SNO+ BACKGROUND STUDY: POLONIUM ON ACRYLIC VESSEL SURFACE AND RADON ASSAY

by

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Abstract

SNO+ is a 780 tonnes organic liquid scintillator neutrino detector located at Vale's Creighton mine, Sudbury, ON. 2 km overburden of rock above helps to achieve the low cosmic radiation background level of SNO+. Meanwhile, radioactive material in the rock can decay and produce radiation in the region of interest for the search of $0\nu\beta\beta$ decay. SNO+ is looking for neutrinos at very low energy and thus it is crucial to have a low background environment. My thesis evaluates two kinds of background sources: ^{222}Rn and ^{210}Po. ^{222}Rn is the progeny of ^{238}U in the rock. The water and gas assays are used to monitor the ^{222}Rn concentration in the surrounding cavity water and other parts of the experiment or other gas volumes in SNOLAB. The analysis of the SNO+ data helps to understand the ^{210}Po activity on the internal surface of the detector's acrylic vessel. The ^{222}Rn level in the cavity water is below the target of 4.5×10^{-13} gU^{238}/gH_2O. The Rn levels in the LN_2 plant and international dewar are at a 10^{-4} reduction factor compared to mine air. The ^{210}Po background level in the internal AV is holding a relatively constant level of about 1800 events per second. Spatially, the ^{210}Po backgrounds are more active at the equator and the belly plate regions. The estimated number of ^{210}Pb atoms deposited on the AV inner surface is 1.84×10^{12}.

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List of Acronyms

AV - Acrylic Vessel.

DCR - Deck Clean Room - tent-like structure on deck around the top of the detector neck.

LAB - Linear Alkyl Benzene. Primary component of the scintillator mix to be deployed in SNO+.

MC - Monte Carlo.

Nhits - the number of live hit PMTs in a detector for a given event.

PMT - PhotoMultiplier Tube, detects the flash from neutrino events.

PPO - (2, 5) Di-Phenyl Oxazole. Wavelength shifter in the scintillator mix.

PSUP - PMT SUPport structure. The geodesic structure on which all the PMTs are mounted.

ROI - Region of Interest.

UI - Universal Interface, glove box above the neck of the AV.

UPW - Ultra-Pure Water.

Chapter 1

Introduction

The study of neutrinos is one of the most active research topics in physics. The SNO+ experiment is using a liquid scintillator detector searching for the neutrinoless double beta ($0\nu\beta\beta$) decay and other physics goals [1]. This thesis will discuss SNO+ background studies, namely the ^{210}Po analysis and ^{222}Rn assays.

1.1 Neutrino Physics

In particle physics research, the standard model is an important theory that unifies three fundamental forces (electromagnetic, weak and strong interaction) and includes all known elementary particles, except for gravity. The standard model theory was developed in stages in the latter half of 20^{th} century and has predicted many experimental results 1.1 [2].

The elementary particles of the standard model are shown in figure 1.1 [2]. The last particles discovered were the W and Z bosons in 1983 [3], the top quark in 1995 [4], the tau neutrino in 2000 [5], and the Higgs bosons in 2012 [6].

The standard model contains six leptons and three of them (electron, muon, and tau) are charged. Corresponding to each one of the charged leptons, there is a neutral lepton. The three neutral leptons are the neutrinos, namely electron neutrinos (ν_e), muon neutrinos (ν_μ) and tau neutrinos (ν_τ) [7].

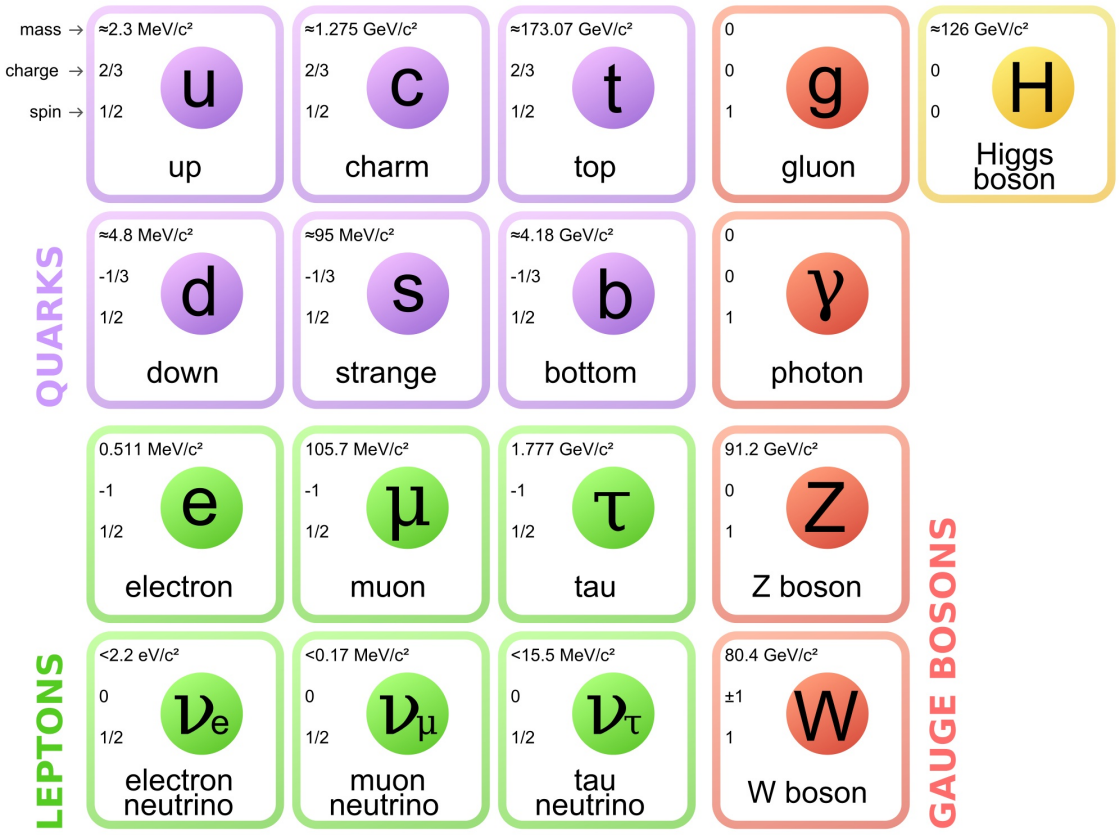

Figure 1.1: Schematic diagram of the standard model.

Source: Fermilab, Office of Science, United States Department of Energy, Particle Data Group

Neutrinos are lightweight particles which can only interact via weak and gravity forces. They are produced when atomic nuclei are combined or broken. In the standard model theory, neutrinos were initially implemented in the standard model as massless [7]. However, the neutrinos oscillation observed by Super-Kamiokande Observatory (Super K) and the Sudbury Neutrino Observatories (SNO) showed the neutrinos have mass [8] [9].

The SNO experiment was a heavy-water Cherenkov detector designed to detect neutrinos produced by fusion reactions in the Sun. By observing the neutrinos from the Sun, the SNO experiment solved the solar neutrino problem through the discovery of neutrino oscillation [11]. The solar neutrino problem comes from the discrepancy between the predicted amount of electron neutrinos produced in the Sun and the amount observed by the neutrino detectors. The number of observed electron neutrinos can be as low as one-third of the amount predicted [12]. All experiments before the SNO experiment can only measure the electron neutrinos. However, the SNO experiment has a low background level, therefore, SNO experiment could perform the measurement of neutral current and further solve the solar neutrino problem [11].

Super-Kamiokande experiment first found that neutrinos can change their flavour as they travel from the Sun to the earth [13]. The flavour change of neutrinos is known as neutrino oscillation. The 2015 Nobel prize in physics was awarded to SNO and Super-Kamiokande for their contributions.

1.2 The SNO+ Experiment

Following the end of the SNO experiment, the SNO+ experiment continued to use the main structure of the SNO experiment and changed the detection medium from heavy water to a liquid scintillator. Lower energy neutrinos can be observed because liquid scintillator detectors have higher intrinsic light yield. This will allow SNO+ to explore other physics

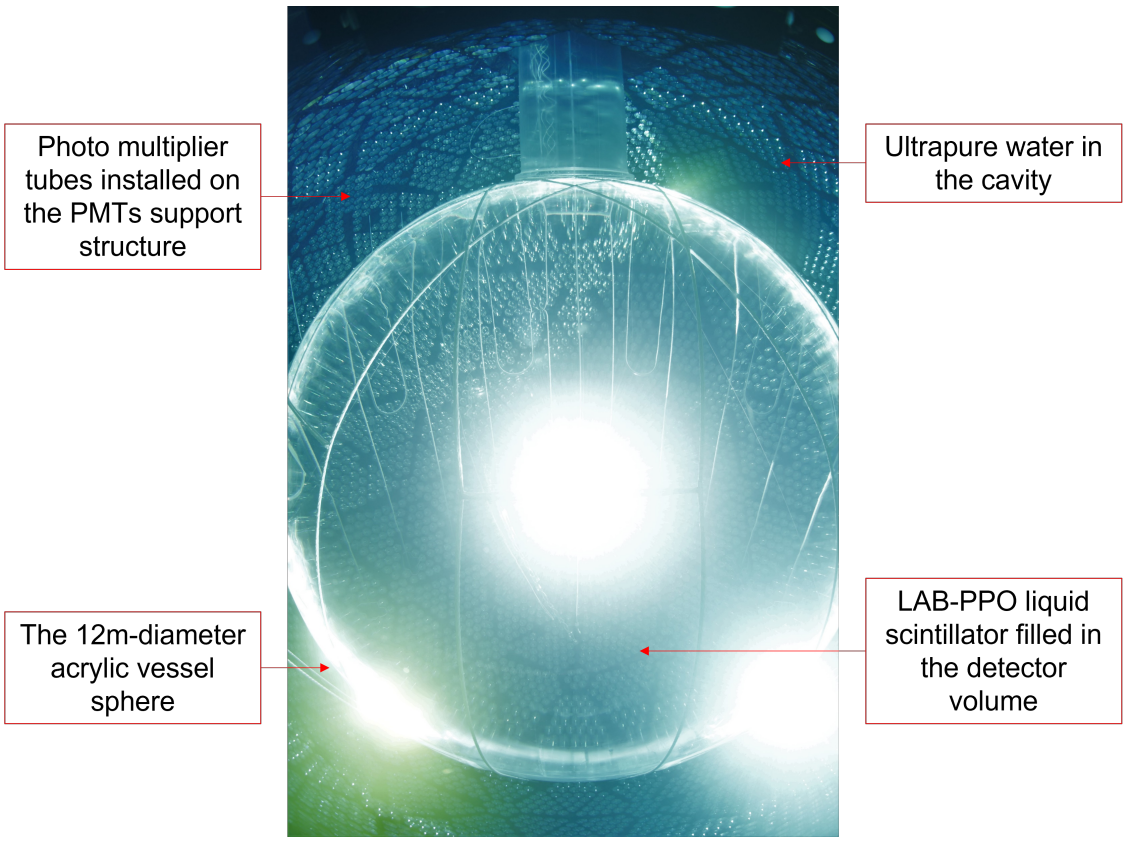

Figure 1.2: Picture of the SNO+ experiment with important structures labelled. The picture was taken when the scintillator fill was completed in April 2021. Source: SNO+ collaboration

like the search of solar neutrinos, anti-neutrinos, and even $0\nu\beta\beta$ decay by adding ^{130}Te [1]. This will be described in chapter 1.2.

SNO+ is located 2 km underground at Creighton mine in Sudbury, ON. The rock overburden on top shields the experiment from cosmic radiations, primarily composed of muons. It is filled with about 780 tonnes of liquid scintillator. The SNO+ experiment is housed at SNOLAB, which is operated as a class 2000 clean laboratory. This clean environment helps to reduce the experimental background radiation.

The SNO+ detector mainly consists of the acrylic vessel (AV), hold-up and hold-down rope systems, about 10,000 photo-multiplier tubes (PMTs), and PMT SUPport structure (PSUP). Figure 1.2 shows the picture of the detector. The cavity is filled with ultra-pure water (UPW) as the shield to the external backgrounds [1].

1.2.1 The Liquid Scintillator

The liquid scintillator in SNO+ is composed of Linear alkylbenzenes (LAB) and 2,5-Diphenyloxazole (PPO). LAB has several advantages as a liquid scintillator solvent:

1. LAB has been demonstrated to be compatible with acrylic and has been shown to be stable over a long time scale [14].

2. LAB has high purity from the manufacturer. LAB can be made near the detector location (at the Cepsa plant in Becancour, Quebec, less than 900 km away); the short transportation time reduced the chances of cosmogenic background contamination.

3. LAB has long attenuation and scattering length. These optical properties of the LAB are important for the light transmission to the PMTs

4. LAB has a high light yield, low energy threshold and linear response to energy. These will help SNO+ to observe low-energy neutrinos to achieve the physics goals.

5. Compared to water, LAB can be purified to a higher level, thus lowering the SNO+ background level [1].

The PPO is added to the detector to act as a wavelength shifter. The target concentration of PPO in LAB of 2g/L was achieved in May 2022 [15]. While dissolved in LAB, PPO can increase the scintillator light yield and change the wavelength of the scintillation light to better fit in the most sensitive wavelength of PMTs, which results in increasing the efficiency of the PMTs. The LAB-PPO liquid scintillator can dissolve Te with long-term stability and minimal impact on the optical properties. About 4 tonnes (0.5% of the detector mass) of Te will be loaded initially to the LAB-PPO liquid scintillator for the search of $0\nu\beta\beta$ decay [1].

1.2.2 The Acrylic Vessel

The acrylic vessel (AV) is a 12 m diameter sphere that contains 780 tons of liquid scintillator for the detection medium. There is a 1.4 m diameter and 7 m height cylindrical neck

at the top of the AV which connects the detector volume to the universal interface (UI). A Clean AV is important to the experiment as it directly contacts the liquid scintillator. During the construction of the detector, the AV was exposed to mine air for several years. The ^{222}Rn in the air can decay to ^{210}Pb and deposit on the AV surface [1]. The inside of AV is in direct contact with the LAB, thus it is crucial to keep it as clean as possible to maintain a low background for the experiment. The ^{210}Pb on the AV surface is a source of the ^{210}Po background to the SNO+ experiment. The ^{210}Po background events from the AV surface will be further discussed in chapter 3.

1.2.3 The Rope System

Before the detection medium in the AV was changed to LAB, as the liquid scintillator ($\rho = 0.86 g/cm^3$ for LAB-PPO at T = $12^o C$) is lighter than the surrounding water, the hold-down rope system was built to counter the buoyancy force of the detector. The hold-down rope system is made of polyethylene fibre (Tensylon) ropes of 38 mm diameter. The original hold-up rope system was also replaced with new Tensylon ropes of 19 mm diameter to reduce its radioactive contamination [1].

1.2.4 The Cavity Water

The AV is surrounded by 7000 tons of ultra-pure water (UPW) in the external cavity. The cavity water can act as a shield to the external backgrounds from the cavity wall and PMTs. The SNO+ experiment has cavity recirculation that takes the UPW from the cavity to the water purification plant for cleaning [1]. One of the external backgrounds, ^{222}Rn can be monitored by the water Radon assay, which will be further discussed in chapter 5.

1.2.5 The PSUP and the PMTs

Outside the AV there is a PMT support structure (PSUP) that supports about 10,000 photomultiplier tubes (PMTs). Due to the photo-electric effect, the PMTs can react to single photons and convert light signals to electric signals. The SNO+ experiment is using the PMT tubes from SNO, and those 8-inch photomultiplier tubes are equipped with a 27 cm diameter concentrator to increase the effective photocathode coverage to about 54% [1]. The SNO+ trigger window is 400 ns long, and in the trigger window, time information and charge are collected from every PMT hit by one or more photons. A dead-time of 30–50 ns separates two trigger windows [16]. This is important for the delayed $\alpha\beta$ coincidence analysis for the background tagging, which will be discussed more in Chapter 2.

1.3 Physics in the SNO+ Experiment

The main purpose of the SNO+ experiment is to search for neutrino-less double beta decay ($0\nu\beta\beta$) of ^{130}Te. In addition, it can also be used to study solar neutrinos, geo anti-neutrinos, reactor anti-neutrinos and supernova neutrinos.

1.3.1 Neutrino-less Double Beta Decay

The SNO+ experiment can be used to answer an important question in the study of neutrino physics, which is whether neutrinos are Majorana particles. A Majorana particle is its own charge conjugate. If neutrinos are Majorana particles, then $0\nu\beta\beta$ decays are allowed. In this process, the lepton number is changed by two units, which violates the standard model [17].

In $0\nu\beta\beta$, no neutrino is emitted, and the energy of the e^- released will carry higher energy than electrons released in $2\nu\beta\beta$ decay.The decay equation is shown in 1.1. $0\nu\beta\beta$ can be achieved by the Majorana neutrino exchange, where the neutrino is absorbed in the vertex, the Feynman diagram is shown in 1.3.

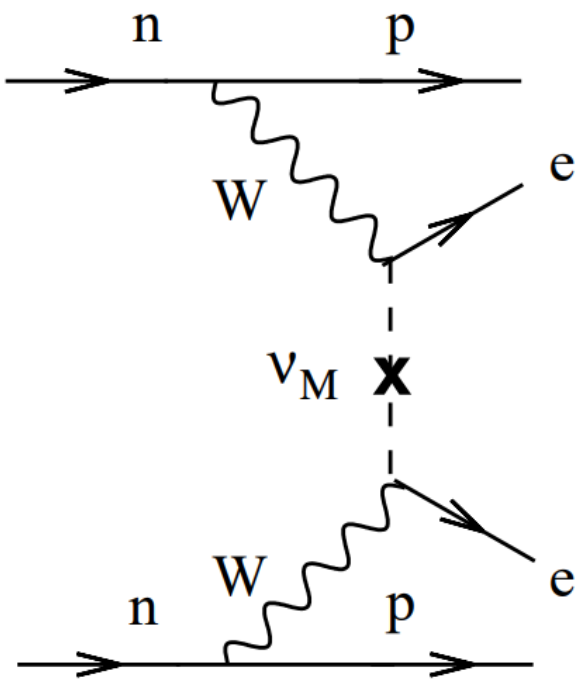

Figure 1.3: Feynman diagram of $0\nu\beta\beta$ decay.

2 ν annihilate with each other and only 2 electrons are produced. Source: https://arxiv.org/pdf/0708.1033.pdf

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- \tag{1.1}$$

The normal 2 ν double-beta decay process ($2\nu\beta\beta$) has been observed in many nuclei, (add references) the decay mode is shown in equation 1.2.

$$(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e \tag{1.2}$$

If $0\nu\beta\beta$ can happen, its rate will be much lower than the rate of $2\nu\beta\beta$. One of the main challenges for $0\nu\beta\beta$ searches is to distinguish $0\nu\beta\beta$ decays from the $2\nu\beta\beta$ decays, which requires the detector to have very high energy resolution and a good understanding of the backgrounds [17]. Also, as the $0\nu\beta\beta$ is a rare event, it will need a large amount of decay element to have a good detection chance [1].

SNO+ will have ^{130}Te as its $0\nu\beta\beta$ decay isotope. ^{130}Te is known to undergo $2\nu\beta\beta$ with a half-life of 8.2×10^{20} years and with a Q-value of 2.527 MeV [18]. With the 34% ^{130}Te natural abundance, which corresponds to about 800 kg of ^{130}Te, a 20% fiducial volume (FV) cut, and five years of data taking, SNO+ can set a lower limit on the half-life of $T_{1/2}^{0\nu\beta\beta} > 9\times10^{25}$ yr at 90% CL [1].

1.3.2 Supernova Neutrinos

Besides the search of $0\nu\beta\beta$ decay, the SNO+ experiment can measure neutrinos from a supernova explosion. In the universe, when a supernova collapse, most of its gravitational binding energy will be released in the form of neutrinos within about 20 seconds. The neutrinos are expected to change the mechanism of supernova explosions. Neutrino heating will energize the supernova shock wave and drive it outward to ultimately cause the supernova explosion. Besides, these neutrinos may be responsible for the creation of heavy elements. [20]

As neutrinos travel close to the speed of light and rarely interact with matter, they can be good messengers of astrophysical events. In the case of a galactic core-collapse supernova, the SNO+ experiment will have the chance to detect several hundred neutrinos in a short burst of about 10 seconds. In case of a neutrino proton scattering event, low-threshold scintillator detectors like SNO+ are needed for detection due to the quenching of the recoiled proton. [19]

1.3.3 Solar Neutrino

As SNO+ is located deep underground, most cosmic rays are shielded by the 2km rock on top. This makes the detection of solar neutrinos including some low-energy ones possible.

Figure 1.4 shows the spectrum of recoil electrons that is expected to be produced by the neutrino fluxes of interest to SNO+.

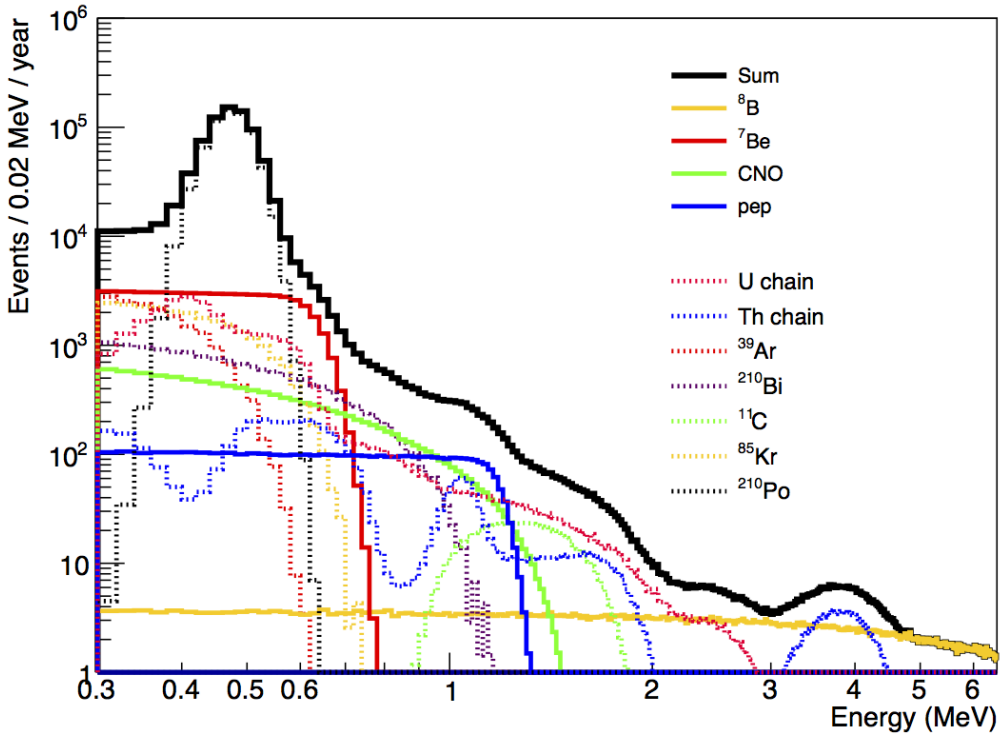

Figure 1.4: The expected electron recoil energy spectrum from solar neutrinos in SNO+. The spectra of all known backgrounds in the region of interest are also shown. The ^{210}Po is one important background for solar neutrinos detection. Source: snoplus.phy.queensu.ca

Inside the Sun, much of the energy and neutrinos released are from the fusion of Hydrogen to Helium. This process can be described as the proton-proton fusion (pp) cycle. The SNO+ experiment can measure the solar neutrino released in the reaction in the pp chain [19].

Besides, SNO+ can measure neutrinos from some other interactions like ^{8}B or pep if a low background level can be achieved. Neutrinos are detected in a scintillator experiment through the elastic scattering interaction as shown in the equation 1.3.

$$\nu_e + e^- \rightarrow \nu_e + e^- \tag{1.3}$$

Part of the energy from the Sun is expected to come from the Carbon, Nitrogen, and Oxygen (CNO) cycle. SNO+ measurements can help to understand the energy contribution of reaction in the CNO cycle. The CNO solar neutrino flux measurement can give information about the chemical composition in the core of the Sun, which is important for understanding of energy production and flow in solar models. The measurement of CNO neutrinos is challenging due to the low events rate and the backgrounds in a similar energy range. Thus it is very important to have a low background in the detector to have accurate solar neutrino measurements [19]. As shown in figure 1.4, the ^{210}Po is an important background for solar neutrino detection and more details will be discussed in chapters 2 and 3.

1.4 Run Plan and Phases of SNO+

Depending on the content of the detection medium in the AV cavity, the SNO+ experiment period is divided into several main phases.

1.4.1 Water Phase

From May 2017 to July 2019, the detector was filled with about 905 tonnes of ultra-pure water. The main physics goal was searching for solar neutrinos, supernova neutrinos and reactor neutrinos. In this stage, the properties of the data acquisition system, PMT response,

and detector performance were evaluated. The attenuation of the external water and acrylic were tested, as well as the response of the PMT concentrators. The backgrounds that come from external sources, such as the acrylic vessel, external water, PMT array, and hold-down ropes were characterized.

1.4.2 Partial Fill Phase

It took about two years to fill the AV with LAB and PPO. During this phase, there were two time periods when the detector has no filling activity. The first period was from July 2019 to Oct 2019 and the second period was from April 2020 to August 2020. During the partial fill period, the detector was filled with LAB on top and UPW at the bottom. In partial fill period, there was no PPO filling activity, the background level was relatively stable.

1.4.3 Full Fill Phase

In April 2021, the detector finished the LAB filling. In May 2022, the PPO loading was completed with the PPO level in the detector reaching the target level of 2.2g/L. Then, the scintillator full fill phase started. In the scintillator phase, the detector is filled with about 780 tonnes of LAB-PPO liquid scintillator. The detector can be used to study physics topics including low-energy solar neutrinos, geo and reactor antineutrinos, and supernova neutrinos. Additionally, at this phase, the optical model and detector response will be checked. The background radiation from both internal and external sources will all be characterized.

1.4.4 Te-Loading Phase

In the Te-Loading Phase, for the search of $0\nu\beta\beta$ decay of 130Te, about 2.3 tonnes of natural tellurium (0.3% by weight) will be loaded into the detector. Besides the $0\nu\beta\beta$ search, the detector can search for the Geo, reactor and supernova neutrinos

Chapter 2

Background in the SNO+ Experiment

The physics goals of SNO+ are searching of $0\nu\beta\beta$ decay, solar neutrinos, supernova neutrinos, geo neutrinos, and reactor neutrinos. Achieving these physics goals requires a low-level background in the experiment. For example, in the measurement of $0\nu\beta\beta$ from ^{130}Te decay, the event rate of $0\nu\beta\beta$ is expected to be very low. Thus, in the region of interest of ^{130}Te $0\nu\beta\beta$ (about 2.5MeV), one needs the background rate to be as low as possible to have a good measurement of $0\nu\beta\beta$. Besides that, a good understanding of the existing background also plays a key role in the success of the experiment [1]. This chapter will discuss the main sources of backgrounds in the SNO+ experiment in several categories, namely; the ^{238}U decay chain, the ^{232}Th decay chain, and other background sources.

2.1 ^{238}U Decay Chain

^{238}U (half-life 4.47×10^9 years) naturally presents in the detector structure like the scintillator, PSUP, PMTs and the surrounding rocks of the SNO+ detector. Figure 2.1 shows the decay chain of the ^{238}U.

The intrinsic ^{238}U content in the experiment structures is hard to get rid of, but they are expected to maintain at a constant low level which does not pose an increasing threat to the experiment. However, if ^{222}Rn gas leaks into the detector, it will bring more contamination

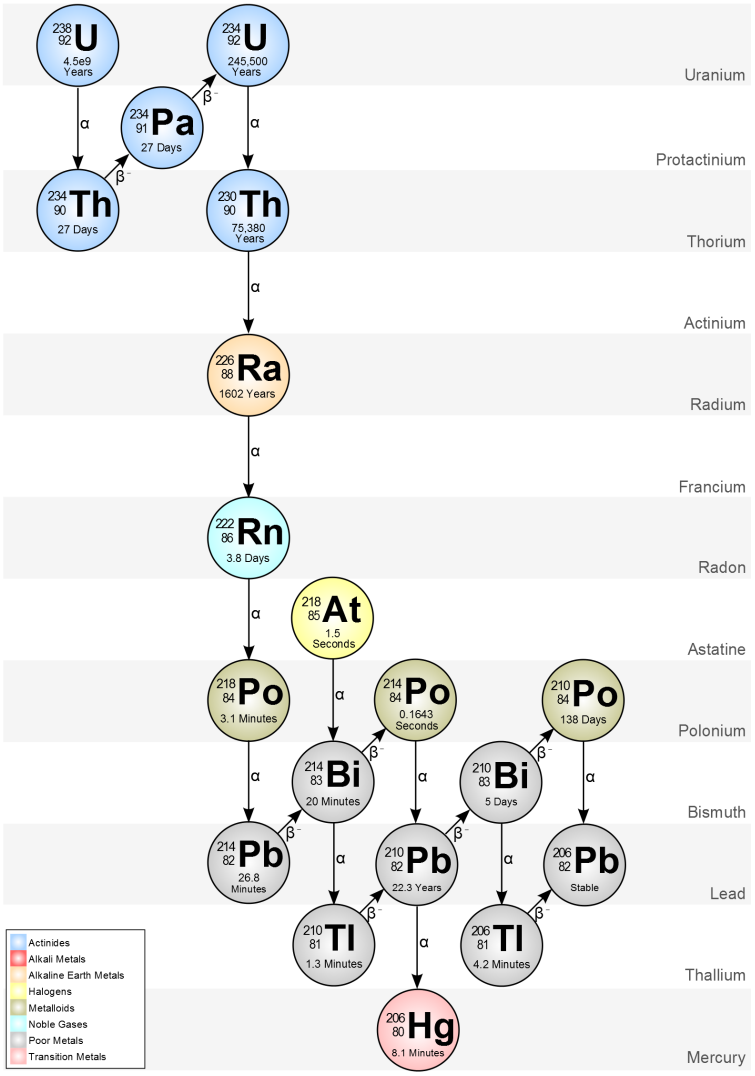

Figure 2.1: Decay chain of ^{238}U.

The most relevant background source to the SNO+ experiment are ^{214}Bi ^{210}Bi and ^{210}Tl. Source: Nuclear Forensic Search Project.

backgrounds in the ^{238}U chain. ^{222}Rn is a noble gas originated from ^{238}U decay. It can mix with the mine air and move around the laboratory easily if no restriction is set in place. When ^{222}Rn gets into the detector, the secular equilibrium of the ^{238}U will be broken.

^{222}Rn decay into ^{214}Bi, which can undergo β decay with the Q-value of 3.27MeV. The γ released in the decay is super close to the ROI for the search of neutrinoless double beta decay of ^{130}Te. To reduce the influence from the backgrounds, the SNO+ experiment uses the delayed Bi-Po coincidence technique to identify the ^{214}Bi events. ^{214}Bi decay to ^{214}Po, ^{214}Po then decay to ^{210}Pb and release a 7.7MeV α. Based on the detector data, it will appear to be a 3.27MeV signal closely followed by a 7.7MeV signal. Thus, such an event can be tagged as Bi-Po delayed coincidence background signal. This method can reduce most of the ^{214}Bi background and help to estimate the level of contamination from ^{238}U chain.

The SNO+ experiment is equipped with hardware to minimize the level of ^{222}Rn ingress to the detector. There is a clean room located on the top of the detector neck, the detector clean room (DCR). The DCR is a separate clean room in SNOLAB, which has an air recirculation system to keep the outside mine air from the detector universal interface (UI). Inside the UI, there is a cover gas system that has clean nitrogen gas flowing to the surface of the liquid scintillator in the detector neck, which helps to reduce the chance of ^{222}Rn in the mine air reaching the detector. The SNO+ experiment also has established a temperature gradient in the cavity water where the top of the cavity is warmer than the bottom. This is aimed to reduce the convection of the liquid to reduce the speed of ^{222}Rn mixing into the detector volume.

In the detector, ^{238}U and ^{222}Rn decay into ^{210}Pb. ^{210}Pb (half-life 22 years) decays into ^{210}Bi and releases a 0.06MeV β. ^{210}Bi (half-life 5.0 days) decays into ^{210}Po and release 1.16 MeV β particles. ^{210}Po has a half-life of 138.4 days, which further decays to ^{206}Pb and releases 5.3 MeV α. The ^{210}Bi and ^{210}Po events do not fall directly into the ROI of $0\nu\beta$ search. However, ^{210}Bi is the background of concern for the solar neutrino search and ^{210}Po affects the $\alpha - \beta$ and $\beta - \alpha$ delayed coincidence and causes mistagging.

^{210}Po also brings the pile-up backgrounds. The most important pile-up backgrounds for $0\nu\beta\beta$ search are due to high-rate ^{210}Po + $2\nu\beta\beta$ and ^{210}Bi + $2\nu\beta\beta$. ^{210}Po and ^{210}Bi may come from the liquid scintillator and the vessel surface. The influence of pile-up backgrounds can be largely reduced by timing-based cuts [1]. The ^{210}Po background will be discussed in more detail in Chapter 3.

2.2 ^{232}Tl Decay Chain

Similarly, ^{232}Tl is naturally present in the mine environment and the scintillator. The most concerning two daughters of ^{232}Tl are ^{212}Bi and ^{208}Tl. Figure 2.2 shows the ^{232}Tl decay chain.

In the ^{232}Tl decay chain, ^{212}Bi may decay into ^{212}Po and release 2.25 MeV β particle. This background can be removed with the PMT timing distribution. ^{212}Bi may also decay to ^{208}Tl and release 5.0 MeV α. $\alpha - \beta$ delayed coincidence can be used to remove this background.

2.3 Other Background Sources

^{40}K (half-life 1.248×10^9 years) has gamma peak at 1.46MeV. Due to the long half-life, it is naturally present in the scintillator and detector materials. ^{39}Ar (half-life 69 years) and ^{85}Kr (half-life 10.8 years) decay with a Q-value of 0.565MeV and 0.687MeV, respectively. The amount of these isotopes can be reduced by minimizing the contacting time of LAB with air and thoroughly degassing the scintillator. [19]

^{7}Be can be created when the scintillator is exposed to cosmic ray neutrons and protons and it will release a 0.48MeV γ (half-life 53.2 days). However, it can be removed very effectively by using the scintillator purification plant.

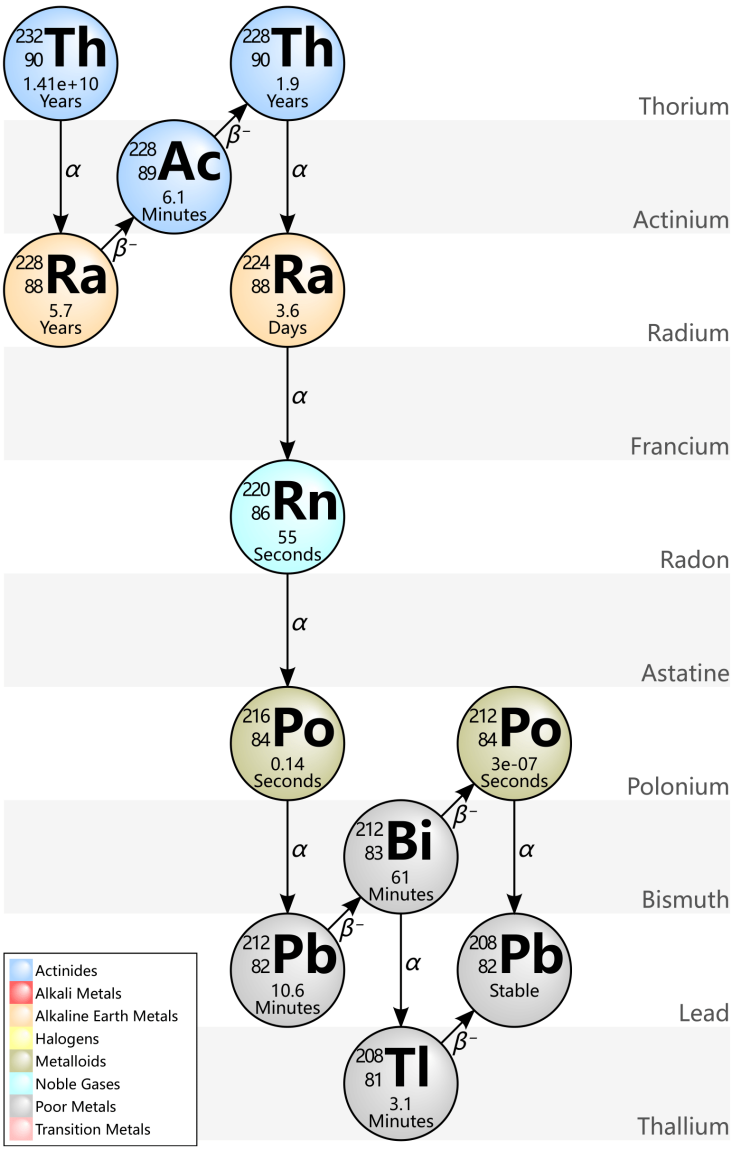

Figure 2.2: Decay chain of ^{232}Tl.

The most relevant background sources to SNO+ are ^{212}Bi and ^{208}Tl. Source: Nuclear Forensic Search Project.

Isotope	1 year	5 years
$2\nu\beta\beta$	6.3	31.6
$^{8}B\nu ES$	7.3	36.3
Uranium chain	2.1	10.4
Thorium chain	1.7	8.7
External	3.6	18.1
(α n)	0.1	0.8
Cosmogenic	0.7	0.8
Total	21.8	106.8

Table 2.1: Expected background counts in the signal ROI and 3.5mFV in SNO+ for the first year (year 1) and 5 years of the 0.5Te-loading phase.

A light yield of 200Nhits/MeV has been assumed [1].

^{14}C (half-life 700 year, Q-value = 0.16MeV) naturally presents in the liquid scintillator. It is a direct background for the very low-energy pp neutrino measurements and may contribute to pile-up backgrounds.

^{11}C can be produced by muon interaction with the scintillator. It will decay with a Q-value of 1.98MeV and a half-life of 20 min. As SNO+ is located 2 km underground, and with an electron-positron discrimination analysis technic, the influence can be minimized [1].

2.4 Conclusion

In summary, for the search of $0\nu\beta\beta$ decay of ^{130}Te, the main sources of backgrounds are solar neutrinos, $2\nu\beta\beta$, ^{238}U and ^{232}Tl chain backgrounds. Table 2.1 indicates the number of the background events in the Te $0\nu\beta\beta$ search ROI after Te is loaded. Figure 2.3 indicates the expected background spectrum of the SNO+ experiment.

For the ^{238}U and ^{232}Tl chain backgrounds, the most important ones are the ^{214}Bi-Po and ^{212}Bi-Po decays. They can be mostly rejected by $\alpha - \beta$ delayed coincidence. For the ^{238}U decay chain, the secular equilibrium can be broken by the ^{222}Rn ingress and surface AV ^{210}Pb leaching. The following chapters will discuss the ^{222}Rn assays and the ^{210}Po background in the detector from the AV surface.

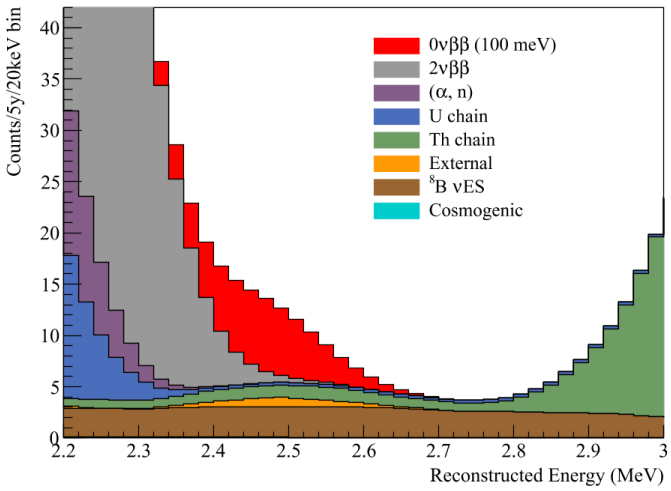

Figure 2.3: Expected backgrounds for SNO+ $0\nu\beta\beta$ decay search.

Backgrounds are shown for a 5-year data-taking period with a fiducial volume of 3.5m and 0.5% of tellurium loading. Source: snoplus.phy.queensu.ca

Chapter 3

AV Surface Po-210 Analysis

As discussed in chapter 2, the SNO+ experiment requires a low background clean laboratory environment to detect rare physics events like $0\nu\beta\beta$. The expected background levels for the search of Te $0\nu\beta\beta$ decay are shown in table 2.1. This chapter will discuss the analysis of ^{210}Po originating from the ^{210}Pb deposit on the inner surface of the AV.

^{210}Po is a background to SNO+ for the measurements of solar neutrinos such as CNO neutrinos. Due to its low energy nature of the decayed α (about 0.5 MeV electron equivalent energy), it is not the direct background to search for Te $0\nu\beta\beta$ decay (about 2.5MeV). However, it is the background to the delayed $\alpha - \beta$ coincidences analysis, which is important for the background removal for $0\nu\beta\beta$ decay search. The ^{210}Po events can result in mistagging of ^{214}Bi events and potential signal sacrifice. Besides, the pile-up events due to ^{210}Po + $2\nu\beta\beta$ and ^{210}Bi + $2\nu\beta\beta$ are in the ROI of the $0\nu\beta\beta$ search [1]. A pile-up event happens when two or more events occur within the same 400 ns trigger window. These events can potentially be registered as a single event. The most important pile-up backgrounds for $0\nu\beta\beta$ search are due to high-rate ^{210}Po + $2\nu\beta$ and ^{210}Bi + $2\nu\beta\beta$. The influence of pile-up events can be significantly reduced using time-based cuts [1].

^{210}Po events in the detector can indicate the background level of the ^{238}U chain elements. ^{210}Po is the daughter of ^{222}Rn and the amount of ^{210}Po events in the detector can give us

information about the background level of ^{214}Bi and ^{222}Rn. The decayed β of ^{214}Bi has the energy in the ROI of the $0\nu\beta\beta$ search, and the ^{222}Rn level in the detector provides the information of possible ^{222}Rn gas leak.

3.1 Po-210 in the SNO+ Detector

^{210}Po is one of the elements in the Uranium decay chain as shown in figure 2.1. It is the decay product of ^{210}Pb. It decays into ^{206}Pb and releases an 5.41 MeV α particle (about 0.5 MeV electron equivalent energy) [29].

^{210}Po events make up a large portion of the SNO+ data spectrum in the Nhits (Number of PMT hits) range of around 70 to 150. The number of PMT hits of an event represents its energy after calibration. The ^{210}Po in the detector may come from several possible sources: the ^{222}Rn gas ingress into the detector, the ^{210}Po from the reticulation pipes, and the ^{210}Pb deposit on the AV surface.

In order to understand the amount of ^{210}Po originating from the Rn ingress, it is essential to understand the ^{210}Po originating from other sources. The ^{210}Po from the surface AV is known as the most relevant source of ^{210}Po in the detector. Therefore, it is important to monitor the ^{210}Po events and chapter 3.2 will discuss the main sources of the ^{210}Po in the detector.

3.2 Pb-210 Deposit and Leaching

The detector was emptied and the AV was exposed to the mine air during the construction of the SNO detector and the transition state of SNO to SNO+. ^{222}Rn gas in the air decayed to ^{210}Pb and deposited it on the AV surface. ^{210}Pb accumulate and form a thin layer of ^{210}Pb on the surface of AV [1].

In the SNO experiment period, the AV was filled with heavy water. Data taking started in May 1999. The ^{210}Pb was deposited on the AV surface more than 20 years ago; however,

the thin layer of ^{210}Pb on the AV surface can last very long as the half-life of ^{210}Pb is 22.3 years. The implanted ^{210}Pb on the AV inner surface is a continuous source of ^{210}Pb, ^{210}Po and ^{210}Bi backgrounds for SNO+ data taking. During the time between SNO and SNO+, the AV was exposed to the air for several years, thus ^{210}Pb was deposited on the inner AV surface.

Currently, the SNO+ detector is filled with LAB, the ^{210}Pb can leach off the AV surface and enter the detector and become the source of ^{210}Po in the detector volume. The leaching of ^{210}Pb from the acrylic to LAB has been studied. The results indicate that at the temperature T= 12^{o}C, leaching time of 7200 days, the leaching rate of ^{210}Pb into LAB is 1.4×10^{-4} per day [21]. Based on the leaching rate of ^{210}Pb to the scintillator (1.4×10^{-4} per day), the amount of ^{210}Pb leached off the AV surface and entered the detector inner volume can be estimated as shown in section 3.6.

3.3 The Cuts for Po-210 Events

Due to the leaching effect, the ^{210}Pb layer on the AV inner surface is a major source of the ^{210}Po in the detector. To have a better understanding of the amount of ^{210}Pb deposited on the AV, the ^{210}Po events found near the AV surface are analyzed. For the analysis, SNO+ data are used, which are reconstructed and processed with a standard technique for SNO+ background analysis [22]. In the data file, the event energy is based on the number of PMT hit in the 400 ns trigger window (NHits). The event position is reconstructed based on the timing of the PMT hits [1].

For the purpose of understanding the ^{210}Pb deposit on the AV surface, ^{210}Po events that happened near the AV surface region are studied. The reason why ^{210}Pb rate is not analyzed directly is that ^{210}Pb undergo β decay at the very low energy (46.5KeV) while the α decay of ^{210}Po decay is at the much higher energy of around 5.41MeV (about 0.5MeV

electron equivalent energy). The 46.5KeV β released in the ^{210}Pb decay cannot be observed by SNO+ since its energy is below the SNO+ threshold of 0.2 MeV.

To extract the ^{210}Po events that happened near the AV surface, proper events selections (cuts) are applied. The cuts include the selection of runs, region, data taking period, and the energy (Nhits). Also, standard SNO+ background analysis data cleaning cuts are applied [22].

3.3.1 The Run Selection

The SNO+ data is divided into runs. A run is a data-taking period of up to 1-hour of detector time. Runs that are good for analysis are selected by the SNO+ run selection group. The Run Selection team is in charge of ensuring the quality of the data taken on a run-by-run basis in near real-time. The team has automated tools to evaluate the goodness criteria and create a golden run list [25]. In this analysis, good physics runs are selected and analyzed in the unit of a day.

3.3.2 Nhits Cut

After applying the cuts (except Nhits cut), the SNO+ data energy spectrum is shown in Figure 3.1. The energy of an event is represented by the number of PMT hits (Nhits). The x-axis indicates the Nhits of events and the y-axis is the corresponding event rates. In Nhits region 10 to 30, only 1% of the events are reconstructed. This is done to reduce the data file size as the events rate below 30 Nhits is very high. In the Nhits range of 30 to 200, high-rate ^{210}Po events correspond to the distinct peak. In the peak at Nhits from 55 to 135, the ^{210}Po is the dominant source. Since the light yield of the LAB-PPO is expected to be about 200Nhits/MeV, the 100 Nhits in the plot represents about 0.5MeV energy. The ^{210}Po peak has a shape of Gaussian distribution, and the event number of ^{210}Po is calculated as the area under the ^{210}Po peak. Since ^{210}Po has a very high event rate, the influence of other kinds of backgrounds in this energy range is minimal. Due to the PPO filling activity in the full fill

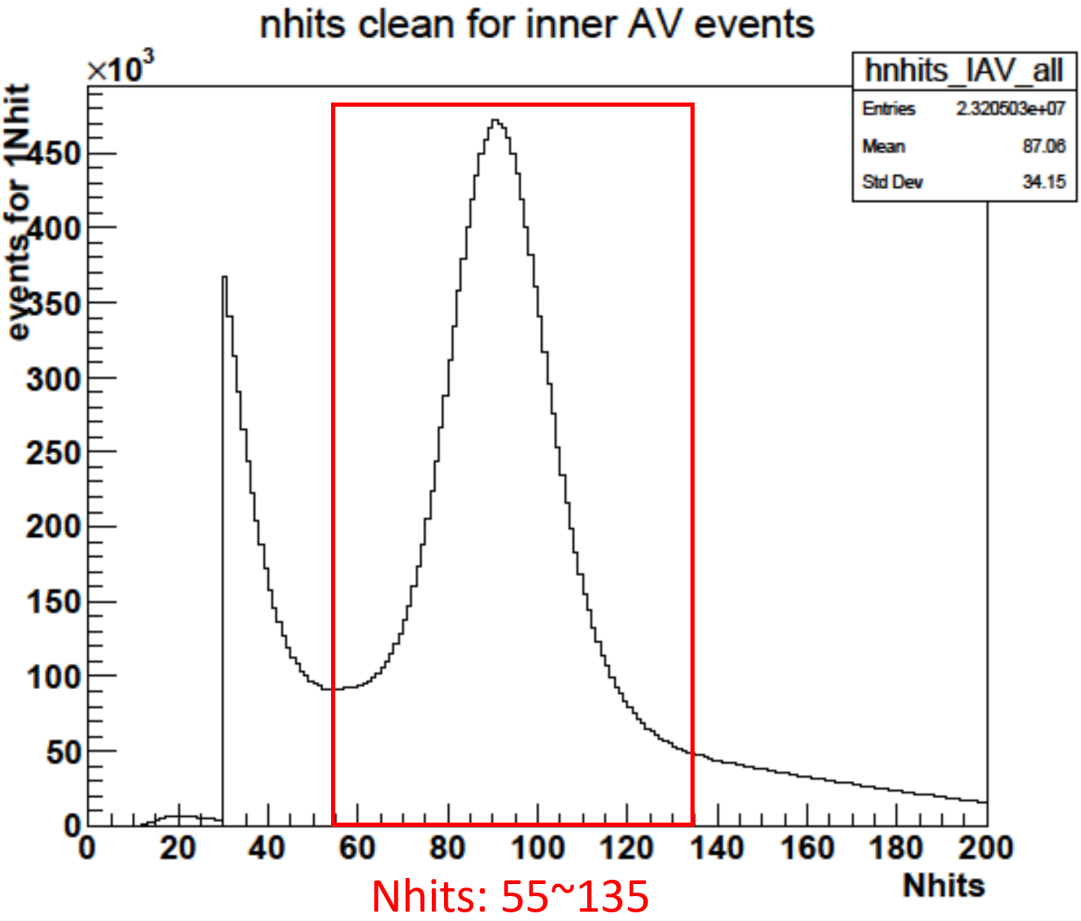

Figure 3.1: The Nhits spectrum of the SNO+ data from April 01, 2021. The peak in the red box corresponds to the ^{210}Po events. Event rate with Nhits smaller than 30 is multiplied by 0.01 to reduce data file size.

period, the light yield of the scintillator and the Nhits of ^{210}Po peak was increasing. With the size of the Nhits cut window remaining unchanged, the cut range of Nhits is adjusted timely to catch the ^{210}Po peak. The ^{210}Po events that happened in the detector volume can be a background for the study of the AV surface ^{210}Po events. They will be removed using the Monte Carlo simulation to get the cut efficiency of catching those detector ^{210}Po events. This will be discussed in details in chapter 3.4.

3.3.3 Partial Fill Period

There are two periods of analysis in this discussion. The detector phases are discussed in chapter 1.4. The first period was the partial fill period (April 2020 to August 2020) when the detector bottom was filled with Ultra pure water (UPW) and the top was filled with liquid scintillator (LAB) with the scintillator level at about $850mm$ above the equator (z = 0). There was no LAB filling activity so the level of the scintillator stayed the same. Since there was no filling activity during that time, the background level was stable, ideal for the background analysis. The PPO level for the partial fill period was 0.6 g/L [23].

3.3.4 Full Fill Period

The second period is the full fill period. The full fill analysis started after the fill of LAB in April 2021. After the scintillator fill was completed, additional material in form of wavelength shifter PPO was added. As the amount of wavelength shifter increased, the light yield of the scintillator and the Nhits of ^{210}Po events increased over time. Thus the Nhits range in the cut has to be adjusted over time to catch the ^{210}Po peak. In April 2021 the Nhits range was 55 to 135, as PPO was added to the detector the Nhits range shifted gradually to 75 to 155 by November 2021. The final PPO concentration is 2.2 g/L [24].

3.3.5 Spacial Cut

Since the region of interest is the inner surface of the AV, the area of a 50 cm radius from the inner surface is studied. As SNO+ reconstruction uncertainty is about 10^{-12} cm, 50 cm is enough to allow the analysis to capture most of the surface AV events. [1]. The shell is divided into two smaller sub-shells. The inner shell is from r range from 5.50m to 5.75m and the outer shell is from 5.75m to 6.00m. The two shells are shown in figure 3.2. The bottom 5 cm in the detector is removed from the analysis as there may be a small amount of UPW left.

To understand how the ^{210}Po events rate varies with different heights in the detector, the region is further divided by z into 26 sub-regions. In the partial fill period analysis, since the scintillator level was at z = 850 mm (z = 0 at the equator of the detector), an additional cut of z > 850 mm was added to the analysis.

The shell is divided into 26 sub-regions for the following reasons.

1. The study of leaching process of ^{210}Pb

   To understand how the leaching may cause ^{210}Po to have a pattern of movement from the AV into the center of the detector, regions are grouped with radii ranging from $5.50m < r < 5.75m$ and $5.75m < r < 6.00m$

2. The spacial distribution of ^{210}Po

   The ^{210}Po events have a spatial distribution pattern because each part of AV is exposed to LAB or UPW for a different duration. The leaching and deposit rates of ^{210}Pb on various parts of AV may differ. Besides, there are two ^{210}Po analyses in the detector, one for the ^{210}Po in the fiducial volume (r < 5.5 m) and the other for the surface AV ^{210}Po. Events near the boundary may be reconstructed to the other region. In the fiducial volume, there are various ^{210}Po rates in different parts, thus the sub-regions of surface AV ^{210}Po analysis are affected differently.

3. The study of ^{210}Po movement

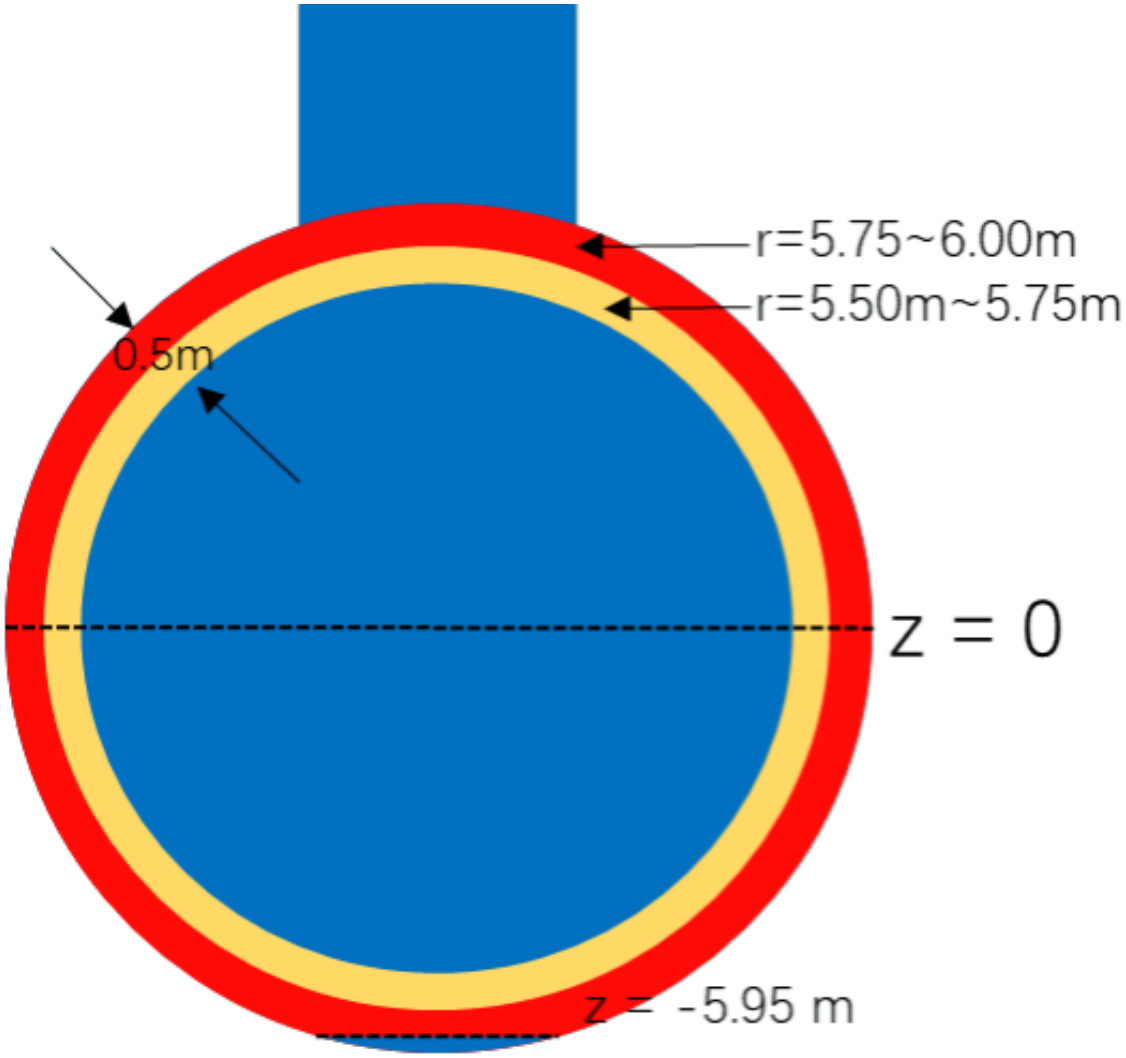

Figure 3.2: Schematic diagram of the two shells of the analysis regions.
The inner shell is yellow and the outer shell is red. Each shell has a thickness of 25 cm.

In the detector volume, the background hot spots move around in the detector over time. Thus, if ^{210}Po backgrounds move in the detector, the activities change in the regions can give a hint to the movement.

For the 26 sub-regions, the vertical (z coordinate) position range, radius (r) range, volume, and surface area of AV the region is attached to are shown in table 3.3.5. The avoid the influence of the recirculation lines, the region with the azimuth angle (ϕ) ranging from 1.15 to 2 is removed from this analysis. Regions 11, 12, 25, and 26 have smaller volumes as they are at the top or bottom of the detector. For the partial fill period, the region of interest is restricted to z $>$ 0.85m as the LAB-water interface is located at z = 0.85m. Thus the z range for region 1 and region 2 would be 0.85m $<$ z $<$ 1.5m. Also, regions below z = 0.85m are not involved in the analysis for the partial fill period.

3.4 The MC Simulation and Analysis

To determine the efficiencies of the cuts to find the ^{210}Po that originated from the AV surface, the Monte Carlo (MC) simulations were studied. The MC files have the ^{210}Po simulated on the inner AV surface and in the detector scintillator. The MC simulations are constructed based on certain states of the detector. To make sure the MC simulations are good representations of the detector mechanism, MC simulations from different states of the detector and different PPO concentrations in the scintillator are analyzed and compared. We compared the MC simulations from the partial fill period, the beginning of the full fill period, and one year after the full fill period, then the results show a similar surface AV ^{210}Po activity, which indicates the MC simulation makes a good representation of the detector. By applying the same cuts to the MC simulation result, and dividing the number of events that passed the cut in each region by the total surface ^{210}Po events simulated, the efficiency of the cut at each region can be obtained. The calculation is shown in equation 3.2.

region #	z range (m)	r range (m)	Volume (m^3)	Area (m^2)
1	$0.5 < z < 1.5$	$5.50 < r < 5.75$	6.45	27.50
2	$0.5 < z < 1.5$	$5.75 < r < 6.00$	6.73	27.50
3	$1.5 < z < 2.5$	$5.50 < r < 5.75$	6.45	27.50
4	$1.5 < z < 2.5$	$5.75 < r < 6.00$	6.73	27.50
5	$2.5 < z < 3.5$	$5.50 < r < 5.75$	6.45	27.50
6	$2.5 < z < 3.5$	$5.75 < r < 6.00$	6.73	27.50
7	$3.5 < z < 4.5$	$5.50 < r < 5.75$	6.45	27.50
8	$3.5 < z < 4.5$	$5.75 < r < 6.00$	6.73	27.50
9	$4.5 < z < 5.5$	$5.50 < r < 5.75$	6.45	27.50
10	$4.5 < z < 5.5$	$5.75 < r < 6.00$	6.73	27.50
11	$5.50 < z < 6.0$	$5.50 < r < 5.75$	0.81	13.75
12	$5.50 < z < 6.0$	$5.75 < r < 6.00$	2.53	13.75
13	$3.5 < z < 4.5$	$5.50 < r < 5.75$	6.45	27.50
14	$3.5 < z < 4.5$	$5.75 < r < 6.00$	6.73	27.50
15	$-0.5 < z < -1.5$	$5.50 < r < 5.75$	6.45	27.50
16	$-0.5 < z < -1.5$	$5.75 < r < 6.00$	6.73	27.50
17	$-1.5 < z < -2.5$	$5.50 < r < 5.75$	6.45	27.50
18	$-1.5 < z < -2.5$	$5.75 < r < 6.00$	6.73	27.50
19	$-2.5 < z < -3.5$	$5.50 < r < 5.75$	6.45	27.50
20	$-2.5 < z < -3.5$	$5.75 < r < 6.00$	6.73	27.50
21	$-3.5 < z < -4.5$	$5.50 < r < 5.75$	6.45	27.50
22	$-3.5 < z < -4.5$	$5.75 < r < 6.00$	6.73	27.50
23	$-4.5 < z < -5.5$	$5.50 < r < 5.75$	6.45	27.50
24	$-4.5 < z < -5.5$	$5.75 < r < 6.00$	6.73	27.50
25	$-5.50 < z < -5.95$	$5.50 < r < 5.75$	0.81	12.37
26	$-5.50 < z < -5.95$	$5.75 < r < 6.00$	2.50	12.37

Table 3.1: Regional cuts of AV surface ^{210}Po analysis.

The volume and area for each region are shown.

$$\varepsilon_{MC} = \frac{N_p}{N_{MC}} \tag{3.1}$$

Where ε_{MC} is the efficiency of the cut of one region, N_p is the number of events that pass the cuts, and N_{MC} is the total simulated number of events. The MC is generated in two ways. The first MC file is simulating 1.10×10^7 ^{210}Po events on the AV surface. For each region, with the number of events that pass the cuts, we can get the cut efficiency of each region to find ^{210}Po events.

The second MC simulates 8.49×10^6 ^{210}Po events in the detector inner volume, by comparing the simulated ^{210}Po in the detector volume and the number of those that pass the cuts, the efficiency of the cuts to find the ^{210}Po events originated from the scintillator can be calculated and removed from the result.

Using the surface area of the AV and the data-taking period, the expected surface AV ^{210}Po activity can be calculated based on the cut efficiencies. It is represented as the normalized event rate per unit time per unit area of AV. The calculation is shown in the equation 3.2.

$$f = \frac{N}{A \times T \times (\varepsilon_{AV\_Po210} - \varepsilon_{detector\_Po210})} \tag{3.2}$$

Where f is the expected surface AV ^{210}Po activity given in the unit of $m^{-2}s^{-1}$; N is the total number of ^{210}Po events in one species in the selected region; A is the surface area of AV that the region is attached to; T is data taking the time of that day. $\varepsilon_{AVPo210}$ is the cut efficiency to catch surface AV ^{210}Po events. $\varepsilon_{detector\_Po210}$ is the cut efficiency to catch ^{210}Po events in the detector volume. The efficiencies of the two MC simulations for each region are shown in table 3.2.

Region	AV surface Po210	efficiency	Scint Po210	efficiency
Simulated	11023112	100.00%	8487548	100.00%
All regions	1.73E+06	15.70%	1.12E+06	13.22%
1	37266	0.34%	53314	0.63%
2	95993	0.87%	44875	0.53%
3	40907	0.37%	53687	0.63%
4	106912	0.97%	45674	0.54%
5	39847	0.36%	53906	0.64%
6	104950	0.95%	45673	0.54%
7	38696	0.35%	54739	0.64%
8	103594	0.94%	46043	0.54%
9	38134	0.35%	54859	0.65%
10	103864	0.94%	47091	0.55%
11	7590	0.07%	6848	0.08%
12	40423	0.37%	17778	0.21%
13	29793	0.27%	51923	0.61%
14	74359	0.67%	42929	0.51%
15	41436	0.38%	52522	0.62%
16	102574	0.93%	44026	0.52%
17	46527	0.42%	53226	0.63%
18	115558	1.05%	44006	0.52%
19	48190	0.44%	52111	0.61%
20	117363	1.06%	42952	0.51%
21	49563	0.45%	51608	0.61%
22	117502	1.07%	42901	0.51%
23	50845	0.46%	51544	0.61%
24	120569	1.09%	42634	0.50%
25	5585	0.05%	6063	0.07%
26	52294	0.47%	18925	0.22%

Table 3.2: Table of efficiencies for two kinds of MC simulated events to pass the cuts of each region.

The two kinds of MC simulations are ^{210}Po events simulated on the AV surface and from the scintillator in the detector volume.

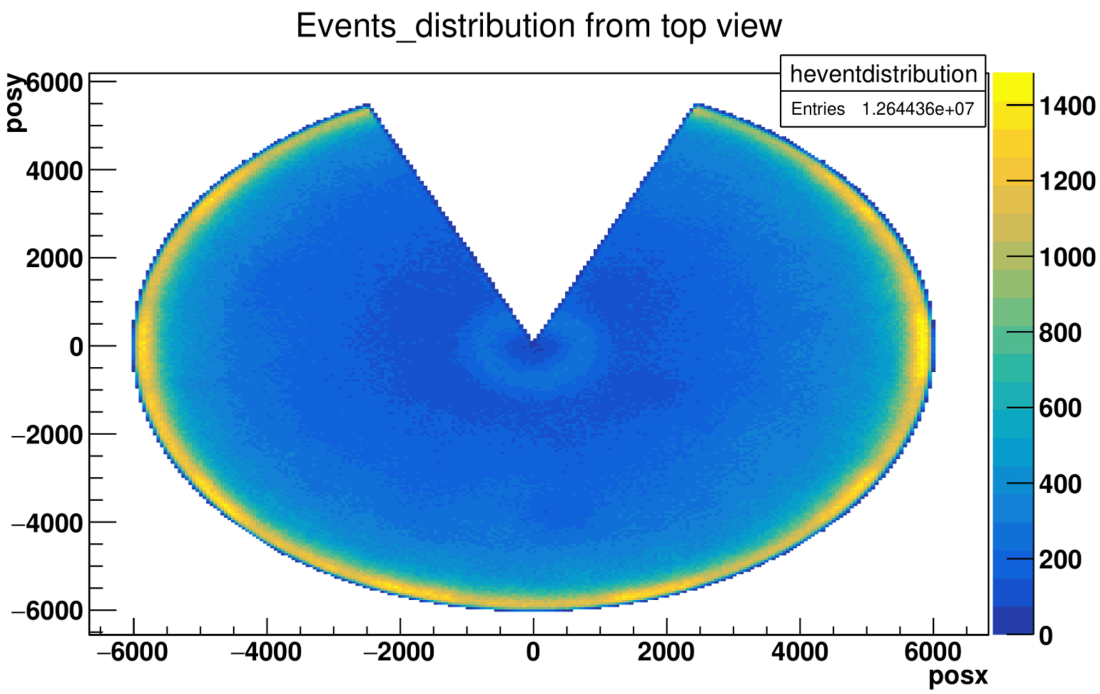

Figure 3.3: Distribution plot of ^{210}Po events with x position vs. y position. The active area is found near the AV surface. Near the neck of the AV, the event rate is also higher than its surrounding parts.

3.5 Results

3.5.1 The spatial distribution of Po-210 events

Plotting the ^{210}Po events on a color scale shows the spatial distribution. For example, the spatial distribution plots for June 1, 2022 are shown in figure 3.3, 3.4 and 3.5.

From figure 3.4 we can see that more ^{210}Po events are distributed near the equator of the detector ($z = 0$) region. There are several "rectangular" shaped hot regions located along the line of the equator. Their locations are where the "Belly plates" are located. At the Belly plates location, the rope system wraps around the AV and the acrylic is thicker to hold the ropes. The event rate is found to be gradually decreasing as we move away from the equator.

From figure 3.3 and 3.5, the event rate is higher near the AV surface. This agrees with the expectation as the ^{210}Po events originated from the AV surface. In addition, there is a

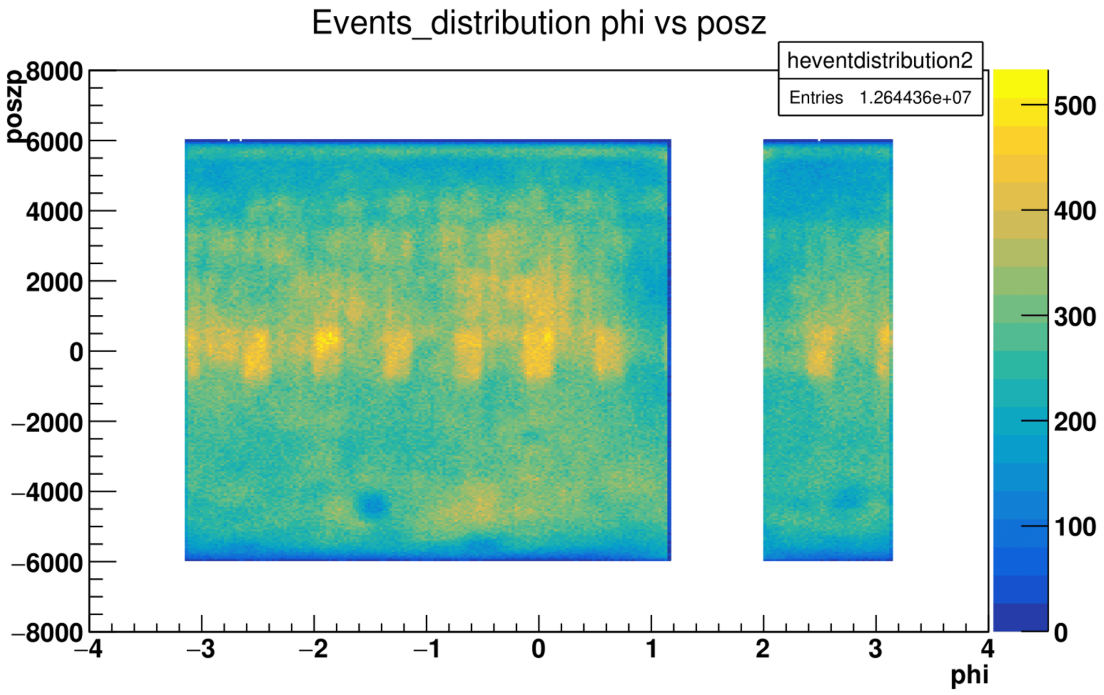

Figure 3.4: Distribution plot of ^{210}Po events with ϕ vs. z position.

Active areas are found to be near the equator of the detector where the belly plates are located. Event rates gradually go down if one moves away from the equator.

hot spot on the top of the detector near the neck region. This could indicate that the ^{222}Rn is coming from the UI and cover gas at the top of the detector. This is expected as the cover gas has a higher ^{222}Rn concentration than the detector LAB.

3.5.2 Partial Fill Period Po-210 Events

For the partial fill period, the analysis period is from April 2020 to October 2020, and the run number ranges from 257596 to 264799. Using equation 3.2, the event rate is normalized based on the data taking time and the surface area of AV. Since the event rate of the surface ^{210}Po is high, this analysis uses a good size of data for the statistic. Figure 3.6 shows the daily ^{210}Po event rate and the data taking time for the analysis during the partial fill period. The ^{210}Po rate is on the order of 10^6 events, and the run time is on the order of 10^4 seconds per day, which provides confidence in the statistic data size.

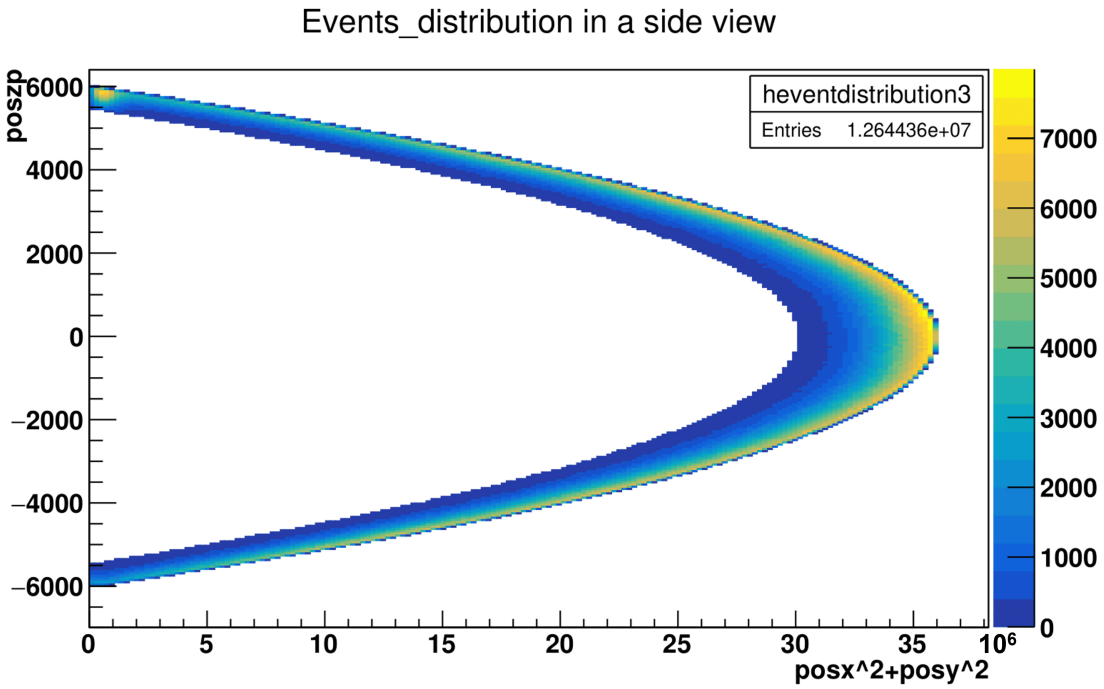

Figure 3.5: Distribution plot of ^{210}Po events with $x^2 + y^2$ vs z position.

More ^{210}Po events are found near the surface of AV. There is a hot spot near the neck of the detector.

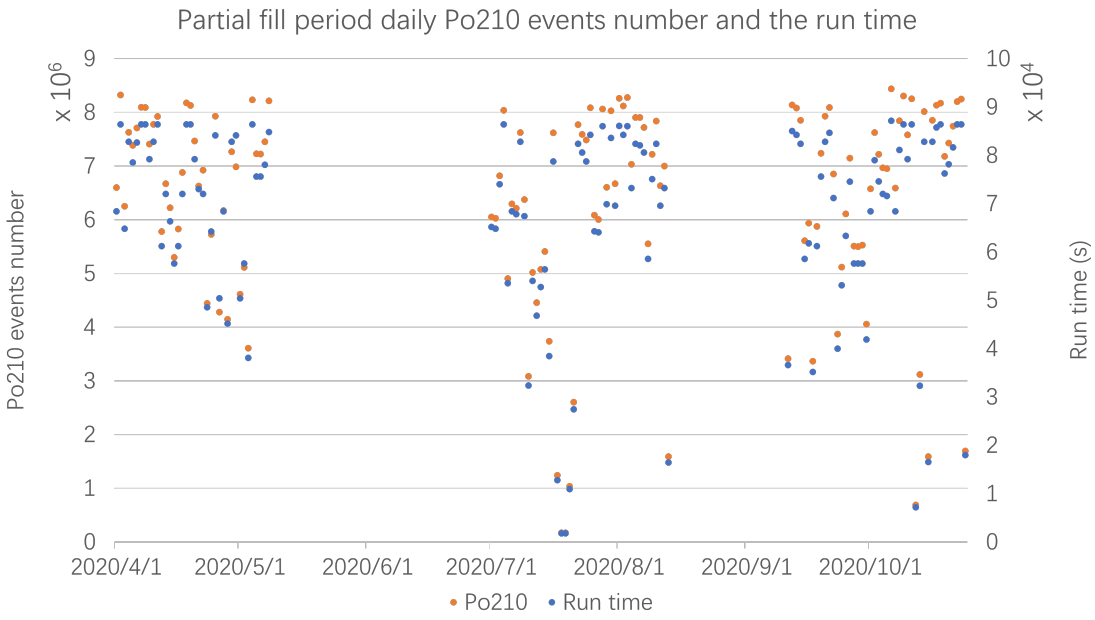

Figure 3.6: Daily ^{210}Po event rate and the data taking time for the analysis during the partial fill period.

The left vertical axis shows the ^{210}Po event rate; The right vertical axis shows the data taking run time in the unit of second.

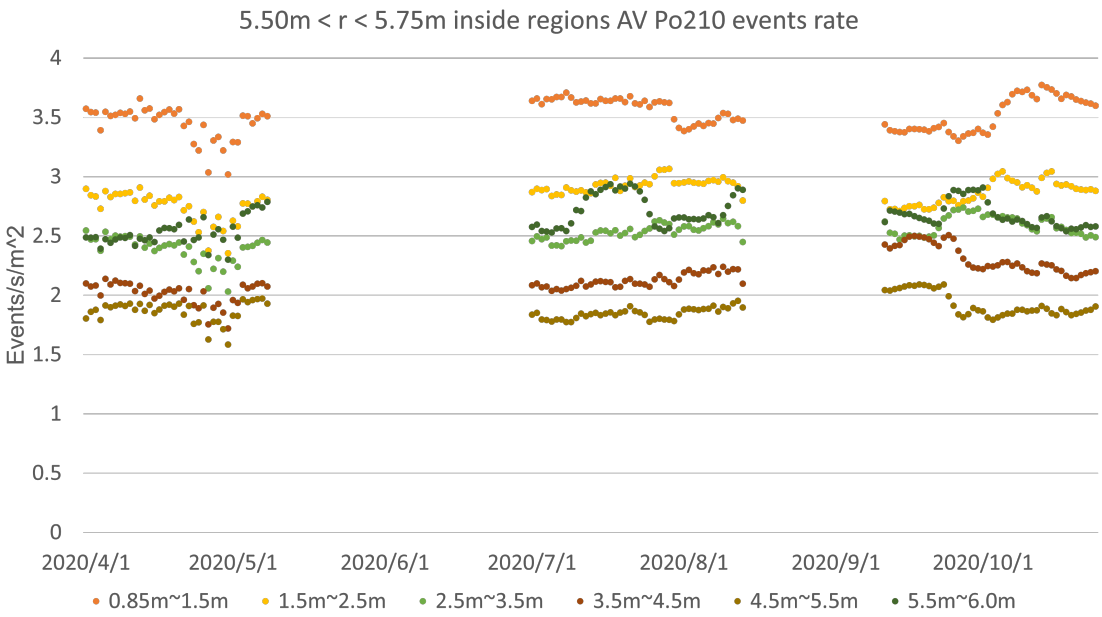

Figure 3.7: The event rate of ^{210}Po in regions with $z > 0.85m$.
The event rates are normalized based on unit time and unit area of the AV. The radius r range is $5.50m < r < 5.75m$.

Plotting the normalized ^{210}Po (event rate $/s/m^2$) each day visualizes the time variation of the AV's ^{210}Po activity. The regions are plotted on two separate plots: Figure 3.7 shows the ^{210}Po event rate of the regions away from AV ($5.50m < r < 5.75m$); the figure 3.8 shows the ^{210}Po event rate for regions near the AV($5.75m < r < 6.00m$).

As shown in figure 3.7 and figure 3.8, the ^{210}Po event rate is approximately at a constant level throughout this period. The result is as expected as the ^{210}Pb has a long half-life of 22 years. As indicated in both plots, the event rate is the highest in the region of 0.85m < z < 1.5m, and the events rate gradually decreases as the z position of the region increases. This is consistent with the observation of the distribution plot figure 3.4. The one exception is in region 5.5m < z < 6.0m region in figure 3.7. The event rate of this region is not the lowest. Some of the ^{210}Po in this region may come from the ^{222}Rn in the cover gas rather than the surface AV. By comparing the ^{210}Po event rate in regions away from the AV (figure 3.7) and the regions near the AV (figure 3.8), we found that the near AV regions have a higher event

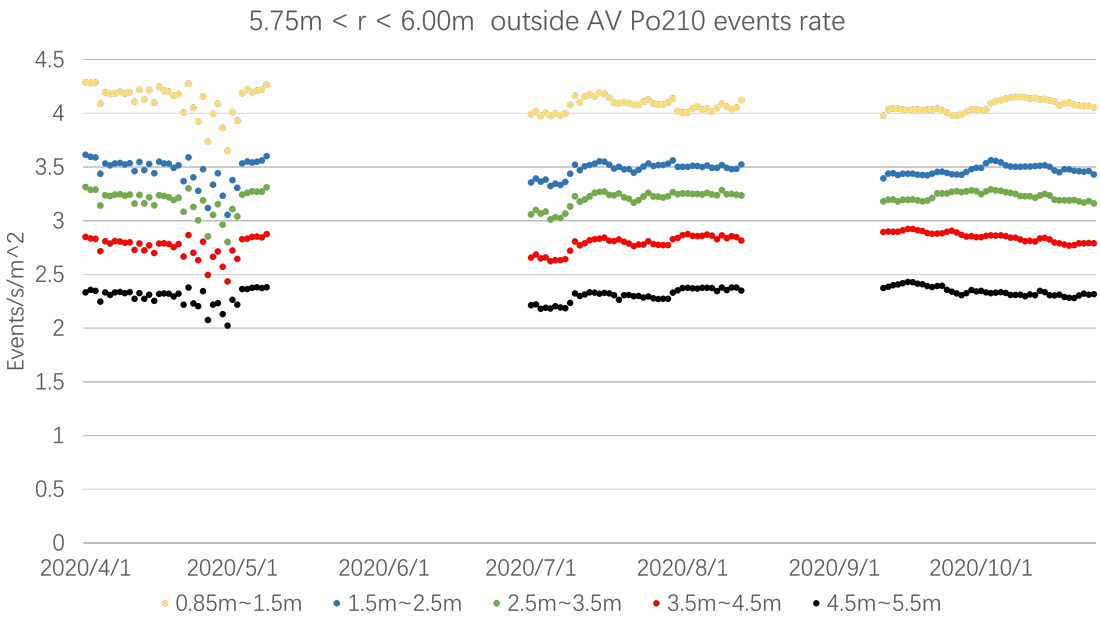

Figure 3.8: The event rate of ^{210}Po in regions with $z > 0.85m$.
The event rates are normalized based on unit time and unit area of the AV. The r range is $5.75m < r < 6.00m$.

rate for same z range, which indicates that the ^{210}Po comes from the ^{210}Pb deposit on the AV surface and this observation is consistent with figure 3.5.

3.5.3 Full Fill Period Po-210 Events

The time variation of ^{210}Po during the full fill period is calculated using equation 3.2. It is similar to the calculation in the partial fill period. The analysis period for full fill is from April 2021 to April 2022, with the run number ranging from 269334 to 282077. Figure 3.9 shows the daily ^{210}Po event rate and the data taking time for the analysis during the full fill period. Figure 3.9 shows that on each day, the ^{210}Po events are on the order of 10^6 and the run time is on the order of 10^4 seconds. The analysis has enough statistics and data size to have a fair representation of the ^{210}Po events.

Figure 3.10, 3.11, 3.12, and 3.13 show the event rate at the given time period. Figure 3.10 shows the plot for region with $5.50m < r < 5.75m$, $z > 0.5m$; Figure 3.11 shows the plot for region with $5.75m < r < 6.00m$, $z > 0.5m$; Figure 3.12 shows the plot for

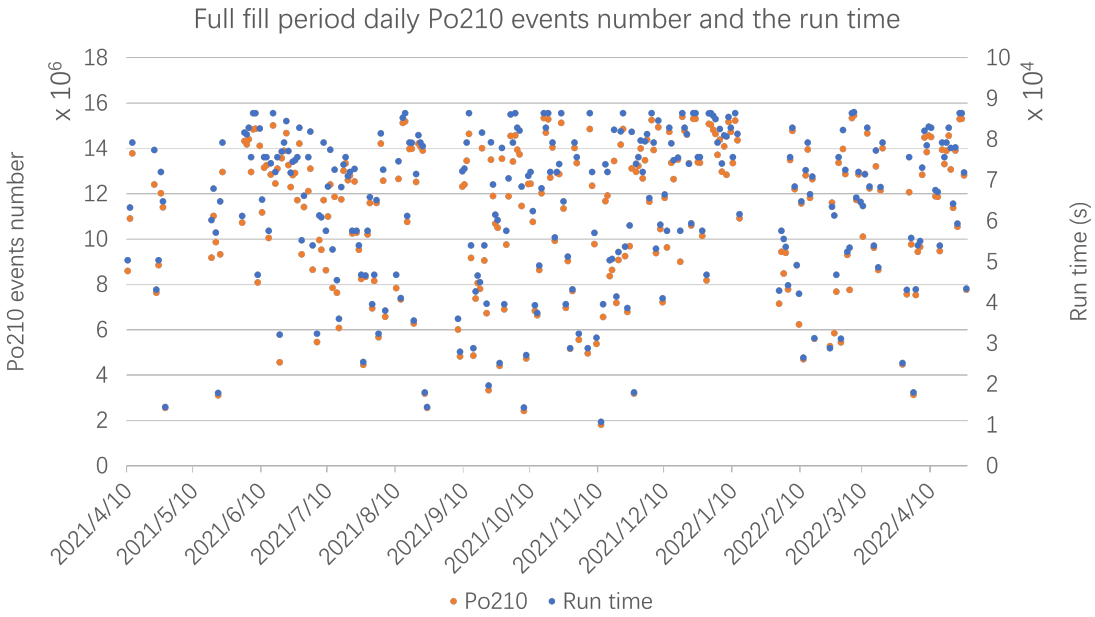

Figure 3.9: Daily ^{210}Po event rate and the data taking time for the analysis during the full fill period.

The left vertical axis shows the ^{210}Po event rate and the right vertical axis shows the data taking run time in the unit of seconds.

region with $5.50m < r < 5.75m$, $z < 0.5m$; Figure 3.13 shows the plot for region with $5.75m < r < 6.00m$, $z < 0.5m$;

Unlike the stable ^{210}Po level in all regions in the partial fill period, ^{210}Po event rate in inner regions (away from the AV) and the outside regions (near the AV) behave differently. Figure 3.10 and 3.11 show that in the regions away from the AV, the ^{210}Po activity is dropping over time before Dec 2021 and hold a relatively stable level from Dec 2021 to April 2022. However, in the region at the top with 5.5m < z < 6.0m, the ^{210}Po event rate does not show a decreasing trend as other regions which might be due to the ^{210}Po decaying from the ^{222}Rn coming from the Neck and UI. In figure 3.10 and 3.11, as the regions are further away from the AV than those outside regions, these patterns are more associated with the ^{210}Po in the LAB rather than the AV surface. As a result, in figure 3.10 and 3.11, the efficiencies to catch the surface AV ^{210}Po event are relatively lower than the near AV regions, and their

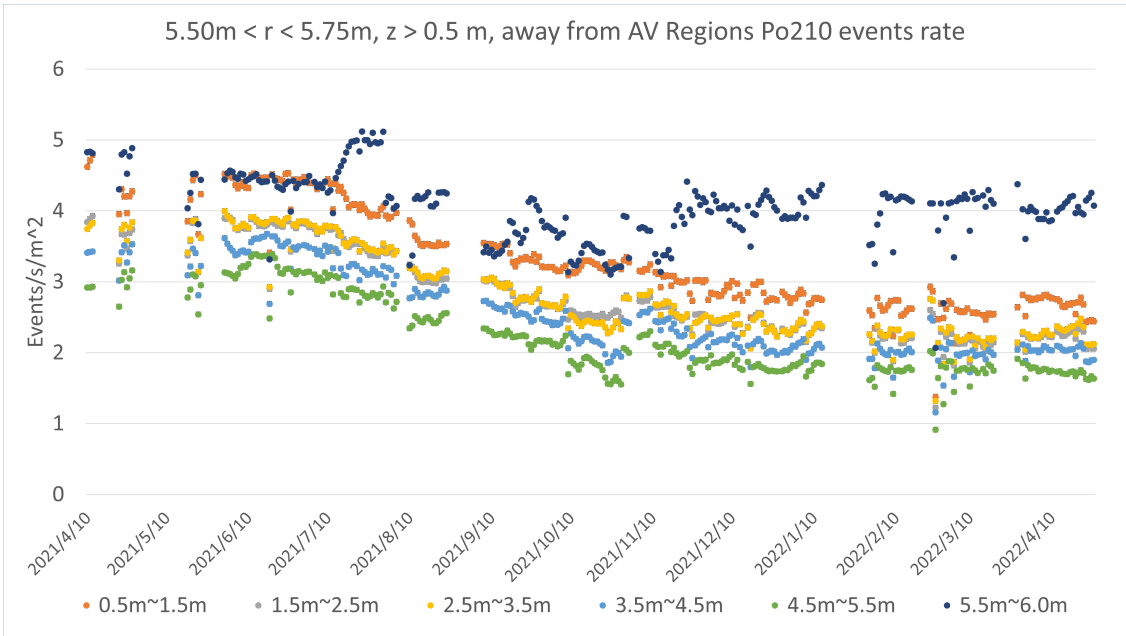

Figure 3.10: The event rate of ^{210}Po in regions with $z > 0.5m$.

The event rates are normalized based on unit time and unit area of the AV. The radius r range is $5.50m < r < 5.75m$.

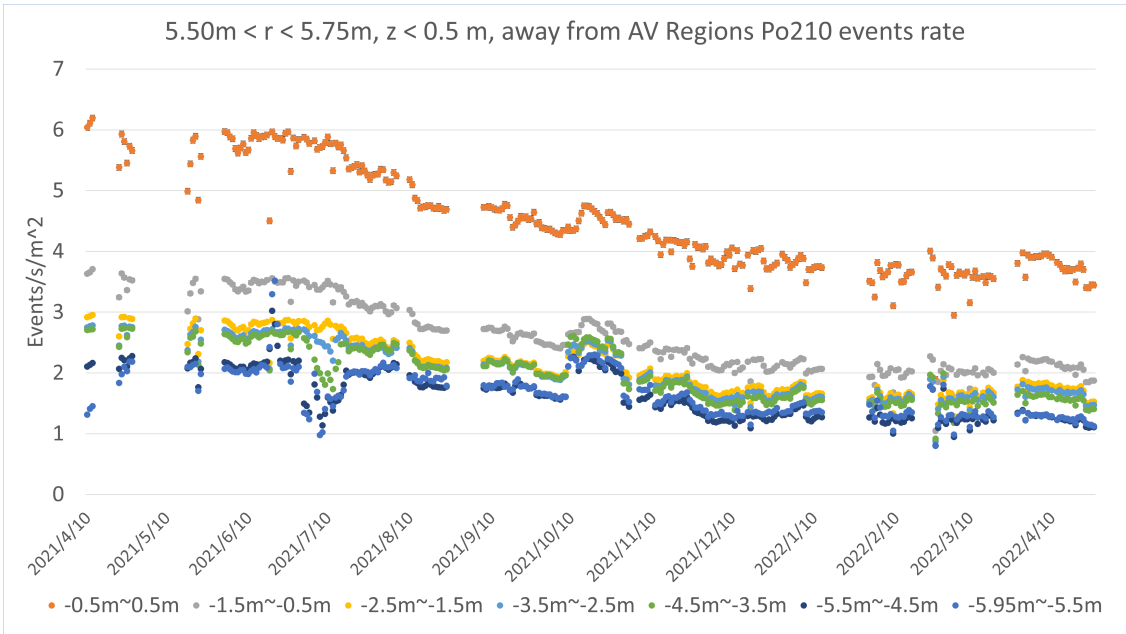

Figure 3.11: The event rates of ^{210}Po in regions with $z > 0.5m$.

The event rates are normalized based on unit time and unit area of the AV. The radius r range is $5.75m < r < 6.00m$.

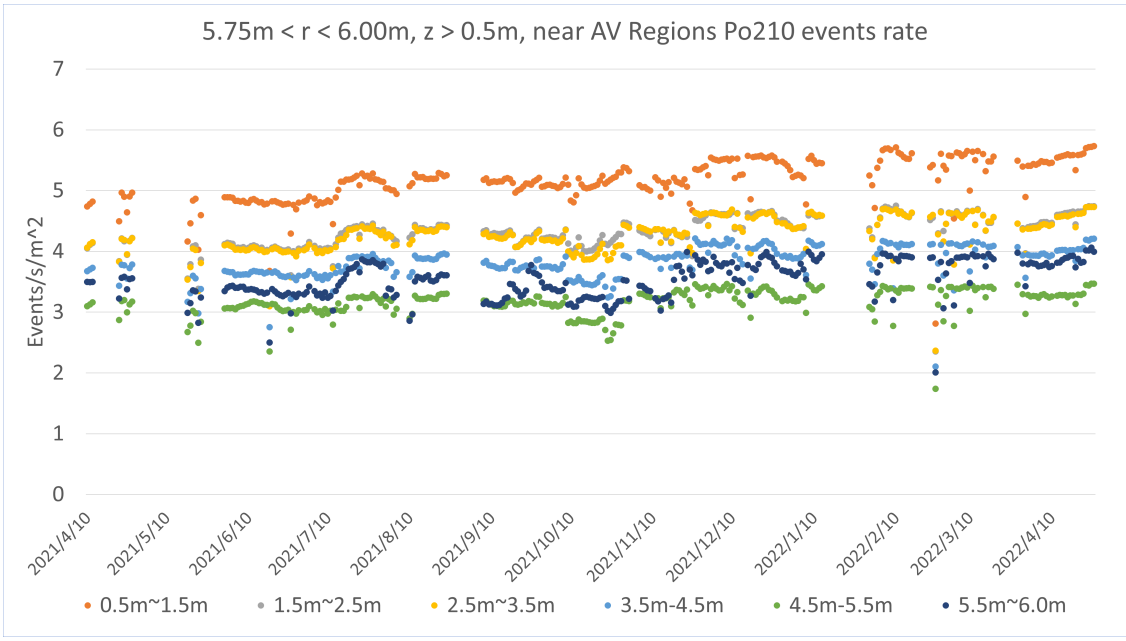

Figure 3.12: The event rates of ^{210}Po in regions with $z < 0.5m$.

The event rates are normalized based on unit time and unit area of the AV. The r range is $5.50m < r < 5.75m$.

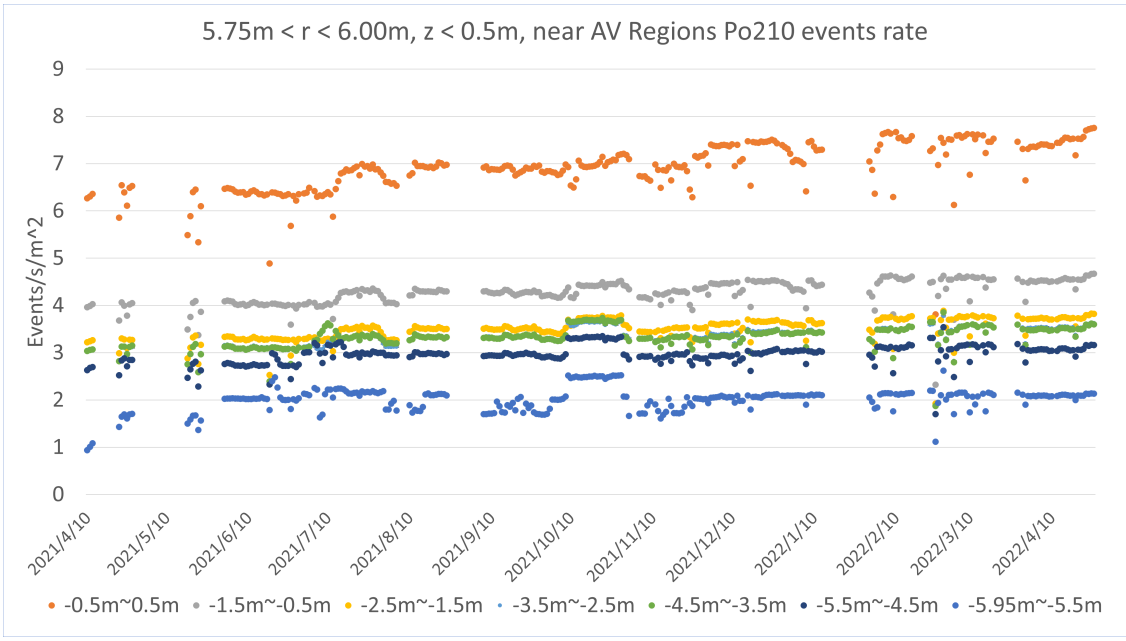

Figure 3.13: The event rates of ^{210}Po in regions with $z < 0.5m$.

The event rates are normalized based on unit time and unit area of the AV. The radius r range is $5.75m < r < 6.00m$.

efficiencies to catch the LAB ^{210}Po events are relatively higher (see table 3.2), results in the regions away from AV are more sensitive to the ^{210}Po events rate change in the LAB.

For the regions near the AV, figure 3.12 and 3.13 are showing different patterns. Since outside regions (near the AV) is in contact with the AV surface, their efficiencies to catch the surface AV ^{210}Po events are relatively higher (see table 3.2). Thus the figure 3.12 and 3.13 provide a better representation of the pattern of ^{210}Po from the AV surface. The ^{210}Po event rate is found to be gradually increasing over time.

In terms of the spatial pattern of the sub-regions, patterns similar to the partial fill period are found. From figure 3.10 and 3.12, for the regions above the equator, the event rate is the highest in the region of 0.5m $<$ z $<$ 1.5m, and the event rate gradually decreases as the z position of the region increase. The result is consistent with the observation of the distribution plot figure 3.4. The one exception is in region 5.5m $<$ z $<$ 6.0m region in figure 3.7. The event rate of this region is not the lowest. Some of the ^{210}Po in this region may come from the ^{222}Rn in the cover gas rather than the surface AV. Figure 3.11 and 3.13 reveal that the event rate is highest at the equator and gradually decreases as moving down in the z-direction.

3.6 Discussion

3.6.1 ^{210}Po spacial distribution

The spatial distribution of ^{210}Po events near the surface AV shows that the events are concentrated in several regions:

1. The surface AV

   ^{210}Po events are concentrated near the edge of AV, indicating the origin of the events as expected.

2. The equator of the detector

Near the equator of the detector where the belly plates are located, the ^{210}Po events rate is higher. For the regions above and below the equator, it is found the further away from equator, the lower the ^{210}Po events rate. Since the ropes wrap around the belly plates, the background from the rope may have contributed to the ^{210}Po event rate.

3. The top of the detector

   As the top of the detector is connected to the neck and the cover gas. ^{222}Rn and its ^{210}Po daughter from the cover gas may move to the detector and make the expected surface AV activity in the top region to be higher than the actual value.

3.6.2 ^{210}Po Time Variation

The overall time variation is small, and it is not strongly related to the detector activities because they come from a stable source (^{210}Pb deposit on the AV surface) which is about 22 years half-life. During the partial fill period, as shown in figure 3.7 and 3.8, the event rate is holding at a relatively constant value. However, for the full fill period, different regions have different results. For the inside regions ($5.50m < r < 5.75m$), the event rate was decreasing over time at a relatively fast rate; for the outside regions ($5.75m < r < 6.00m$) the event rate is increasing over time at a relatively slow rate. One possible explanation for the ^{210}Po rate increase is that ^{210}Pb from in the U chain backgrounds in the detector deposits on the AV surface at a rate faster than the rate of AV-surface ^{210}Pb decays.

3.6.3 Surface AV Po-210 Calculation

As for the expected amount of ^{210}Pb to be leached into the detector from the surface of AV, the calculation can be done with the average ^{210}Po events in the full-fill period. In the outside regions during the full fill period, the average event rate in the whole detector can be seen in figure 3.14

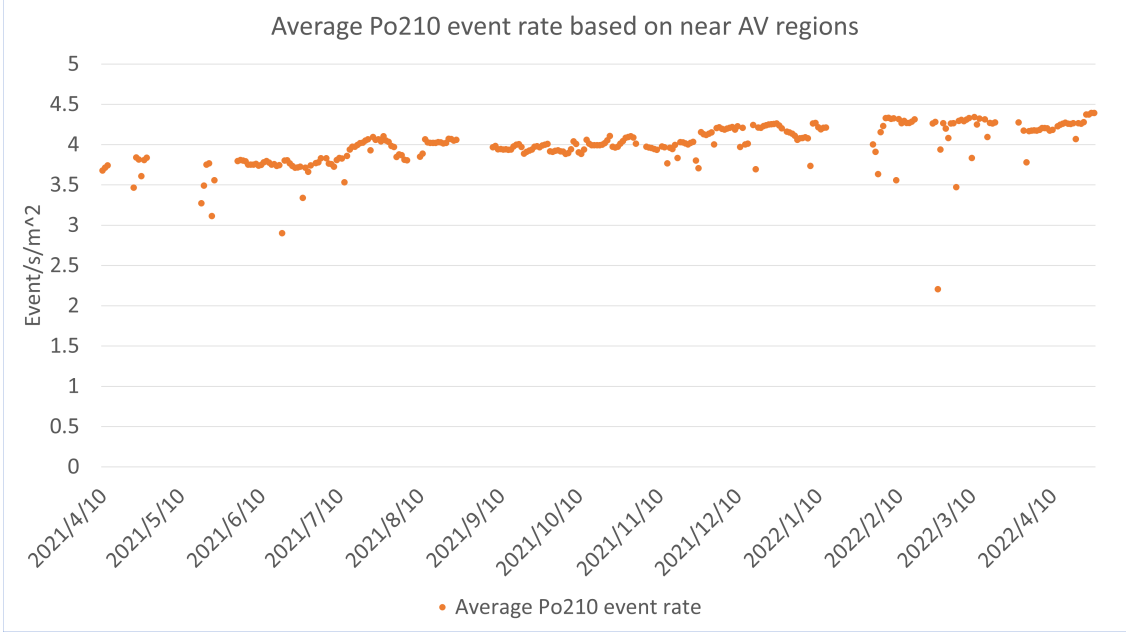

Figure 3.14: The average event rate of ^{210}Po in all regions.
The event rates are normalized based on unit time and unit area of the AV. The radius range is $5.75m < r < 6.00m$.

$$A = A_{ave} \times S \tag{3.3}$$

From the Figure 3.14, the average ^{210}Po activity is $4s^{-1}m^{-2}$. The ^{210}Po activity over the entire detector volume can be calculated using the equation 3.3. In the equation 3.3, A is the total ^{210}Po activity, A_{ave} is the average ^{210}Po activity and S is the surface area of the AV inner side (S = $450.84m^2$). The result is A = 1803.38 s^{-1}

$$A = \lambda N \tag{3.4}$$

$$N_A = \frac{\lambda_B N_B}{\lambda_A} \tag{3.5}$$

Equation 3.4 is the radioactive decay formula, where A is the activity of some element, λ is its decay constant and N is the number of atoms of the element. There are about

3.12×10^{10} ^{210}Po atoms on the surface AV by using the equation 3.4. As the ^{210}Pb and ^{210}Po have been present for a long time and ^{210}Pb have a way longer half-life than ^{210}Po, the secular equilibrium of the two elements can be assumed. Thus, using the secular equilibrium equation shown in the equation 3.5, the ^{210}Pb atoms deposited on the AV can be calculated. In equation 3.5, N_A is the number of ^{210}Pb atoms and λ_A is its decay constant. While N_B is the number of ^{210}Po atoms and λ_B is its decay constant. As a result, the estimated number of ^{210}Pb atoms on the AV surface is 1.84×10^{12}. Since the rate of ^{210}Pb to leach from acrylic to LAB is 1.4×10^{-4} per day. The amount of ^{210}Pb leached into LAB will be 2.57×10^{7} atoms per day.

It is found that the expected surface AV ^{210}Po activity is increasing during the partial fill period. On the one hand, this change may be caused by the potential ^{210}Pb increase on the surface of AV. A possible source of ^{210}Pb is the contamination in the U decay chain in the detector, bringing additional ^{210}Pb atoms to the AV surface. On the other hand, the increased AV ^{210}Po activity may be influenced by other ^{210}Po sources, which means if U chain contamination brings ^{210}Po to the detector, the cut efficiency from the MC simulation needs to be adjusted accordingly to make a precise estimation of the surface ^{210}Po activity.

3.6.4 Po-210 as Background to Solar Neutrino Search

Solar neutrinos search is one of the physics goals of SNO+. Figure 1.4 shows the part of the expected SNO+ data spectrum from solar neutrinos. In the plot, ^{210}Po events have an energy peak at about 0.5 MeV, which is in the region of interest of many solar neutrinos. Due to its high event rate, ^{210}Po events can cover up the signal of solar neutrinos. For example, as shown in figure 1.4, ^{7}Be neutrino events have an energy range close to ^{210}Po events, which makes the ^{210}Po events cover almost all the ^{7}Be spectrum and increase the difficulty of the detection. For the detection of solar neutrinos, since the ^{210}Po events cover part of their spectrum, the detection of those neutrinos events is challenging. Therefore, for the current level of ^{210}Po rate in the detector, the search for solar neutrinos still is a challenging task.

As the surface AV ^{210}Pb deposit is the main source of ^{210}Po in the detector, reducing the amount of ^{210}Pb deposit can help to achieve the physics goal of solar neutrino search.

Chapter 4

Gas Radon Assay

^{222}Rn is a radioactive gas in the mine environment. It is a noble gas with a 3.86 days half-life. Since ^{222}Rn can break the secular equilibrium of the ^{238}U decay chain and decay to ^{214}Bi, it is an important background to SNO+. In the daughters of ^{222}Rn, the most important background for SNO+ is the ^{214}Bi, which can produce high energy γs in the ROI of $0\nu\beta\beta$ search.

The ^{222}Rn activity in the underground air at SNOLAB is about 100 Bq/m^3 (50 Rn atoms /cm^3) [26]. If the mine air reaches equilibrium with the water/LAB in the detector, the background level will be a factor of 10^6 more than the tolerable level [26]. Thus, SNO+ has taken considerable precautions in the design and construction to prevent the leakage of ^{222}Rn into the detector. For example, all components of the experiment are selected for low radon diffusion and emanation. There is a "cover gas" on top of the detector, consisting of nitrogen [26]. Assays are done to determine the ^{222}Rn concentration, this will be discussed in chapter 4.5.

Assays are performed to monitor the ^{222}Rn background levels in various parts of the experiment; gas, water, and LAB. They are carried out using the gas Radon board and water assay plant. Chapters 4 and 5 will discuss the gas and water assays in detail respectively.

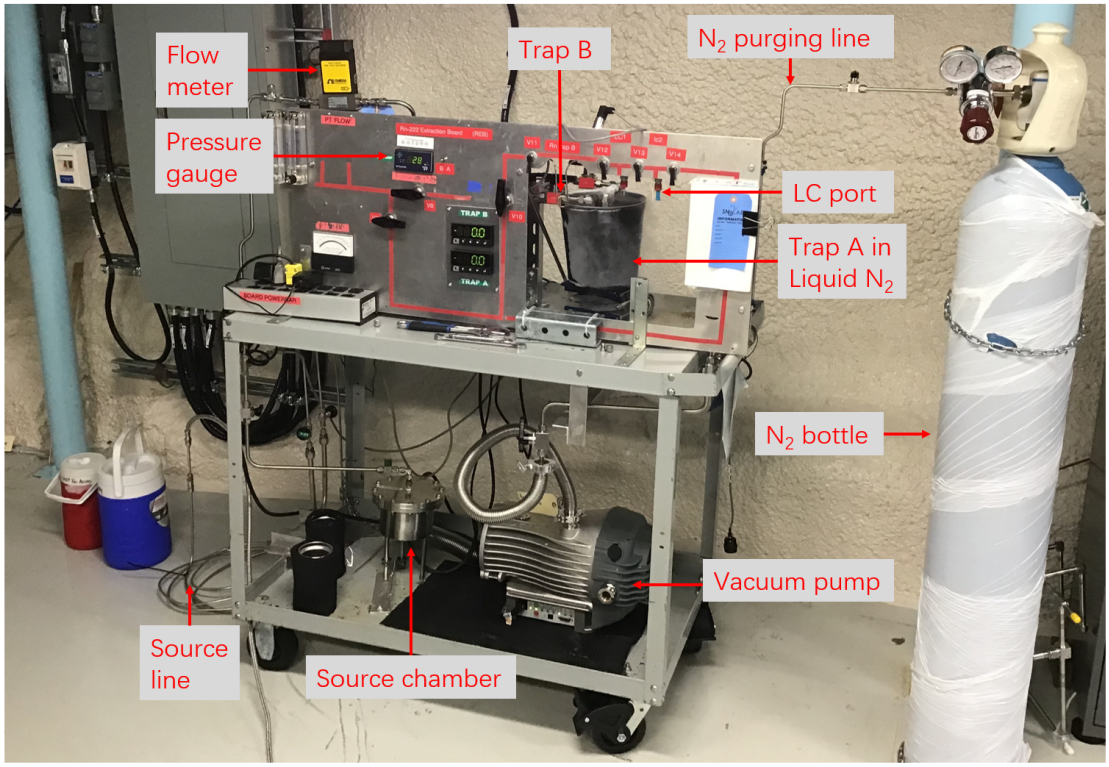

Figure 4.1: Picture of the mobile Radon gas assay board with important parts labeled.

4.1 The Mobile Radon Gas Assay Board

To monitor the Radon gas background level of a certain gas volume, the mobile gas Radon board has been built to carry out the Radon gas assays. Its picture is shown in figure 4.1. And the flow diagram of the Radon gas board is shown in figure 4.2.

The mobile Radon board was constructed during the SNO experiment. In the beginning, the board was used for the emanation measurement to determine material with low emanation. The board was leak checked during SNO+, the result shows the baseline leak rate was at 10^{-8} mbar 1/s [30]. The board was built on a mobile metal cart to allow it to access different assay locations in the lab. The board lines were made with 3/8" inches of stainless steel tube with Swagelok connections and gate valves [30].

The main goal of a gas assay is to extract the ^{222}Rn gas from the source. In a gas assay, a gas source will flow through the board, the ^{222}Rn gas will stay in a cooled trap and other gas components are removed by a pump.

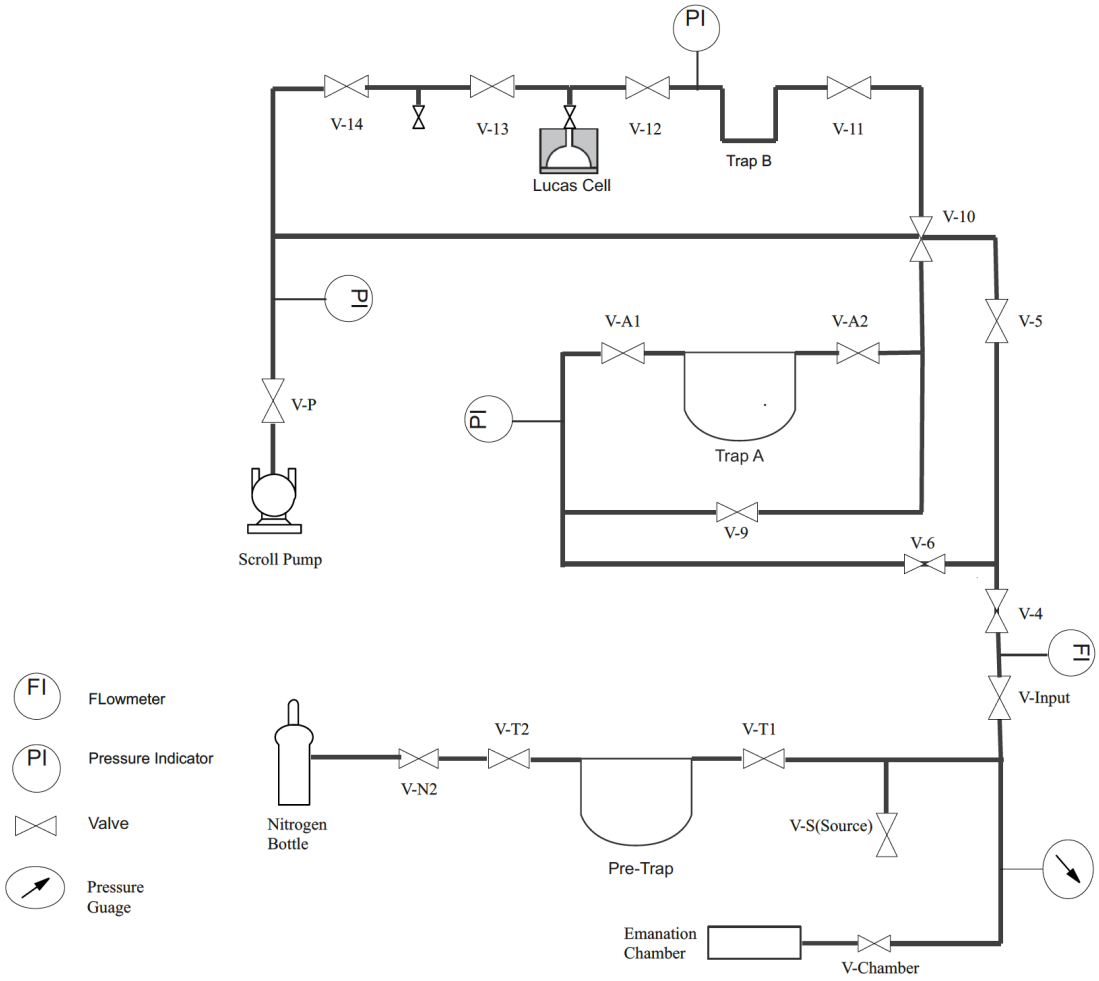

Figure 4.2: Flow diagram of the mobile Radon gas assay board [30].

The mobile Radon gas assay board mainly consists of a vacuum pump, a primary Radon trap, a secondary Radon trap, a Radon pre-trap, 2 Lucas' cell (LC) ports, some pressure meters and flow meters, a source chamber, and an ice bath.

The **vacuum pump** is used to pull vacuum on the whole board. It can be used to clean the board during purging and used to pull gas from the source during an assay.

The **Radon traps** have bronze wires inside to increase the surface area of contact with the gas that flows through it. They are used to trap radon atoms when submerged in Liquid nitrogen (temperature: about –90°C) as Radon freezes at the temperature of −71 °C.

The **LC ports** are used to attach a LC to collect the Radon atoms in the assay.

The **Pressure meters** are used to look at the board vacuum level near the pump; Trap A and Trap B pressure. The **Flow meter** monitors the flow rate of the gas inside the board.

The **chamber** can be used to measure Radon emanation of a solid source.

We use **Lucas Cells (LC)** to collect the Radon atoms from assays. The LC is a container mainly made of acrylic. The inner side is coated with a ZnS scintillating layer. As Radon decays and releases alpha particles, the alpha particles will interact with the ZnS and release a photon. The photon can then be detected by a PMT in the DAQ to calculate the number of decay alphas.

The **Ice bath** is used in some assays like UI assays and mine air efficiency assays. The input line is cooled by the ice bath. The ice bath is made by mixing ice, ultra pure water (UPW) and salt. The temperature is usually at about -10°C. It helps to remove water vapour, and LAB vapour and improves the assay efficiency.

4.2 The Radon gas Assay Procedure

The Radon gas assay procedure is shown in appendix A. The main steps are the following:

1. Cleaning the Board: Pumping and Purging

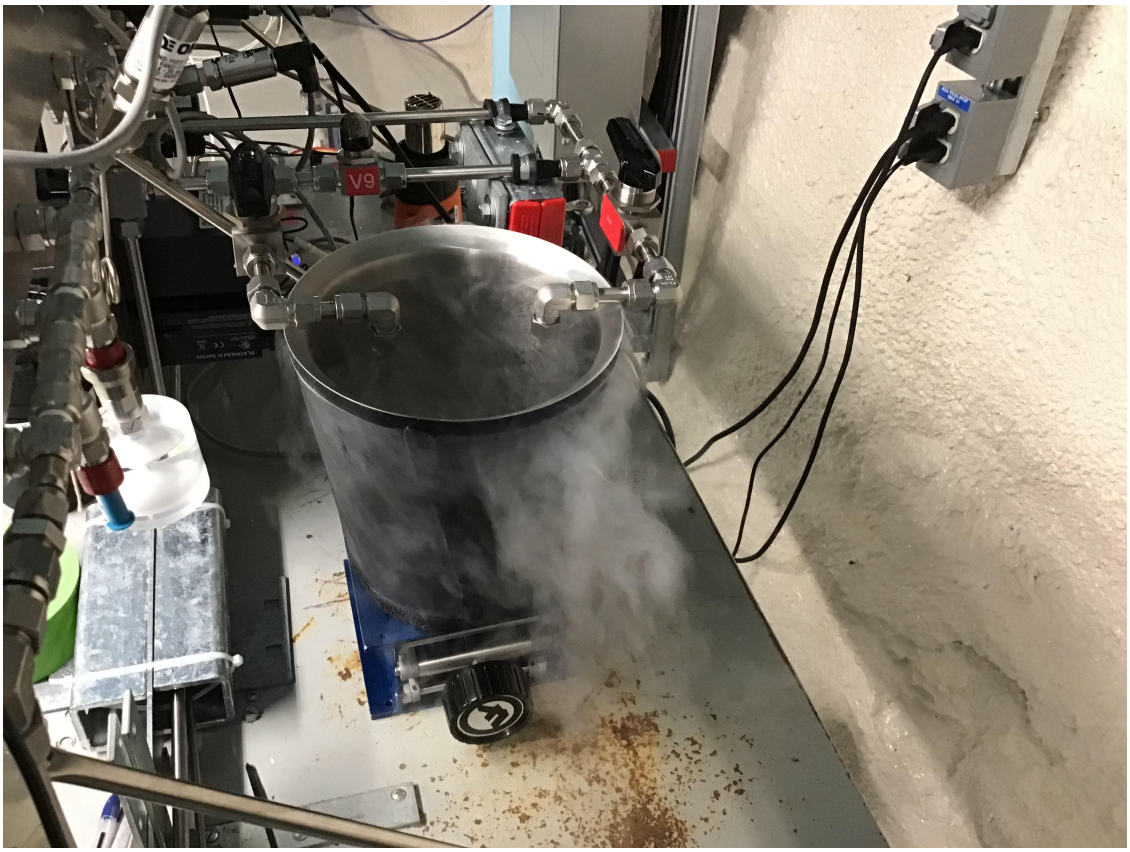

Figure 4.3: The Radon board with trap A submerged in liquid nitrogen.

The traps are baked using a heat gun to remove the remaining Rn atoms, then the board and LC are purged with nitrogen and pumped into a vacuum, and the line to the assay source can be pumped and purged using the gas from the source.

2. The Main Assay

   During the assay, trap A is cooled with liquid nitrogen, then Radon atoms in the source are frozen into the trap and the remaining gas can be removed by the vacuum pump.

3. The Transfer of Radon Atoms

   After the assay is finished, the Rn atoms cooled in the primary trap can be transferred to the secondary trap and then the LC. The transfer involves baking the traps with a heat gun to release the Rn atoms

4. The LC Counting

The LC is placed on a PMT counter in the surface clean lab. The counting usually lasts 7 to 14 days. When the Radon gas undergoes α decay, 3 α particles are released and trigger scintillation light on the ZnS coating in the inner surface of the LC cell.

4.3 The Assay and Rn Calculation

The PMT counter and DAQ system output the number of alphas counted in the sample during the counting time, then the Rn concentration in the sample can be calculated. To derive the equation to calculate the assay result, we start from the radioactive decay formula given in equation 4.1

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda N \tag{4.1}$$

Where N is the number of Rn atoms, t is the time, λ is the decay constant of ^{222}Rn. Integrating the equation 4.1 over time gives the equation 4.2

$$N = N_1 e^{-\lambda t_{count}} \tag{4.2}$$

Where N_1 is the number of ^{222}Rn when counting started and t_{count} is the LC counting time. For the case of the alpha counter data acquisition system (DAQ), since the PMT has an efficiency of collecting the α released in the ^{222}Rn decay, the equation 4.1 can be expressed as equation 4.3

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\lambda \varepsilon_{count} N_1 e^{-\lambda t_{count}} + B_{LC} \tag{4.3}$$

Where ε_{count} is the counting efficiency of the PMT to catch the α; B_{LC} is the LC background activity. Integrating equation 4.3 over time gives the total number of events detected by the PMT counter as shown in equation 4.4.

$$N = N_1 \varepsilon_{count}(1 - e^{-\lambda t_{count}}) + B_{LC} t_{count} \tag{4.4}$$

Since the assays are usually done underground and the DAQ system is located in the surface clean lab, there is a delay time t_{delay}, which is the time difference between the assay finish time and the counting started time. The equation 4.5 shows the relation between the number of Rn atoms on the LC at the end of the assay (N_0) and the start of counting (N_1).

$$N_1 = N_0 e^{-\lambda t_{delay}} \tag{4.5}$$

Combining the equations above and replacing N_0 with R to represent the number of Rn atoms in the sample gives the main equation of the assay calculation. The result is shown in equation 4.6.

$$R = \frac{N_{counts} - B_{lc} t_{count}}{\varepsilon_{global}(e^{-\lambda t_{delay}})(1 - e^{-\lambda t_{count}})} - R_{bg}, \tag{4.6}$$

N_{counts} is the number of α counts from the DAQ system; ε_{global} is the over efficiency; R_{bg} is the number of Rn atoms background in the board during the assay time.

In terms of the efficiency ε_{global}, it is calculated based on the product of several efficiencies as shown in equation 4.7.

$$\varepsilon_{global} = \varepsilon_{trap} \times \varepsilon_{transfer} \times \varepsilon_{count} \tag{4.7}$$

The value of those efficiencies are: Trapping efficiency ($\varepsilon_{trap} = 100.5 \pm 2.3\%$); Transfer efficiency ($\varepsilon_{transfer} = 64 \pm 2.0\%$); Counting efficiency ($\varepsilon_{count} = 3 \times 74 \pm 2.1\%$);

4.4 Board Background and Efficiency Measurement

To determine the background level of the board and calculate for R_{bg}, background assays are performed. In a background assay, the process is similar to the actual assay, the difference

date	Assay Time(min)	Efficiency
20/04/2021	1.5	153%
16/04/2021	5.5	119%
07/10/2019	10	92.00%
07/07/2021	30	36.30%
26/07/2021	30	34.50%
06/08/2021	30	44.80%
Averaged	30	38.50%
07/07/2021	45	23.85%
26/07/2021	60	9.23%

Table 4.1: Board efficiency with different assay times with the flow rate of 1L/min.

is that the valve to the source will stay closed, also, the board and the line will remain in a vacuum during the assay [30].

In terms of the efficiency of the board to trap Rn atoms, it is found that the assay time will affect the efficiency of the board. The longer the assay, the lower the efficiency. To measure the efficiency of the board, a source with known activity can be assayed. In this case, mine air is taken as an assay source. 1 L of mine air contains about 6.4×10^4 Rn atoms. Since the Rn trapping efficiency of the traps is reduced by the over-pressuring, moisture and CO_2 need to be removed from mine air. Thus, drierite and NaOH columns are connected before the entry of the board to absorb the moisture and CO_2. To better remove the water vapour in the mine air, an ice bath of temperature -10^{o}C is used. After the connection of the drierite and NaOH columns, the metal line is submerged in the ice bath.

To determine the relationship between the board efficiencies and the assay duration, various efficiency measurement assays with different assay times were performed. The flow rates of the assays were 1L/min. As a result, The efficiencies and assay time are shown in table 4.1 and the data points are plotted in figure 4.4 [30].

The pattern shown in figure 4.4 may be due to the warming up of trap A during an assay. The gas flowing through the trap may cause its temperature to raise and Rn atoms will have a higher chance to escape. The shown efficiencies are the global efficiency of the board which includes the LC counting efficiency. As the Rn decay produces 3 alphas, the

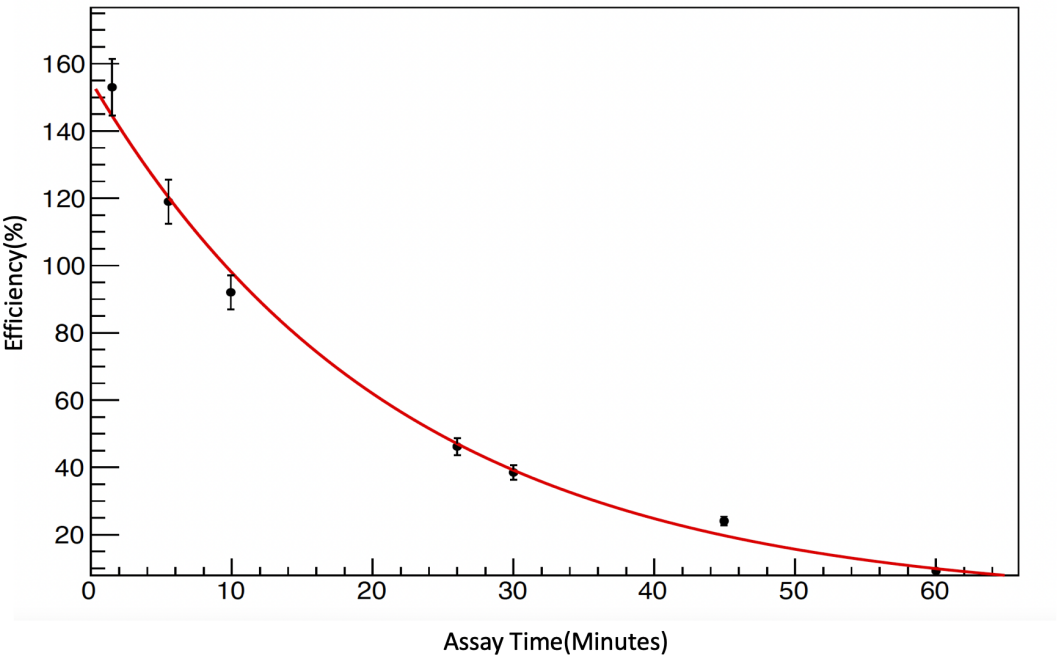

Figure 4.4: The trapping efficiencies of the board at different assay duration [30].

The efficiencies drop exponentially as the assay time duration increase. The efficiency can be more than 100% as the Rn decay produces 3 alphas.

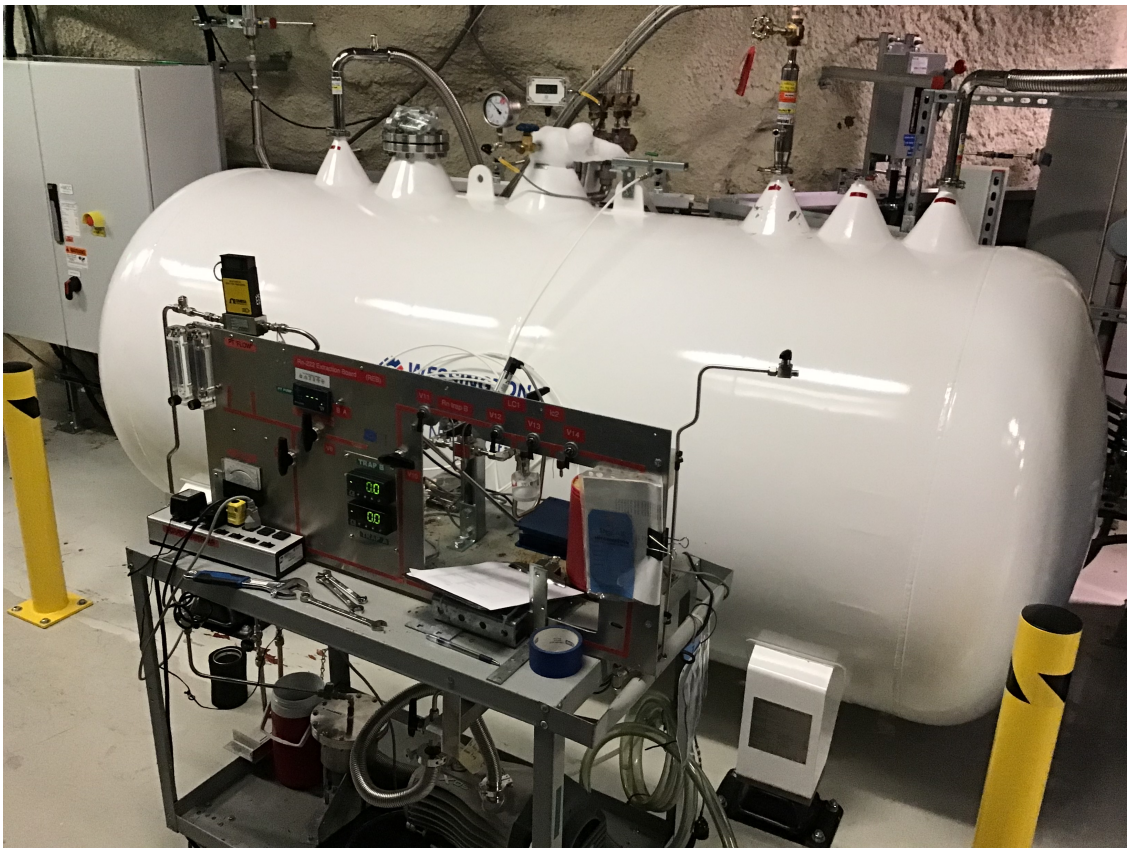

Figure 4.5: Underground LN_2 Plant.

efficiency may be greater than 100%. As the figure 4.4 shows, longer assay times give more statistics and less efficiency. To balance efficiency and statistics, 30 min duration is chosen for most assays.

4.5 Liquid N_2 Plant and International Dewar Assays

In early 2022, there was a Liquid nitrogen (LN_2) plant built underground in SNOLAB. Figure 4.5 is the picture of the LN_2 plant during an assay. The plant produces liquid nitrogen underground for all experiments including SNO+. This reduces the demand for shipping liquid nitrogen dewars underground from the surface and saves operation costs of the experiments.

Date	April 25, 2022	May 11, 2022	May 13, 2022
Assay Condition	Board	Board	Board + Line
LC ID	LC27	LC21	L17
B_{LC} (up)	5.33	2.6	5.47
t_{assay} (minutes)	30	30	30
Alphas	53	39	82
t_{delay} (hours)	2	5	5
$t_{counting}$ (days)	9.61	7.83	5.13
R_{bcg} (Rn/sample)	1.51 ± 0.08	18 ± 1	64.3 ± 3.53

Table 4.2: Board background levels under vacuum.

The May 13 assay result with the connection line is used as the background of the international dewar and LN_2 assays.

One possible use of LN_2 underground is for filling the underground international dewar. And SNO+ uses nitrogen from the international dewar. Thus, it is important to make sure the Rn level in the international and the LN_2 plant is ideal. Several Rn assays were performed for this task.

To compare the result with the international dewar Radon level, assays were done on the international dewar and the LN_2 plant respectively. Meanwhile, the background assays were done to understand the board's background level. The background assay results are shown in table 4.2.

Table 4.3 shows the assay results for the international dewar. The level of Radon in international is about 10^{-4} compared to mine air.

Table 4.4 shows the assay result for the LN_2 plant. The level of Radon is about 10^{-4} compared to mine air.

As the assay results show, the international dewar and the LN_2 plant have similar Rn levels of about 10^{-4} reduction factor compared to mine air. Thus using the LN_2 from the plant is safe and will not increase the Rn level into SNO+.

Date	May 13, 2022	May 20, 2022	May 20, 2022
LC ID	LC27	LC17	L27
B_{LC} (cpd)	5.33	5.47	5.33
t_{assay} (minutes)	30	30	30
Alphas	152	87	116
t_{delay} (hours)	2	4	2
ϵ_{global}	0.385	0.385	0.385
$t_{counting}$ (days)	6.54	4.95	4.95
R_{bcg} (Rn/sample)	64.3 ± 3.53	64.3 ± 3.53	64.3 ± 3.53
R_{IN} (Rn/sample)	380.13 ± 21	206.2 ± 9	334.3 ± 18
C [rel. to Mine Air]	1.98×10^{-4}	1.07×10^{-4}	1.74×10^{-4}

Table 4.3: International Dewar assays results.

It shows a consistent 10^{-4} Rn reduction factor compared with the mine air.

Date	April 21, 2022	April 27, 2022	May 05, 2022	May 17, 2022
LC ID	LC23	LC23	LC13	LC13
B_{LC} (cpd)	5.68	5.68	3.81	3.81
t_{assay} (minutes)	30	30	30	30
Alphas	120	157	145	139
t_{delay} (hours)	3	2.5	4	3
ϵ_{global}	0.385	0.385	0.385	0.385
$t_{counting}$ (days)	6.08	11.61	8.075	8
R_{bcg} (Rn/sample)	64.3 ± 3.53	64.3 ± 3.53	64.3 ± 3.53	64.3 ± 3.53
R_{LN_2} (Rn/sample)	275.2 ± 15.1	210 ± 11.5	333.3 ± 18.3	312.1 ± 17.1
C [rel. to Mine Air]	1.43×10^{-4}	$1.09 \times 10–4$	$1.74 \times 10–4$	$1.63 \times 10–4$

Table 4.4: Liquid nitrogen plant assays results.

It shows a consistent 10^{-4} Rn reduction level compared to mine air. The reduction factor is shown to be similar to the international dewar.

Chapter 5

Water Rn Assay

5.1 Rn in the External Water Cavity

As discussed in previous chapters, SNO+ consists of 780 tonnes of LAB inside the AV. An array of about 10,000 photomultiplier tubes are placed on an approximately 18 m diameter stainless-steel geodesic support structure to detect the light signals from the detector volume. The volume between the AV and PSUP is filled with 1700 tonnes of water to shield outside backgrounds. Outside the PSUP, there is an additional 5700 tonnes of water shield. The two shielding regions are separated by a nearly impermeable water seal [26].

^{214}Bi from the ^{238}U decay chain is one important background for the search of $0\nu\beta\beta$. The high energy γ released by the backgrounds in the external water cavity has a chance to enter the detector and become background to the $0\nu\beta\beta$ signal. Thus it is very important for SNO+ to monitor and control the level of ^{238}U decay chain backgrounds in the external cavity water.

For the external water, two assay techniques were developed to measure the concentration of ^{226}Ra from ^{238}U decay chain [27] [28]. However, knowledge of the concentration of ^{226}Ra is not sufficient to understand the ^{238}U decay chain background level. This is because ^{222}Rn, a noble gas with 3.86 days half-life is naturally present in the mine environment, and it may

Region	Atoms Rn/L	mBq Rn/m^3	g U/g water
H_2O (I)	3	6	4.5×10^{-13}
H_2O (O)	7	14	1.1×10^{-12}

Table 5.1: Target ^{222}Ra concentration in the water cavity.

The region between the AV and PSUP is indicated as H_2O (I), and the region between PSUP and cavity wall is indicated as H_2O (O).

leak into the system and break the equilibrium between ^{226}Ra and ^{214}Bi. Therefore, a good understanding of the level of ^{222}Rn in the external water is required to understand the level of ^{214}Bi in the external water. To achieve the physics goals, SNO+ has determined the target concentration of ^{222}Rn in the external water to be as shown in table 5.1 [26].

5.2 The Water Assay Plant

The SNO+ experiment has a water assay system to monitor the Radon background level in the cavity water. Picture 5.1 shows part of the water assay plant. The assay operates by pumping water out of the cavity to the degasser and collecting Rn from the water vapour using liquid nitrogen traps.

The water assay plant is mainly composed of the following parts: The two **water pumps** are used to establish a water loop that extracts water from the cavity and sends it back to the cavity through the assay system. The **gas pump** is connected to the assay system and pulls a vacuum on the traps. There is a **Vlad trap** located before the gas enters the gas pump. When Vlad trap is filled with LN_2, it will freeze water vapour and prevent it from entering the pump. The **Degasser** is used to turn the input cavity water into gas. The **refrigerant column (FTS)** will cool the input gas to around –50°C. Any water vapour is frozen in the FTS while Radon atoms are allowed to pass through. The **Radon traps** are similar to the gas Radon board. But the water assay system is not mobile as it is an integral part of the water system. It has a primary trap and a secondary trap. The primary trap can trap Radon atoms during assay when it is submerged in LN_2. After the assay, Radon

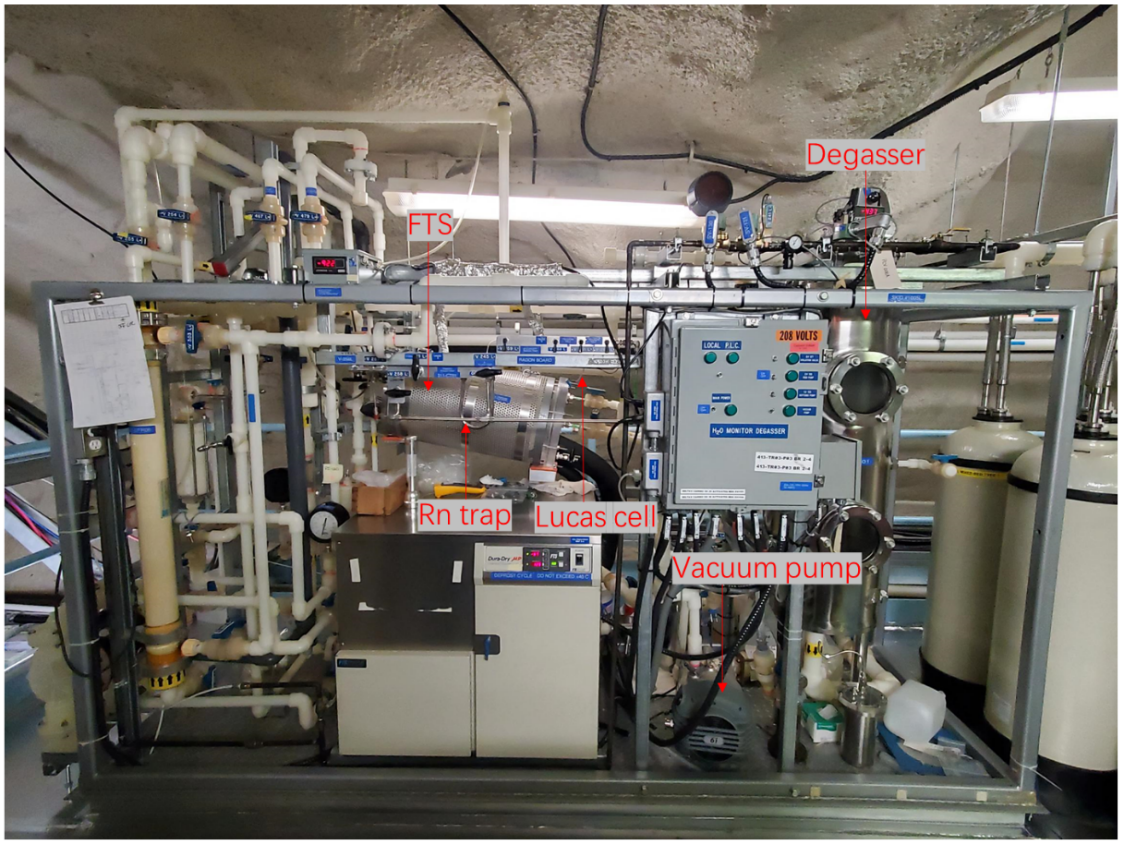

Figure 5.1: Part of water assay plant on the second floor.

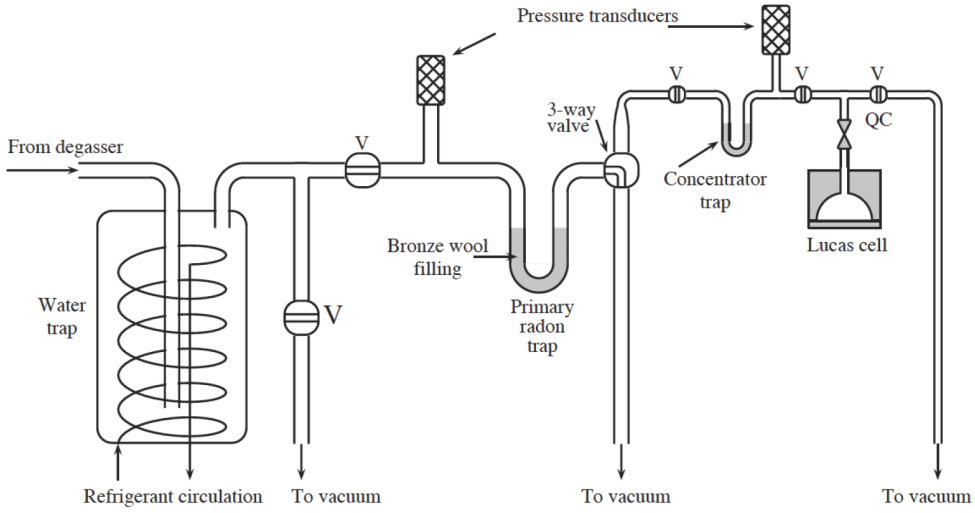

Figure 5.2: Schematic diagram of water assay system.
Source: SNO+ collaboration

atoms are transferred from the primary trap to the secondary trap and then the **LC** at the **LC port**.

The water assay can be done at various locations in the cavity. Figure 5.3 shows the port's location and the valve number. Figure 5.2 is showing the flow diagram of the water assay plant.

5.3 The Water Assay Procedure

The water assay procedure is similar to the gas assay procedure, however, they differ in the preparation work. The main steps are the following and the complete procedure is shown in Appendix B.

1. Pumping and purging of the system

   Unlike the gas assay, the water assay does not require N_2 gas purging each time. For the pumping, the Vlad trap is cooled with LN_2 to prevent any water from getting into the vacuum pump. The parts being pumped includes the assay LN_2 traps, the FTS,

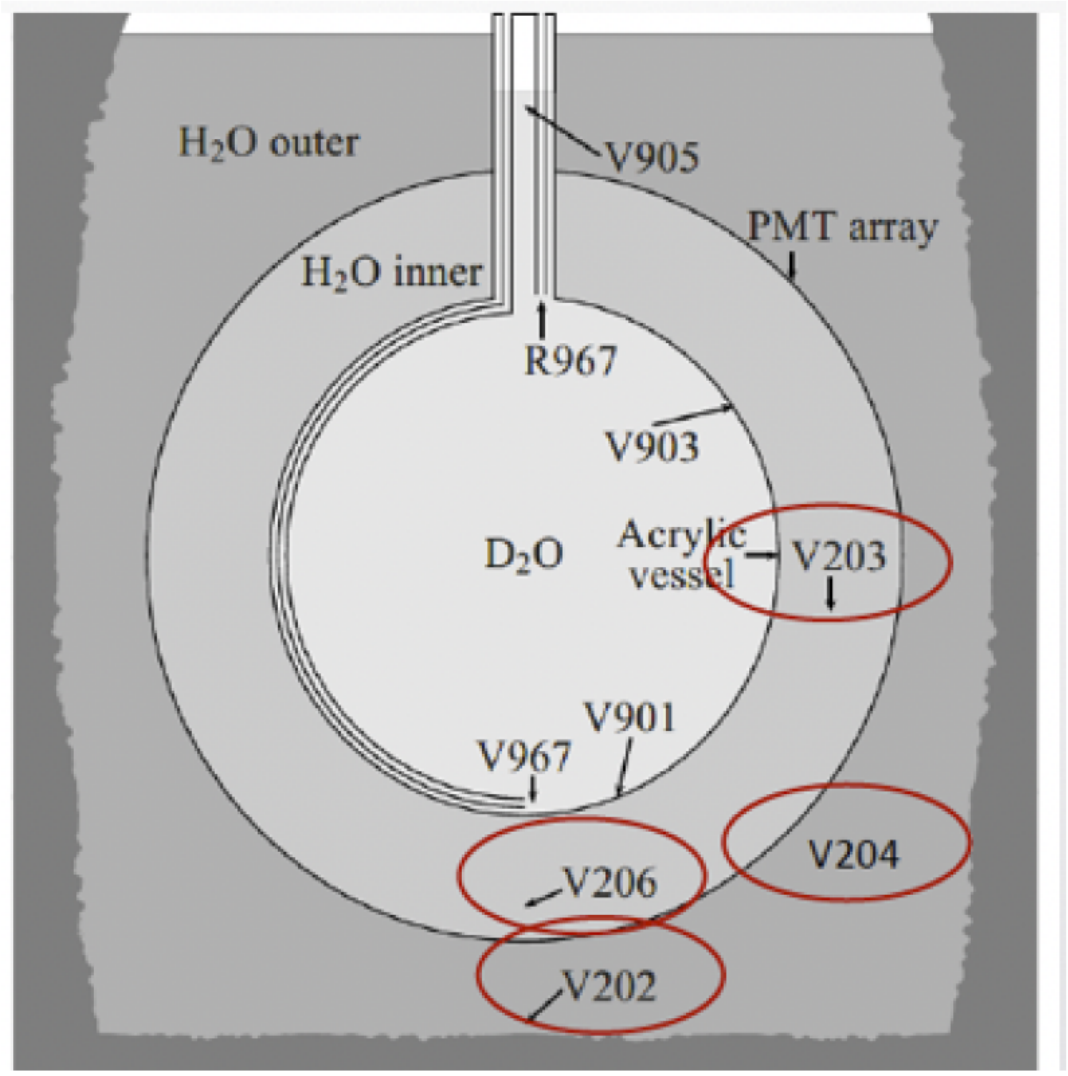

Figure 5.3: Possible cavity assay locations and the corresponding port numbers.

Source: SNO+ collaboration

and the line to the degasser. The primary and secondary LN_2 traps are baked with the heat gun.

2. Setting up the water flow

   Once the traps and line are clean and ready, water flow can be established. The valve to the cavity is opened and two water pumps work together, where one pump feeds water to the degasser while the other pump returns water to the cavity.

3. The main assay

   Once the water level in the degasser and flow is stable, the primary trap can be submerged in LN_2 and the main assay can begin. During the assay, the water level in the degasser, and water flow rate are kept constant carefully.

4. The transfer of collected Rn atoms

   Similar to the gas assay, once the assay is finished, the Rn atoms in the primary trap are transferred to the secondary trap and then the LC.

5.4 The Water Assay Calculation

The same LC and counting system are used in the gas and water assays. After the LC counting is completed, the Radon concentration C can be determined by the equation 5.1.

$$C = \frac{1}{\varepsilon_{degas} F} \times \left[\frac{(N_{coounts} - B_{Lucas} t_{count})\lambda}{\varepsilon(1 - e^{-\lambda t_{assay}}) e^{-\lambda t_{delay}} (1 - e^{-\lambda t_{count}})} - R_{back} \right] \tag{5.1}$$

$\varepsilon_{degas} = 0.6$ is the degasser efficiency; F is the flow rate, which is usually about 18L/min; N_{count} is the number of counts of the sample in the PMT counter; B_{Lucas} is the Lucas cell background; t_{count} is the LC counting time; λ is the ^{222}Rn decay constant; $\varepsilon = \varepsilon_{trap}\varepsilon_{transfer}\varepsilon_{count}$ is the overall efficiency given by the product of the trapping efficiency, transfer efficiency and counting efficiency. They are given as: $\varepsilon_{trap} = 1$, $\varepsilon_{transfer} = 1$,

Date	2020/11/18	2021/04/20	2021/07/01	2021/07/26	2022/02/08	2022/10/25
LC ID	L16	L17	L18	L18	L18	L18
B_{LC} (cpd)	7	6	6	6	6	6
t_{assay} (min)	45	60	45	30	60	60
Alphas	101	160	20	78	17	57
t_{delay} (days)	0.08	0.13	0.13	0.08	0.08	0.1
t_{count} (days)	6.96	7.34	0.95	6.13	1.67	1.5
Rn atoms #	52.13	113.55	64.82	43.96	18.9	144.62

Table 5.2: Closed-loop assay results that show the background level of the water assay plant. The backgrounds of the system are shown to be at a consistently low level.

$\varepsilon_{count} = 3 \times 0.74$ (where 3 indicates there are 3 prompt αs in the decay of ^{222}Rn, each has a counting efficiency of 0.74). t_{delay} is the time difference between the assay finish time and the counting start time. R_{back} is the assay system background.

5.5 Background of Water Assay System

To understand and monitor the background level of the water assay system closed-loop assays are performed. For a closed-loop assay, the valve to the cavity will remain closed. Only one water pump is needed to establish the water flow. The water in the pipeline will form a closed-loop through the system only. Closed-loop assays are usually done with the same flow rate and assay time as the cavity assay to achieve a good representation of the background level. Table 5.2 is showing the results of some closed-loop assays.

The closed-loop assays are used to ensure the system is leak-free and ready for a cavity assay to ensure a good measurement. It is found that the water assay system background has been consistently holding at a low level for the period of this thesis.

5.6 Water Assay Results

With the water assay system and background level understood, the cavity Rn level can then be measured. Water assays were done at different port locations. Table 5.3 and 5.4 are showing the results of recent water assays.

Date	2019/5/9	2019/6/5	2019/6/20	2019/7/4	2019/7/23	2020/11/19
Assay port	V-202	V-203	V-206	V-204	V-203	V-203
LC ID	#8	#8	#8	#8	#8	L18
B_{LC} (cpd)	15.00	15.00	15.00	15.00	15.00	5.21
t_{assay} (min)	40	60	60	60	30	30
Alphas	517	375	481	513	71	267
t_{delay} (days)	0.04	0.04	0.04	0.08	0.08	0.75
t_{count} (days)	3.62	5.00	3.86	4.74	0.88	7.13
background/ sample	52.42	78.63	78.63	78.63	39.32	0.00
Mass ^{238}U/water	2.98×10^{-13}	1.04×10^{-13}	1.45×10^{-13}	1.40×10^{-13}	1.40×10^{-13}	1.07×10^{-13}

Table 5.3: (Part 1) Water assay result at different port location.

Date	2021/4/23	2021/7/27	2022/1/27	2022/2/10	2022/2/17	2022/3/15
Assay port	V-203	V-204	V-206	V-203	V-202	V-206
LC ID	L18	L17	L17	L20	L17	L17
B_{LC} (cpd)	6.00	5.40	5.40	8.14	5.40	5.40
t_{assay} (min)	45	45	60	30	60	45
Alphas	663	775	988	467	12664	2550
t_{delay} (days)	0.13	0.04	0.08	0.08	0.08	0.08
t_{count} (days)	2.24	7.50	4.25	6.67	13.85	8.76
background/ sample	0.00	22.00	151.58	16.35	32.71	24.53
Mass ^{238}U/water	4.75×10^{-13}	2.27×10^{-13}	3.15×10^{-13}	2.17×10^{-13}	2.59×10^{-12}	7.88×10^{-13}

Table 5.4: (Part 2) Water assay result at different port location

Except for the assay result for V-202, the external cavity Rn level is holding on the order of 10^{-13} in terms of g/g concentration of ^{238}U to water. V-202 is located at the bottom of the cavity, due to the temperature gradient of the cavity water, the Radon atoms at the cavity bottom are expected to stay and the influence on the experiment is limited. The SNO+ target for the background in the external cavity is shown in table 5.1. Thus, it can be concluded the assay results show the cavity background level is below target.

5.6.1 Result Uncertainty

In water and gas assays, there are many uncertainties that impact the result. The precision of the equipment is limited; therefore, the flow meter can read one digit after the decimal point and the flow rate may vary during an assay depending on the pump condition. The trap efficiency may change due to the variation of trap pressure; therefore, the composition of the assayed water source may differ and change the trap pressure.

Chapter 6

Conclusions

The SNO+ detector is a liquid scintillator neutrino detector aiming to search for the neutrino-less double beta decay ($0\nu\beta\beta$) with ^{130}Te. A clear understanding of the background is important to the success of the experiment. Among the backgrounds, the ^{214}Bi from ^{238}U decay chain is the most important. The reason is that ^{214}Bi decay falls in the region of interest of the $0\nu\beta\beta$ search. ^{214}Bi can get into the detector through the ^{222}Rn gas ingress and its decay. This thesis demonstrates two methods of evaluating the backgrounds; the first is the analysis of the ^{210}Po on the inner AV surface, and the second is the measurement to monitor Radon levels in the gas and cavity water.

A detailed study of ^{210}Po is completed in many subdivided regions in two data-taking periods (partial fill and full fill). The results indicate that the amount of ^{210}Pb leached into LAB is holding approximately constant over time. There are about 2.57×10^7 ^{210}Pb atoms leaching into the detector LAB per day.

The mobile gas Rn board is used to carry out the assays on the LN_2 plant and the international dewar. The results indicate that the Radon reduction factor of the LN_2 plant and international dewar was similar at about 10^{-4}. Therefore, using the LN_2 plant to fill the international dewar will be safe in terms of the Rn background.

The water assay plant was used to carry out the water assays on the external cavity water. As the results show, the Rn level expressed in g/g of $^{238}U/H_2O$ is below the SNO+ target level of 4.5×10^{-13} g^{238}U/gH_2O.

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Appendix A

Gas Rn Assay Procedure

Background Assay Procedure for Mobile Radon Board

Title:
Date:
Crew:

1.0 Preparation of the board for extraction

1.1 Preliminary Confirmed Closed List

V-P	Confirm Closed	
V-5	Confirm Closed	
V-4	Confirm Open	
V-input	Confirm Closed	
V-chamber (Green Valve)	Confirm Closed	
V-C1	Confirm Closed	
V-S(Source)	Confirm Closed (Needle Valve)	
V-S2	Confirm Closed(Next to needle valve)	
V-T1	Confirm Closed	
V-T2	Confirm Closed	
V-N2	Confirm Closed	
V-6	Confirm Closed	
V-9	Confirm Closed	
V-A1	Confirm Closed	
V-A2	Confirm Closed	
V-10	Confirm Closed	
V-11	Confirm Closed	
V-12	Confirm Closed	
V-13	Confirm Closed	
V-14	Confirm Closed	

2.0 Preliminary Setup

Plug in board power bar and Pump	
Turn on the Scroll Pump	
Turn on PT Flow	
Turn on PT Pump	
Turn on PT Traps	

Notes:

3.0 Pumping/Baking the Traps

3.1 Baking and pumping the Nitrogen trap:

V-P	Open	
Record Time:	hh:mm	
Ensure Pressure is below 150 mT. (Allow up to 15 minutes)		
Record Pressure on PT pump	mTorr	
Record Final Time	hh:mm	
V-5	Open	
V-4 **normally left Open**	Open	
V-S	**Confirm Closed**	
V-N2	**Confirm Closed**	
V-Input	Open	
V-S2	Open (Next to needle valve)	
V-T1	Open	
V-T2	Open	
Bake Trap N for twenty minutes		
Record Bake start time	hh:mm	
Record Bake end time	hh:mm	
Record Pressure on PT pump	mTorr	
V-T2	Close	
V-T1	Close	
V-Input	Close	
V-5	Close	

3.2 Baking and pumping the Primary trap A:

V-10	Open (Pen Downwards)	
V-9	Open	
V-6	Open	
V-A1	Open	
V-A2	Open	
Bake trap A for 15 minutes		
Record Initial trap A Pressure		
Record Bake start time	hh:mm	
Record Bake end time	hh:mm	
Record Pressure on PT pump	mTorr	
Record Final trap A Pressure		
V-6	Close	

V-9	Close	
V-A1	Close	

V-A2	Close	
V-10	Close	

3.3 Baking and pumping the Primary trap B:

V-14	Open	
V-13	Open	
V-12	Open	
V-11	Open	
Bake Trap B for 10 minutes		
Record Initial trap B Pressure		
Record Bake start time hh:mm		
Record Bake end time hh:mm		
Record Pressure on PT pump mTorr		
Record Final trap B Pressure		
V-11	Close	
V-12	Close	
V-13	Close	
V-14	Close	
Attach Lucas Cell to second port (Leak in First one)		
V-14	Open wait for pressure to go down	
Record Pressure on PT pump: mTorr		
V-14	Close	

4.0 Purging the entire system for two hours.

- **Ensure Board is securely connected to the nitrogen bottle.**
- **Inspect the line before use.**

V-Input	Open	
V-5	Open	
V-6	Confirm Closed	
V-A1	Open	
V-A2	Open	
V-10	Confirm Close	
V-11	Open	
V-12	Open	
V-13	Open	
V-14	Confirm Closed	

Turn regulator to < 10 PSI. Caution(Make sure it doesn't go above 10 PSI. Periodically check the pressure on the guage.		
V-N2	Open	
V-S1	Open (Next to needle valve)	
V - Source	Slowly open until 1L/M	
Initial Time: hh:mm		
Let it run for 5 minutes.		
V-6	Open (After 5 minutes)	
V-10	Open (Pen Upwards)	
V-5	Close	
Let the pressure in the trap reach up to 20 before CLOSING V-S1 and opening V-14. Once the pump pulls vacuum on the board. Repeat steps in 4.0 up till this point for one hour. After one hour repeat steps again but this time start a continuous flow for 30 minutes.		
After 30 min, record time: hh:mm		
V-Source	Close	
Allow 20 minutes before proceeding in order to pull vacuum		
Record pressure on PT pump: mTorr		
V-S	Close	
V-Input	Close	
V-6	Close	
VA1	Close	
VA2	Close	
V-10	Close	
V-11	Close	
V-12	Close	
V-13	Close	
V-14	Close	

5.0 Preparation for the Assay:

V-P	Confirm Closed	
V-5	Confirm Closed	
V-4	Confirm Closed	
V-input	Confirm Closed	
V-chamber (Green Valve)	Confirm Closed	
V-S(Source)	Confirm Closed	
V-S1	Confirm Closed	
V-T1	Confirm Closed	

V-T2	Confirm Closed	
V-N2	Confirm Closed	
V-6	Confirm Closed	
V-9	Confirm Closed	
V-A1	Confirm Closed	
V-A2	Confirm Closed	
V-10	Confirm Closed	
V-11	Confirm Closed	
V-12	Confirm Closed	
V-13	Confirm Closed	
V-14	Confirm Closed	

5.1 Main Assay

5.1.1

Cool down Trap A in liquid N2. Follow SNOLAB Liquid N2 procedure: SL-OPS-ANS-10-004-P		
V-S	**Confirm Closed**	
V-Input	Open	
V-S1	Open next to needle valve	
V-4	Confirm Open	
V-6	Close	
V-5	Open	
Establish line between the source and board		
V-S	Open all the way (Allow 10 minutes to run vacuum on the line)	
(Allow 15minutes to run vacuum on the line)		
V-S	**Close**	
Source	Open	
V-S	Open at 1L/M	
V-9	**Confirm Closed**	
V-A1	Open	
V-A2	Open	
V-10	Open (Pen Downwards)	
V-6	Open	
V-5	Close	
Record Assay start time: hh:mm		
Record Trap A Initial Pressure		
Record Assay Finish time: hh:mm		
V-S	Close	
V-6	Close	

VA-1	Close	
V-A2	Close	
V-10	Close	
Source	Close	
Record Final Trap A pressure:		

5.1.2 Transfer from A to B

Remove Dewar from Trap A.		
Cool Trap B with LN2 using the smaller Dewar.		
Heat trap A to approx. room temp		
Record pressure of gauge A:		
V-10	Pen upwards	
V-11	Open	
V-A2	Open	
Record Time(15 Minutes)	hh:mm	
Bake Trap A during Transfer		
V-14(If lucas cell Attached)	Open	
Wait for pressure to go to original value		
V-14	**Close**	
V-A2	Close	
V-11 **End of transfer**	Close	
V-10	Close	
Record Final Time:	hh:mm	
Record PT Trap A pressure:		

5.1.3 Transfer from B to Lucas cell

Remove the liquid Nitrogen from Trap B		
Heat Trap B until it is warm (approx. room temp)		
Record Pressure on B(PT Trap)		
V-14	**Confirm Closed**	
V-12	Open	
V-13	Open	
Record Time (10 minutes):	hh:mm	
Heat Trap B throughout transfer		
V-12	Close	
V-13	Close	
Record final time (End of Transfer)	hh:mm	
Record Pressure on B(PT Trap)		
Detach Lucas Cell.		
Record Final Pressure on B(PT Trap)		

6.0 Shut down Procedure

V-P	Close	
Scroll Pump	Turn Off	
PT pressure	Turn Off	
PT Flow	Turn Off	
PT trap	Turn Off	

Appendix B

Water Rn Assay Procedure

SNOLAB	**Radon Assay**	
Document Number: SL-OPS-PCS-30-350-P		**Revision Number: 11**
Document Owner: Operations Manager		
Reviewer: Lee Herechuk		
Name:	**Signature:**	**Date: <2022-03-03>**
Approval Authority:		
Name:	**Signature:**	**Date: <YYYY-MM-DD>**

Refer to Flowsheets C,Y,V,Z

1. Scope

This procedure allows an assay of the H_2O in the cavity at different levels from several different sample points, both inside and outside of the PSUP. This procedure also allows a Radon assay from a number of different sample valves in the purification loop. The Radon board traps radon from the vacuum degasser into Lucas cells to be taken to the surface for counting. Before assaying, the sample line might need to be flushed (refer to SL-OPS-PCS-30-430-P) and the FTS water trap emptied of any residual H_2O, which is collected and the volume recorded. To supply pressure to clear the water trap, a flow of "clean" nitrogen from a gas cylinder in the chemistry area is used to fill the trap. A checklist must be filled in when running the procedure.

2. Procedure

2.1 Authorization to Implement

One of the key changes to this procedure has been to add several places where UPWSS authorization is required. The first UPW authorization is for the tasks of draining the FTS trap and Vlad trap. This is specifically authorized even though it is a fairly benign task because it is frequently done a day or two before the actual assay, and is the only action completed that day. The second UPW authorization is for baking and pumping on the Radon board. Normally this is also an activity that does not affect the water systems, but it is normally done first thing the morning of a H_2O Rn assay, and the UPW needs to be aware of the activity taking place. The UPW may also choose to authorize both of these first two places at the beginning of the day of the assay, to allow the Assay Operator to get all of their preparations done without further interaction with the UPW required. The third UPW authorization is required before the assay proper is allowed to begin. This is the most important authorization, because water system valves are to be opened, pumps started, etc.

2.2 Draining the Traps

2.2.1 UPW Authorization

See above explanation. This is more of a UPW notification than authorization.

2.2.2 Defrosting the FTS (if required)

¨ If required, the FTS can be defrosted by using the defrost function. Normally this is not required.

2.2.3 Preliminary Confirmed Closed List

¨ Follow and fill in section 2.2.3 of the checklist to confirm closed valves to prepare to drain the trap.

2.2.4 Preliminary Confirmed Open List

¨ Follow and fill in section 2.2.4 of the checklist to confirm valves that are normally left open.

2.2.5 Preliminary Setup

¨ Follow and fill in section 2.2.4 to ensure the N2 gas bottle supply is connected, and the regulator and needle valve are set properly.

2.2.6 Flushing the Lines

¨ Follow and fill in section 2.2.5 to flush air out of the N2 lines

2.2.7 Valve Open List

¨ Follow and fill in section 2.2.6 to open a path from the trap to the pressure gauge.

2.2.8 Pressurizing and Draining the Trap

¨ Follow and fill in section 2.2.7 to pressurize and drain the trap

¨ Note that attention must be paid to only pressurize the trap with a slight positive pressure. There is no safety relief valve on the trap, so if it is over pressurized it would break, perhaps explosively.

2.2.9 Return System to Normal Configuration

¨ Follow and fill in section 2.2.8 to return the valves to a normal configuration. Often draining the trap is done the day before the day of the assay, but assays can be cancelled or deferred, so it is important to leave the system in a normal or standard configuration.

2.2.10 Draining the "Vlad" Trap

¨ Follow and fill in section 2.2.9 if the Vlad trap needs to be drained. This is not done as frequently as draining the Titan Trap, so is considered an optional section. If there are two people working on the Rn assay, it can also be done simultaneously with draining the Titan Trap to save time.

2.3 Pumping the Trap and Baking the Board

2.3.1 UPW Authorization

See explanation in section 2.1. This is also more of a UPW notification than authorization, because it doesn't affect the rest of the water systems.

2.3.2 Initial Set-up

¨ Follow and fill in section 2.3.2 of the checklist to turn on the FTS system and the vacuum pump.

2.3.3 Cool 'Vlad' Trap

¨ Follow and fill in section 2.3.3 of the checklist to fill the Vlad trap with LN2. Note that the Assay Operator must also be authorized on the LN2 handling procedure, UPW-OP-0100-01.

2.3.4 Pumping the Trap

¨ Follow and fill in section 2.3.4 of the checklist to confirm closed valves on the Radon board and open a path from the vacuum pump to the vapour trap.

2.3.5 Flushing the Lucas Cells

¨ Follow and fill in section 2.3.5 to flush the Lucas cells.

2.3.6 Baking the Radon Board

¨ Follow and fill in section 2.3.5 to bake the Radon board lines with a heat gun to drive off any moisture in the lines.

2.4 Main Assay

2.4.1 UPW Authorization

See explanation in section 2.1. This is the most critical UPW authorization, because actions taken after this affect the water systems and the water in the cavity.

2.4.2 Initial Considerations

¨ Follow and fill in section 2.4.2 to make notes on the assay run plan for the day. Notes taken here will help later interpretation of the assay results, and also help the Assay Operator and UPW consider all the potential implications of the assay on the water systems.

2.4.3 Delta V Checklist

Follow and fill sections 2.4.3 to ensure that Delta V is up to date and in case of a previous SDS trip, valves SV-131 and SV-134 can be manually turned on by the water operator.

2.4.4 Confirm Closed Valves

¨ Follow and fill in section 2.4.4

2.4.5 Confirm Open Valve

¨ Follow and fill in section 2.4.5 to confirm the valve that is normally left open.

2.4.6 Confirm/Establish Initial Set-up

¨ Follow and fill in section 2.4.6 to set up the two diaphragm pumps in preparation for the assay flow path to be established.

2.5 OPTION #1 Sample Line Assay

2.5.1 Confirm Closed or Close Key Valves

¨ Follow and fill in section 2.5.1 to confirm that key valves are closed. These are valves that may have been opened if OPTION #2 has been completed first. If the valves are confirmed closed, which would be the normal situation, enter CC on each line. If the valves require closing, enter a checkmark.

2.5.2 Confirm Closed Deck Valves

¨ Follow and fill in section 2.5.2 to confirm deck valves are closed. If for some reason a deck valve is found open, fill out a UOR, talk to the UPW and try to figure out why.

2.5.3 Open Key Valves

¨ Follow and fill in section 2.5.3 to confirm that key valves are opened. Note that when V-254L is opened, the suction side of P26 is open all the way out to deck.

2.5.4 Notify Detector Operator, Deck Considerations and Open Valves

¨ Follow and fill in section 2.5.4 to open the selected deck sample line valve. Confirm with UPWSS before opening.

2.5.5 Establishing Flow

¨ Follow and fill in section 2.5.5. This part of the procedure requires coordination between the UPW and the Assay Operator.

2.6 OPTION #2 Loop Sample Assay

2.6.1 Confirm Closed or Close Key Valves

¨ Follow and fill in section 2.6.1 to confirm that key valves are closed. These are valves that may have been opened if OPTION #1 has been completed first. If the valves need to be closed, which would be the normal situation, enter a check mark on each line. If the valves are already closed, it probably means that you did not complete a sample line assay first, and you should enter 'CC' on each line for Confirm Closed.

2.6.2 Loop Adjustments

¨ Ask the UPW to follow and fill in section 2.6.2 to adjust the H_2O purification loop. This is required because for a loop sample assay, the assay flow is returned to the loop between the P15 throttle valve V-536L, and the inlet of the PDG. The UPW can add throttle to V-536L, which will reduce the pressure after V-536L, and allow P05 to stroke when it is turned on. The UPW may also want or need to adjust the throttle on V-165L at the inlet to the PDG, to bring the pressure at the inlet to the PDG down, although they will need to make sure they don't lower it too far (no lower than 15 psi), or the PDG will trip offline on low inlet pressure

2.6.3 Valve Open List

¨ Follow and fill in section 2.6.3 to open the loop sample flow path valves.

2.6.4 Establishing Flow for Loop Sample

¨ Follow and fill in section 2.6.4. This part of the procedure requires coordination between the UPW and the Assay Operator.

2.7 OPTION #3 Sample Line Assay to Drain

2.7.1 Confirm Closed or Close Key Valves

¨ Follow and fill in section 2.7.1 to confirm that key valves are closed. These are valves that may have been opened if OPTION #1 or if Option #2 has been completed first. If the valves need to be closed, which would be the normal situation, enter a check mark on each line. If the valves are already closed, it probably means that you did not complete a sample line assay first, and you should enter 'CC' on each line for Confirm Closed.

2.7.2 Confirm Closed Deck Valves

¨ Follow and fill in section 2.7.2 to confirm deck valves are closed. If for some reason a deck valve is found open, fill out a UOR, talk to the UPW and try to figure out why.

2.7.3 Loop Adjustments

¨ Ask the UPW to follow and fill in section 2.7.3 to adjust the H_2O purification loop. This is required because for a loop sample assay, the assay flow is returned to the loop between the P15 throttle valve V-536L, and the inlet of the PDG. The UPW can add throttle to V-536L, which will reduce the pressure after V-536L, and allow P05 to stroke when it is turned on. The UPW may also want or need to adjust the throttle on V-165L at the inlet to the PDG, to bring the pressure at the inlet to the PDG down, although they will need to make sure they don't lower it too far (no lower than 15 psi), or the PDG will trip offline on low inlet pressure

2.7.4 Valve Open List

¨ Follow and fill in section 2.7.4 to open the loop sample flow path valves. Confirm with UPWSS before opening.

2.7.5 Establishing Flow for Loop Sample

¨ Follow and fill in section 2.7.5 This part of the procedure requires coordination between the UPW and the Assay Operator.

2.8 Flow Adjustments

¨ Follow and fill in sections 2.8.1 – 2.8.3 to adjust the two diaphragm pumps to get a steady assay flow and utilize the accumulator. For future reference/troubleshooting reasons, record the air pressures for both pumps.

2.9 Assay Details

2.9.1 Subsequent Assay Preparations

¨ Follow and fill in section 2.9.1 of the checklist for subsequent assays only (i.e. not required for the first sample line assay nor for the first loop sample assay). Note that the main purpose of this section is to make a note of the sample valve selected, and then open it.

2.9.2 Recommence Flow through the MDG

¨ Follow and fill in section 2.9.2 to restart the two diaphragm pumps and to open the inlet and outlet valve to the MDG.

2.9.3 Running the Vacuum Degasser

¨ Follow and fill section 2.9.3 of the checklist to bleed P-26 and make final preparations before starting the extraction

2.9 – 2.13 Radon Assay Sheets

¨ Note that Sections 2.9 to 2.13 have been set up to run a number of Radon assays, following identical steps so that there are no differences in procedure between assays.

2.10 Extraction from the water

¨ Follow and fill out section 2.10.1-2.10.4 to extract the radon from the gas coming out the vacuum degasser. Periodic checks of pressures, every 15 minutes, are to be recorded as indicated on the MDG extraction sheet and the liquid Nitrogen filled every 30-40 minutes in the "Vlad" trap (311-VT-01). Follow and fill in section 2.10.3 of the checklist during the extraction time. At the end of the assay follow and fill in section 2.10.5 to shut off the water flow and prepare for the transfer of radon.

2.11 Transfer of Radon

¨ Follow 2.11.1-2.11.5 to transfer the radon to the Lucas cell. Note that the transfer time from trap A to trap B is 15 minutes, and the transfer time from Trap B to the Lucas cell is 10 minutes. During the warming of trap B, the pressure in B may rise off scale (>700 on gauge B). If so, open to the cell immediately and record the time. Should the pressure still continue to rise too quickly, open the valve either to the next cell in line or to the small closed section of piping between where the cells should be. There is some margin of error, but at a pressure greater than 1500 or so (well off scale) the meter will be damaged.

2.12 Bake Board again

¨ To prepare for the next assay follow section 2.12 to evacuate the traps.

2.13 Assay Shutdown and Preparation for Next Assay

¨ Follow and fill in section 2.13 to record the current sample valve and close it. Note that instructions are given here to go back to the beginning of Section 2.9 for the next sample point or to move on to OPTION #2 or #3 or to continue on to a full shutdown of the procedure

2.14 System Shutdown at the End of All Assays

¨ Follow and fill in section 2.14.1 – 2.14.4 to proceed with a full shutdown of the procedure. Note that there are some valves that will already be closed. If valves are already closed, enter CC for confirm closed. If the valves require closing, enter a check mark.

2.15 Checklist Completion and Filing

¨ Follow and fill in section 2.15.1– 2.15.2 to prepare and file the checklist and complete the assay.

2.16 MDG Extraction Experiment Record Sheet

¨ Follow and fill in section 2.16 MDG Extraction Experiment record sheets.

3. Potential Hazards and Risks

The following are considered to be hazards to be aware of in the implementation of this procedure:

- The sample line part of this procedure draws H_2O directly from the cavity. Although previous experience has shown it does not to generate a large amount of light, the detector operator must be notified and care exercised when opening the sample line valves.
- Proper equipment must be used when working with and pouring liquid nitrogen. Gloves for pouring, and a protective face shield. Note also that any LN2 spills may drip through the mezzanine floor onto people below, so the utmost care must be used when pouring LN2 and if needed, the people working below should be warned and asked to move away from the area.
- Potential for H_2O loss which would upset the levels in the detector.
- Too much air entering P15 through V-544L will trip the whole H_2O recirculation system.
- When draining the FTS, do not over pressurize with nitrogen gas, exercise caution while working with compressed nitrogen bottle
- When warming the radon trap, watch the pressure rise. If it gets too high, then open the appropriate valves to relieve the pressure.

4. Revision History

ORIGINATING DATE: 2013-08-01			
REV NO.	**EFFECTIVE DATE (YYYY-MM-DD)**	**AUTHOR**	**SUMMARY OF CHANGE**
0	Unknown	H. Lee	Initial procedure development
1	Unknown	G. Carnes	Procedure revision
2	200-02	H. Lee	New plumbing between V-551L and V-255L
3	2001-02	S. Fostner, L. Wrightson	Adjusted to include board procedure, FTS drain, Record Sheet. Debugged and edited; added assay of V-535L
4	2005-09	M. Baillie, R. Rodriguez, R. Lange	Comprehensive revision. Added Henry's mark-ups on Rev. 3, the recording of vacuum values on preparation of Lucas Cell. Eliminated the need for help to open valves on deck. Added flexibility to perform loop assays as well as sample line assays
5	2005-09	M. Baillie	Incorporated mark-ups from commissioning
6	2009-07-17	J. Reynolds	Updating to the new format and from PR-140. Section 2.13.4 was added and some other changes were incorporated as per markups -Revise format to new SLOG procedure number
7	2013-08-01	S. Clark	Update to Docushare format
8	2017-08-14	P. Woosaree	Changed 2.2.4 and 2.2.8 to reflect current N2 set up. Changed 2.3.3 to include caution tape set up. Section 2.3.5 is now the Lucas Cell flushing procedure, thus 2.3.6 is Baking the Radon Board. Updated 2.4.2 to reflect current procedure references. Updated 2.4.3 to include location for V-209L. Updated 2.4.5 to include a valve (V-577L) to be confirm opened. and changed the formatting of cells so PCVs can be read. Reformatted 2.5.5, 2.6.4, 2.9.2, 2.10.4, and 2.11.2 to include missing information. Added Option 3 to assay options - in turn changed numbering of all following lines. Added a step to 2.10.2 to turn on stroke counter. Changed the required pressure gauge in 2.11.5. Recording PT006 did not make sense as the LC was not connected to that pressure gauge at that point in the procedure. Record Trap B pressure instead. Added a caution tape removal note to 2.14.3. Implemented emergency shut down procedures throughout.
9	2019-03-18	L. Anselmo	Added new P-05 isolation valves: V-2078L and V-2079L to Section 2.4.4 Confirmed Open Valve. Added V-780L to Section 2.5.2 Confirmed Closed Deck Valves and to 2.7.1 Confirmed Closed Deck Valves. Added UPWSS confirmation before opening selected valves. V-201L & V-206L not possible with split flow in Section 2.7.4. Updated the procedure numbering system to reflect the additional steps made in the checklist.
10	2019-04-	C. Paquette	Added "Disable autofill" step in Section 2.5.4. Added Close V-294L,V-248L and V-471L in Section 2.14.1. Added P26 and P05 "Toggle Off" steps and accumulator shutdown steps in Section 2.14.2. Added enable autofill in Section 2.14.2.
11	2022-03-02	S. Adil Hussain	Added section 2.4.3 Delta V checklist. Added necessary steps to be completed in order to endure that SV-131 and SV-132 are active on Delta V in case of a previous

			SDS trip. Changed the order of the opening of valves of FTS in section 2.3.4; V-222, V-224, and V-242. V-242 now opens first followed by V-224, and then V-222. Changing this order ensured that purge gas in FTS can be safely pumped out without damaging the vacuum pump. Minor alterations to spelling, wording, and spacing.

Personnel:
_____

_____

Day/Date:
_____

Time:
_____

2.1 Authorization to Implement (Explanation)

Note: UPWSS authorization is required in **3 places** for this procedure (2.2 - Draining the Trap, 2.3 - Pumping the Trap and Baking the Board, 2.4 - Main Assay Procedure).

Sometimes the UPWSS will be asked by the assay operator for authorization for 2.2 (Draining the Traps) on the day prior to the assay. This might be all that is done on a given day.

The day of the assay, the UPWSS may be asked for authorization for 2.2 and 2.3 together or 2.3 by itself, and then will normally wait until these sections are complete before asking for authorization to complete from 2.4 on (Main Assay Procedure).

2.2 Draining the Traps

2.2.1 Authorization to implement

UPWSS initials to implement Section 2.2 Draining the Trap	

2.2.2 Defrosting the FTS (if required) * OPTIONAL SECTION *****

One may melt the ice on the coils of the FTS simply by leaving it over night with the power off **OR**	
Press and hold the defrost button and wait for a click. (if not done, enter NR)	
Monitor trap when defrosting. Turn off defrost before the temp. exceeds 40 ^{O}C. (if not done,	

2.2.3 Preliminary Confirmed Closed List

Valve on top of degasser	[Y]	V-215L	Confirm Closed	
Behind control panel	[Y]	V-189L	Confirm Closed	
Beside FTS	[Y]	V-243L	Confirm Closed	
Beside FTS	[Y]	V-224L	Confirm Closed	
Beside FTS	[Y]	V-222L	Confirm Closed	
Beside FTS – green	[Y]	V-226L	Confirm Closed	
N2 supply to vapour trap	[Y]	V-669L	Confirm Closed	
N2 flush line – behind MDG skid	[Y]	V-659L	Confirm Closed	

2.2.4 Preliminary Confirmed Open List

Formerly actuated valve (normally left open)	[Y]	V-537L	Confirm Open	

2.2.5 Preliminary Setup

Connect the hose from the N2 regulator in the chem. lab to the line leading to the degasser				
Main N2 bottle supply valve (N2 cylinder - beside fume hood)	[Y]		OPEN ¼ Turn	
Regulator diaphragm valve (N2 cylinder - beside fume hood)	[Y]		OPEN P ~ 5	
Needle valve on regulator	[Y]	V-660L	OPEN 1 Turn	

2.2.6 Flushing the Lines

Back of MDG Skid, N2 Flush valve	[Y]	V-659L	OPEN	
Open V-745L	[Y]	V-745L	OPEN	
Flush the line for 20 seconds.				
Close V-745L	[Y]	V-745L	CLOSE	
Back of MDG Skid	[Y]	V-659L	CLOSE	

2.2.7 Valve Open List NOTE: Be sure to open the valves slowly

N2 PP Isolation valve (upstairs, backside of skid)	[Y]	V-225L	OPEN slowly	
MDG Vapour Trap N2 inlet (backside of skid)	[Y]	V-222L	OPEN slowly	
N2 SS supply line (backside of skid)	[Y]	V-579L	OPEN slowly	
Note: Pressure gauge along the line should drop to –30 inches of Hg (red scale) if FTS is under				

2.2.8 Pressurizing and Draining the Trap

Important Note: The Vapour Trap must not be over-pressurized (>2 psi) or it will break.					
Watch PI 647 during the next two steps to pressurize the trap to 0.5 psi					
N2 supply valve (backside of skid)	[Y]	V-669L	OPEN Slowly		
N2 supply valve (backside of skid)	[Y]	V-669L	CLOSE P ~ 0.5		
Place a bucket below the outlet drain pipe			Bucket Placed		
FTS Drain	[Y]	V-226L	OPEN		
Drain water only to a level just above the outlet tube					
Drain of FTS	[Y]	V-226L	CLOSE		
NOTE: If the gauge indicates that the pressure has fallen below atmosphere, repeat the above steps					

2.2.9 Return System to Normal Configuration

N2 PP Isolation valve (upstairs, backside of skid)	[Y]	V-225L	CLOSE	
MDG Vapour Trap N2 inlet (backside of skid)	[Y]	V-222L	CLOSE	
N2 SS supply line (backside of skid)	[Y]	V-579L	CLOSE	
Drain of FTS	[Y]	V-226L	Confirm Closed	
N2 Supply Valve (behind MDG)	[Y]	V-669L	Confirm Closed	
Measure the amount of water taken from the FTS, Record this number in the MDG log book				
Main N2 bottle supply valve (in chem. lab)		[Y]	CLOSE	
Regulator diaphragm valve (in chem. lab)		[Y]	BACK OFF	
Needle valve on regulator (in chem. lab)	[Y]	V-660L	CLOSE	
Disconnect the hose leading to the degasser skid				

2.2.10 Draining "Vlad" Trap (321-VT-01) *** OPTIONAL SECTION*** May be Done in Parallel With Draining the FTS Trap

Inlet to Vlad Trap (near VP02, Alcatel pump)	[Y]	V-539L	Confirm Closed	
Outlet of Vlad Trap (near VP02, Alcatel pump)	[Y]	V-247L	Confirm Closed	
Loosen one clamp (NW vacuum fitting style) and vent the vacuum				
Reconnect / tighten clamp once vented				
Remove top section of Vlad trap				
Use syringe to draw water out of Vlad trap				
Measure the amount of water in Vlad trap and record amount in MDG log book				

Notes:

2.3 Pumping the Trap and Baking the Radon Board

2.3.1 Authorization to implement

UPWSS initials to implement Section 2.3 Pumping the Trap and Baking the Radon Board	

2.3.2 Initial Setup

Turn on FTS main power and activate the cooling cycle by depressing the Start/Stop button				
Record Time:			hh:mm	
Inlet to Vlad Trap (near VP02, Alcatel pump)	[Y]	V-539L	Confirm Closed	
Outlet of Vlad Trap (near VP02, Alcatel pump)	[Y]	V-247L	Confirm Closed	
Start the Alcatel vacuum pump. The switch is on the control panel.				

2.3.3 Cool "Vlad" Trap (321-VT-01)

Confirm Vlad trap is connected	
Obtain Liquid N_2 according to SNOLAB-SOP-022 (LN2 handling procedure)	
Place caution tape on main floor below Rn skid in case LN2 drips below	
Cool "Vlad" trap by filling with liquid N_2.	
NOTE: do not overfill as O-ring will freeze and trap will begin leaking	

2.3.4 Pumping Trap

Drain of FTS	[Y]	V-226L	Confirm Closed	
Rn Board (Radon Trap bypass)	[Y]	V-258L	Confirm Closed	
Rn Board (3-way valve after Radon Trap)	[Y]	V-245L	Confirm Closed	
Rn Board (outlet of last Lucas Cell)	[Y]	V-262L	Confirm Closed	
Rn Board (capped)	[Y]	V-256L	Confirm Closed	
Rn Board (inlet to Radon trap)	[Y]	V-244L	Confirm Closed	
Rn Board (secondary isolation from FTS)	[Y]	V-243L	Confirm Closed	
Radon Board bypass to Vlad Trap and vacuum pump	[Y]	V-242L	Confirm Closed	
Valve on top of degasser	[Y]	V-215L	Confirm Closed	
N2 PP Isolation valve (backside of skid)	[Y]	V-225L	Confirm Closed	
Rn Board, valve **normally left open**	[Y]	V-257L	Confirm Open	
Rn Board, valve **normally left open**	[Y]	V-538L	Confirm Open	
Formerly actuated valve (**normally left open**)	[Y]	V-537L	Confirm Open	
* Outlet of Vlad Trap (near VP02, Alcatel pump)	[Y]	V-247L	OPEN Slowly	
* Inlet to Vlad Trap (near VP02, Alcatel pump)	[Y]	V-539L	OPEN Slowly	
* Watch pressure on FTS panel, make sure it is going down or else check for leaks before continuing.				
Confirm pressure is below 20 mTorr before proceeding.				
Record pressure reading (PT 007, display on FTS panel)			mTorr	
Confirm FTS has cooled for 10 minutes before pumping on it				
Record Time:			hh:mm	
Vapour Trap inlet, beside FTS	[Y]	V-242L	OPEN slowly	
Vapour Trap outlet, beside FTS. If there is a lot of gas in FTS, keeping opening and closing several times in order to ensure safety of pump.	[Y]	V-224L	OPEN slowly	
* Radon Board bypass to Vlad trap and vacuum pump	[Y]	V-222L	OPEN	
Note: Open V-242L in small stages, not letting the Alcatel pump to strain too much from the gas load.				
Check and Fill "Vlad" trap when needed (~ every 30-40 min)				
Confirm pressure is below 50 mTorr before proceeding.				
Record pressure reading (PT 007, display on FTS panel)			mTorr	
Radon Board bypass to Vlad Trap and vacuum pump	[Y]	V-242L	CLOSE	
Plug in trap/MDG pressure gauges (2 plugs) and heat gun (120 VAC)				

2.3.5 Flushing the Lucas Cells

Two Lucas Cells may be flushed at the same time, even if only one is being used for the actual assay.				
Rn Board (Radon Trap bypass)	[Y]	V-258L	Confirm Closed	
Rn Board (3-way valve after Radon Trap)	[Y]	V-245L	Confirm Closed	
Rn Board (between Lucas Cell ports)	[Y]	V-261L	Confirm Closed	
Rn Board (outlet from last Lucas Cell)	[Y]	V-262L	Confirm Closed	
Rn Board bypass to Vlad trap and vacuum pump	[Y]	V-242L	Confirm Closed	
Rn Board (secondary isolation from FTS)	[Y]	V-243L	Confirm Closed	
Rn Board (Radon trap inlet)	[Y]	V-244L	Confirm Closed	
N2 Supply valve (backside of skid)	[Y]	V-669L	Confirm Closed	
Backside of skid	[Y]	V-668L	Confirm Closed	
Near Vlad Trap	[Y]	V-539L	Confirm Open	
Outlet of Vlad Trap (near VP02, Alcatel pump)	[Y]	V-247L	Confirm Open	
Rn Board, valve **normally left open**	[Y]	V-257L	CLOSE	
Remove the blue plastic protective cap from the lucas cell and nozzle. Attach the Lucas Cell to quick connect port 2 for a single Lucas cell or ports 1 and 2 for two Lucas Cells	[Y]	311-LUC-01	Attach Lucas Cells	
Open Rn Board (outlet from last Lucas Cell) for LC evacuation until pressure is stable (P < 10mTorr)	[Y]	V-262L	OPEN	
If using Port 1	[Y]	V-261L	OPEN	
Rn Board (outlet from last Lucas cell)	[Y]	V-262L	CLOSE	
Near Vlad trap	[Y]	V-539L	CLOSE	
Rn Board	[Y]	V-256L	OPEN	
Open black circular valve on regulator of N2 cylinder. Establish pressure of 6psi.	[Y]	V-660L	OPEN	
Back of MDG Skid	[Y]	V-659L	OPEN	
Open Rn Board (outlet from last Lucas Cell)	[Y]	V-262L	OPEN	
LC N2 Flush #1: Fill LC with N2 (should be fast, wait 10-				
Rn Board (Radon trap bypass)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
LC flushes for 30 sec				
Open near Vlad trap valve for evacuation. Wait for stable pressure (P < 10mTorr)	[Y]	V-539L	OPEN	
Near Vlad trap	[Y]	V-539L	CLOSE	
LC N2 Flush #2: Fill LC with N2				
RnBoard (Radon trap bypass)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)		V-258L	CLOSE	
LC flushes for 30 sec				
Open near Vlad trap valve for evacuation. Wait for stable pressure (P < 10mTorr)	[Y]	V-539L	OPEN	
Near Vlad trap	[Y]	V-539L	CLOSE	
LC N2 Flush #3: Fill LC with N2				
RnBoard (Radon trap bypass)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
LC flushes for 30 sec				
Open near Vlad trap valve for evacuation. Wait for stable pressure (P < 10mTorr)	[Y]	V-539L	OPEN	
Record pressure reading (PT 007, display on FTS panel)			mTorr	
Rn Board (outlet from last Lucas Cell)	[Y]	V-262L	CLOSE	
If using 2 Lucas Cells, Rn Board (between Lucas Cells)	[Y]	V-261L	CLOSE	
Remove Lucas Cells and reattach blue caps				
Rn Board (Radon trap bypass)	[Y]	V-258L	Confirm Closed	
Rn Board (outlet from last Lucas Cell)	[Y]	V-262L	Confirm Closed	

Rn Board (between Lucas Cells)	[Y]	V-261L	Confirm Closed	
Back of MDG Skid	[Y]	V-659L	CLOSE	
Rn Board	[Y]	V-256L	CLOSE	
Rn Board, valve	[Y]	V-257L	OPEN	
Near Vlad trap	[Y]	V-539L	Confirm Open	
Regulator valve			BACK OFF	
Needle valve on regulator	[Y]	V-660L	CLOSE	
Red Clip down				

2.3.6 Baking the Radon Board

Use heat gun to bake the two radon traps (311-CT01, 311-RTR02). Take care not to point heat gun at FTS chamber or wiring for pressure gauges A and B. Traps should be heated until they are hot to touch (approx. 40°C)				
Radon Board bypass to Vlad Trap and vacuum pump	[Y]	V-242L	Confirm Closed	
Radon Board (isolation from N2 supply)	[Y]	V-243L	Confirm Closed	
Radon Board (Radon Trap inlet)	[Y]	V-244L	Confirm Closed	
Radon Board (outlet from last Lucas Cell)	[Y]	V-262L	OPEN	
Radon Board (between Lucas Cells)	[Y]	V-261L	OPEN	
Radon Board (inlet to first Lucas Cell)	[Y]	V-260L	OPEN	
Radon Board (inlet to Secondary Radon Trap)	[Y]	V-259L	OPEN	
Heat Trap B (311-RTR-02)				
Close when P < 15 mTorr	[Y]	V-259L	CLOSE	
Record pressure reading (PT 007, display on FTS panel)			mTorr	
Radon Board (inlet to first Lucas Cell)	[Y]	V-260L	CLOSE	
Radon Board (between Lucas Cells)	[Y]	V-261L	CLOSE	
Radon Board (outlet from last Lucas Cell)	[Y]	V-262L	CLOSE	
Radon Board (3-way valve after Radon Trap)	[Y]	V-245L	OPEN Down	
Heat Trap A (311-CT01)				
Close when P < 15 mTorr	[Y]	V-245L	CLOSE	
Record pressure reading (PT 007, display on FTS panel)			mTorr	
Note the baseline pressures on the “MDG extraction/ experiment record sheet.”				

************Emergency Shut Down Procedure for Sections 2.1 - 2.3************

IF YOU ARE RETURNING:				
Leave everything as is. If you can, ensure there is enough LN2 in the Vlad trap. The system is stable at this point.				
IF YOU ARE NOT RETURNING (or unsure of your return):				
Radon Board (outlet from last Lucas Cell)	[Y]	V-262L	CLOSE	
Rn Board (Radon trap bypass)	[Y]	V-258L	CLOSE	
FTS inlet valve	[Y]	V-222L	CLOSE	
FTS outlet valve	[Y]	V-224L	CLOSE	
Shut off Cooling Switch on FTS	[Y]	FTS Panel **(on/off)**	OFF	
Turn off FTS	[Y]	FTS Panel **(1/0)**	0	
Near Vlad trap	[Y]	V-539L	CLOSE	
Shut off vacuum pump	[Y]	Control Panel	OFF	
Vent vacuum pump		[Y]	VENT	
Bring Lucas Cell(s) with you				

2.4 Main Assay

2.4.1 Authorization to Implement

UPWSS initials to implement Section 2.4 – Main Assay	

2.4.2 Initial Considerations (to be completed with help from the UPW)

Run UPW-OP-3300-01 to purge sample line if assay is following H_2O HTiO assay	
Confirm that SL-OPS-PCS-30-200-P is running	
Record cavity level (LT100)	

Make notes describing the current circulation & run plan, i.e.:

- Is cavity autofill (checked in Paragon)? Is this what we want? - Is this a closed loop assay for some reason? - Is the (new) polishing RO on-line or off-line?	- Is parallel flow (the cavity cooling flow path through the UFR bank) on-line or off-line? - Any other unusual circumstances?

2.4.3 Delta V Checklist

Ensure no SDS has occurred since the last Assay. If yes then continue	Y/N
Click on “Beaker” on Delta V	
Should say “High flow skid” on top	
Bottom right should say “MDG” with SV-131 and SV-134	
Ensure SV-131 is green	
Ensure SV-134 is green	
If either one or both valves are red, click on the button for the solenoid and change the "new value" from 0 to 1.	
Ensure the clicking sound of the pump is heard and valves turn green	

2.4.4 Confirm Closed Valves

Above FTS, back	[Y]	V-550L	Confirm Closed	
On side of degasser	[Y]	V-208L	Confirm Closed	
MDG Skid, back near P26	[Y]	V-168L	Confirm Closed	
MDG Skid, by P26 (P26 outlet valve)	[Y]	V-285L	Confirm Closed	
Near Dummy Column	[Y]	V-232L	Confirm Closed	
Near Dummy Column	[Y]	V-234L	Confirm Closed	
MDG Skid, above P26	[Y]	V-255L	Confirm Closed	
MDG Skid, above P26	[Y]	V-254L	Confirm Closed	
MDG Skid, above P26	[Y]	V-467L	Confirm Closed	
MDG Skid, above P26	[Y]	V-479L	Confirm Closed	
MDG Skid, by UF (Injection Port)	[Y]	V-641L	Confirm Closed	
On side of Degasser	[Y]	V-228L	Confirm Closed	
Top of Degasser	[Y]	V-189L	Confirm Closed	
Top of Degasser	[Y]	V-215L	Confirm Closed	
Inlet to Degasser	[Y]	V-248L	Confirm Closed	
Beside Degasser (Capped)	[Y]	V-576L	Confirm Closed	
Bottom of Degasser	[Y]	V-294L	Confirm Closed	
UFR06 permeate	[Y]	V-302L	Confirm Closed	
UFR06 permeate	[Y]	V-303L	Confirm Closed	
MDG skid	[Y]	V-209L	Confirm Closed	
Above FTS	[Y]	V-551L	Confirm Closed	

Loop sample valve after PDG (by UV skid)	[V]	V-535L	Confirm Closed	
P15 inlet loop sample and return line (downstairs)	[V]	V-544L	Confirm Closed	
To Forced Drain (downstairs)	[V]	V-558L	Confirm Closed	
Loop sample valve after HX01 and new RO (downstairs)	[V]	V-229L	Confirm Closed	
P15 outlet return line (downstairs, PDG pit)	[V]	V-470L	Confirm Closed	
To drain (downstairs, PDG pit)	[V]	V-471L	Confirm Closed	
PDG pit	[Y]	V-171L	Confirm Closed	
PDG pit	[Y]	V-252L	Confirm Closed	
PDG pit	[Y]	V-540L	Confirm Closed	

2.4.5 Confirm Open Valves

Above Degasser, by PT-004 (normally left open)	[Y]	V-241L	Confirm Open	
P05 inlet isolation valve	[Y]	V-2078L	Confirm Open	
P05 outlet isolation valve	[Y]	V-2079L	Confirm Open	

2.4.6 Confirm/Establish Initial Set-Up

Compressed air valve for P05 (PDG Pit)	[NN]	V-577L	Confirm Open	
Set P_{air} to bottoms pump P05 (PDG Pit)		PCV-135	Set to 40 psi	
P05 inlet (PDG Pit)	[Y]	V-171L	OPEN	
P26 outlet valve (upstairs)	[Y]	V-285L	OPEN	
Set P_{air} to degasser feed pump P26	[NN]	PCV-132	Set to 60 psi	
Compressed air valve for P26	[Y]	V-170L	OPEN	

Notes:

Note:
This procedure has been re-designed so that at this point, the Assay Operator can initiate a sample line assay (OPTION #1, V-201 to 206), or a loop sample assay (OPTION #2, V-535, 544, or 229).

A "Normal" Radon Assay Suite
Normally, a sample line assay is done first (OPTION #1, Section 2.5), followed by a second and sometimes even a third sample line assay (subsequent sample line assays are covered entirely in Sections 2.8 to 2.12). Then, after the sample line assays are completed, a loop sample assay (normally V-535L) is often desired. The directions in Section 2.8 to 2.12 direct the Operator back to OPTION #2, Section 2.6 to start up the loop sample assay.

Closed Loop or Loop Troubleshooting Assay Suite
For troubleshooting Radon ingress into the purification loop, sometimes a series of loop sample point assays are required. OPTION #2 Section 2.6 is selected for the first loop sample point, and subsequent loop sample points are covered in Sections 2.8 to 2.12.

Other permutations and combinations are possible, but should be planned in advance with Richard Ford.

** **OPTION 1 - SAMPLE LINE ASSAY** ***

2.5 Flow Path Preparation

2.5.1 Confirm Closed or Close Key Valves

Confirm closed OR close possible skid inlet valve	[Y]	V-255L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible P05 outlet valve	[Y]	V-252L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible loop sample valve	[V]	V-229L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible loop sample valve	[V]	V-535L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible loop sample valve	[V]	V-544L	Confirm Closed (CC) or CLOSE (checkmark)	

2.5.2 Confirm Closed Deck Valves

Bottom of Cavity sample line	[Z]	V-201L	Confirm Closed	
Cavity sample line	[Z]	V-202L	Confirm Closed	
PSUP top sample line	[Z]	V-203L	Confirm Closed	
PSUP bottom sample line	[Z]	V-204L	Confirm Closed	
Cavity sample line	[Z]	V-205L	Confirm Closed	
PSUP south pole sample line	[Z]	V-206L	Confirm Closed	
Purification loop to PSUP south pole	[Z]	V-175L	Confirm Closed	
Purification loop to Cavity bottom	[Z]	V-176L	Confirm Closed	
Cavity Cooling loop to Cavity bottom	[Z]	V-177L	Confirm Closed	
Capped cavity line	[C]	V-780L	Confirm Closed/	

2.5.3 Open Key Valves in Utility Room

Open P05 outlet to V7Y (above FTS)	[Y]	V-550L	OPEN	
Open P05 connection to line V7Y (above FTS)	[Y]	V-551L	OPEN	
Record amount of gas by height in pipe section above V-254L			% gas	
Supply to MDG skid & P26 inlet	[Y]	V-254L	OPEN Slowly	
Note: When V-254L is opened, the inlet side of P26 is open all the way out to deck isolation valves. P26 may stroke, which is a good confirmation that the inlet is under suction.				

2.5.4 Notify Detector Operator & Open Valves

Notify detector operator of water assay, valve number(s), and location of assay sample				
Record amount of gas by height in pipe section above V-206L			% gas	
Indicate First Sample Valve Chosen: (201, 202 ,203 , 204, 205, or 206)				
Confirm Valve with UPWSS before opening. Note: V-201L and V-206L not possible with split flow				
Open chosen sample valve	[Z]	V-	OPEN	
Ask UPWSS to disable cavity autofill			DISABLED	

2.5.5 Establishing Flow

Note: The Assay Operator needs to work with the UPW for this section. The UPW will slowly open V-544L, with an eye on air bubbles flowing through to the inlet of P15. The Assay Operator will simultaneously open the flow path in and out of the MDG, with an eye on the MDG level.				
UPW and Assay Operator activities discussed, and both people in position				
Turn on power for P26 (feed pump toggle switch)		Control Panel	TOGGLE ON	
Do the next four steps in quick succession (Assay Operator can call down to the UPW to proceed):				
Slowly open H_2O return-to-loop valve (UPW)	[V]	V-544L	Slowly OPEN	
Inlet to MDG (Assay Operator)	[Y]	V-248L	OPEN	
Turn on power for P05 (bottoms pump toggle switch)		Control Panel	TOGGLE ON	
Outlet of MDG (Assay Operator)	[Y]	V-294L	OPEN	
MDG Vacuum Valve (Top of MDG)	[Y]	V-215L	OPEN	
Open V-242L slowly until pressure reads 3HHH (off scale)	[Y]	V-242L	OPEN Slow	
Skip the next page and move on to Section 2.7 (diaphragm pump adjustments to set flows)				

Notes:

OPTION 2 – LOOP SAMPLE ASSAY

2.6 Flowpath Preparation

2.6.1 Confirm Closed or Close Key Valves

Confirm closed OR close possible return path valve	[Y]	V-550L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible return path valve	[Y]	V-551L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible skid inlet	[Y]	V-254L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible return to loop valve	[V]	V-544L	Confirm Closed (CC) or CLOSE (checkmark)	

2.6.2 Loop Adjustments

Ask the UPW to reduce the outlet pressure between V-536L and the PDG inlet by adding more throttle to V-536L and or taking throttle off the PDG inlet valve – UPW to target ~12 psi at theF PDG inlet	
Loop adjustment(s) complete UPW's signature required here	

2.6.3 Valve Open List

Open P05 outlet valve (PDG pit)	[Y]	V-252L	OPEN	
Open return path to loop	[V]	V-470L	Slowly OPEN	
Open inlet valve to skid	[Y]	V-255L	Slowly OPEN	

2.6.4 Establishing Flow for Loop Sample

Note: The Assay Operator needs to work with the UPW for this section. The UPW will slowly open the loop sample valve – we are sampling from the loop here, not returning to the loop as we do for a sample line assay. The Assay Operator will simultaneously open the flow path in and out of the MDG, with an				
UPW and Assay Operator activities discussed, and both people in position				
Turn on solenoid valve power for P26		Control Panel	TOGGLE ON	
Increase P_{air} to bottoms pump P05 (PDG Pit)	[NN]	PCV-	Set to 70 psi	zF
List the loop sample valve (V-229L, V-535L or V-544L)				
Do the next four steps in quick succession (Assay Operator can call down to the UPW to proceed):				
Slowly open H_2O sample valve	[V]	V-	Slowly OPEN	
Inlet to MDG (Assay Operator)	[Y]	V-248L	OPEN	
P05 power (Assay Operator)		Control	On	
Outlet of MDG (Assay Operator)	[Y]	V-294L	OPEN	
(MDG Vacuum Valve) Top of MDG	[Y]	V-215L	OPEN	
V-242L, Open Slowly until Pressure reads 3HHH	[Y]	MDG	OPEN Slow	
Ensure P05 is pumping				
If P05 will not stroke, then follow the next 5 steps, otherwise mark them as NR (not required)				
Assay Operator to close inlet to MDG	[Y]	V-248L	CLOSE	
UPW to adjust P05 air pressure	[Y]	PCV-135	Adjust	
and/or UPW to adjust V-536L throttle	[V]	V-536L	Adjust	
and/or UPW to adjust V-165L throttle	[X]	V-165L	Adjust	
When P05 starts stroking then Assay Operator to open V-248L	[Y]	V-248L	OPEN	

*** OPTION 3 - SAMPLE LINE ASSAY TO DRAIN ***

2.7 Flow Path Preparation

2.7.1 Confirm Closed Deck Valves

Bottom of Cavity sample line	[Z]	V-201L	Confirm Closed	
Cavity sample line	[Z]	V-202L	Confirm Closed	
PSUP top sample line	[Z]	V-203L	Confirm Closed	
PSUP bottom sample line	[Z]	V-204L	Confirm Closed	
Cavity sample line	[Z]	V-205L	Confirm Closed	
PSUP south pole sample line	[Z]	V-206L	Confirm Closed	
Purification loop to PSUP south pole	[Z]	V-175L	Confirm Closed	
Purification loop to Cavity bottom	[Z]	V-176L	Confirm Closed	
Cavity Cooling loop to Cavity bottom	[Z]	V-177L	Confirm Closed	
Capped cavity line	[C]	V-780L	Confirm closed/ Capped	

2.7.2 Confirm Closed or Close Key Valves

Confirm closed OR close possible return path valve	[Y]	V-550L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible return path valve	[Y]	V-551L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible skid inlet	[V]	V-254L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible return loop valve	[V]	V-544L	Confirm Closed (CC) or CLOSE (checkmark)	
Confirm closed OR close possible P15 outlet return line	[V]	V-470L	Confirm Closed (CC) or CLOSE (checkmark)	

2.7.3 Loop Adjustments

Ask the UPWSS to reduce the outlet pressure between V-536L and the PDG inlet by adding more throttle to V-536L and or taking throttle off the PDG inlet valve – UPW to target ~12 psi at the PDG inlet		
Loop adjustment(s) complete	UPW's signature required here□	

2.7.4 Valve Open List

Open P05 outlet valve (PDG Pit)	V-252L	OPEN	
To drain (PDG Pit)	V-471L	Slowly OPEN	
Indicate First Sample Valve Chosen: (201, 202 ,203 , 204, 205, or 206)			
Confirm Valve with UPWS before opening. Note: V-201L and V-206L not possible with split flow			
Open chosen sample valve [Z]	V-	Slowly OPEN	

2.7.5 Establishing Flow for Loop Sample

Note: The Assay Operator needs to work with the UPW for this section. The UPW will slowly open the loop sample valve – we are sampling from the loop here, not returning to the loop as we do for a sample line assay. The Assay Operator will simultaneously open the flow path in and out of the MDG, with an				
UPW and Assay Operator activities discussed, and both people in position				
Turn on solenoid valve power for P26 (feed pump)		Control Panel	TOGGLE ON	
Increase P_{air} to bottoms pump P05 (PDG Pit) [NN]		PCV-135	Set to 70 psi	
List the loop sample valve (V-229L, V-535L or V-544L)				
Do the next four steps in quick succession (Assay Operator can call down to the UPW to proceed):				
Supply to MDG Skid & P26 inlet (UPW)	[Y]	V-254L	Slowly OPEN	
Inlet to MDG (Assay Operator)	[Y]	V-248L	OPEN	
P05 power (bottoms pump) (Assay Operator)		Control Panel	TOGGLE ON	
Outlet of MDG (Assay Operator)	[Y]	V-294L	OPEN	
(MDG Vacuum Valve) Top of MDG	[Y]	V-215L	OPEN	
Open Slowly until Pressure reads 3HHH (off scale, MDG	[Y]	V-242L	OPEN Slowly	
Ensure P05 is pumping				
If P05 will not stroke, then follow the next 5 steps, otherwise mark them as NR (not required)				
Assay Operator to close inlet to MDG	[Y]	V-248L	CLOSE	
UPW to adjust P05 air pressure	[Y]	PCV-135	Adjust	
and/or UPW to adjust V-536L throttle	[V]	V-536L	Adjust	
and/or UPW to adjust V-165L throttle	[X]	V-165L	Adjust	
When P05 starts stroking then Assay Operator to open V-	[Y]	V-248L	OPEN	

2.8 Flow Adjustments

This Section is needed for OPTION #1, OPTION #2 or OPTION #3

2.8.1 Adjusting Flow

Adjust P26/P05 air pressures to about 73 psi to get a steady flow of 20 – 24 lpm			
Note flow after adjustments are made	FIT121		lpm

2.8.2 Accumulator (ACC04) Setup and Flow Dampening (if required)

Record P26 outlet pressure	[Y]	PI 120		psi
Air supply isolation valve (above sink in chem. area)	[Y]	V-578A	Confirm Open	
Set accumulator regulator to ~50 psi on associated gauge	[Y]	PCV-	Set to 50 psi	
Monitor the flow; should read about 24 lpm when stable	[Y]	FIT-121		lpm
Skip ahead to 2.9 Assay Details				

2.8.3 Note Diaphragm Pump Air Supply Pressures

Record P26 air supply pressure	[Y]	PCV-	psi
Record P05 air supply pressure	[Y]	PCV-	psi

Notes:

************Emergency Shut Down Procedure for Sections 2.4 - 2.8************

IF YOU ARE RETURNING:				
Radon Board	[Y]	V-244L	CLOSE	
P05 Power (bottoms pump)	[Y]	Control	OFF	
P26 Power (feed pump)	[Y]	Control	OFF	
MDG Inlet	[Y]	V-248L	CLOSE	
MDG Outlet	[Y]	V-294L	CLOSE	
Radon Board	[Y]	V-245L	CLOSE	
IF YOU ARE NOT RETURNING (or unsure of your return):				
Radon Board	[Y]	V-244L	CLOSE	
P05 Power (bottoms pump)	[Y]	Control	OFF	
P26 Power (feed pump)	[Y]	Control	OFF	
MDG Inlet	[Y]	V-248L	CLOSE	
MDG Outlet	[Y]	V-249L	CLOSE	
Rn Board	[Y]	V-245L	CLOSE	
Radon Board (outlet from last Lucas Cell)	[Y]	V-262L	CLOSE	
Rn Board (Radon trap bypass)	[Y]	V-258L	CLOSE	
FTS inlet valve	[Y]	V-222L	CLOSE	
FTS outlet valve	[Y]	V-224L	CLOSE	
Shut off Cooling Switch on FTS	[Y]	FTS Panel **(on/off)**	OFF	
Turn off FTS	[Y]	FTS Panel **(1/0)**	0	
Near Vlad trap	[Y]	V-539L	CLOSE	
Shut off vacuum pump	[Y]	Control Panel	OFF	
Vent vacuum pump		[Y]	VENT	
Bring Lucas Cell(s) with you				

2.9 Assay Details

	Sample Line Assays			**Loop Sample Assays**		
Assay Valve #						
Lucas Cell Number LC #						
Record baseline pressures on extraction sheet						

2.9.1 Subsequent Assay Preparations (for subsequent assays only)

Record amount of air in the 5 ft pipe section above sample	% air						
List new sample line valve or loop sample valve							
Open new sample line valve or loop sample valve							
On your way back to the Utility Room, let the detector operator know you have opened the sample valve and will be starting the sample line flow shortly.							

2.9.2 Recommence flow through MDG (for subsequent assays only)

Turn on P26 (local control panel)									
Open MDG inlet	[Y]	V-248L	OPEN						
Turn on P05 (local control panel)									
Open MDG outlet	[Y]	V-294L	OPEN						
Adjust P26 and P05 pressures if needed to maintain MDG level									
Gradually open to pump down	[Y]	V-242L	Slowly OPEN						

2.9.3 Running the Vacuum Degasser (311-DG01)

Start time of water flow						
Watch Alcatel pressure, it should settle to ~2500 mTorr, with V-242 wide open. MDG pressure should settle around						
CLOSE V-242L						
OPEN V-258L						
Bleed the air from P26 by opening D-011*						
*Bleed air by holding a jar under the plastic tubing located on the bleed valve D-011 and **slowly open** the valve until no more air is escaping. **Be careful the tube does not pop off due to pressure**.						
Wait at least **25 minutes** with a water flow of 20 lpm						

2.10 Extraction from the Water

2.10.1 Radon Trap Setup

Fill the large Dewar with LN2 and place it around the Trap A (311-CT01). Use the support elevator to lift the Dewar until the top is even with the Swagelok elbow at the top of the trap.						

2.10.2 Trap A Extraction

CLOSE **V-258L**, quickly open **V-244L**, turn **V-245L** downward and start pump **stroke counter**						
Record Start Time: run for **~30 min, or as required** (At this point the gas flow is into the board through V-257L, through the primary trap, and out V-245L)						

2.10.3 Record Data

Flow rate FIT-121	Behind Rn Board (yellow)	lpm						
Feed Pump Pressure	PI-120 (range)	psi						
Feed Pump Air Pressure	PI-171 (maximum)	psi						
Strokes P26	Time per 20 strokes	sec						
Bottoms Pump Pressure	Near P05	psi						
Bottoms Pump Air	PI-172 (maximum)	psi						
Strokes P05	Time per 20 strokes	sec						
Temperature of MDG walls	Thermometer (after 25	°C						

Trap A = Primary Radon Trap = 311-CT01 ; Trap B = Secondary Radon Trap = 311-RTR-02

2.10.4 Extraction Monitoring

	Sample Line			**Loop Sample**		
Check the Vlad trap periodically and fill with LN_2 as req'd (every 30-						
Fill out the Rn extraction log sheet every **15 min**						

2.10.5 Water Extraction Completion [PROCEED QUICKLY]

Radon Board	V-244L	CLOSE						
P05 Power (bottoms pump)	Control Panel	Off Quickly						

P26 Power (feed pump)	Control Panel	Off Quickly						
MDG inlet	V-248L	CLOSE						
MDG outlet	V-294L	CLOSE						
Rn Board, close when P<100	V-245L	CLOSE						
Record Time **Immediately (time of V-244L**		Time						
Record time and pump stroke counter final number on the Rn extraction log sheet as well								

2.11 Transfer of Radon

2.11.1 Preparing Trap A and Trap B

Remove Dewar from **Trap A**.							
Cool **Trap B** with LN2 using the smaller Dewar. Support it with wooden box and scissors jack							
Heat trap A to approx. room temp							
Record pressure of gauge A on the Radon extraction sheet							
NOTE: If pressure on trap A exceeds +200, abort by opening V-245L into the down position							

2.11.2 Transfer from Trap A to Trap B

Radon Board	V-259L	OPEN						
Radon Board (**start of**	V-245L	OPEN Upwards						
Allow the transfer to continue for **15 minutes** (meanwhile continue with 2.10.3)								

2.11.3 Preparing The Lucas Cell

Remove the blue plastic protective cap from the Lucas cell and nozzle, secure one Lucas cell to the left quick connect port								
Record Lucas Cell #		LC #						
Radon Board	V-261L	OPEN						
Radon Board	V-262L	OPEN						
Cell normally jumps to 20-30 mTorr on FTS and drops to stable pressure <2 mTorr								
Record maximum pressure		Pmax: mTorr						
Record low stable pressure		Pstable: mTorr						
Radon Board	V-261L	CLOSE						
Radon Board	V-262L	CLOSE						

2.11.4 End of Transfer from Trap A to Trap B

V-259L Close at 15 min mark (**end of transfer**)	Radon Board	CLOSE						
Record Pressures **A** and **B** on Rn Extraction Sheet								
V-245L Turn to downward position to pump trap A	Radon Board	OPEN Down						

2.11.5 Transfer from Trap B to the Lucas Cell

			Sample Line			Loop Sample		
Remove the liquid Nitrogen from **Trap B**								
Heat Trap B until it is warm (approx. room temp).								
If pressure on gauge **B** goes above **+600**, open **V-260L** to relieve the pressure and allow the radon to flow into the								
Record Pressure **B** on Extraction Sheet								
Start Transfer to Lucas Cell	V-260L	OPEN						
Record Pressure **B** immediately after start of transfer on Extraction Sheet								
Note transfer start time (or use stop watch):								
Bake **Trap A** for ~ 5 min (start of	Radon Board	Bake						
Close when P < 15 mTorr (end of	V-245L	CLOSE						
Note time: (having allowed transfer to take place for 10 minutes)								
Before removing Lucas cell, note	PT006	mTorr						
Remove the Lucas cell and re-attach the blue caps								
Note Pressure B again	PT006	mTorr						
Close (end of transfer)	V-260L	CLOSE						
Extraction is now complete.								

2.12 Bake Trap B

Use the heat gun to bake Trap B (311-RTR-02). Take care not to point the heat gun at the FTS chamber or the wiring for the pressure gauges A and B. Trap B should be heated until hot to touch (approx. 80°C)								
Radon Board	V-262L	OPEN						
Radon Board	V-261L	OPEN						
Radon Board	V-260L	OPEN						
Radon Board	V-259L	OPEN						
Heat Trap B (~ 3 min)								
Rn Board Close when P <15	V-259L	CLOSE						
Radon Board	V-260L	CLOSE						
Radon Board	V-261L	CLOSE						
Radon Board	V-262L	CLOSE						

2.13 Assay Shutdown

2.13.1 Sample Line Assay Completion

Record amount of air in the 4 foot pipe section **above**	% air							
Notify Detector Operator of assay shutdown and whether or not you are doing another sample line assay								
Record number of currently open sample valve on deck	Valve #							
Close currently open sample line valve	CLOSE							
If doing another sample line assay, go back to the beginning of Section 2.8, otherwise enter “done”								
If done the sample line assays and moving on to a loop sample assay go to Section 2.4 Option 2, otherwise enter “done” again and								

2.13.2 Loop Sample Assay Completion

Record number of currently open loop sample valve	Valve #				
Close currently open loop sample valve	CLOSE				
If doing another loop sample assay, go back to the beginning of Section 2.8, otherwise enter “done”, and go to Section 2.13.					

2.14 System Shutdown at the End of All Assays

2.14.1 Degasser Shutdown

Valve on top of degasser	[Y]	V-215L	CLOSE	
Close MDG outlet	[Y]	V-294L	CLOSE	
Close MDG inlet	[Y]	V-248L	CLOSE	
Record Time		Time		hh:mm

2.14.2 Valve Close List

MDG Skid, P26 outlet	[Y]	V-285L	CLOSE	
Turn down P_{air} to P26 MDG Skid, above control panel	[NN]	PCV-	BACK OFF	
MDG Skid, by P26, compressed air to P26	[Y]	V-170L	CLOSE	
Turn off power to P26 (feed pump toggle switch)	Control Panel		Toggle OFF	
Turn off power to P05 (bottoms pump toggle switch)	Control Panel		Toggle OFF	
Confirm close or close	[Y]	V-550L	CLOSE	
Confirm close or close	[Y]	V-551L	CLOSE	
Confirm close or close skid inlet	[Y]	V-255L	CLOSE	
Confirm close or close skid inlet	[Y]	V-254L	CLOSE	
Downstairs Near P05	[Y]	V-171L	CLOSE	
PDG Pit, by P05, Turn down P_{air} to P05	[NN	PCV-	BACK OFF	
PDG Pit, by P05, compressed air to P05	[Y]	V-172L	CLOSE	
Confirm close or close P05 outlet (downstairs)	[Y]	V-252L	CLOSE	
Confirm close or close sample line return to loop	[V]	V-544L	CLOSE	
Enable cavity autofill		Delta-V	ENABLE	
Confirm close or close loop sample return (downstairs)	[V]	V-470L	CLOSE	
Turn down P_{air} on accumulator regulator (above old chem	[Y]	PCV-	BACK OFF	
Close air supply isolation valve (above old chem area)	[Y]	V-578A	CLOSE	
If using Option #3, close drain valve (PDG pit)	[V]	V-471L	CLOSE	

2.14.3 FTS and Radon Board

FTS, inlet valve	[Y]	V-222L	CLOSE	
FTS, outlet valve	[Y]	V-224L	CLOSE	
Shut off Cooling Switch on FTS	FTS Panel, **(on/off)**		OFF	
Turn off FTS	(Panel, **(0/I)**			
Near Vlad Trap	[Y]	V-539L	CLOSE	
Shut off vacuum pump	Control Panel		OFF	
Vent vacuum pump, at Vlad trap			Vent	
Near Vlad Trap	[Y]	V-247L	CLOSE	
Unplug heat gun, meter for A/B and meter for MDG			Unplug	
Store liquid N2 (fill XRF detector in the junction if needed)			Store	

2.14.4 Return H2O System to Standard Configuration (Option 2 Only)

If Option2: Loop Assay was run, then ask the UPW to increase the outlet pressure between V-536L and the PDG inlet by adding less throttle to V-536L and/or adding throttle to the PDG inlet valve	
Loop adjustment(s) complete UPW's checkmark required here	

2.15 Checklist Completion and Filing

2.15.1 Ultrapure Water Systems Supervisors Review and Sign-off

Signature of the Ultrapure Water System Shift Supervisor	

2.15.2 Copy and File Checklist, Report

* Xerox checklist pages and send the copy to surface with the cell(s)
* File Completed checklist in the “Completed Basket”
* Fill in the "Shift Report"

Notes:

2.16 MDG Extraction Experiment Record Sheet

DATE _____/_____/200____

Operators:_____

MDG EXTRACTION EXPERIMENT

Rn extraction is made from the monitor degasser. On surface the Lucas cell is put onto the appropriate PMT and counted to determine number of Rn atoms extracted.

DESCRIPTION of the EXPERIMENT:_____
_____
_____
_____
_____

COUNTING of the LUCAS CELL

Lucas cell # _____ Segment _____

Start: _____/_____/200 ___, _____ HV On ?? (Y/N) _____
m d time

Stop: _____/_____/200 ___, _____ File Name: _____
m d time

Counts/ Live time:

Bkg: _____ Net Counts/day _____

COMMENTS_____

_____

_____

_____

_____

_____

_____

SETTING UP: Baseline pressures A: B: Alcatel: mTorr

EXTRACTION DETAILS

Extraction: Start_____ Stop_____ Elapsed_____

Lucas cell #_____

Outlet Pressure (PI-120, psig): Inlet Pressure (PI-171, psig):

MDG Temp (°C): Flow Rate (FIT 121, lpm):

Time	MDG	Trap A	Alcatel Pressure (mTorr)	Trap Temp (°C)	Strokes (Sec/20 strokes)	Comments

Total Strokes On Meter: _____

A --> B TRANSFER

A reading when warm:

Start time of transfer:

Stop time of transfer: Transfer duration:

A reading at end of transfer:

B reading at end of transfer:

B --> LC TRANSFER

B reading when warm:

Start time of transfer:

B reading just after start of transfer:

Stop time of transfer: Transfer duration:

B reading with LC attached:

B reading with LC dis-attached: