 network encompasses 178 radionuclide monitoring stations in 29 (mainly European) countries. The Ro5 has successfully detected large [1–3], medium [4] and small [5–7] releases of anthropogenic radionuclides, including ^{106}Ru, ^{131}I, ^{137}Cs, and other fission/activation products.

Since 1996, the Comprehensive Nuclear-Test-Ban Treaty (CTBT) has been open for signature and an International Monitoring System (IMS), consisting of seismic, hydroacoustic, infrasound and radionuclide stations has been established by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) for its verification. [8]

On Thursday, August 8, 2019, around 06:00 UTC, an explosion occurred at the Nenoksa (russ. Нёнокса) Missile Test Center near Severodvinsk, Arkhangelsk Oblast, Russian Federation. According to the IMS-analysis conducted by the CTBTO International Data Centre, four geophysical detectors (3 seismic, 1 infrasound) recorded the detonation that occurred at an offshore platform in the White Sea. [8] This incident caused eight injuries of technical and scientific staff, five of which were reported fatal. [9]

Immediately after the accident, the Ministry of Defence of the Russian Federation released a statement confirming an explosion during a test of a liquid-propellant rocket engine, without specifying the exact location. Although little information is available on the nature of the test at the Russian naval test range near Nenoksa, the Rosatom State Nuclear Energy Corporation said that the test involved a nuclear-powered engine, allegedly a cruise missile of the 9M730 Burevestnik type (NATO reporting name: SSC-X-9 Skyfall). [10] The testing of this type of nuclear-propelled engine may be in direct context with Russian Federation President Vladimir V. Putin's 2018 announcement of the on-going development of nuclear-powered engines [11] with "basically unlimited range, unpredictable trajectory and ability to bypass interception boundaries." [12] The Burevestnik was already tested the year before, but has not yet been made to fly. [13]
Jeffrey Lewis, who is professor and the director of the East Asia Non-Proliferation Program at Middlebury Institute of International Studies [14], made several observations that support his suspicion like commercial satellite pictures. The ship Serebryanka, a

specialized nuclear fuel carrier, which is needed to recover a nuclear propulsion unit from the sea floor, was found on these pictures. It was tracked with AIS (Automatic Identification System) in the exclusion zone right after the incident, that was created one month before the incident to prevent unauthorized ships from entering. The same ship was used a year before to disassemble a facility at the site in Novaya Zemlya, where the Burevestnik was tested before. [10] The Norwegian Arctic news website (Barents Observer) confirms this observation. [15]
Other possibilities for the weapon involved in the blast are the long-range Zircon, an hypersonic "anti-ship cruise missile" [15] which is able to reach a speed of "eight times the speed of sound" [15] according to the Russian military, and the so called Poseidon, a "long-range underwater drone". [15]

Although early reports indicated no release of dangerous substances, [16] NGO reports and governmental measurements indicated a short (and innocuous) spike of radiation levels in Severodvinsk, about 30 km east-southeast from Nenoksa. [10]
While Greenpeace announces a brief rise of radiation from 0.11 μSv/h to 2 μSv/h for about 40 minutes (based on data released by the Russian Emergency), [10, 16] the national weather service, Rosgidromet, said the radiation level had a maximum of 1.78 microsievert/h with a duration of the peak of two and a half hours. [15] This peak was not high enough to cause health consequences. Nevertheless, the citizens of Severodvinsk and Arkhangelsk started stocking up on medical iodine to reduce possible effencts of radiation exposure. [9]
Rosatom reported that the test had involved a "radio-isotope propellant source," [10] or "isotope power sourc" according to different sources. [17] Without further specifications, this may refer to either a small reactor or alternatively to a radiothermal generator (RTG) (vulgo radionuclide battery).The rocket test was completed, but the fuel caught fire afterwards, this lead to an explosion which threw several people into the sea. [10]

Atmospheric transport modelling conducted by the CTBTO indicated that the plume would travel toward the southeast and remain over Russian territory for a considerable time. [18]

According to P. Seibert, [19] the plume from the explosion would have reached IMS station RUP61 Dubna (south of Nenoksa) on August 10, 2019; station RUP54 Kirov (south-southeast of Nenoksa) on August 11, 2019; station RUP59 Zalesovo on August 13, and later possibly also the stations at Norilsk (RUP55; under construction) and Bilibino (RUP57). However, radionuclide data from these stations were never received. On August 18, 2019, Executive Secretary of CTBTO, Lassina Zerbo, tweeted that CTBTO was working with station operators to solve "technical problems" that had been reported on the IMS stations Dubna and Kirov after they had stopped transmitting data previously. Later, also stations Zalesovo, Peleduy (RUP56), and Bilibino also stopped transmission of data. [19]

On August 20, 2019, in an interview with Interfax, Deputy Foreign Minister of the Russian Federation Sergei Alexeyevich Ryabkov, argued that "Russia's transmission of data from radiation stations to the Vienna-based CTBTO was voluntary, and in any case was not subject to the organization's consideration," [17] thereby indirectly admitting that the cessation of data transmission was not due to technical problems.

The Russian Federal Service for Hydrometeorology and Environmental Monitoring (Rosgidromet) reported on its website that, from August 8 to 23, 2019, it found short-lived fission products ^{91}Sr (for half-lives and nuclear properties see Experimental Section), ^{139}Ba, ^{140}Ba, and ^{140}La in aerosols and deposition samples from the Arkhangelsk region. [20]

The objective of this paper is to summarize the efforts to trace radioactive contaminations that may explain some circumstances of the release. In other words, the objective of this study was finding a nuclear "smoking gun" of this release.

3. Results and Discussion

Various samples were investigated in this study. For basic radionuclide data, see Experimental Section.

3.1. Vessel air filters and cargo paper cover

A total of two air filters were retrieved from two vessels that were in the Severodvinsk/Arkhangelsk region of the White Sea at the time of the accident. They were analyzed by gamma spectrometry, targeting short- and medium lived fission products. Filter 1 was a commercial plastic fleece from an air condition inlet of vessel 1. In addition to this filter, also a paper cover covering the cargo was retrieved for analysis from this ship. Filter 2 was the inlet air filter of the second ship's engine.

In various consecutive measurements at the University of Bremen, low-level laboratory VKTA Felsenkeller, and the Advanced Radionuclide Gamma-spectrOmeter (ARGO) system at Pacific Northwest National Laboratory (PNNL) (in this order), no traces of short-/medium-lived anthropogenic radionuclides were found (Table 1). Find descriptions of the labs' instrumentation below.

Of all possible fission products, ^{131}I, ^{140}La (daughter of ^{140}Ba), ^{129m}Te, ^{103}Ru, and ^{137}Cs were selected for Table 3.1. No detections of other fission products were observed either.

Table 3.1.: Tabulated results of the gamma spectrometry (in mBq) or limits of detection (LoD) of radionuclides in vessel air filters no.1 and 2, and in cargo paper cover. Note that short-lived radionuclides are mentioned in early measurements only, whereas long-lived radionuclides are relevant for later measurements only. Activities and LoDs are given for the time of measurement.

Samle/ Laboratory	Days since Accident	^{7}Be [a]	^{103}Ru	^{129m}Te	^{131}I	^{137}Cs	^{140}La
Air filter no.1/ U. Bremen	11	6200± 400	<10	<370	<12	<13	<23
Paper cover/ U. Bremen	11	<480	<54	<1820	<66	<100	<110
Air filter no.1/ Felsenkeller	30	5100± 500	N/A	N/A	<1.5	2.2± 0.5	<2.0
Paper cover/ Felsenkeller	30	<26	N/A	N/A	<2.2	29± 3	<2.9
Air filter no.1/ PNNL-ARGO	90	5330± 50	<5	<140	<7.7	11.3± 2.7	<18
Air filter no.2/ PNNL-ARGO	60	50100± 200	<6	<170	<10	36.7± 3.8	<16
Greek air filter/ PNNL-ARGO	69	41000± 100	<4	<130	<9	6.0± 1.0	<27
	[a] N/A	Natural atmospheric radionuclide Not applicable					

For the air filters, presence of natural atmospheric ^{7}Be can be viewed as quality control indicating the airflow through the filter. Presence of ^{137}Cs in air is due to the normal radiocesium background in northern Europe.
Other radionuclides found in the vessel air filters and greek filters during the measurement at PNNL that exceed the LoD are listed in the appendix, including their origin (see Table A.1 - A.3).

Since all filters were taken from ships north of the blast site, whereas the plume was carried in southward direction, the negative result can be explained by the specific meteorological conditions in the area.

3.2. Ro5 air filters

Although the plume from the detonation was carried inland into the Russian Federation for several days, two Ro5 stations in northern and southern Europe were possibly affected days after the accident by a very diluted plume. The Norwegian Radiation and Nuclear

Safety Authority (DSA) air filter station at Svanhovd, according to meteorological models published by Environment and Climate Change Canada [21], would have been hit by a diluted plume around August 12/13, 2019 (see Figure 3.1). During the sampling period from August 9-12, 2019, this station reported minute concentrations of particulate ^{131}I in the low μBq/m^3 range. [22] It shall be noted that ^{131}I detections are occasionally (6-8 times a year) reported in the very north of Europe. [22] The detection, therefore, cannot be linked unequivocally to the Nenoksa incident.

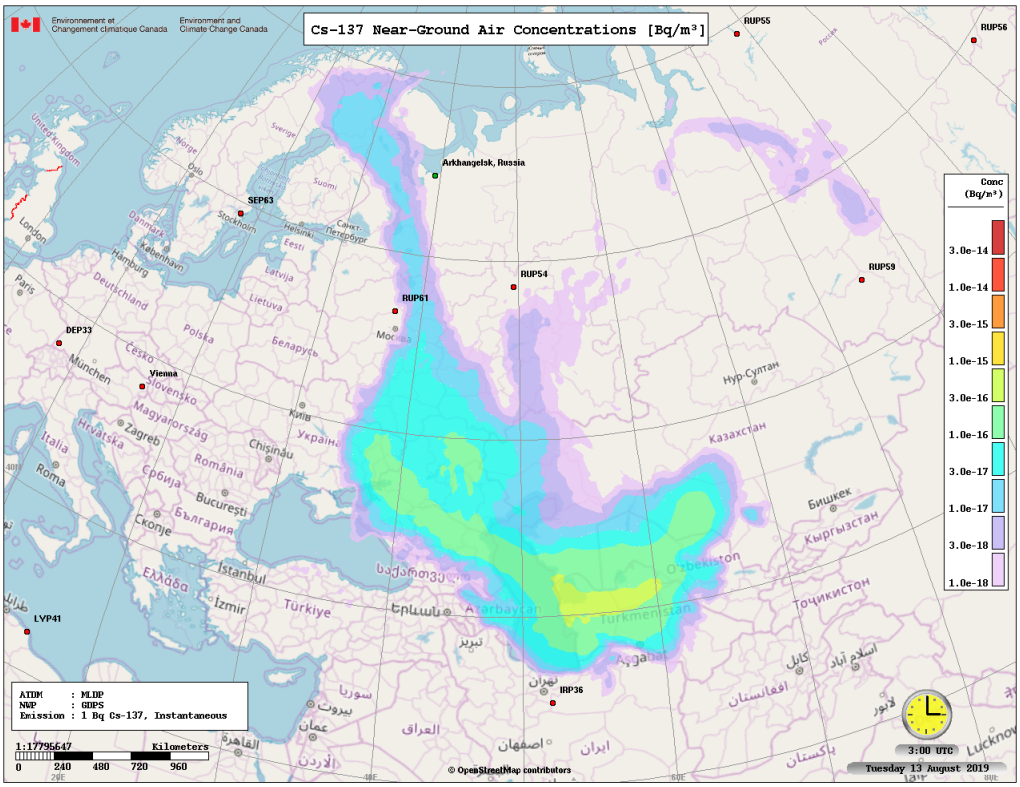


Figure 3.1.: Environment and Climate Change Canada simulation of the plume finally reaching Northern Norway (Svanhovd monitoring station) by August 12/13, 2020. Taken from [21].

CTBTO's atmospheric transport models [18] (see Figure 3.2) indicated that the plume might have reached Greece on August 16-17, 2020. In order to investigate any radioactive traces in this area, an atmospheric aerosol sample on a filter collected at the Ro5/Global Atmosphere Watch (GAW) station operated by the Environmental Radioactivity Lab, Institute of Nuclear & Radiological Sciences and Technology, Energy & Safety (INRASTES) in Athens, Greece was included in this study. The filter was taken in a high volume impactor from August 13-20, 2019.

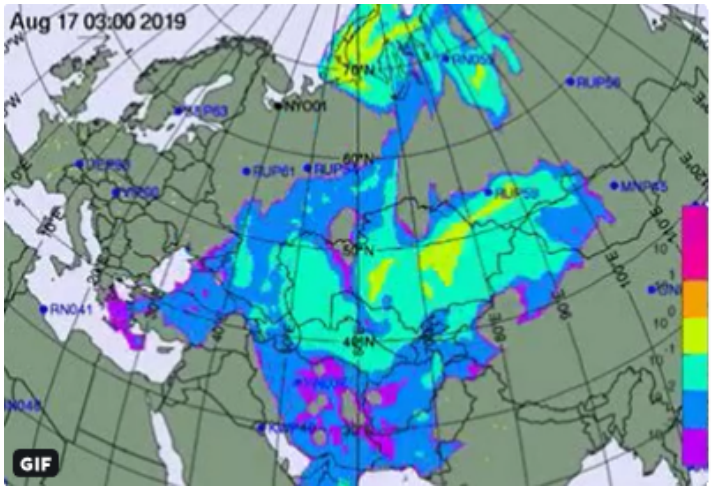


Figure 3.2.: CTBTO simulation of the simulated (highly diluted) plume reaching Greece by August 17, 2020. Taken from [18].

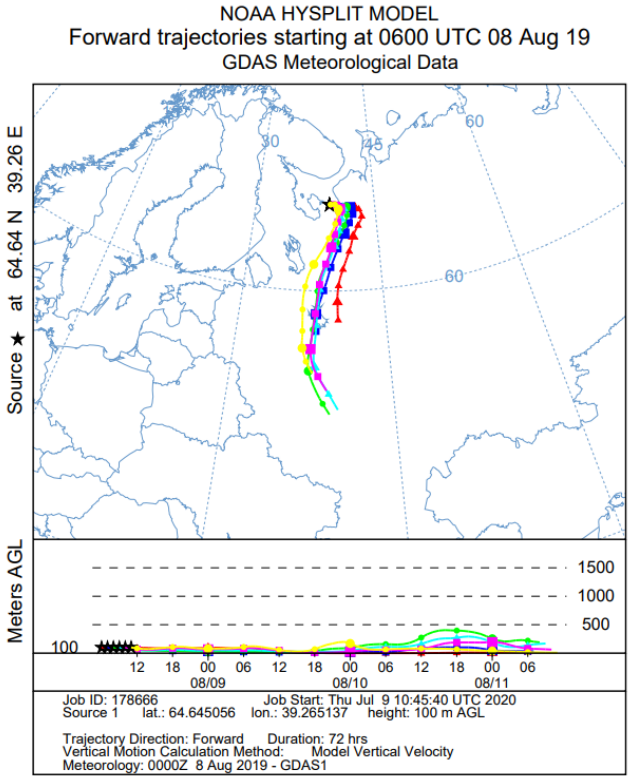


Figure 3.3.: 72 h forward atmospheric transport simulation (HYSPLIT forward modelling) from the Nenoksa test site beginning on August 8, 2019, 06:00 UTC.

The measurement of the high-volume sampler in Greece, however, did not reveal any detectable traces of anthropogenic radionuclides other than ^{137}Cs in the air filter. The ^{137}Cs activity concentration was in the normal range and can be attributed to the typical background (resulting from Chernobyl fallout and atmospheric nuclear weapons testing from the 20th century).

It is likely that the air-mass passing over the test site did not reach the vessels' location because the plume was carried first in eastern and then in southern direction (see HYSPLIT plot in Figure 3.3).

In conclusion, no "smoking gun" was identified in our independent air filter measurement. When considering the reports from Rosgidromet, [20] it is obvious that the list of fission products detected after the release (^{91}Sr, ^{139}Ba, ^{140}Ba, ^{140}La) excludes ^{131}I, which, due to its volatility, is considered one of the most prominent (and radiotoxic) fission products. A similar pattern (most notably the absence of radioiodine) has been observed previously at a non-seismic event in the Democratic People's Republic of Korea in 2010. [23] It was concluded then that the event most likely only released radioactive noble gases but held back other elements. β^- emitting radioiodine nuclides have no noble gas precursor, but radiostrontium fission products have a radiokrypton precursor, and radiobarium and radiolanthanum both have radioxenon precursors. It could then be concluded that the release only included noble gas emissions (followed by radioactive decay to other elements). This characteristic is a familiar pattern for underwater releases (in particular underwater nuclear tests), which usually scavenge metal ions, but mainly release noble gases. A confirmation of this hypothesis would have been possible by IMS monitoring data from the Russian (noble gas) stations, but no radioxenon data were transmitted either. If a release to the atmosphere only included noble gases, the detection of ^{131}I in northern Norway was indeed the result of an independent event and uncorrelated to the Nenoksa incident.

3.3. Argon

Another hypothesis about the circumstances of release was put forward by Mietelski and Povinec [11], who suggested that the nuclear jet-engine may have been based on ^{42}Ar-^{42}K. ^{42}Ar is a long-lived pure beta emitter with a short-lived daughter (^{42}K) that emits highly energetic beta particles and characteristic gamma-rays. In an RTG, ^{42}Ar acts as a generator nuclide that constantly produces ^{42}K, which would be trapped in the heat exchanger and heat the surrounded air through its highly energetic beta particles. Measuring the gamma emission from ^{42}K diluted in the atmosphere would be extremely challenging. However, by measuring gamma emissions from a tank with liquefied argon, the radionuclide would be accumulated, which would allow detection of a release of ^{42}Ar. Argon is produced from atmospheric argon through the Hampson-Linde cycle. It is assumed that in the Hampson-Linde cycle, the isotopic ratios remain unaffected, thus measuring liquefied argon does not involve the risk of isotopic shifts (through which ^{42}Ar

might be depleted). Similarly, ^{85}Kr (dispersed globally by nuclear fuel reprocessing) can be found in liquified krypton gas, in considerable activity concentrations. [24]

Mietelski and Povinec proposed an activity > 1 PBq ^{42}Ar for this type of propulsion. This activity may be split into several gas tanks, though. If 1 PBq of ^{42}Ar injected into the atmosphere is assumed, a count rate at the ^{42}K 1525 keV photopeak of 0.1 cts/s would be expected in the measurement setup at the argon tank, summing up to 2370 cts over the measurement period. However, the LoD of 41 cts over the period of the measurement was not exceeded. Assuming complete and homogeneous mixing and assuming that 100% of the argon contained in the tank was collected from the atmosphere after the release, any release of ^{42}Ar above $1.7 * 10^{13}$ Bq would have exceeded the LoD.

In conclusion no trace of ^{42}Ar was found, hence indicating that the circumstances of the release did not yet result in homogeneous mixing, did not involve ^{42}Ar, or were much smaller amount than proposed by Mietelski and Povinec. [11]

4. Conclusion

In all the measurements conducted in this study, no traces of radionuclides were found that would provide any clues about the nature of the release. It is likely that the two vessels whose air filters were part of this study were located north of the plume and were not reached by it. For the Greek air filter investigated in this study, the plume was likely too diluted to yield detectable traces (provided that the plume reached Greece within a reasonable timeframe). If detections of radiostrontium, radiobarium, and radiolanthanum isotopes reported by Rosgidromet are considered, a possible explanation would be that only radioactive Kr and Xe noble gases were released from an underwater detonation. Any traces indicating a release of radioactive Ar were not found. Therefore, it cannot be confirmed that the release involved radioargon from a ^{42}Ar-fueled RTG.

5. Experimental Section

5.1. Nuclides of interest

For a list of relevant radionuclides and their nuclear characteristics, see Table 5.1.

Table 5.1.: Nuclear data of relevant radionuclides.

Radionuclide	Decay type	Half-life	Dominant γ-photo peak (keV)	γ-emission probability (%)
^{7}Be [a]	ec/β^+, γ	53.22 d	477.6035	10.44
^{42}Ar	β^-	32.9 y		
^{42}K	β^-, CE, γ	12.360 h	1524.67	17.9
^{91}Sr	β^-, CE, γ	9.63 h	1024.3	33.5
^{103}Ru	β^-, CE, γ	39.247 d	497.085	91.0
^{106}Ru	β^-	371.8 d		
^{106m}Rh	β^-, CE, γ	131 m	511.7 621.93	85 9.93
^{129m}Te	β^-, CE, γ	33.6 d	695.88	3.1
^{131}I	β^-, CE, γ	8.0252 d	364.489	81.5
^{137}Cs	β^-, (γ)	30.08 y	(283.5)	5.8E-4
^{137m}Ba	CE, γ	2.552 m	661.657	90.1
^{139}Ba	β^-, CE, γ	83.06 m	165.864	24
^{140}Ba	β^-, CE, γ	12.7527 d	537.311	24.0
^{140}La	β^-, CE, γ	1.67855 d	1596.21	95.4
	[a] ec CE	Natural, cosmogenic radionuclide Electron capture Conversion electron emission		

5.2. Monitoring stations

One Greek Ro5 station participated in this study, in particular, the Environmental Radioactivity Lab at INRASTES belonging to the National Centre for Scientific Research (NCSR) "Demokritos". [25] The monitoring station is located at N37°59', E23°49'. The cellulose air filters (quantitative Whatman41) were inserted on August 13, 2019 at 12:40 (local time) and exchanged on August 20, 2019 at 12:35 (local time) (total sampling duration 167.6 h, total volume 5738 m^3). The sampling station employed a high volume impactor with two stages and a backup filter however, all fractions were measured

together to assess the accumulation of the entire particulate matter suspended in air.

5.3. Vessel air filters

Air filters for this study were provided from the captains of their vessels under the condition that the names and positions of the ships would remain undisclosed, unless a positive result was found in the investigation. This was not the case. Both vessels were cruising in the White Sea not very far from Severodvinsk at the time of the accident. Vessel filter no.1 was collected from the air condition inlet on August 19, 2019 and weighed 7.7 g. It was made of a commercial plastic fleece. In addition to the air filter, a paper cover protecting the cargo was provided for this study as well. The paper cover was exposed to the atmosphere and covered approx. 1 m^2 and weighed about 200 g. The second vessel filter originated from a different ship and was used to clean the incoming air to the engine. Although this filter was oily and dirty, presence of natural atmospheric radionuclides indicated a reasonable airflow and contact to the surrounding atmosphere.

5.4. Gamma-ray spectroscopy

Various gamma spectrometers were used in this study. The first measurements (for vessel air filter no.1 and cargo paper cover from vessel no.1 only) were conducted at University of Bremen, followed by the VKTA lab Felsenkeller (vessel air filter no.1 and cargo paper cover only), the ARGO system at PNNL (for vessel air filter nos.1 and 2, and the Greek air filter), and Leibniz University of Hannover (liquid argon tank measurements).

5.4.1. University of Bremen laboratory

Two high-purity germanium (HPGe) gamma-ray spectrometers with similar characteristics were used for the measurements of vessel air filter no.1 and the paper cover. One detector had a volume of 213 cm^3, relative efficiency of 50% at the 1332 keV peak of ^{60}Co, and a resolution (full width at half maximum, FWHM of 1.9 keV at the 1332 keV peak of ^{60}Co. The second detector had a volume of 193 cm^3, relative efficiency of 50%, and FWHM of 2.1 keV at the 1332 keV peak of ^{60}Co.

5.4.2. VKTA Felsenkeller

The low level underground laboratory Felsenkeller [26] of VKTA provides geological shielding equivalent to the shielding of 138 m of water. [27] Gamma measurements were conducted with a HPGe detector (92% relative efficiency) installed inside a graded shield and with nitrogen flushing of the interior. [28]

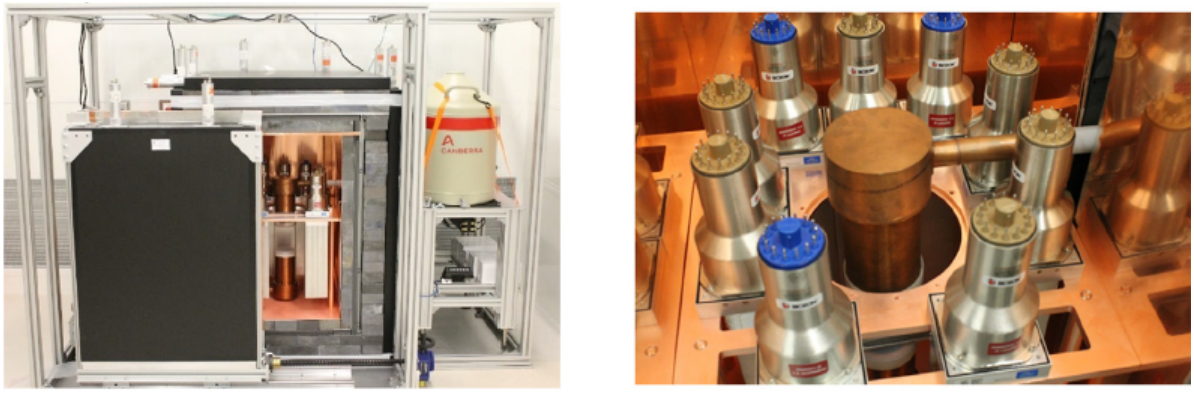
5.4.3. PNNL-ARGO

In Ocotber 2019, the provided samples were examined at the Pacific Northwest National Laboratory (PNNL) in Washington (USA). The PNNL researches on solutions for current

issues that affect the whole world like earth's climate, national security and development to keep ports around the world safe from nuclear smuggling [29].
In 1965, the Pacific Northwest Laboratory (renamed to Pacific Northwest National Laboratory in 1996) [30] was founded for development of nuclear technology and the environmental and health effects of radiation, when research at Hanford Site was separated from Hanford operations. [31].
The lab with its "Pacific Northwest roots" [29] is operated by Batelle for the Department Of Energy (DOE) [31]. The main campus is located in Richland, (WA) [32], but there are also other labs belonging to the PNNL in Seattle (WA), Portland (OR), Washington D.C., and in Sequim (WA) [33].

The PNNL main campus buidlings include the Shallow Underground Laboratory (SUL). It hosts some of the most sensitive detection systems in the world [34]. One of them is the ARGO system, which was used to analyze the provided samples.
The SUL is located 39 feet or respectively 12 m under the surface (30 m water equivalent) [35, 36], to provide ultra-low-background for measurements, because the earth's surface already shields the cosmic radioation. [34] To keep the underground lab clean from radiation from dust or other particles, a cleanroom air filtration system is installed, special clean clothing is needed, and there is a pressure equalization in the building [35].

The Advanced Radionuclide Gamma-spectrOmeter (ARGO) system (see Figure 5.1 a)) in the SUL includes two Broad Energy Germanium Detectors (BEGe; relative efficiency 60%) with a germanium crystal with 5000 mm^2 active area. The BEGe detectors are surrounded by 12 NaI detectors (10,000 cm^3) for Compton suppression purposes (see Figure 5.1 b)). The ARGO system is located in a low-background graded shield consisting of 200 mm Pb, 12.5 mm 30% borated polyethylene (PE), 1 mm Cd, 50 mm Pb, 1 mm Sn and 1 mm Cu. The interior of the system is flushed with N_2 for removal of Rn and its progeny. As a cosmic radiation veto system, the shield is surrounded by 6 Eijen Technology polyvinyltoluene (PVT) plastic scintillator plates, each with two photomultipliers installed. [37] The ARGO system is optimized for the gamma energy range between 3 and 3000 keV. Samples were installed in a calibrated geometry between the BEGe detectors.



(a) (b)

Figure 5.1.: Pictures of the Advanced Radionuclide Gamma-spectrOmeter (ARGO), (a) shows the whole system with an open door revealing the inside, (b) shows the inside with the two BEGe detectors surrounded by several NaI detectors. [37]

5.4.4. Leibniz University Hannover

For the investigations of gamma emission from the argon tank at Leibniz University Hannover, a HPGe detector was installed at half filling level of the tank at a distance of less than 3 cm (Fig. 4). The HPGe detector was a horizontally mounted coaxial Ge crystal with a volume of 252 cm^3 and a relative efficiency of 65%, and a FWHM of 1.8 keV at the 1332 keV peak of ^{60}Co.

5.5. Argon measurements

For testing of the ^{42}Ar-^{42}K hypothesis, [11] several assumptions had to be made. The total mass of the atmosphere is $5,1441 * 10^{18}$ kg. Natural Ar constitutes an abundance of 1.288 mass %. The liquid argon tank at Leibniz University Hannover had dimensions of 7.375 m in height and 2 m in diameter. The tank was refilled with argon in November 2019, and had a filling level of 45% (of a maximum content of 21198 kg) at the time of the measurement (December 12, 2019, Figure 5.2). By this date, a homogeneous atmospheric mixing of any radioargon with the atmosphere of the northern hemisphere only is assumed.

Measurements were conducted with the aforementioned gamma spectrometer and lasted 23192 s. The peak efficiency of this cylindrical source was calculated according to Aguiar. [38] The gamma spectrum was evaluated using the Snakedance Scientific, LLC, gamma spectrum software VRF.

Figure 5.2.: Measurement setting of gamma emission from the argon tank.

In the relevant energy range around 1525 keV (characteristic for ^{42}K), no signs of a peak were detected in the spectrum. The only anomaly in the spectrum was an anomalous quadruple peak between 1578 and 1607 keV, as shown in the portion of the spectrum in Figure 5.3 below. A least-squares best fit decomposed this feature with minimal error into four peaks centered at 1589.5, 1594.2, 1599.0, and 1602.3 keV. No source of these peaks could be identified. Until further investigation is possible it is presumed that the source of these peaks is either as-yet unexplained natural causes or possible problems with instrumental processing.

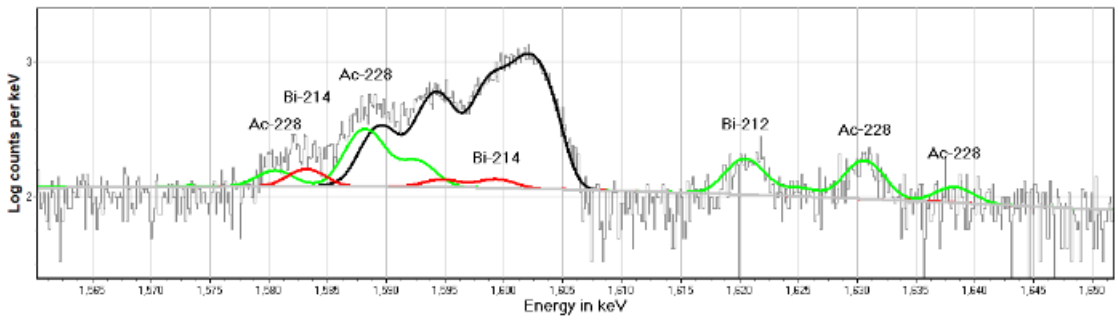


Figure 5.3.: In black, the anomalous quadruple peak in the gamma spectrum of a tank of liquid argon as observed with VRF software.

5.6. Atmospheric transport modelling

READY NOAA HYSPLIT trajectory model (online version) using the archived GDAS (Global Data Assimilation System) meteorological data was used to model the early atmospheric transport of the plume. [39–43]
Starting at Nenoksa test site, the simulation begins on August 8, 2019, 06:00 UCT (09:00 local time) with a duration of 72 hours. Because the exact release time is not known, several trajectories were created at different points in time in a 1 hour cycle.
The model can be found in Figure 3.3 in section 3.2.

6. Acknowledgements

We thank the Ro5 members for fruitful collaboration. PNNL is gratefully acknowledged for their hospitality and for providing resources for gamma measurements at the ARGO system. Especially Jon Burnett, Ted Bowyer and Daniela Erickson should be named for making my stay the best experience in my life so far. The most important people I would like to thank are Tobias Blenke and Dorian Zok, who helped me in every way, and of course Prof. Dr. Steinhauser for his patience, his understanding and that he was always open to suggestion if there was a problem.

Bibliography

[1] O. Masson, A. Baeza, J. Bieringer, K. Brudecki, S. Bucci, M. Cappai, F. P. Carvalho, O. Connan, C. Cosma, A. Dalheimer, D. Didier, G. Depuydt, L. E. De Geer, A. De Vismes, L. Gini, F. Groppi, K. Gudnason, R. Gurriaran, D. Hainz, O. Halldorsson, D. Hammond, O. Hanley, K. Holey, Z. Homoki, A. Ioannidou, K. Isajenko, M. Jankovic, C. Katzlberger, M. Kettunen, R. Kierepko, R. Kontro, P. J. M. Kwakman, M. Lecomte, L. Leon Vintro, A. P. Leppanen, B. Lind, G. Lujaniene, P. McGinnity, C. McMahon, H. Mala, S. Manenti, M. Manolopoulou, A. Mattila, A. Mauring, J. W. Mietelski, B. Moller, S. P. Nielsen, J. Nikolic, R. M. W. Overwater, S. E. Palsson, C. Papastefanou, I. Penev, M. K. Pham, P. P. Povinec, H. Rameback, M. C. Reis, W. Ringer, A. Rodriguez, P. Rulik, P. R. J. Saey, V. Samsonov, C. Schlosser, G. Sgorbati, B. V. Silobritiene, C. Soderstrom, R. Sogni, L. Solier, M. Sonck, G. Steinhauser, T. Steinkopff, P. Steinmann, S. Stoulos, I. Sykora, D. Todorovic, N. Tooloutalaie, L. Tositti, J. Tschiersch, A. Ugron, E. Vagena, A. Vargas, H. Wershofen, O. Zhukova: Tracking of Airborne Radionuclides from the Damaged Fukushima Dai-Ichi Nuclear Reactors by European Networks. In: *Environmental Science & Technology* 45 (2011), S. 7670–7677

[2] O. Masson, G. Steinhauser, D. Zok, O. Saunier, H. Angelov, D. Babić, V. Bečková, J. Bieringer, M. Bruggeman, C. I. Burbidge, S. Conil, A. Dalheimer, L.-E. De Geer, A. de Vismes Ott, K. Eleftheriadis, S. Estier, H. Fischer, M. G. Garavaglia, C. Gasco Leonarte, K. Gorzkiewicz, D. Hainz, I. Hoffman, M. Hýža, K. Isajenko, T. Karhunen, J. Kastlander, C. Katzlberger, R. Kierepko, G.-J. Knetsch, J. Kövendiné Kónyi, M. Lecomte, J. W. Mietelski, P. Min, B. Møller, S. P. Nielsen, J. Nikolic, L. Nikolovska, I. Penev, B. Petrinec, P. P. Povinec, R. Querfeld, O. Raimondi, D. Ransby, W. Ringer, O. Romanenko, R. Rusconi, P. R. J. Saey, V. Samsonov, B. Šilobritienė, E. Simion, C. Söderström, M. Šoštarić, T. Steinkopff, P. Steinmann, I. Sýkora, L. Tabachnyi, D. Todorovic, E. Tomankiewicz, J. Tschiersch, R. Tsibranski, M. Tzortzis, K. Ungar, A. Vidic, A. Weller, H. Wershofen, P. Zagyvai, T. Zalewska, D. Zapata García, B. Zorko: Airborne concentrations and chemical considerations of radioactive ruthenium from an undeclared major nuclear release in 2017. In: *Proceedings of the National Academy of Sciences of the United Stated of America* 116 (2019), S. 16750–16759

[3] O. Saunier, A. Mathieu, D. Didier, O. Masson, J. Dumont le Brazidec: Atmospheric modeling and source reconstruction of radioactive ruthenium from an undeclared major release in 2017. In: *Proceedings of the National Avademy of Sciences of the United Stated of America* 116 (2019), S. 24991–25000

[4] O. Masson, G. Steinhauser, H. Wershofen, J. W. Mietelski, H. W. Fischer, L. Pourcelot, O. Saunier, J. Bieringer, T. Steinkopff, M. Hýža, B. Møller, T. W. Bowyer, E. Dalaka, A. Dalheimer, A. de Vismes-Ott, K. Eleftheriadis, M. Forte, C. Gasco Leonarte, K. Gorzkiewicz, Z. Homoki, K. Isajenko, T. Karhunen, C. Katzlberger, R. Kierepko, J. Kövendiné Kónyi, H. Malá, J. Nikolic, P. P. Povinec, M. Rajacic, W. Ringer, P. Rulík, R. Rusconi, G. Sáfrány, I. Sykora, D. Todorović, J. Tschiersch, K. Ungar, B. Zorko: Potential Source Apportionment and Meteorological Conditions Involved in Airborne 131I Detections in January/February 2017 in Europe. In: *Environmental Science & Technology* 52 (2018), S. 8488–8500

[5] G. Steinhauser, S. Merz, A. Kübber-Heiss, C. Katzlberger: Using Animal Thyroids as Ultra-Sensitive Biomonitors for Environmental Radioiodine. In: *Environmental Science & Technology* 46 (2012), S. 12890–12894

[6] M. Bysiek, M. Biernacka, P. Lipiński: Radioactivity of ground-level air in Poland in 1998-1999. Results from ASS-500 stations network. In: *Nukleonika* 46 (2001), S. 171–173

[7] K. Pham, M. Betti, H. Nies, P. P. Povinec: Temporal changes of 7Be, 137Cs and 210Pb activity concentrations in surface air at Monaco and their correlation with meteorological parameters. In: *Journal of Enironmental Radioactivity* 102 (2011), S. 1045–1054

[8] CTBTO: *Tweet.* 2019. – `https://twitter.com/ctbto_alerts/status/1160130156922642433`; Accessed: July 2020

[9] BBC: *Russia explosion: Five confirmed dead in rocket blast.* 2019. – `https://www.bbc.com/news/world-europe-49301438`; Accessed: July 2020

[10] BBC: *Rocket mystery: What weapon was Russia testing in Arctic?* 2019. – `https://www.bbc.com/news/world-europe-49319160`; Accessed: July 2020

[11] J. W. Mietelski, P. P. Povinec: Environmental radioactivity aspects of recent nuclear accidents associated with undeclared nuclear activities and suggestion for new monitoring strategies. In: *Journal of Environmental Radioactivity* 214-215 (2020), S. 106151

[12] V.V. Putin: *Presidential Address to the Federal Assembly.* 2018. – `http://en.kremlin.ru/events/president/news/56957`; Accessed: July 2020

[13] Business Insider: *The blast that killed 5 Russian engineers was apparently caused by another failed test of Putin's doomsday missile.* 2019. – https://www.businessinsider.com/failed-test-of-putins-new-missile-may-have-caused-explosion-2019-8?r=DE&IR=T; Accessed: July 2020

[14] Reuters: *U.S.-based experts suspect Russia blast involved nuclear-powered missile.* 2019. – https://www.reuters.com/article/us-russia-blast-usa-idUSKCN1UZ2H5; Accessed: July 2020

[15] BBC: *Russia says rocket explosion caused 16-fold radiation spike.* 2019. – https://www.bbc.com/news/world-europe-49339895; Accessed: July 2020

[16] Reuters: *Two dead in Russian rocket engine explosion; radiation spikes, shipping shut.* 2019. – https://uk.reuters.com/article/uk-russia-blast-rocket-radiation/two-dead-in-russian-rocket-engine-explosion-radiation-spikes-shipping-shut-idUKKCN1UY1CL; Accessed: July 2020

[17] Bellona: *Russian radiation detectors went dark in wake of mysterious explosion.* 2019. – https://bellona.org/news/nuclear-issues/2019-08-russian-radiation-detectors-went-dark-in-wake-of-mysterious-explosion; Accessed: July 2020

[18] L. Zerbo: *Tweet.* 2019. – https://twitter.com/sinazerbo/status/1163094836569882625?lang=en; Accessed: July 2020

[19] P. Seibert: *The nuclear accident of 8 August 2019 in Nyonoksa near Severodvinsk (Russia).* 2020. – https://homepage.univie.ac.at/petra.seibert/nyonoksa.html; Accessed: July 2020

[20] Rosgidromet: *Об аварийном, экстремально высоком и высоком загрязнении окружающей среды и выявленных случаях изменения радиационной обстановки на территории Российской Федерации в период с 10 по 23 августа 2019 года.* 2019. – http://www.meteorf.ru/product/infomaterials/91/19679/?sphrase_id=243581 (in Russian); Accessed: July 2020

[21] Environment and Climate Change Canada: *Cs-137 near-ground air concentrations [Bq/m^3].* 2019. – https://eer.cmc.ec.gc.ca/people/eer/eW0ZuBB1wwZSjPJDTMgM/118_Archangelsk_missile_explosion/anim.html; Accessed: July 2020

[22] DSA: *Tiny amounts of radioactive iodine in air measured in Finnmark.* 2019. – https://www2.dsa.no/en/news/94883/tiny-amounts-of-radioactive-iodine-in-air-measured-in-finnmark; Accessed: July 2020,

[23] G. Wotawa: Meteorological analysis of the detection of xenon and barium/lanthanum isotopes in May 2010 in Eastern Asia. In: *Journal of Radioanalytical and Nuclear Chemistry* 296 (2013), S. 339–347

[24] H.W. Fischer, T. Bielefeld, B. Hettwig: Krypton gas cylinders as a source of radiation. In: *Health Physics* 99 (2010), S. 58–65

[25] Global Atmosphere Watch Station Information System: *Demokritos Athens (Greece)*. 2020. – `https://gawsis.meteoswiss.ch/GAWSIS//index.html#/search/station/stationReportDetails/0-20008-0-DEM`; Accessed: June 2020

[26] S. Niese, M. Koehler, B. Gleisberg: Low-level counting techniques in the underground laboratory "Felsenkeller" in Dresden. In: *Journal of Radioanalytical and Nuclear Chemistry* 233 (1998), S. 167–173

[27] F. Ludwig, L. Wagner, T. Al-Abdullah, G. G. Barnaföldi, D. Bemmerer, D. Degering, K. Schmidt, G. Surányi, T. Szücs, K. Zuber: The muon intensity in the Felsenkeller shallow underground laboratory. In: *Astroparticle Physics* 112 (2019), S. 24–34

[28] M. Köhler, D. Degering, M. Laubenstein, P. Quirin, M. O. Lampert, M. Hult, D. Arnold, S. Neumaier, J. L. Reyss: A new low-level gamma-ray spectrometry system for environmental radioactivity at the underground laboratory Felsenkeller. In: *Applied Radiation and Istotopes* 67 (2009), S. 736–740

[29] Pacific Northwest National Laboratory: *A National Lab is a Different Kind of Research Institution*. 2020. – `https://www.pnnl.gov/about`; Accessed: April 2020

[30] PNNL News & Media Relations: *What's in a name? – PNL goes national*. 1995. – `https://www.pnnl.gov/news/release.aspx?id=694`; Accessed: April 2020

[31] Pacific Northwest National Laboratory: *A community partner for 50 years*. 2015. – `https://www.pnnl.gov/news/50th/pdfs/01-15_advtrl.pdf`; Accessed: April 2020

[32] Pacific Northwest National Laboratory: *Laboratory Contact Info*. 2020. – `https://www.pnnl.gov/contacts`; Accessed: April 2020

[33] Pacific Northwest National Laboratory: *Pacific Northwest National Laboratory is DISCOVERY in Action*. Brochure, 2018

[34] Pacific Northwest National Laboratory: *Shallow Underground Laboratory*. – `https://www.pnnl.gov/shallow-underground-laboratory`; Accessed: April 2020

[35] Pacific Northwest National Laboratory: *Shallow Underground Laboratory*. – `https://tour.pnnl.gov/shallow-lab.html`; Accessed: April 2020

[36] J. L. Burnett, J. L. Slack, J. M. Bowen: Time sequence gamma-spectrometry of irradiated salt. In: *Nuclear Instruments and Methods in Physics Research Section A* 947 (2019), S. 162648

[37] A. V. Davies, J. L. Burnett, R. Britton: Performance testing of a Compton suppressed coincidence measurements using the Advanced Radionuclide Gamma-spectrOmeter. In: *Nuclear Instruments and Methods in Physics Research Section A* 951 (2020), S. 163009

[38] J. C. Aguiar: An analytical calculation of the peak efficiency for cylindrical sources perpendicular to the detector axis in gamma-ray spectrometry. In: *Applied Radiation and Istotopes* 66 (2008), S. 1123–1127

[39] A. F. Stein, R. R. Draxler, G. D. Rolph, B. J. B. Stunder, M. D. Cohen, F. Ngan: Inline Coupling of WRF-HYSPLIT: Model Development and Evaluation Using Tracer Experiments. In: *Bulletin of the American Meteorological Society* 96 (2015), S. 2059–2077

[40] G. Rolph, A. Stein, B. Stunder: Real-time Environmental Applications and Display sYstem: READY. Environmental Modelling & Software. In: *Environmental Modelling & Software* 95 (2017), S. 210–228

[41] R. R. Draxler, G. D. Hess: An overview of the HYSPLIT4 modeling system of trajectories, dispersion, and deposition. In: *Australian Meteorological Maganzine* 47 (1998), S. 295–308

[42] R. R. Draxler: HYSPLIT4 user's guide. NOAA Air Resources Laboratory, Silver Spring, MD. In: *NOAA Air Resources Laboratory, Silver Spring, MD* (1999)

[43] R. R. Draxler, G. D. Hess: Description of the HYSPLIT4 modeling system. NOAA Tech. Memo. ERL ARL-224. In: *NOAA Air Resources Laboratory, Silver Spring, MD* (1997)

List of Figures

List of Tables

List of Acronyms

AIS	Automatic Identification System
ARGO	Advanced Radionuclide Gamma-spectrOmeter
BEGe	Broad Energy Germanium Detector
CTBT	Comprehensive Nuclear-Test-Ban Treaty
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organisation
DOE	Department Of Energy
DSA	Norwegian Radiation and Nuclear Safety Authority
FWHM	Full width at half maximum
GAW	Global Atmosphere Watch
GDAS	Global Data Assimilation System
HPGe	High-purity germanium detector
HYSPLIT	HYbrid Single-Particle Lagrangian Integrated Trajectory
IMS	International Monitoring System
INRASTES	Institute of Nuclear & Radiological Sciences and Technology, Energy & Safety
IRS	Institut für Radioökologie und Strahlenschutz/ Institute of Radioecology and Radiation Protection
LLC	Limited Liability Company
LoD	Limit of Detection
NCSR	National Centre for Scientific Research
NGO	Non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
PE	Polyethylene

PNL	Pacific Northwest Laboratory
PNNL	Pacific Northwest National Laboratory
PVT	Polyvinyltoluene
READY	Real-time Environmental Applications and Display sYstem
Ro5	Ring of Five
RTG	RadioThermal Generator
SUL	Shallow Underground Laboratory
UCT	Coordinated Universal Time
VRF	Visual Robust Fitting

A. Appendix

A.1. Measurement of vessel air filter no.1 at PNNL

Table A.1.: Vessel air filter no.1: Measured activites of radionuclides beyond nuclides of interest. Everything below the limit of detection considering the background is neglected.

Radionuclide	Halflife	Dominant γ-photo peak (keV)	γ-emission probability (%)	Activity (mBq)	Origin
^{40}K	$1.248 * 10^9$ y	1460.822	10.66	690 ± 40	primordial
^{210}Pb	22.16 y	46.539	4.22	6700 ± 100	^{238}U decay chain, lead shielding
^{214}Pb	26.8 min	351.932	35.35	284 ± 13	^{238}U decay chain, lead shielding
^{214} Bi	19.9 min	609.320	45.49	255 ± 5	^{238}U decay chain, lead shielding
^{234}Th	24.1 d	63.290	3.7	323 ± 63	^{238}U decay chain

A.2. Measurement of vessel air filter no.2 at PNNL

Table A.2.: Vessel air filter no.2: Measured activites of radionuclides beyond nuclides of interest. Everything below the limit of detection considering the background is neglected.

Radionuclide	Halflife	Dominant γ-photo peak (keV)	γ-emission probability (%)	Activity (mBq)	Origin
^{40}K	$1.248 * 10^9$ y	1460.822	10.66	1250 ± 60	primordial
^{210}Pb	22.16 y	46.539	4.22	19500 ± 200	^{238}U decay chain, lead shielding
^{212}Pb	10.64 h	238.632	43.6	25 ± 5	^{232}Th decay chain, lead shielding
^{214}Pb	26.8 min	351.932	35.35	87 ± 18	^{238}U decay chain, lead shielding
^{214} Bi	19.9 min	609.320	45.49	57 ± 16	^{238}U decay chain, lead shielding

A.3. Measurement of greek air filters

Table A.3.: Greek air filters: Measured activites of radionuclides beyond nuclides of interest. Everything below the limit of detection considering the background is neglected.

Radionuclide	Halflife	Dominant γ-photo peak (keV)	γ-emission probability (%)	Activity (mBq)	Origin
^{22}Na	2.6027 y	1274.537	99.941	10.0 ± 1.9	cosmogenic
^{40}K	$1.248 * 10^9$ y	1460.822	10.66	332 ± 26	primordial
^{208}Tl	3.053 min	2614.511	99.754	18.2 ± 2.7	^{232}Th decay chain
^{210}Pb	22.16 y	46.539	4.22	19500 ± 200	^{238}U decay chain, lead shielding
^{212}Pb	10.64 h	238.632	43.6	25 ± 5	^{232}Th decay chain, lead shielding
^{214}Pb	26.8 min	351.932	35.35	87 ± 18	^{238}U decay chain, lead shielding
^{214} Bi	19.9 min	609.320	45.49	57 ± 16	^{238}U decay chain, lead shielding
^{226} Ra	$1.6 * 10^3$ y	186.211	3.59	454 ± 53	^{238}U decay chain
^{234}Th	24.1 d	63.290	3.7	1140 ± 50	^{238}U decay chain