^{222}Rn Measurements within the Water Phase of the SNO+ Experiment

by

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Abstract

The SNO+ experiment is a large multipurpose scintillator detector. In the first phase of the experiment, close monitoring is done to determine radioactivity background levels, in particular the monitoring of $^{222}\mathrm{Rn}$ as its presence can obscure or mimic physics data. This thesis focuses on a cryogenic technique used to collect and concentrate $^{222}\mathrm{Rn}$ in the water used for the SNO+ experiment. The target level for $^{222}\mathrm{Rn}$ using this system is 3.5×10^{-14} g^{238}U/gH_2O equivalent for the initial water phase. The radon assay technique and resulting measurements are discussed.

Further analysis was done to determine the content and locations of areas within the detector emitting higher than expected rate of events. This is informally known as the "hotspot" problem.

Keywords: neutrino detector, radon assay, backgrounds, SNO+, hotspot

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List of Abbreviations

0$\nu\beta\beta$	Neutrinoless double beta decay
2$\nu\beta\beta$	Double beta decay
AV	Acrylic vessel
cpd	Counts per day
DCR	Detector CleanRoom
DOS	Disk Operating System
GEANT4	GEometry ANd Tracking toolkit developed by CERN
LAB	Linear AlkylBenzene
LC	Lucas cell
lpm	Litres Per Minute
MCA	MultiChannel Analyzer
MDG	Monitor DeGasser
Ra	Radium
RAT	Reactor Analysis Tool
Rn	Radon
PMT	PhotoMultiplier Tube
PDG	Process DeGasser
PSUP	PMT SUPport structure
SNO	Sudbury Neutrino Observatory
SNO+	The next generation SNO experiment
SRAS	Scintillator Radon Assay Skid
Te	Tellurium
TeA	Telluric Acid
UPW	UltraPure Water

List of Symbols

β	Electron
η	Efficiency
n	Neutron
ν	Neutrino

For Dylan Nolan. . .

Chapter 1

Introduction

1.1 Neutrinos

Of massive abundance but small in size and with near zero mass, the neutrino is among the most difficult particles to detect. Like the electron, the neutrino interacts weakly with matter. However, unlike the electron, the neutrino is neutral in charge. Due to these properties, neutrinos can travel immense distances through space, Earth, and even the human body with a very small cross section for interaction.

1.1.1 The Discovery of the Neutrino

> I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.
>
> **Wolfgang Pauli**

Wolfgang Pauli presented the idea of a neutrino in 1930 [50]. At that time, he proposed the neutral particle be known as the neutron. However in 1932, James Chadwick discovered a particle

of neutral charge and mass near that of a proton that was then dubbed the neutron [7]. Thus, Enrico Fermi, a leading expert in neutrons [36], established that Pauli's neutron shall be known as the neutrino, and the search continued.

Neutrinos took their place in the standard model; a topic that will be described in detail on page 3. As reactor technology developed, the discovery of the free neutrino was made 26 years after Pauli's declaration by Frederick Reines and Clyde Cowan [52]. Until this time, there was not a neutrino source in existence powerful enough to use in neutrino observation experiments. With the use of particles emitted from nuclear reactors, they found the electron antineutrino: one of three neutrinos described in the standard model, next to the muon neutrino and the tau neutrino.

The nuclear reactor was expected to emit an antineutrino flux of the order of 10^{12} to 10^{13} neutrinos per second per squared meter via a large tank of water loaded with scintillator and cadmium chloride, as cadmium is an effective neutron absorber. As seen from the inverse beta decay reaction

$$\bar{\nu} + p \rightarrow n + e^{+} \tag{1.1}$$

the resulting positron annihilates with an electron, producing two gamma rays whose signals are picked up by PMTs once they scintillate within the tank. About 5 µs after these 2 signals is the possibility of a third when the neutron is captured by the cadmium. This is what distinguishes the neutrino signal from a background signal. Because of the electron associated with this particular interaction, the neutrino in question was dubbed the electron neutrino, ν_e.

The next neutrino to be discovered was the muon neutrino (ν_μ) in 1962 by Jack Steinberger, Leon Lederman, and Melvin Schwartz, thus proving that neutrinos had "flavours". The muon neutrino was discovered at the Alternating Gradient Synchrotron (AGS) [41] in Brookhaven. At the time, it was the most powerful accelerator in the world. To make the discovery, AGS produced a proton beam to produce a shower of charged or neutral particles known as pi mesons. As they travel, they decay to muons and neutrinos. The neutrinos passed into a spark chamber surrounded by aluminium plates. As neutrinos hit the aluminium, they created muon spark trails that were photographed [42]. Hence the observation of muon neutrinos.

Neutrino flavours all share the same properties, however the method of production could differ. This was shown again in 1976 with the proposal of the tau neutrino (ν_τ) [32] by Martin Lewis Perl. Direct measurement of the tau neutrino did not occur until the year 2000 with the Direct Observation of the Nu Tau (DONUT) experiment [30]. The length of time between the initial proposal and the observation of the tau neutrino was mainly due to the development of accelerator technologies. DONUT required an 800 GeV proton beam, provided by Fermilab's Tevatron, to hit an emulsion target in order to produce products such as tau particles through particle showers. The tau particle would then decay to the tau neutrino, and a measurement on the neutrino's energy could be made.

The Standard Model

The Standard Model is to physicists what the Periodic Table of Elements is to chemists. Started in the 1970s, the Standard Model depicts fundamental particles and how they interact. The table now holds seventeen elementary particles, including the neutrinos, as seen in Figure 1.1. The

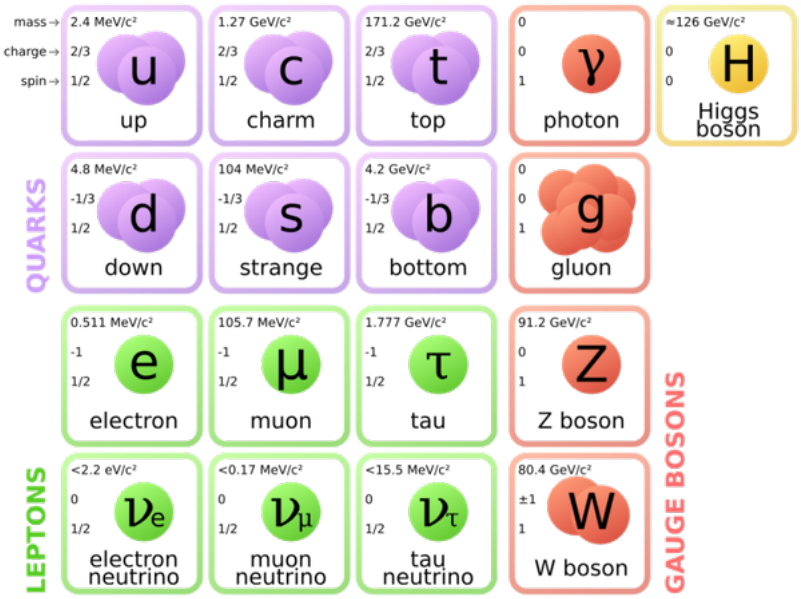


FIGURE 1.1: The Standard Model [48]. The model is divided into two main groups: bosons and fermions. In this figure, fermions are the collective groups of quarks and leptons. They are the fundamental particles that form the matter around us. The bosons are what mediate interactions.

model is divided into two core groups: bosons and fermions. The fermions, with spin 1/2, are essentially the building blocks of matter, and are further divided into two groups: quarks and leptons. The nuclei of protons and neutrons are made of a combination of quarks as they interact with the strong nuclear force, whereas leptons do not. The bosons, with spin 1, are the mediators of fundamental particle interactions. Many of these particles were seen at Gargamelle in CERN in the 1970s [6]. As it was a large bubble chamber, Gargamelle was capable of providing evidence for the existence of quarks and neutrinos.

Physics beyond the Standard Model evolved with the discovery of more than one neutrino. Believed massless, very little was known about neutrinos until the discovery of neutrino oscillations in 2015 (to be discussed). This proved that neutrinos did indeed have a mass, albeit quite small.

1.2 Neutrino Sources

Neutrinos may come from several sources, such as nuclear reactors and supernovae. However one of the sources studied the most are neutrinos from the Sun. These neutrinos are produced via fusion processes in the Sun's core known as the proton-proton (pp) chain (Figure 1.2) and proton-electron-proton (pep) chain where each process emits neutrinos at different energies. These energies once detected are used to determine the fusion process which produced the neutrino, and thus the neutrino is labelled using the resulting fusion process. The expected neutrino spectrum is shown in Figure 1.3, where the basics for the solar interior such as temperature originate from the Standard Solar Model (SSM) [59].

Predicted energy fluxes did not correlate to what was found experimentally. Experiments such as Kamiokande (which later upgraded to become Super-Kamiokande) used water to search for neutrino scattering with an electron. Gallex (which later upgraded to become GNO) and Sage used gallium to observe inverse beta decay with the electron neutrino. All these experiments reported less than 60% of the total expected solar neutrino flux and can be seen in figure 1.4). This became known as the Solar Neutrino Problem (SNP) and was what prompted the design for the Sudbury Neutrino Observatory (SNO). The SNP suggested that either the neutrino flux calculations were incorrect, and as such the solar model for neutrino production was not adequate or that neutrinos oscillate and change flavours, the latter of which we now know to be true.

In October of 2015, Arthur McDonald was awarded the Nobel Prize in Physics alongside Takaaki Kajita for their contributions to the discovery of neutrino oscillations [58].

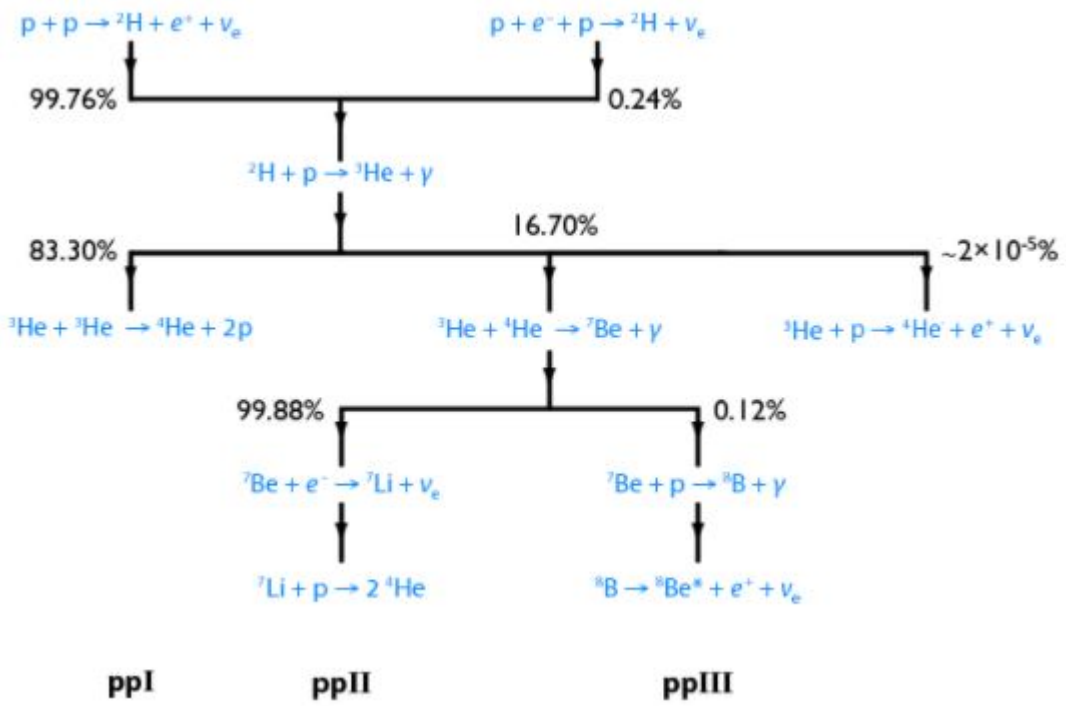


FIGURE 1.2: The proton-proton chain describes the process of converting Hydrogen to Helium within the Sun's core through fusion reactions. In turn, energy and neutrinos are created. [22]

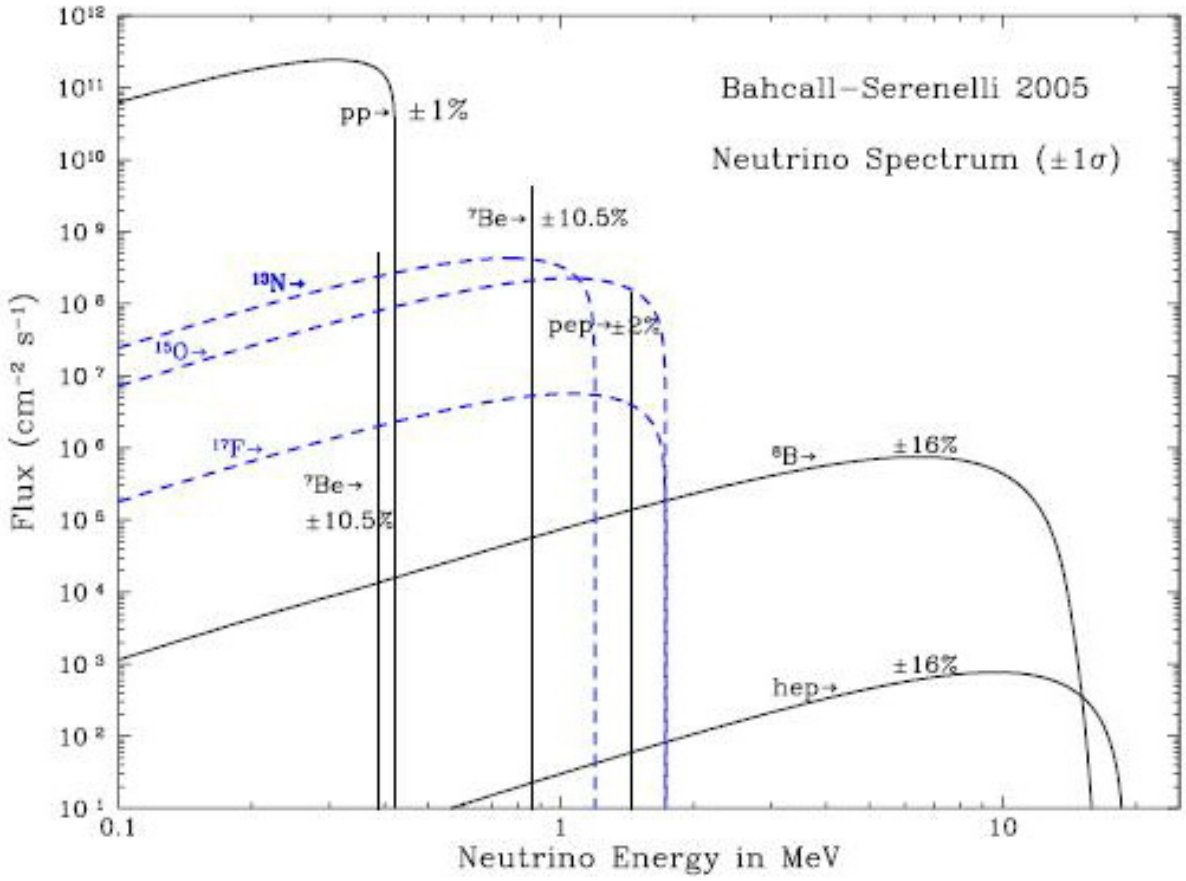


FIGURE 1.3: The calculated solar neutrino energy spectrum, within 1 standard deviation uncertainty. It is based on the Standard Solar Model (SSM), which describes the basic information for the solar interior [59][38].

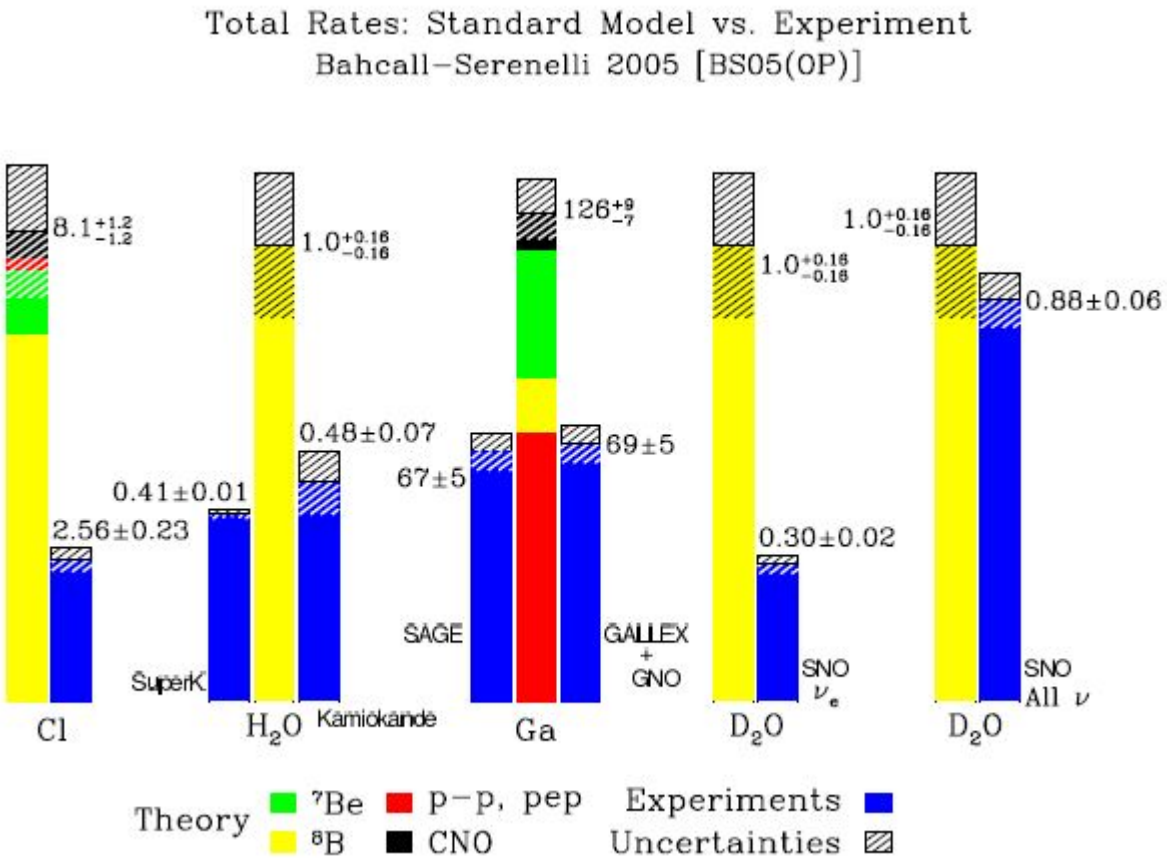


FIGURE 1.4: The Solar Neutrino Problem [2]. Several experiments are shown here using different mediums of neutrino detection, alongside the expected number neutrinos from the Sun. Each experiment reported observing fewer than 60% of the expected neutrinos, except for the SNO experiment for neutral current interactions.

1.3 The Neutrino Mass Problem

Neutrino oscillation measurements cannot define the mass of the neutrino; rather the neutrino mass is determined through differences in mass states. The probability of a neutrino oscillating whilst propagating through vacuum of either flavour eigenstate can be represented by equation 1.2. In this case, L is the travel distance for the neutrino, E is energy, and the difference in mass eigenstates is represented by $\Delta m^2_{ij} = m^2_i - m^2_j$, where m_i is the mass of the *i*th neutrino mass eigenstate [18].

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = \sum_i [U_{\alpha i} U^*_{\beta i}] - 4 \sum_{i>j=1}^{3} \left[Re(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}) sin^2 \left(\frac{\Delta m^2_{ij} L}{4E} \right) \right] \\ +2 \sum_{i>j=1}^{3} \left[Im(U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}) sin \left(\frac{\Delta m^2_{ij} L}{4E} \right) \right] \end{aligned} \tag{1.2}$$

The lepton mixing matrix U_{ij}, known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, represents the flavour to left-handed neutrino mass eigenstates transformation:

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle \tag{1.3}$$

where the matrix components of $U_{\alpha i}$ are [17]:

$$
\begin{aligned}
U_{PMNS} &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \\
&= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P \\
&= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} P
\end{aligned}
$$

where $c_{ij} = cos\theta_{ij}, s_{ij} = sin\theta_{ij}$ with θ_{ij} being the mixing angle, and δ_{CP} is a CP violating phase. Mixing angles are within the range of $0 \leq \theta \leq \pi/2$, and the phase is $0 \leq \delta_{CP} \leq 2\pi$. The *P* matrix is what will distinguish the PMNS matrix from the Majorana case and the Dirac case, which is further explained in Section 1.4. If neutrinos are found to be Dirac, then *P*$= 1$. In the Majorana case, the *P* matrix is of the form seen in equation 1.4.

$$
P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i(\phi_3 + \delta_{CP})} \end{pmatrix} \tag{1.4}
$$

The ϕ terms are Majorana phases.

Over the last several decades, experiments have been successful in confirming the PMNS matrix and its values. The next steps are to place a limit on θ_{23}, the neutrino ordering (Section 1.4) and ultimately the neutrino mass, and claim a measurement of the CP violating phase.

The existence of CP violation plays a key role in explaining why there is more matter than antimatter in the universe, as it had to occur within seconds after the Big Bang. If CP symmetry was preserved at the moment of the Big Bang, equal parts matter and antimatter would have been produced. These equal parts would then have annihilated, and we would not exist today.

Determining the CP phases from the PMNS matrix above can only be true if neutrinos are Majorana particles. In other words, neutrinos would be their own antiparticle. This can be determined experimentally through the rare process known as neutrinoless double beta decay.

1.4 Neutrinoless Double Beta Decay

In 1935, Maria Goeppert-Meyer first proposed the concept of double beta decay. $2\nu\beta\beta$ is a second order weak decay in which 2 neutrons convert to 2 protons whilst emitting 2 electrons and 2 antineutrinos, as seen in equation 1.5 [8] and Figure 1.5. Another possibility is presented in equation 1.6 where protons decay to neutrons and emit 2 positrons and 2 neutrinos, because in those elements single beta decay is not seen as it is not energetically allowed.

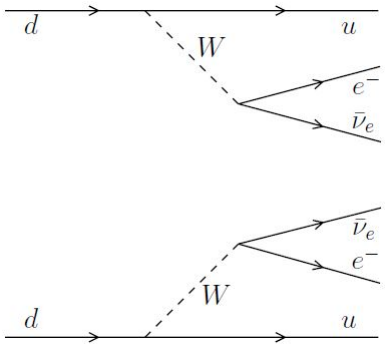


FIGURE 1.5: Feynman diagram of double beta decay [19]

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{X}' + 2e^- + 2\bar{\nu}_e \tag{1.5} $$

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-2}\mathrm{X}' + 2e^+ + 2\nu_e \tag{1.6} $$

In 1939, W. H. Furry proposed the more controversial topic of neutrinoless double beta decay. By the name alone, this reaction is similar to double beta decay in which 2 neutrons convert to 2 protons whilst emitting 2 electrons, with the most important difference being no antineutrinos are emitted, as seen in equation 1.7, and is commonly referred to as neutrinoless double beta decay ($0\nu\beta\beta$).

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+2}\mathrm{X}' + 2e^- \tag{1.7} $$

The expected energy spectra for $0\nu\beta\beta$ can be seen as the small peak in Figure 1.6 due to all the energy being captured by only the electrons. Due the non-ideal energy resolution, the $2\nu\beta\beta$ peak can obscure the $0\nu\beta\beta$. In addition, unknown backgrounds will also mask the expected data. This topic will be further discussed in Chapter 3. Therefore excellent energy resolution

Isotope	Energy Q (MeV)	Natural Abundance (%)	Halflife Limit(yrs)
^{48}Ca	4.2737	0.187	>1.4$\times10^{22}$ [25]
^{76}Ge	2.0391	7.8	>3.0$\times10^{25}$ [31]
^{82}Se	2.9551	9.2	>1.0$\times10^{23}$ [33]
^{100}Mo	3.0350	9.6	>1.1$\times10^{24}$ [34]
^{130}Te	2.5303	34.5	>4.0$\times10^{24}$ [28]
^{136}Xe	2.4578	8.9	>1.1 $\times10^{25}$ [26]
^{150}Nd	3.3673	5.6	>1.8 $\times10^{22}$ [27]

TABLE 1.1: Isotopes producing $0\nu\beta\beta$ and their natural abundances and energies [37].

and highly controlled backgrounds are imperative to the discovery of $0\nu\beta\beta$.

Some of the isotopes that will produce $0\nu\beta\beta$ are described in Table 1.1 along with their respective end point energies.

The square of the effective Majorana mass, $\langle m_{ee}\rangle^2$ is proportional to the neutrinoless double beta decay rate, $\Gamma^{0\nu\beta\beta}$ as seen in equation 1.8, where $G_{0\nu}$ is the phase space factor and $M^{0\nu\beta\beta}$ is the nuclear matrix element.

The neutrino mass is still unknown, however each tau, muon, and electron neutrino mass is ranked according to the normal or inverted hierarchy (see Figure 1.7). Each composition of mass eigenstates is known, however the ordering is not. Experiments like SNO+ will probe the inverted hierarchy, aiming to set limits on m_{ee} until detector enhancements can be made to probe the normal hierarchy regions.

$$\Gamma^{0\nu\beta\beta} = G_{0\nu}|M^{0\nu\beta\beta}|^2\langle m_{ee}\rangle^2 \tag{1.8}$$

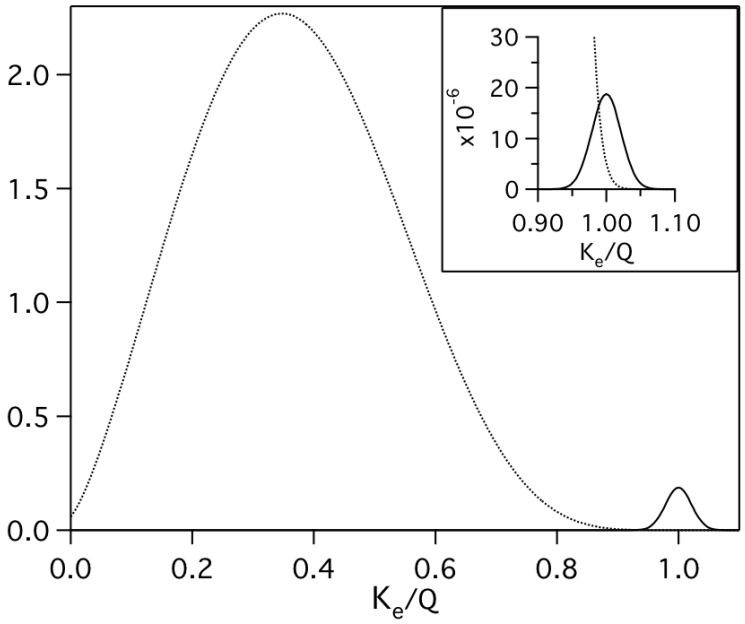


FIGURE 1.6: The ideal $0\nu\beta\beta$ spectrum, where the large peak on the left on the image is the expected energy spectrum for double beta decay, and the small peak on the right is the expected neutrinoless double beta decay energy spectrum. Experimentally, there is an expected overlap between the $2\nu\beta\beta$ and $0\nu\beta\beta$ spectra, resulting in the plot in the upper right corner. In both plots, the y-axes have arbitrary units.

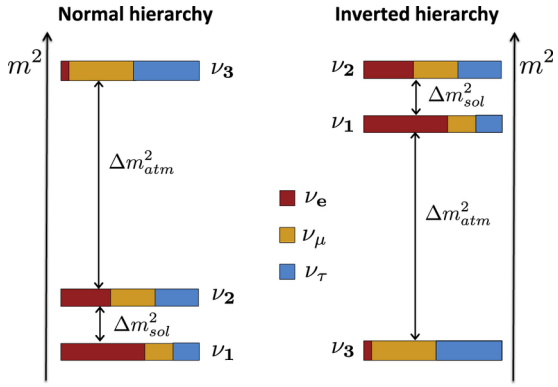


FIGURE 1.7: Inverted and normal mass hierarchy [40] in terms of mass squared. Each line is a flavour composition of mass eigenstates. $\delta m^2_{atm} \sim |\delta m^2_{31}| \sim |\delta m^2_{32}|$ and $\delta m^2_{sol} \sim \delta m^2_{21}$ [51].

Chapter 2

The SNO+ Experiment

SNO+, located at SNOLAB in Sudbury, Ontario, inherited much of its hardware from the previous SNO experiment. SNO was an experiment first proposed in the 1980s to observe neutrino flavours for neutral current interactions. The environment necessary for such an observation required shielding from non-neutrino particles such as muons, as they would obscure the data. The rocky terrain found within the Canadian Shield, and the Greater Sudbury region in particular was found to be norite rock; a natural shield against cosmic rays. Hence the idea to build a detector within a mine was pursued. SNO was built inside a cavity 2 kilometers underground in an active mine, resulting in 5890 ± 94 meters water equivalent (m.w.e) overhead. With the increasing success of the SNO experiment came the development of SNOLAB. Now a world-leading physics laboratory featured as a Class 2000 cleanroom, SNOLAB hosts a range of particle physics experiments and non-physics experiments, and can be seen in Figure 2.1. Figure 2.2 compares SNOLAB to other physics laboratories in the world, and how to depth of the lab protects against unwanted cosmic rays, especially muons.

SNO+ repurposed the SNO detector to be a multipurpose liquid scintillator detector designed to search for neutrinoless double beta decay ($0\nu\beta\beta$) and solar neutrinos, along with other neutrino

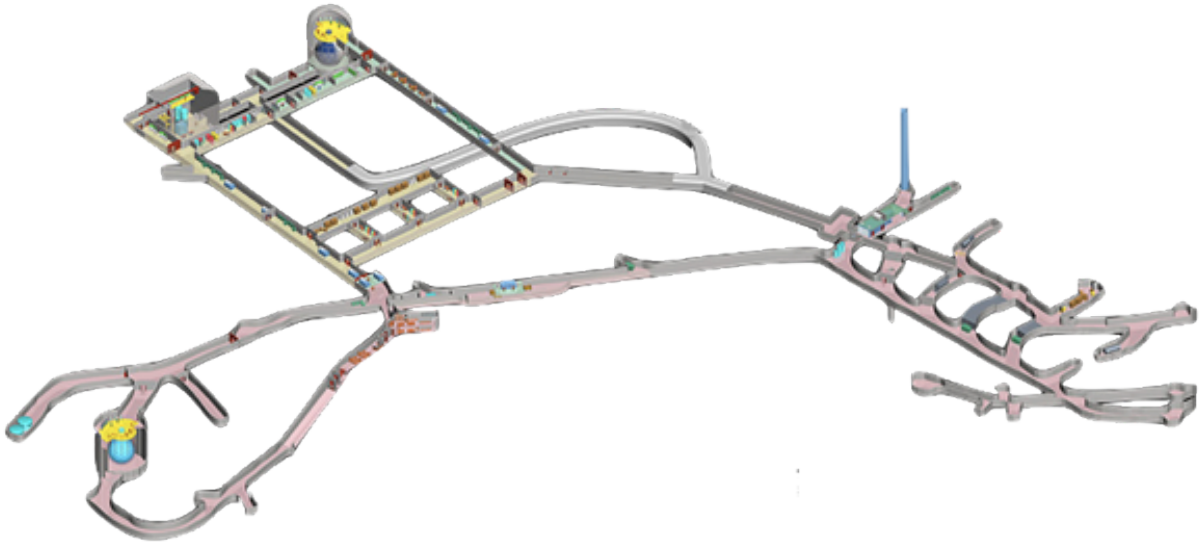


FIGURE 2.1: An interior schematic of SNOLAB. Various physics experiments are being run or built within SNOLAB, the most significant to note being the SNO+ experiment, located at the far left of the drawing and depicted as a bright blue sphere. [1]

physics as seen in Table 2.1. The existing 12 m diameter acrylic vessel (AV) will be taking data in 3 stages: ultrapure water, scintillator, and tellurium-loaded scintillator. This AV is surrounded by a PMT support structure (PSUP) which as its name implies, hosts over 9,500 photomultiplier tubes (PMTs) (see Figure 2.3. The vast majority of these PMTs face inwards to detect photons from particle interactions withing the AV, offering 54% effective coverage. Some will face outwards, and are known as OWLs. If the OWLs detect a signal, it signifies that an interaction occurred outside of the AV, and is then likely identified as muons.

The SNO detector held a medium much denser than water within the AV: deuterium oxide ($\mathrm{D_2O}$) or heavy water ($\rho = 1.108 g/cc$). To keep the AV from dropping in height due to the heavier mass inside compared to outside the AV, 10 sets of tension ropes were added all along the equator of the acrylic to account for the heavier mass. Now with SNO+, the proposed plan is to fill the AV with a liquid scintillator known as Linear Alkyl Benzene (LAB), which has a density lower than

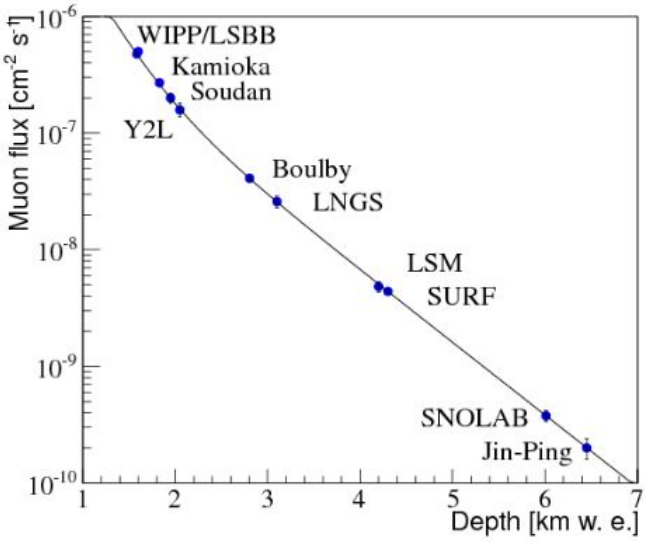


FIGURE 2.2: Expected muon flux as a function of meters water equivalent (m.w.e.) for various underground laboratories. SNOLAB is amongst the deepest laboratories in the world, and provides excellent shielding from muons due to the overbearing norite rock. [21]

water at 0.86 g/cm^3. The UPW within the cavity will exert a buoyant force upon the LAB-filled AV, thus another transformation from SNO to SNO+ was to add a hold-down rope net.

2.1 Phase I: Water

The water phase is important to the function of the SNO+ detector as it is the main calibration phase. It is also required as a starting point to fill the AV with scintillator by volume displacement, as well as to examine backgrounds due to leaching. Filling the acrylic vessel with ultrapure water (UPW) ensures the impurities within the acrylic will leach-out of the vessel into the water, whilst primarily observing the leaching of $^{210}\mathrm{Pb}$ (a daughter isotope of $^{222}\mathrm{Rn}$). The water can be recirculated through the UPW plant, where it is stripped of impurities and returned to the detector. The water phase also offers the opportunity to calibrate the detector's electronics,

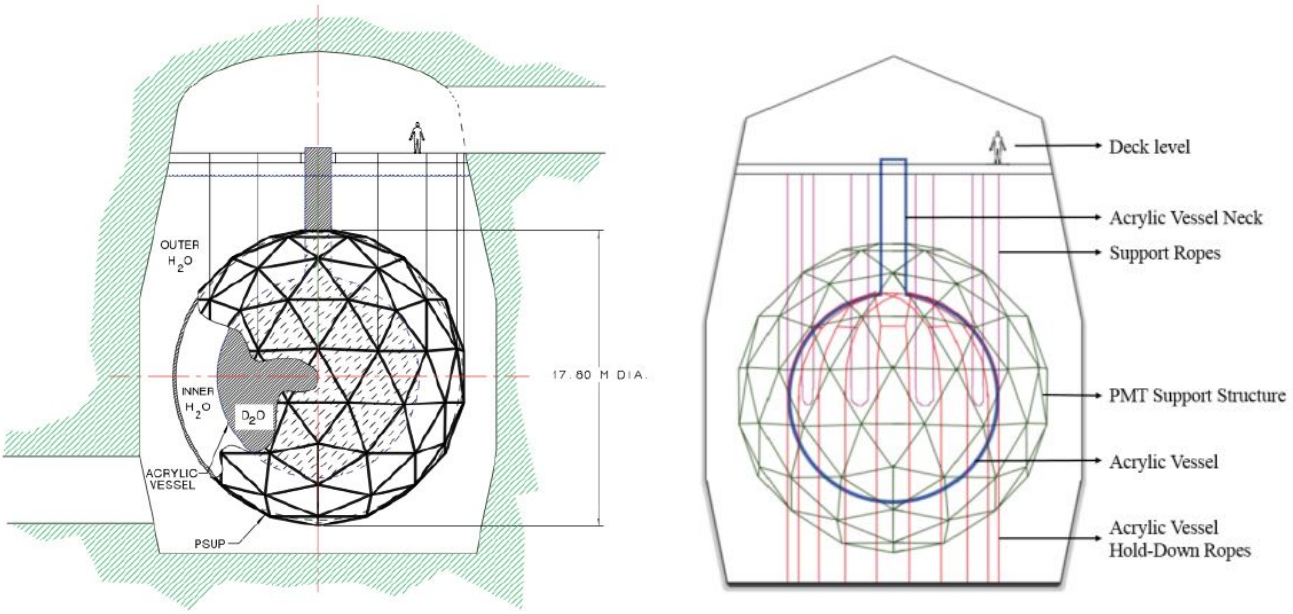


FIGURE 2.3: On the left is the SNO, with its hold up ropes visible as the vertical lines from the AV to the deck. On the right is SNO+; essentially the same as SNO visually, but with the addition of hold down ropes.

Target	Phase I	Phase II	Phase III	Goals
Nucleon decay	✓			Improve neutron and proton lifetime limits to $> 10^{30}$ years
Reactor antineutrinos	✓	✓		Constrain neutrino oscillation parameters
Geo-antineutrinos	✓	✓		Constrain radiogenic heat flow of the Earth
Supernova	✓	✓	✓	Study supernova neutrinos, join SNEWS
Solar neutrinos	✓	✓		Uncover metallicity of the Sun, further understanding of neutrino oscillations
$0\nu\beta\beta$			✓	Determine Majorana or Dirac properties of neutrinos

TABLE 2.1: Goals of each phase of the SNO+ experiment [53]. Although the primary goal is to observe neutrinoless double beta decay, SNO+ has devised various physics targets it would like to accomplish throughout the data taking process.

test the data acquisition systems, and determine how to deploy and analyze calibration sources. Such sources include the N16 source (a gamma source), the laserball (a light source), and an AmBe source (a neutron source). The N16 and AmBe sources emit signals at known energies, which when detected by the PMTs, allows for Monte Carlo versus data comparisons.

During this phase, SNO+ will be setting a limit on invisible nucleon decay, a process that defines baryons as unstable and will therefore decay. The Grand Unified Theory (GUT) predicts such a process as it looks to correlate baryons and leptons [4]. The lifetime of this decay exceeds that of the Universe; the current estimate is over 10^{30} years. Specifically, the halflife is expected to be $\tau_n = 1.25 \times 10^{30}$ years for the neutron, and $\tau_p = 1.38 \times 10^{30}$ years for the proton. The energies are also estimated to range from 10^{14} to 10^{16} GeV [57], which cannot be reached directly accelerators to detect, but can be explored indirectly with large Cherenkov detectors such as SNO+. Examples of what the decay might look like can be seen in equation 2.1. SNO had set the best neutron disappearance limit of $\tau(n \rightarrow inv) > 1.9 \times 10^{29}$ years [35]. The experiment could not obtain a more accurate measurement as it was dominated by ^{8}B background. The best limit currently has been set by Kamland, with $\tau(n \rightarrow inv) > 5.8 \times 10^{29}$ years [13].

$$p \rightarrow (e^+, \mu^+)\pi^0 \qquad\qquad p \rightarrow \nu K^+ \tag{2.1}$$

The lifetime measurements are found using equation 2.2, where the number of expected nucleons is 2.4×10^{32} [13], ϵ is the efficiency of detecting the decay in the signal window, f_T is the livetime, and $S_{90\%}$ is the expected signal events at 90% confidence.

$$\tau = \frac{N_{nucleons} \epsilon f_T}{S_{90\%}} \tag{2.2}$$

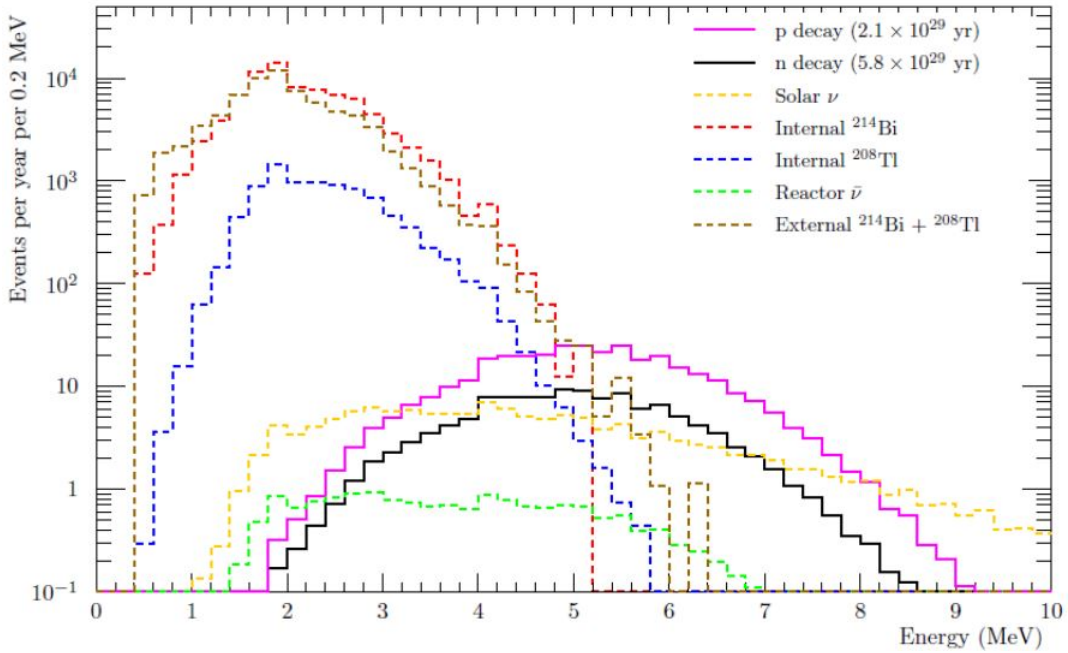


FIGURE 2.4: Simulated energy spectrum of backgrounds from neutrino sources and uranium and thorium decays, to be discussed further in Chapter 3. The solid pink and black lines show the energy spectrum from proton and neutron decay, respectively.

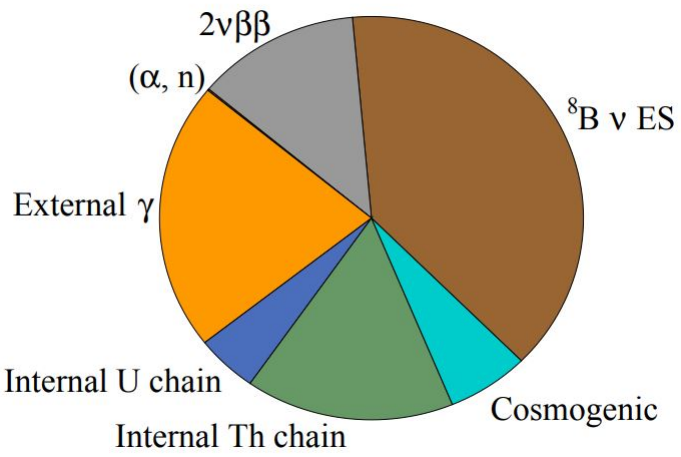


FIGURE 2.5: Simulated backgrounds within the SNO+ detector within the ROI after 1 year of data taking. This chart includes fiducial volume, energy, and life-time cuts. The components are are irreducible except for the internal U and Th chain, as well as the cosmogenics.

The expected proton and neutron decay can be seen in Figure 2.4 for the SNO+ experiment. The proton decay is depicted in pink, and the neutron decay is black. The dashed lines are expected backgrounds from the Sun and detector elements, where backgrounds are non essential and undesired events. The specific backgrounds will be discussed in depth in Chapter 3. It is critical to note that given these backgrounds, the decays will be difficult to distinguish. Therefore it is essential to aim for as low of backgrounds as possible. The simulated target background budget is shown in Figure 2.5. This pie chart represents 1 year of data taking within the region of interest (ROI) for phase III. Fiducial volume cuts, energy cuts, and lifetime have already been excluded, and what is left are irreducible backgrounds, such as ^8B, $2\nu\beta\beta$, (α, n), and external gammas as well as the backgrounds that can be reduced such as the internal U and Th chains and cosmogenics. The expected backgrounds for the U chain can be seen in Table 2.2. The internal water background is based off of results from the SNO experiment. The internal scintillator background is derived from what the Borexino experiment observed, as well as tests run by the SNO+ experiment on the scintillator purity. During Te-loading, the backgrounds will be expected to increase from the scintillator phase as $^{130}\mathrm{Te}$ is being introduced.

2.2 Phase II: Scintillator

As the water is being drained from the bottom of the detector, LAB will be added to the top for the simplest method of volume replacement. The slow fill will allow for further background studies in preparation of Phase III. Observations of solar, reactor, and geo-neutrinos will take place as well. By observing reactions expected from the Sun's core, SNO+ can make significant contributions towards determining the solar neutrino flux from the Carbon-Nitrogen-Oxygen (CNO) cycle. This measurement will help determine the Sun's elemental composition, or solar

Phase	Internal g^{238}U/g
Water	3.5 $\times 10^{-13}$
Scintillator	1.6 $\times 10^{-17}$
Te-Loading	3.5 $\times 10^{-14}$

TABLE 2.2: Target background levels in terms of gU/g of material for the 3 stages of data taking in SNO+

metallicity [20].

2.3 Phase III: Tellurium Loading

0.5% of natural tellurium will be added to the liquid scintillator in order to commence the search for neutrinoless double beta decay. To do this, tellurium in the form of telluric acid $Te(OH)_6$ will be reacted with 1,2 butanediol, which forms Te-diol. It is then dissolved in the liquid scintillator [54]. The total expected Te mass within the AV will be 1600 kg [5].

2.4 $0\nu\beta\beta$ in SNO+

The effective Majorana neutrino mass $m_{\beta\beta}$ is proportional to the half-life $\tau^{0\nu}_{1/2}$ of the $^{130}\mathrm{Te}$ $0\nu\beta\beta$ decay, as seen in Equation 2.3. The half-life is a function of the detector efficiency ϵ, the number of $^{130}\mathrm{Te}$ atoms in the detector, the data collection time T, the Gaussian significance level σ, a mass-dependent background factor that is dependent on the amount of isotope loading b, the total mass of $^{130}\mathrm{Te}$ used in the detector, a constant background C, and the width of the energy in the region of interest δE [53][3][54].

$$(m_{\beta\beta})^{-2} \propto \tau_{1/2}^{0\nu} = \frac{\epsilon N_{^{130}Te} \ln(2) T}{\sigma \sqrt{(bM + C) \cdot T \delta E}} \tag{2.3}$$

Chapter 3

SNO+ Backgrounds

Backgrounds within experiments, particle physics experiments in particular, are detrimental to the results obtained if they are too high. The search for rare interactions such as $0\nu\beta\beta$ occur at very low energies. If there are enough backgrounds present, the signals from these physics interactions will be hidden below the backgrounds.

The first step SNO+ has taken to reduce such backgrounds is enhancing the existing SNO detector placed 2km underneath norite rock, as mentioned in Chapter 2. SNOLAB is the second deepest lab in the world, next to China's JinPing Underground Laboratory which sits at 2.4km beneath the surface of the Earth. For SNOLAB, such a depth results in a reduced muon flux of $0.27\mu/m^2/$day. Other backgrounds are irreducible, such as $2\nu\beta\beta$ decay, whilst others are extrinsic such as internal backgrounds, activated cosmogenics, and external backgrounds. Most backgrounds can be traced to Uranium (see Figure 3.2) and Thorium decay chains (see Figure 3.3). In the case of SNO+, the expected rates of those backgrounds within 1 and 5 years of data taking can be seen in Table 3.1. Internal backgrounds include everything listed in Table 3.1 except for the external counts. External backgrounds originate from sources such as PMTs, the norite rock, and the ropes. Low counts are seen for the external backgrounds as the sources are far from the fiducial volume.

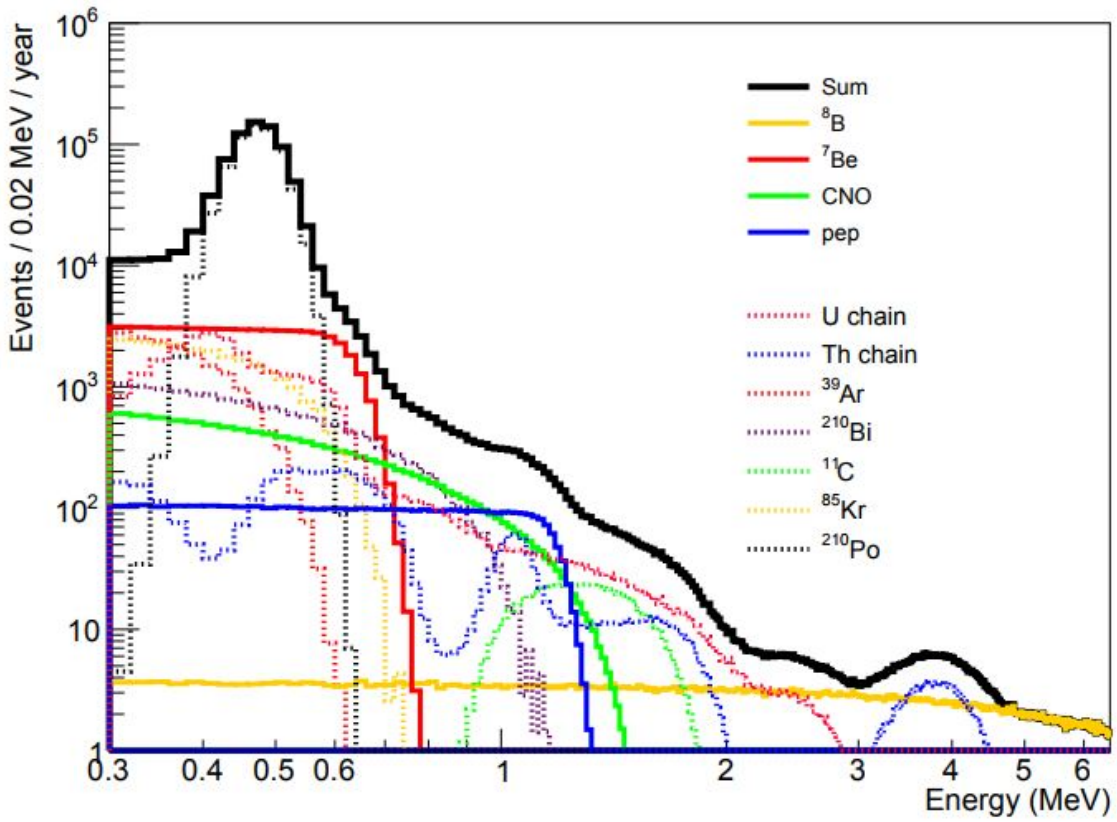


FIGURE 3.1: Simulated solar event spectrum within the scintillator phase of SNO+. The total rate is shown as the solid black line, and the expected backgrounds such as the U and Th chain are represented as dashed lines.

3.1 Backgrounds in SNO+

The backgrounds in SNO+ are described here:

- Internal Backgrounds

  Signals which are considered non-physics events and occur inside the AV are known as

Background	1 Year	5 Years
$2\nu\beta\beta$	6.3	31.6
$^8B\nu$ 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
Cosmogenics	0.7	0.8
Total	**21.8**	**106.8**

TABLE 3.1: Expected backgrounds in the region of interest (R.O.I) and 3.5m fiducial volume (FV) for $0\nu\beta\beta$ in SNO+. Listed are the expected counts after 1 year and after 5 years of data taking. All sources listed are considered internal backgrounds except for external.

internal backgrounds. Several isotopes are of concern, particularly $^{238}\mathrm{U}$, $^{214}\mathrm{Bi}$, $^{210}\mathrm{Th}$, and $^{210}\mathrm{Bi}$. Of particular interest to this thesis, $^{238}\mathrm{U}$ will decay to isotopes with significantly long half-lives, until $^{226}\mathrm{Ra}$ is reached, at which point comparatively short and detectable half-lives will occur.

- **$2\nu\beta\beta$**

  As discussed in Section 1.4, double beta decay presents itself as one of the most dominant backgrounds for SNO+ since it is essentially a consequence of the search for neutrinoless double beta decay.

- **^8B**

  Boron solar neutrino flux via elastic scattering is another inevitable background that arises from the pp and pep chains, as explained in Section 1.2. As can be seen from Figure 3.1,

the ^8B background is a nearly flat irreducible continuum. This has the positive outcome that the SNO+ experiment can measure ^8B accurately enough to contribute towards the solar metallicity problem [11].

- Uranium and Thorium Chains

  As $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$ decay, the resulting alphas, betas, and gammas at sufficient energies will produce light in the detector. The biggest backgrounds in the region of interest for SNO+ are ^{214}Bi-Po and ^{212}Bi-Po, which can be detected and identified using β-α delayed coincidence.

- External Backgrounds

  External backgrounds are of concern as they are detected within the AV, however their source is outside of the AV. Such sources include the cavity water, the hold-up and hold-down ropes, the PSUP, the PMTs, and the surrounding rock. Over the course of the SNO experiment, the PMTs proved to be one of the larger sources of external backgrounds due to the radiation in their bases. Methods used to reduce the noise include darkening the entire area above the detector and limiting the number of people who work on deck, as well as cooling the cavity water ensure a low PMT break-down rate. It is also essential to make note of disturbances so as to exclude them from the analyses.

  Disturbances could easily be seen using a software known as XSNOED. Displayed are all 19 crates holding the electronics of SNO+. Each PMT is denoted as a square pixel on the screen. Certain event pathologies are known from the days when SNO was operating as the same software was used. Both physics and non physics events can be monitored in

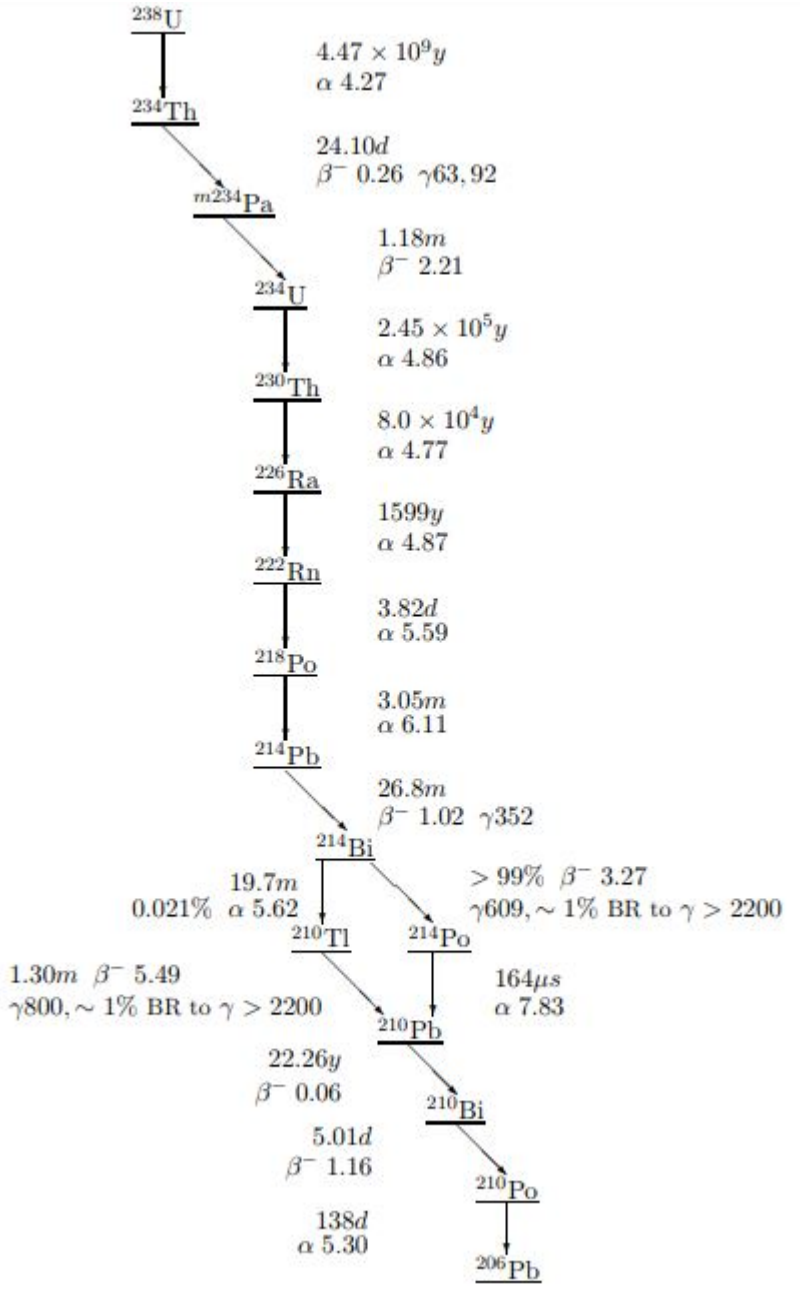


FIGURE 3.2: Uranium decay chain. Diagonal arrows designate beta decays, with the beta energy in MeV and gamma energy in keV. The vertical lines are alpha decays, with Q values in MeV. [49]

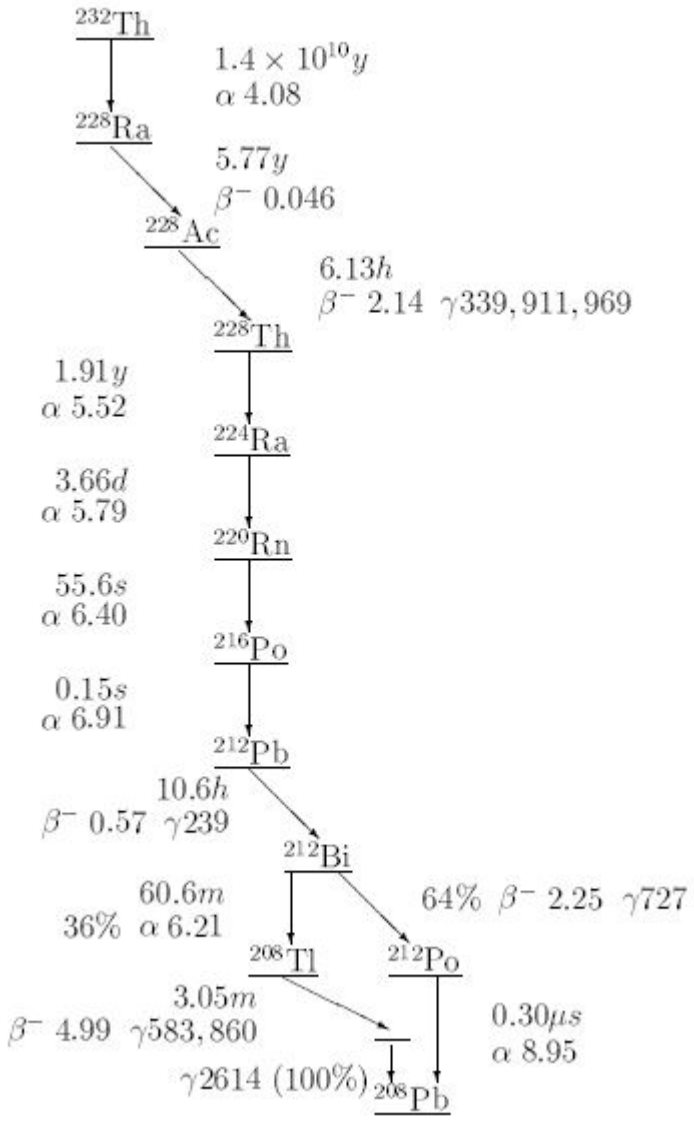


FIGURE 3.3: Thorium decay chain. Diagonal arrows designate beta decays, with the beta energy in MeV and gamma energy in keV. The vertical lines are alpha decays, with Q values in MeV. [49]

live time.

- (α, n)

  The alphas produced from the decay of $^{238}\mathrm{U}$ and $^{232}\mathrm{Th}$ can in turn produce neutrons through interactions with $^{2}\mathrm{H}$, $^{17}\mathrm{O}$, $^{13}\mathrm{C}$, and $^{18}\mathrm{O}$; the last two of which are present in LAB and ^{2}H and ^{1}7O are present in the little amount of water that remains from Phase I. During thermalization, the neutrons will scatter from protons, resulting in light in the detector at the region of interest.

- Cosmogenically Activated Backgrounds

  The cosmogenics are considered short-lived compared to the radioactivity from U and Th chains. Cosmogenic muons are particularly troublesome in that they can create fast neutrons and radioactive products within their region of interest for $0\nu\beta\beta$ decay. An example of cosmogenics, like the cosmogenic activations expected within UPW, can be seen in Table 3.2. Of main concern are $^{22}\mathrm{Na}$, $^{26}\mathrm{Al}$, $^{60}\mathrm{Co}$, and $^{208}\mathrm{Bi}$, all of which can be further reduced by storing materials underground for an extended period of time.

3.2 Cover Gas

A cover gas system is being put in place at the top of the detector to functions as a barrier from the lab air. SNOLAB has a high amount of Rn in the air; approximately 150 Bq/m^3 (SNOLAB surface lab air is around 9 Bq/m^3) as measured here: [43]. The gas will consist of nitrogen, and

Isotope	**decays/t/y**	**% in ROI and FV**	**decays/t/y in ROI and FV**
^{22}Na	6.87E+00	6.6	4.54E-01
^{26}Al	4.34E+00	0.29	1.26E-02
^{42}K	1.89E-03	1.6	3.02E-05
^{44}Sc	2.62E-05	5.34	1.39E-06
^{46}Sc	1.34E-01	0.03	4.01E-05
^{56}Co	1.99E-01	0.011	2.19E-05
^{58}Co	2.61E-01	0.002	5.21E-07
^{60}Co	3.16E-01	11.97	3.78E-02
^{68}Ga	2.47E-02	0.74	1.83E-04
^{82}Rb	2.76E-04	2.21	6.11E-06
^{84}Rb	4.49E-02	0.14	6.28E-05
^{88}Y	9.07E-02	8.99	8.16E-03
^{90}Y	1.34E-04	0.0002	2.68E-10
^{102}Rh	1.75E-02	0.003	5.25E-07
^{106}Rh	1.39E-04	1.29	1.79E-06
^{110}Ag	1.85E-05	0.28	5.17E-08
^{110m}Ag	1.36E-03	4.41	5.99E-05
^{124}Sb	1.62E-03	4.84	7.86E-05
^{126}Sb	2.84E-06	1.94	5.51E-08
^{126m}Sb	4.16E-04	3.57	1.48E-05
^{134}Cs	8.40E-02	$\sim$1.00E-06	8.40E-10
^{144}Pr	3.53E-05	$\sim$3	1.06E-06
^{144}Pm	1.44E-03	$\sim$0.03	4.32E-07
^{146}Eu	6.38E-04	$\sim$15	9.57E-05
^{148}Eu	8.47E-04	$\sim$12	1.02E-04
^{172}Lu	5.17E-03	$\sim$1	5.17E-05
^{188}Re	7.11E-08	$\sim$3.00E-06	2.13E-15
^{194}Ir	2.15E-04	$\sim$0.002	4.30E-09
^{194}Au	1.04E-03	$\sim$0.4	4.16E-06
^{208}Bi	1.31E-02	$\sim$87	1.14E-02
Totals	1.24E+01		5.24E-01

TABLE 3.2: Expected background cosmogenics found UPW. Also shown if the percentage expected within the region of interest (ROI) and the fiducial volume (FV) [47].

will be siphoned into 2 systems: one will cover the AV target material, and the other will cover the cavity water. Cavity water must remain with as low of backgrounds as possible as external backgrounds contribute towards the background budget.

Chapter 4

Radon Assays in SNO+

Backgrounds emanating from the surrounding cavity wall and SNO+ materials are attenuated by ultrapure water (UPW). Over time, the possibility of significant amounts of radiation, such as radon, can build in the UPW. Constant monitoring of the water is necessary to watch for this growth, and determine the sources of radioactivity. Monitoring the water can be achieved in a few ways, however this thesis will focus on the radon assay technique.

UPW contamination would be detrimental to the experiment, as the effects of radiation obscure the physics data, as discussed in Chapter 3. In the days of the SNO experiment, $^{238}\mathrm{U}$ levels were measured to be 3.5×10^{-13} g^{238}U/gH_2O, and will therefore be the set target for SNO+. Such a target is difficult to achieve as sources of contamination are prominent everywhere, inside and outside the detector. Concentrations this small therefore require innovative experimental techniques, like the one described in this chapter. Comparisons to prominent neutrino experiments such as KamLand and Borexino are shown in Table 4.1, which set the target values for SNO+. Expected radiopurity levels throughout the SNO+ detector are shown in Table 4.2. The units expressed in the tables have varied over the years, therefore the following conversions (equation **??**) can be applied in order to compare with other values in the tables:

Isotope	Location	Kamland Level (g/g)	Borexino Level (g/g)
^{238}U	Internal	5.60×10^{-17} [29]	1.60×10^{-17} [16]
^{232}Th	Internal	3.40×10^{-18} [29]	6.80×10^{-18} [16]
^{210}Pb	Internal	$\sim 10^{-20}$ [39]	6.11×10^{-25}
^{210}Bi	Internal	$\sim 6 \times 10^{-24}$	3.78×10^{-28} [23]
^{210}Po	Internal	$\sim 2 \times 10^{-22}$	4.15×10^{-24} [23]
^{40}K	Internal	2.70×10^{-16} [39]	$< 1.30 \times 10^{-18}$ [23]
^{39}Ar	Internal	1.84×10^{-19} [39]	$< 2.75 \times 10^{-24}$ [23]
^{85}Kr	Internal	3.68×10^{-20} [39]	$< 2.40 \times 10^{-25}$ [23]
^{14}C	Internal	1.00×10^{-18}	1.00×10^{-18} [23]

TABLE 4.1: Target radiopurity levels for the SNO+ experiment as compared to the KamLAND and Borexino experiments [9].

$$\begin{aligned} 1\text{ppm} &= 10^{-6}\text{g/g} \\ 1\text{ppb} &= 10^{-9}\text{g/g} \\ 1\text{ppt} &= 10^{-12}\text{g/g} \end{aligned} \tag{4.1}$$

4.1 UPW System

Phase I of SNO+ is to calibrate the detector, measure physics events, and determine external backgrounds using ultrapure water, as mentioned in section 2.1. The water is supplied from Vale. It runs through several purification systems before the water is ready to enter the detector. As seen in Figure 4.1, the water coming from Vale (or INCO as it was previously known) is transferred to water tanks in the mine before being passed through a deaerator. A deaerator separates and removes saturated air from the water. The deaerated water then flows through several filters and zeolite softeners, until it undergoes reverse osmosis (RO). Zeolite softeners exhange ions within the water, as the incoming water is considered hard. Hard water is rich

Isotope	Location	SNO+ Target Level	Measured Level
^{238}U	External (Ropes)	0.004 ppb [46]	0.10 ppb [10]
^{232}Th	External (Ropes)	0.178 ppb [46]	0.17 ppb [10]
Natural K	External (Ropes)	1 ppm [46]	250 ppb [10]
^{238}U	External (Acrylic)	N/A	< 1.1 ppt [14]
^{232}Th	External (Acrylic)	N/A	< 1.1 ppt [14]
Natural K	External (Acrylic)	N/A	< 2.3 ppt [12]
^{238}U	External (H_2O)	21×10^{-14} g/g [46]	$35^{+10}_{-5} \times 10^{-14}$ g/g [49]
^{232}Th	External (H_2O)	5×10^{-14} g/g [46]	$3^{+9}_{-1.9} \times 10^{-14}$ g/g [49]
^{238}U	External (PMTs)	N/A	100 μg per PMT [14]
^{232}Th	External (PMTs)	N/A	100 μg per PMT [14]

TABLE 4.2: Target sensitivities for the SNO+ detector components. [9]

in minerals, whereas soft water consists of one ion: sodium. Reverse osmosis is a filtering technology that removes ions and molecules from the water. Now the clean water will enter the ultraviolet (UV) columns, where the UV photons will "break" the water into H^+ and OH^- ions, effectively reducing the amount of organics in the water. The next step is to pass the ion exchange columns, where the water is demineralized. Essentially in this step, any remaining unwanted ions are exchanged for H^+ and OH^- ions. Finally, the water is passed through the process degasser (PDG), which degases the water, removing as much of the remaining gas in the water as possible. Such gases includes Rn, Ar, Kr, and O_2. Removing as much oxygen as possible is important in the prevention of bacterial growth and scintillator quenching. However, the detector's PMTs do not operate optimally under degassed water, therefore N_2 is introduced to the water. A second set of UV filters sterilizes the water, until it is sent to the chillers, where the temperature is reduced to 12°C. The water must remain cool to prevent bacterial growth, and to keep PMT noise at a minimum. Therefore water recirculation is an important component of the UPW plant operations. Water in the cavity and the AV is continuously recirculated to ensure maximum cleanliness.

4.2 Radon Assay Technique

By processing large volumes of water, and concentrating the impurities within, a sample can be created and counted for radioimpurities. This is what constitutes an assay; a procedure used to determine the contents of a sample. In the case of this chapter, $^{222}\mathrm{Rn}$ is removed from water, concentrated within an acrylic cell, and counted to determine to amount of $^{222}\mathrm{Rn}$ present. Within the cavity and AV are sample lines: a series of acrylic, stainless steel, and polypropylene piping connected to the UPW plant. Using these lines, water can be extracted from various points and undergo an assay process. For Rn extraction, the water is siphoned to the Rn skid system, where the procedure for doing so was tested and developed for the SNO experiment. All of the steps that follow are based on this procedure, where timings, pressures, and temperatures used were determined by inputting known amounts of radon into the Rn skid system. The Rn skid system is comprised of a monitor degasser (MDG), which is a smaller version of the PDG. The water is sprayed into the MDG via spray nozzles, leaving mm droplets of water to run along the side of the MDG and collect at the bottom. The gas that is separated in this process collects at the top. The gas is then vacuumed into an enclosed refrigeration system known as an FTS Titan-Trap; a commercially available trap normally used for freeze drying [56]. The trap is a cylindrical acrylic vessel surrounding coils that cool the surrounding air to -60°C. Once the gas enters this chamber, the remaining water vapour is frozen, and the gas continues to the radon trapping system. The first step in the Rn trap is the primary trap, or Trap A. It is a stainless steel U-bend tube filled with bronze wool that is cooled externally to -196°C using liquid nitrogen. Rn in the gas that flows through Trap A will freeze to the bronze because of the large surface

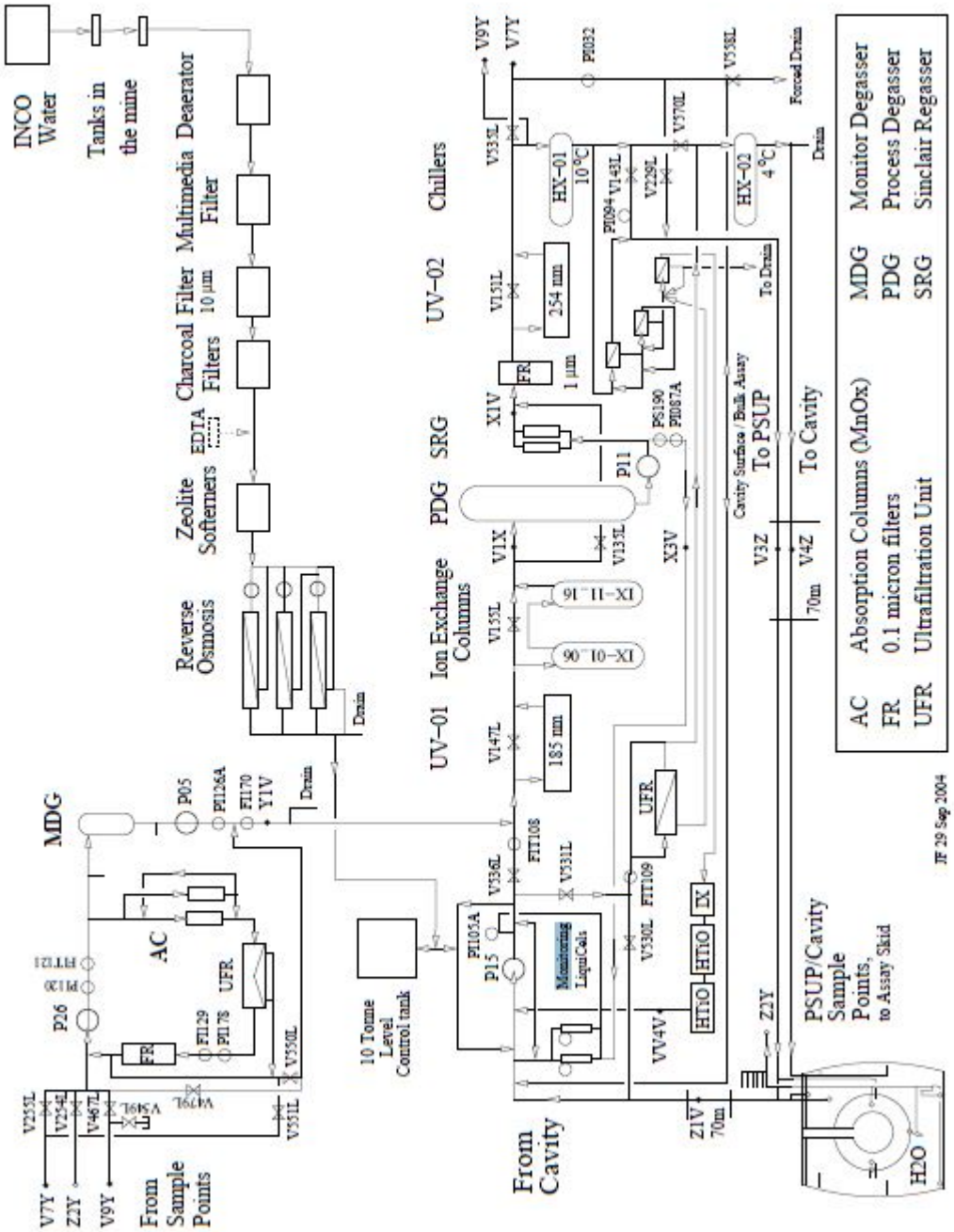


FIGURE 4.1: UPW Plant Configuration (2004). Water from Vale (or INCO as it used to be known) is delivered to SNOLAB where it undergoes deaeration and filtration to remove gases and particles from the water. The water is then softened by exchanging ions within the water to sodium ions. The next step is reverse osmosis, where ions and molecules are removed from the water. Following that is water filtration through UV columns, where UV photons separate the water into H^+ and OH^- ions. Next are the ion exchange columns, where remaining unwanted ions are again exhanged for H^+ and OH^- ions. The water is then passed through a process degasser (PDG) where more gases present are removed. Nitrogen is added to the water, as the PMTs do not function optimally under degassed water. The water can then be sent to various areas within the detector.

area [15]. After 30 minutes, the gas flow is stopped, and the liquid nitrogen is removed. The trap is then heated using a heat gun until the trap is warmer than room temperature. Careful attention must be paid to the differential pressure within the trap in case of O_2 and CO_2 build up, which is displayed using a pressure transducer above the trap. Pressure transducers convert the mechanical force detected into an electrical signal, resulting in a unitless reading. Readings exceeding +200 will damage the trap. During this heating process, liquid nitrogen is placed around a secondary trap known as Trap B. It is a twice coiled stainless steel tubing with a total inner volume of less than 1 cm^3. The now gaseous Rn will flow into Trap B, and freeze in a small concentration. After 15 minutes, 100% transfer efficiency is expected between Traps A and B [53][24]. The final steps are to isolate Trap B, remove the liquid nitrogen, heat Trap B, and let the gas flow to a collection device so the sample may be counted.The easiest device to make is a custom Lucas Cell (LC), which is further discussed in Subsection 4.2.1. Via a quick connect port, the Lucas Cell is attached to the Rn skid near Trap B. As Trap B is being heated, the gas will move into the LC. After 10 minutes, the sample collection is complete, and the LC is brought to the SNOLAB surface lab for counting. The detailed assay procedure can be found in Appendix C, and the radon skid system can be seen in the schematic denoted as Figure 4.2. Not seen in the figure, but should be mentioned, is a component known as a Vlad trap. It is a simple stainless steel chamber placed near the vacuum pump that is used to draw Rn through the Rn skid system. The Vlad trap is filled with liquid nitrogen throughout the assay procedure and aids with preventing Rn from entering the Rn skid system through the vacuum pump.

4.2.1 Background Counting System

The current set up requires the Lucas Cells to be placed upon a 50 mm diameter Phillips XP2262B 12-dynode PMT. These PMTs are placed within black PVC pipes to ensure a dark

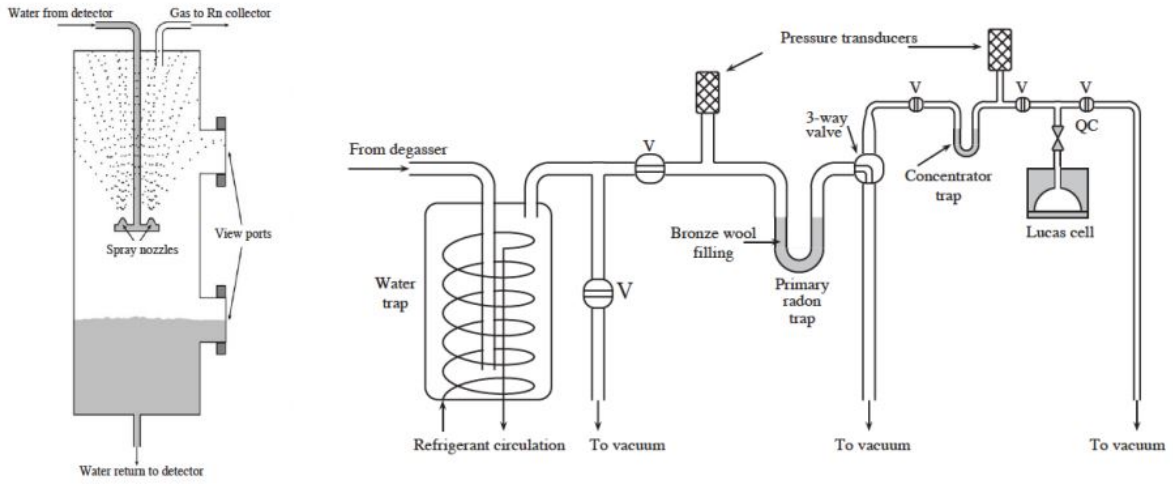


FIGURE 4.2: The radon skid system. On the left is the monitor degasser (MDG), the system used to pump water into the radon skid and separate the gas from the water. The gas then goes to the FTS system depicted in the middle of the image. Excess moisture is frozen inside the FTS, and the gas continues to the radon trapping system. The trapping system consists of 2 traps: a primary trap and a concentrator trap. Once the radon is concentrated, it will flow into a Lucas Cell.

environment, as any light leak will obscure the data. The sensitive wavelength range of these PMTS is 290 nm to 650 nm, with a peak wavelength at 420 nm. The ZnS photon production is at a wavelength of 450 nm, making ZnS the ideal scintillator for the Lucas Cells. As Rn decays, it will emit alpha particles that will interact with the ZnS, thus emitting light detected by the PMTs. The signal is amplified, then sent to the multibuffer channel and multiplexer before going to the PC DOS for further analysis. A schematic of the counting process is shown in Figure 4.3.

Lucas Cells

The Lucas Cells (see Figure 4.4) were designed for the SNO experiment, as commercially available Lucas cells produced high background rates. The ZnS scintillator for these custom cells have a background of 15 counts per day per gram (cpd/g), where 10 mg/cm^2 of ZnS coats the

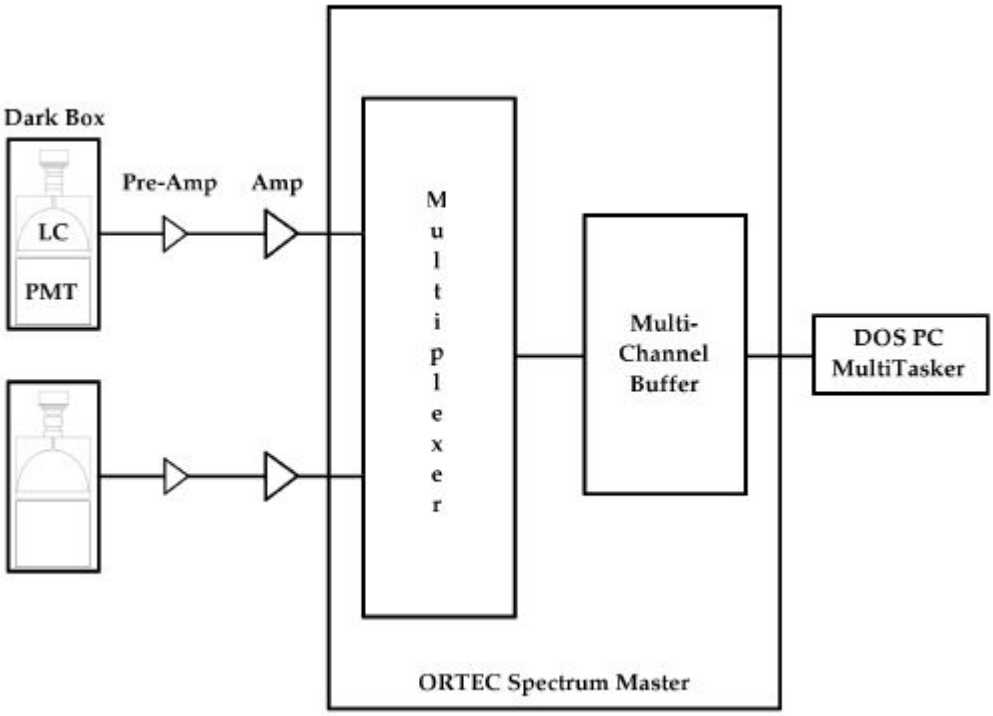


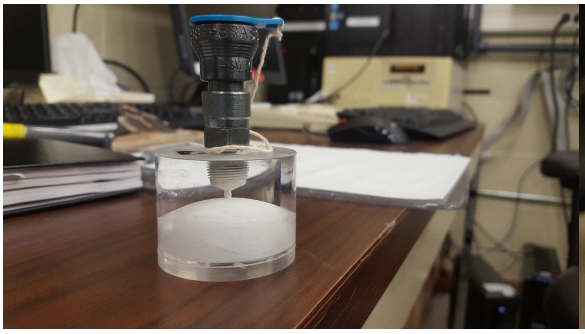
FIGURE 4.3: Surface lab Lucas Cell counting system. The LCs are placed inside black PVC piping where they can optically couple to PMTs already inside the piping. The alpha particles in the LC emit scintillation light when they interact with the ZnS coating inside the LC. The light is detected by the PMT, where it produces a signal that is amplified and sent to a multiplexer and multibuffer channel. The signal is then sent to a PC DOS where the data may be analyzed further.

inner hemisphere of the LC. The inner volume of the LC is 15.5 cm^3. They are designed to optically couple to Philips XP2262B PMTs, and are expected to have backgrounds of approximately 3 counts per day (cpd) from their manufacturing process [53]. Many of the Lucas Cells have been used for analysis, which normally takes place underground. The underground lab air has a radon concentration of 130-150 Bq/m^3 [43], which is approximately an order of magnitude larger than what would be expected above the mine. Therefore, after even one use, the background of the Lucas Cell can easily increase from exposure in the lab due to Rn daughter buildup of $^{210}\mathrm{Pb}$ within the cell.

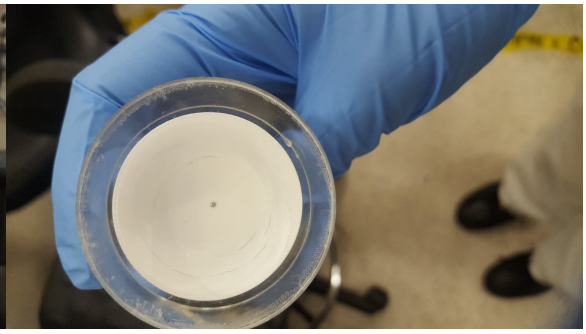
The last time the Lucas Cell backgrounds were monitored was during September 2014, and July and August of 2015. Not all the cells were counted during either of these periods. A list of every Lucas Cell found within SNOLAB's surface building and the underground lab can be seen in Appendix A. The table also includes the last known whereabouts of each cell, their last known background, and the current backgrounds if tested.

New Underground Counting System

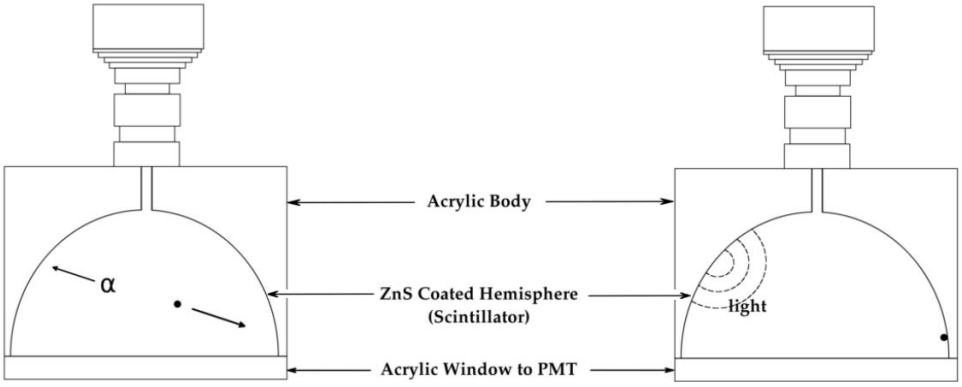
Given the technological age of the surface lab counting system, a new underground counting system has been proposed as a joint cooperation between the SNO+ experiment and SNOLAB. The new system should allow for reliable and efficient data acquisition. Similar to the surface system, the underground system will require PMTs held in a darkened chamber, which will also hold the Lucas Cell. The signal from the PMT is read by a digitizer, undergoes digital pulse processing (DPP), and is then sent to the computer for further analysis. Each PMT will have its own high voltage source and channel within the digitizer. The digitizer will be used in place of traditional analyzers, making it a compact and digital device that uses digital processing. It can



(A) The side view of the Lucas Cell.



(B) The bottom view of the Lucas Cell.



(C) Schematic of a Lucas Cell.

FIGURE 4.4: Images of a Lucas Cell. On the top left, it is clear to see the neck of the Lucas Cell with its quick connect port, in this case covered with a blue cap. The acrylic cylinder houses a hollow hemisphere seen in white. On the top right is a view of this hemisphere from the bottom. The white coating is the ZnS scintillator. The bottom image is a schematic showing each component of the LC and how light is produced.

also be controlled remotely, making it easier for a user to monitor the counting system.

The underground counting system will be set up within the low radon cleanroom to be built in SNOLAB, and a schematic of the set up can be seen in Figure 4.5. It will include the following components:

- N6725 8 Channel 14 bit 250MS/s Digitizer
  - Converts analog signals into digital signals
  - Allows for no dead time due to continuous buffering
- NIM8301/60Y NIM 7U crate, 12 slot 600W
  - Electrical chassis used for electronic components such as the digitizer
- N1470 4 Channel Programmable HV Power Supply
  - Provides high voltage (HV) to the PMTs
- Digital Pulse Processing
  - Output signal from digitizer is analyzed for signals of interest
- COMPASS Readout
  - CAEN Multi-PArametric Spectroscopy Software (COMPASS)
  - Acquires energy, time, and pulse discrimination information from the digitizer
  - user-friendly software to manage data acquisition and produce plots
- Photonics XP2262 PMTs
  - Same PMTs as those used in the current Lucas Cell counting system
  - Used to detect light from Rn interactions within Lucas Cells
- Possibility of adding N978 4 Channel Variable Gain Fast Amplifier
  - Improves signal read by PMT by adjusting the gain

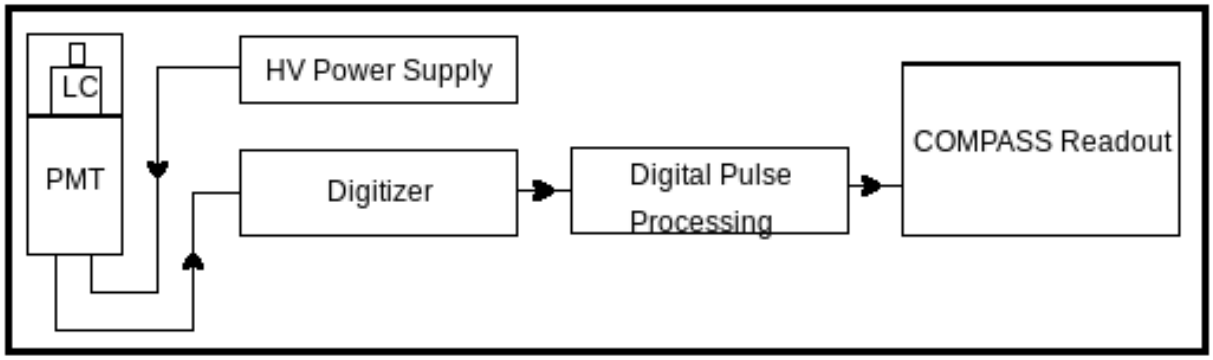


FIGURE 4.5: New Lucas Cell counting system schematic, which includes a CAEN digitizer, new HV power supply, digital pulse processing, and COMPASS readout.

4.3 Radon Calculations

After obtaining the counting data from the counting system, the files must be analyzed using specific calculations in regards to the time of radon collection, trap efficiencies, and other factors as described below.

4.3.1 3 Alpha Production

As a radon atom decays, it will emit 3 alphas over the course of the counting period: 2 weeks. The first alpha will come from the decay of $^{222}\mathrm{Rn}$ to $^{218}\mathrm{Po}$, where we know the Rn half life to be 3.82 days. The next alpha is from $^{218}\mathrm{Po}$ to $^{214}\mathrm{Pb}$, where the half life of $^{218}\mathrm{Po}$ is 3.10 min. The final alpha is minutes down the decay chain, where $^{214}\mathrm{Po}$ decays with a half life of 162 μs to $^{210}\mathrm{Pb}$, which has a half life of 22.20 years. This can be seen from Figure 3.2 in Chapter 3. Therefore, for every radon decay, there are an expected 3 PMT signals. Given the short half lives of all the isotopes involved, secular equilibrium within the Lucas Cell is reached after 3 hours, meaning the production rate of radon is equal to its decay rate. Therefore, as long as the start of counting begins 3 hours after the end of the assay, then the expected rate is 3 α/Rn decay.

4.3.2 Rn Concentration

When a sample is counted, data such as the total number of counts, total counting time, and start and end time of counting are essential to determining the radon concentration. The data obtained through the counting system shows the number of cumulative counts per 3 hour time bin. This can be plotted and fitted with an exponential decay, resulting in a Rn decay curve with a half life of 3.82 days. What follows are the calculations necessary to determine the actual concentration of Rn in a given sample after counting.

The radioactive decay law is stated as equation 4.2, where its solution is stated to the right by integration. The solution is written in terms of the number of radon atoms found within the Lucas Cell at any time during the counting process, t_{count} with respect to the number of atoms within the LC at the start of counting (SOC), N_{SOC}.

$$\frac{dN}{dt} = -\lambda N \qquad \Rightarrow \qquad N(t_{count}) = N_{SOC}e^{-\lambda t_{count}} \tag{4.2}$$

Specific to our system, the decay law must account for the LC background rate, B_{LC}, and the counting efficiency, ϵ_{count}. The counting efficiency is due to the Lucas cell geometry, and the optical coupling between the cell and the PMT. It also includes the 3 alphas emitted for every $^{222}\mathrm{Rn}$ decay. These variables can be seen in equation 4.3:

$$\frac{dN}{dt} = -\lambda\epsilon_{count}N_{SOC}e^{-\lambda t_{count}} + B_{LC} \tag{4.3}$$

Integrating equation 4.3 will yield N:

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

As such, the number of radon atoms at the start of counting may be found by rearranging the above formula:

$$N_{SOC} = \frac{N - B_{LC} t_{count}}{\epsilon_{count}(1 - e^{-\lambda t_{count}})} \tag{4.5}$$

However, the decay law can also be rewritten in terms of the number of radon atoms collected at the end of the assay, N_{EOA}. The end of the assay is defined as the moment trap A is isolated from the rest of the system, at which point the maximum number of $^{222}\mathrm{Rn}$ has been collected and will only decay from this point on. The time between the end of the assay and the start of counting is the delay time, t_{delay}.

$$N_{SOC} = N_{EOA} e^{-\lambda t_{delay}} \tag{4.6}$$

However, we can take N_{EOA} to be the number of radon atoms in the sample taken, N_{sample} in addition to the background number of atoms within the extraction system, $N_{background}$, such that

$$N_{SOC} = \epsilon_{transfer}(N_{sample} + N_{background}) e^{-\lambda t_{delay}} \tag{4.7}$$

where $\epsilon_{transfer}$ is the transfer efficiency from Trap A to the Lucas Cell. It is being assumed that the transfer efficiency between Traps A and B (ϵ_{trap}) is 100% [24].

The decay rate of the sample can be described via the radioactive decay law as

$$\frac{dN_{sample}}{dt} = R - \lambda N_{sample} \tag{4.8}$$

where R is the rate of $^{222}\mathrm{Rn}$ atoms produced from the sample in Rn atoms per day. Integration gives the number of $^{222}\mathrm{Rn}$ atoms during the assay, t_{assay} to be

$$N_{sample}(t_{assay}) = \frac{\epsilon_{trap} R(1 + Ce^{-\lambda t_{assay}})}{\lambda} \tag{4.9}$$

where C is a constant of integration. For the background $^{222}\mathrm{Rn}$ atoms,

$$\frac{dN_{background}}{dt} = R_{background} - \lambda N_{background} \tag{4.10}$$

which can be similarly integrated for the number of background $^{222}\mathrm{Rn}$ atoms:

$$N_{background}(t_{assay}) = \frac{\epsilon_{trap} R_{background}(1 + Ce^{-\lambda t_{assay}})}{\lambda} \tag{4.11}$$

Equations 4.11 and 4.9 can be substituted into equation 4.7 such that

$$N_{SOC} = \epsilon_{transfer}\epsilon_{trap}\Big(\frac{R(1 + Ce^{-\lambda t_{assay}})}{\lambda} + \frac{R_{background}(1 + Ce^{-\lambda t_{assay}})}{\lambda}\Big)e^{-\lambda t_{delay}} \tag{4.12}$$

Equation 4.12 can now be substituted into equation 4.4 to give

$$N(t) = \epsilon_{count}\Big(\epsilon_{transfer}\epsilon_{trap}\Big(\frac{R(1+Ce^{-\lambda t_{assay}})}{\lambda}+\frac{R_{background}(1+Ce^{-\lambda t_{assay}})}{\lambda}\Big)e^{-\lambda t_{delay}}\Big)(1-e^{-\lambda t})+B_{LC}t \tag{4.13}$$

Finally solving for R

$$R = \frac{(N-B_{LC}t)\lambda}{\epsilon_{count}\epsilon_{transfer}\epsilon_{trap}(e^{-\lambda t_{delay}})(1-e^{-\lambda t_{assay}})(1-e^{-\lambda t})} - R_{background} \tag{4.14}$$

In terms of concentration C [atoms/L], equation 4.14 must be written in terms of the flow rate F from the degasser, which has an efficiency ϵ_{degas}.

$$\begin{aligned} C &= \frac{R}{F\epsilon_{degas}} \\ &= \frac{1}{F\epsilon_{degas}}\Big(\frac{(N-B_{LC}t)\lambda}{\epsilon_{count}\epsilon_{transfer}\epsilon_{trap}(e^{-\lambda t_{delay}})(1-e^{-\lambda t_{assay}})(1-e^{-\lambda t})} - R_{background}\Big) \end{aligned} \tag{4.15}$$

The values for efficiencies can be seen in Table 4.3, and are the same values determined from the SNO experiment when the assay system was being commissioned. Efficiencies were found by inputting a known amount of radon into the traps, and counting the amount of radon collected after the traps.

Variable	Value
ϵ_{count}	$3 \times 0.74 \pm 0.21$
ϵ_{trans}	0.64 ± 0.02
ϵ_{trap}	1.005 ± 0.023
ϵ_{degas}	0.58 ± 0.17

TABLE 4.3: These are the efficiencies that were calculated in the SNO days and are used in the current radon calculations [53].

If we now assume that $^{222}\mathrm{Rn}$ can achieve secular equilibrium with $^{238}\mathrm{U}$, we can write the concentration in terms of the more common units of g^{238}U/gH_2O. Using N_{Rn} to be the number of radon atoms, and N_U to be the number of uranium atoms, equilibrium can be shown in terms of their respective half lives, $t_{Rn_{1/2}}$ and $t_{U_{1/2}}$, and respective decay rates, λ_U and λ_{Rn}. The radioactive equilibrium equation is

$$\frac{dN_U}{dt} = \lambda_{Rn} N_{Rn} - \lambda_U N_U \tag{4.16}$$

For secular equilibrium, $\frac{dN_U}{dt} = 0$, therefore

$$\frac{N_U}{N_{Rn}} = \frac{\lambda_{Rn}}{\lambda_U} \tag{4.17}$$

Using the definition for half life, $\lambda = ln(2)/t_{1/2}$

$$\rightarrow \frac{N_U}{N_{Rn}} = \frac{t_{U_{1/2}}}{t_{Rn_{1/2}}} = \frac{4.468 \times 10^9 \text{years}}{0.010475 \text{years}} = 4.26(525) \times 10^{11} \tag{4.18}$$

Finally we see that the concentration for ^{238}U in grams per gram of liquid Lq is

$$C[\text{g}^{238}\text{U/g Lq}] = C[^{222}\text{Rn/L}] \times \frac{1.69 \times 10^{-13}}{\rho} \tag{4.19}$$

As we are only interested in the water phase currently, we will use $\rho_{H_2O} = 1.0$ g/cm^3 such that

$$C[\text{g}^{238}\text{U}/\text{gH}_2\text{O}\,] = C[^{222}\text{Rn/L}] \times 1.69 \times 10^{-13} \tag{4.20}$$

The constant seen in equation 4.20 is derived as such:

$$\text{Rn atoms/L} \cdot \frac{1\text{L}}{1000\text{cm}^3} \cdot \frac{t_{U_{1/2}}}{t_{Rn_{1/2}}} \cdot \frac{1\text{mole}}{6.022 \times 10^{23}\text{atoms}} \cdot 238.0289\text{g/mole} = [\text{g}^{238}\text{U}/\text{gH}_2\text{O}] \tag{4.21}$$

Radiation concentrations are commonly expressed in terms of Bq per unit volume. The previous equation can easily be used to express the concentration in terms of mBq/m^3:

$$\frac{\text{mBq}}{\text{m}^3} = \frac{\text{g}^{238}\text{U}}{\text{gH}_2\text{O}} \cdot \rho_{H_2O} \cdot \frac{\ln(2)A}{M_U t_{U_{1/2}}} \cdot 10^{-3} \tag{4.22}$$

where ρ_{H_2O} is in g/m^3, M_U is the molar mass of ^{238}U, and A is Avogradro's number. It should also be noted that $t_{U_{1/2}}$ be in units of seconds. The conversion can be used for any liquid given the mass of ^{238}U in grams per gram of liquid, then multiply by the density of the liquid in question.

4.4 Water Assay Results

The primary goal of the water assays is to monitor the radon concentrations within the water of the detector. This work began in 2015, where the entire Rn skid was inspected, untagged, and assembled. A few assays had been performed, and the system appeared to be functioning as it had back in the days of SNO. One of the concerns was whether there were any minor leaks in the system, therefore in 2016, the work began with leak checking the connections from the vacuum pump to the radon traps and FTS trap using a helium leak checker. No leaks were found. The process then continued with observing the smallest loop possible with no water. These were known as MDG background runs, as the MDG was believed to be the primary source of background within these loops.The MDG background results are described first, and were found to be much higher than expected. The suspected cause is a leak to the lab air in the piping between the MDG and the Lucas Cell port.

4.4.1 MDG Backgrounds

MDG background assays involved running assays for the Rn skid system, and are known as MDG background assays as the MDG is the largest component of the system and therefore thought to be the dominant source of background. The backgrounds of the monitor degasser in general did not involve a water flow. Therefore the radon levels are reported in terms of either radon counts per day or radon atoms per day. The results can be seen in Table 4.4, and are visually represented by a plot in Figure 4.6. Each run processed 30 min of gas flow, or water flow in certain cases. The Lucas Cell identification (LCID) and PMT used are also recorded. Overall, there was some fluctuation in the results, likely due to several types of assays, such as

UPW plant assays, PSUP, and AV assays (to be discussed in the following sections), that were executed intermittently throughout the MDG background assays. Therefore the system being tested would not be constant; changes to temperature and water contents could affect the MDG background results. The assay on May 10, 2018 involved closing the valve that lead to the MDG, so as to determine whether there was a small leak from the FTS system as only the components not involving the MDG were being assayed. The following assay on May 24, 2018 furthers tests this hypothesis by sealing the FTS with plastic and again isolating the system from the MDG. The idea was if there was a small leak in the FTS, then running an assay with the FTS sealed should yield lower results.

On May 17, 2018, a small loop was created to first add purified water from the UPW plant into the MDG, then to cycle that water through the Rn skid system. This was done to determine what the difference was between running the loop with and without water. In the end, the results varied quite a bit. Aug 24, 2018 reported a lower radon concentration as the first several hours of data were lost due to a power outage at SNOLAB.

In the SNO data, the average MDG background performed without water resulted in a Rn concentration of 460 Rn atoms/day. In 2015, a similar assay was done and saw a concentration of 446.6 Rn atoms/day. The results over the past two years are confusingly high, and will be further discussed in Section 4.7. It is the conclusion that there is a leak in the system, however the leak cannot be found until more consistent assays are executed with a systematic leak checking procedure in place.

Type of Assay	Assay Date	LCID	PMT	Total Counts	Total Count Time (s)	Radon Concentration (Rn atoms/day)
MDG Bkg	Mar 29, 2017	N19	16	1099 ± 33.15	1255433.000	26869.4 ± 3312.6
MDG Bkg	May 17, 2017	N19	16	190 ± 13.78	85534.438	38336.3 ± 4996.9
MDG Bkg	Aug 17, 2017	N19	16	690 ± 26.27	579416.938	30461.8 ± 3610.2
MDG Bkg	Aug 24, 2017	N8	14	248 ± 15.74	327977.260	11271.9 ± 2122.7
MDG Bkg	Aug 31, 2017	N19	16	729 ± 27.00	293796.188	52928.7 ± 5893.2
MDG Bkg	Sept 7, 2017	N19	16	573 ± 23.94	221638.906	51606.1 ± 5834.8
MDG Bkg	Sept 14, 2017	N8	14	1434 ± 37.87	1876349.125	33269.4 ± 5408.8
MDG Bkg	May 3, 2018	N19	16	719 ± 26.81	1103002.375	18699.3 ± 2661.1
MDG Bkg	May 10, 2018	N8	14	384 ± 19.60	985672.813	4157.3 ± 2403.9
MDG Bkg with Water	May 17, 2018	N19	16	949 ± 30.81	1071661.375	31623.0 ± 3912.8
MDG Bkg	May 24, 2018	N8	14	747 ± 27.33	514628.031	32900.5 ± 4720.3

TABLE 4.4: This table shows the amount of radon calculated from each 30min background run of the Rn skid, whose primary source of background comes from the monitor degasser (MDG). Most of the runs were performed without any water flow (denoted as MDG Bkg in the table), except for the run on May 17, 2018 which held a small amount of water in a cycle at a rate of 20 lpm. The runs on May 10 and 24, 2018 were isolated from the MDG.

4.4.2 UPW Plant Assays

Assays involving the UPW plant were dependent on the activities of the UPW plant that day, and whether all the systems were performing optimally. The purpose of running these loops was to expand upon the MDG runs, and test larger loops. These flow paths all included a water flow, which had to be held at a constant rate of $\sim$ 20 lpm. A lower water flow rate is not optimal to trapping radon as it would take too long, and a high flow rate is difficult to control as a lot of work was needed to balance the diaphragm pumps in the UPW plant. In addition, 20 lpm was at times difficult to maintain, as the process required lowering the input pressure to the process degasser (PDG) from its normal range to 12 psi. Doing so could sometimes cause the PDG to shut down, at which point the UPW plant operations had to be restarted.

A complete loop of the UPW plant with all the purification systems online was done on December 7, 2017. At this time, a new diaphragm pump had been installed to replace the previous bottoms pump, P05. This pump is what was used to draw water out of the MDG and into the rest of the plant. As there was little Rn expected in this assay, the collection period was extended to an hour (the exact assay time was 61 minutes). There were 112.33 Rn atoms/day collected from this sample. With a flow rate of 20.01 $\pm$ 2.80 lpm, the equivalent rate is 6.50×10^{-3} Rn atoms/L. Without the MDG subtraction, the level of radon is 33381.7 Rn atoms/day. The MDG background assay performed closest to this date was that done on September 14, 2017, which resulted in a radon concentration of 33269.4 Rn atoms/day. Therefore with background subtraction, the UPW plant rate is 112.3 Rn atoms/day. This is a very good result, and indicates the UPW plant is functioning optimally.

In order to determine the efficiency of the PDG, assays could be done where the PDG is

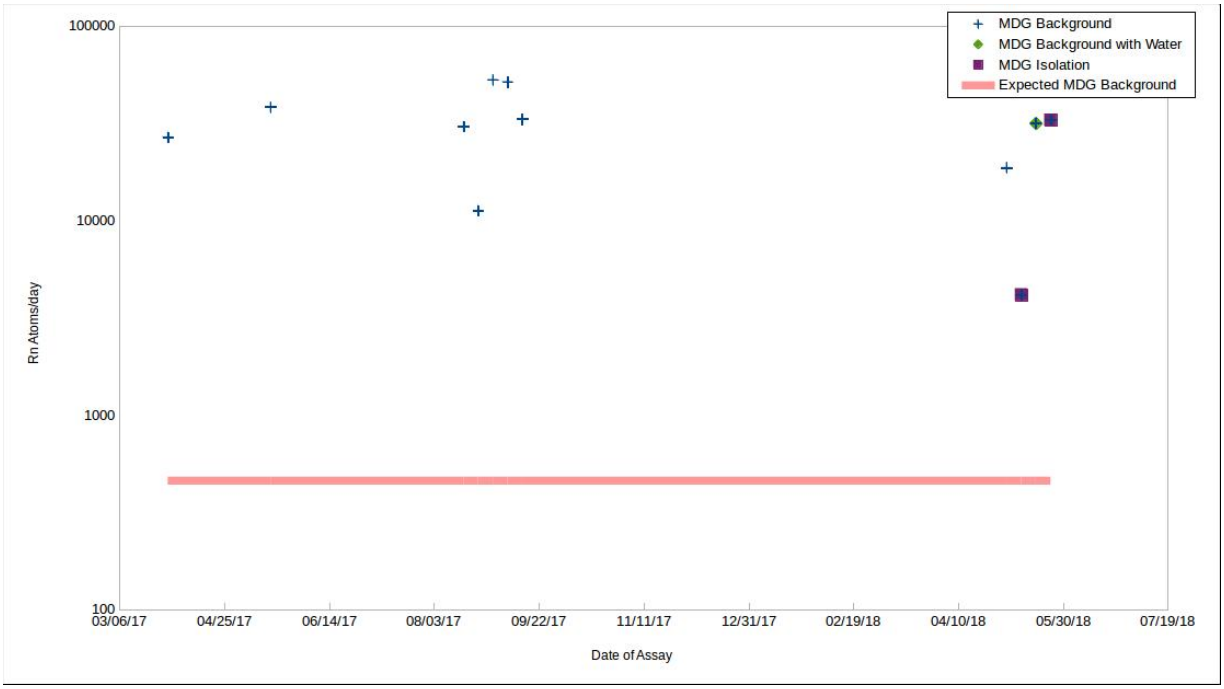


FIGURE 4.6: A plot of the MDG background runs. The blue crosses represent the MDG background runs, the purple squares are the MDG runs done with the valve to the MDG closed (MDG isolation), and the green triangle is the MDG background run done with water. The red line represents the expected MDG background run result of 460 Rn atoms/day.

running for several hours before being turned off and followed with an assay. In this case, there is no MDG degassing period. The water that is normally recirculated through the UPW plant stops running through the purification systems and is pumped into the MDG. The resulting gas is then collected. Such an assay was done on July 26, 2017. The resulting rate is 1.44×10^6 Rn atoms/day without subtracting the MDG background, and 1.40×10^6 Rn atoms/day with an MDG background of 38336 $\pm$ 4997 Rn atoms/day subtracted, as it was the last known background value before this particular assay. Over a 43 minute collection period with a water flow of 17.00 $\pm$ 2.38 lpm, the rate can be expressed as 95.49 Rn atoms/L. It is clear at this point that in comparison with the assay done on Dec 7, 2017, the PDG is nearly 100% efficient at reducing the amount of Rn in the water.

There was concern as to whether the new diaphragm pump, P05, was emanating. Therefore a small closed loop assay was done on January 17, 2018. There was no connection to the PDG or other purification loops in this case. 9.06×10^5 Rn atoms per day was found in this sample over a collection period of 1 hour. With a water flow rate of 19.41 $\pm$ 2.72 lpm, the equivalent rate is 54.02 Rn atoms/L.

On January 31, 2018, a smaller loop was considered to further isolate P05, and was later used as the MDG background run loop for the assay done on May 17, 2018 (See Table 4.4 for the result). This assay was also used to determine the optimal degassing time. Two collections were done: Sample 1 had a degassing time of 32 min and an assay time of 31 min, and Sample 2 had a degassing time of 1 hr 31 min followed by a 40 min assay. With a longer degassing period, it was theorized that Sample 2 would have a lower Rn rate. A leak is suspected somewhere over

the course of this assay, as Sample 1 resulted in 1634.31 Rn atoms/day without MDG subtraction, and Sample 2 contained 18191.70 Rn atoms/day without MDG subtraction.

These 3 previous results are difficult to interpret, as the first diaphragm pump assay resulted in a high result, whereas the 2 samples in a smaller loop resulted in significantly lower Rn concentrations. It is necessary to first determine if there is a leak in the MDG system, then determine if there is a leak elsewhere in the UPW plant.

4.5 PSUP Assays

As per the analysis of the events seen by the detector, there is a region of interest displaying higher than expected event rates. This is what is deemed as the "hotspot".
Table 4.5 outlines the parameters used to determined the final $^{222}\mathrm{Rn}$ values. The assay ended on June 28, 2017 at 14:34 and the counting began the same day at 16:11 using PMT 14 in the surface counting lab. The flow rate stated in the table is an average of the actual flow rate. Water was processed at a rate of 16 lpm for 22 min of the assay, then 19 lpm for the remaining 10 min, for a total of 32 min for assay time. This resulted in processing 542 L of water for the assay.

There are 3201.47 Rn atoms per day emanating from the PSUP with background subtraction. This converts to 0.217 Rn atoms per L, or 3.68 $\times 10^{-14}$ g^{238}U/gH_2O.
The assay was only conducted for 32 min because of time constraints. On June 28, 2017, there was an All Stations underground due to Vale maintenance resulting in an hour of lost time. Also to be noted was the high pressure in Trap B. The gauge above the skid was reading OL, which

Sample Name	PSUP Assay V-203L
LCID	N19
Total Counting Time	2351434.00 s
Total Counts	1343 ± 36.65
LC Bckg	13.10 ± 1.40 cpd
Delay Time	3.62 hrs
Assay Time	0.53 hrs
MDG Background	30461.8 ± 3610.2 Rn/day
Water flow	17.00 ± 2.38 lpm
Log File	17062814.log

TABLE 4.5: This table shows the details of the assay necessary for calculating the amount of radon in the sample.

indicates too much gas in the trap. Once the trap was opened to the LC, there was an immediate release of pressure. It is suspected that we trapped more than just $^{222}\mathrm{Rn}$, likely O_2 or CO_2. With current measured levels of 8.3×10^{-16} g^{238}U/gH_2O found analyzing the detector events, the PSUP assay result does not agree. Once the MDG backgrounds are understood, further PSUP assays should be done.

4.6 AV Assays

An acrylic vessel (AV) assay was conducted to determine the level of $^{222}\mathrm{Rn}$ within the detector. The process degasser (PDG) was offline due to the ELMO vacuum pump needing repairs. As such, a special loop was discussed to bypass the PDG and pump P15. The monitor degasser (MDG) was used instead to degas the incoming water from the middle of the AV using a sample line. The degassing occurred over a 1 hour time span, and was followed by a 35min assay. Listed in Table 4.6 are the parameters used to calculate the amount of radon found, and the results.

Sample Name	AV Assay
LCID	N10
Total Counting Time	1167209.00 s
Total Counts	93396 $\pm$ 305.61
LC Bckg	15.63 $\pm$ 1.52 cpd
Delay Time	2.47 hrs
Assay Time	0.58 hrs
Water flow	20.9 $\pm$ 2.926 lpm
MDG Background	33269.4 $\pm$ 5408.8 Rn atoms/day
Log File	17110715.log

TABLE 4.6: This table shows the details of the assay necessary for calculating the amount of radon in the sample.

There are 6913.43 $\pm$ 22.62 counts per day, which is equivalent to 3.10×10^{6} Rn atoms per day emanating from the AV. With a flow rate of 20.9 $\pm$ 3.0 lpm, this converts to 171.5 Rn atoms per L, which is equivalent to 2.89 $\times10^{-11}$ gU/gH_2O.

The sample lines used for this assay consist of flexible stainless steel piping sealed to the standard polypropylene water lines. There is no PVC nylon reinforced hose as previously suspected, signifying the higher than expected rate is coming from an unknown source. The expected rates with current AV and PSUP assay results are shown in Table 4.7.

The AV result is significantly higher than the target value. It is possible that more Rn was observed in this assay as the water in the AV at the time of the assay had not been recirculated in a while. Other possibilities are a leak in the sample line(s), and/or temperature gradients within the water affecting the results. Executing more assays as the water recirculated would have been ideal to determine how water recirculation and purification helped lower the radon levels, however the risk of introducing more radon into the AV was too high given the possible leaks in the radon skid system.

Assay	Current Value	Typical SNO Value
PSUP Assay V-203L	Jun 28, 2017: 3.68×10^{-14} gU/gH_2O May 30, 2018: 1.28×10^{-12} gU/gH_2O	3.50×10^{-13} gU/gH_2O [9]
AV Assay	Nov 7, 2017: 2.89×10^{-11} gU/gH_2O	6.63×10^{-15} gU/gD_2O [9]

TABLE 4.7: Listed are the current AV and PSUP Rn rates, along with the target levels from the SNO experiment.

4.7 Water Assay Analysis

The results given thus far are difficult to interpret. It can be concluded that there is a clear indication of a leak within the radon extraction system. Given this, other assays including the UPW, PSUP, and AV assays can not yet be used to give any indication as to the true radon content in the water using this method.

There are several steps that can be taken to find this leak. First, the leak rate can be found by taking the average of $\sim$ 30 000 Rn atoms/day leaking from the system. Given the air within SNOLAB has a radon concentration of $\sim$ 150 Bq/m^3, then the leak rate is $\sim 2 \times 10^{-3}$ mbar·L/s, which is detectable with a Helium leak checker. A good seal within the pipes used in the radon skid was observed to be on the order of 10^{-8} mbar·L/s when the pipes nearest the vacuum pump was leak checked in March 2017.

The next steps will be to continue isolating certain sections of the skid system in order to complete the commissioning of the system. Since the MDG was already isolated and the rates did not decrease, it can be interpreted that the leak is not originating from the MDG however more assays and leak checking should be done to conclude this. Another assay should be done where the FTS is isolated, meaning the valve to the MDG is closed and sampling of the FTS is done. If

the rates do not decrease, then in succession assays should be done with V-224L closed (therefore assaying the radon board), V-245L closed (moving forward to assaying the primary radon trap), and finally V-260L closed (assaying the Lucas Cell ports). Each of these components can be seen in Appendix D. Should any of these assays result in suddenly decreased Rn levels, it will be easy to determine the location of the leak, as it must fall between the section of the assay system with high event rates and the section of the assay system with low event rates. Locations near the vacuum pump and Vlad trap have been tested for leaks, and none were found.

When a leak is found, the next steps will be to determine why the location is leaking. Likely, there is a loose connection that can be tightened, or an O-ring that can be replaced.

Chapter 5

Volumes with High Event Rates

Informally known as a "hotspot", certain locations inside the water volume of the AV and PSUP exhibit a higher than expected rate of events. There can be more than one of these volumes or areas at any point in time, and they have the ability to move throughout the detector through water currents. The source of the higher than expected event rates can have multiple reasons, however the rate does decrease with water recirculation and purification, time, and convection. The sources can stem from the temperature differential seen in the detector. It is ideal for water to enter the detector at 12°C to prevent bacteria from growing and for optimal PMT performance, however, likely due to uneven recirculation patterns, there are warmer volumes of water within the detector. This will cause the "hotspot" in the water to flow with a convection current throughout the AV. Another possibility is Rn ingress top of the detector when it was opened to the lab air during maintenance activities. Or, as mentioned in the previous chapter, leaks within the detector's piping were a possibility. Such leaks would have meant a high probability of Rn seeping into the detector. A couple of leaks were found in the acrylic to stainless steel piping of the sample lines inside the AV volume, and were fixed over time.

5.1 High Event Rate Analysis

As of May 2017, there were two to three noticeable "hotspots". One was near the PSUP (photo-multiplier support), around the equator. Another was likely a projection of this "hotspot", lying closer to the acrylic vessel (AV). The third was inside the AV itself. The majority of the events had a positive event direction. *In situ* analysis defines this direction as $u.R$, where u is the unit vector of the event direction, and r is the radial vector position of the event vertex relative to the center of the AV. Mathematically, this is seen in equation 5.1, where the angle θ represents the angle of the resulting vertex. The sign of the dot product of the two vectors shows whether the event was pointing into the detector, or pointing out of the detector, as seen in equations 5.2 and 5.3. A visual representation of this can be seen in Figure 5.1. Observing events for their directionality is useful for determining whether the events are occurring inside the detector, therefore establishing whether the source for the events is inside the detector as well. This can be seen in Figure 5.2 where many of the events have a positive $\cos\theta$ value, signifying events are originating within the detector volume.

$$\boldsymbol{u} \cdot \frac{\boldsymbol{r}}{|\boldsymbol{r}|} = \boldsymbol{u} \cdot \boldsymbol{R} = \cos\boldsymbol{\theta} \tag{5.1}$$

$$u.R > 0 \qquad \text{Outward going event} \tag{5.2}$$

$$u.R < 0 \qquad \text{Inward going event} \tag{5.3}$$

During the months of May and June, cavity recirculation discontinuities have contributed to the development of high event rates. External backgrounds emanating from the PMTs, ropes,

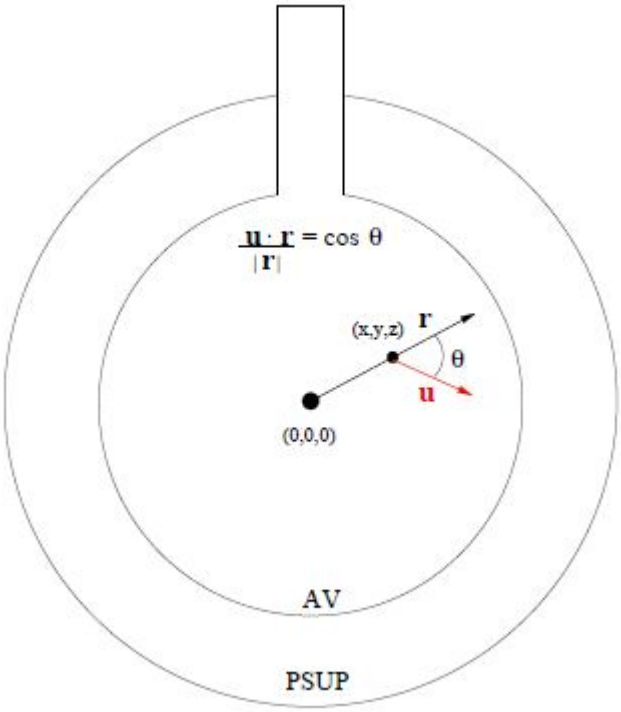


FIGURE 5.1: A representation of **u.R** for an event leaving the detector, where u is the unit vector of the event direction, and r is the radial position vector position of the event vertex relative to the center of the AV [49].

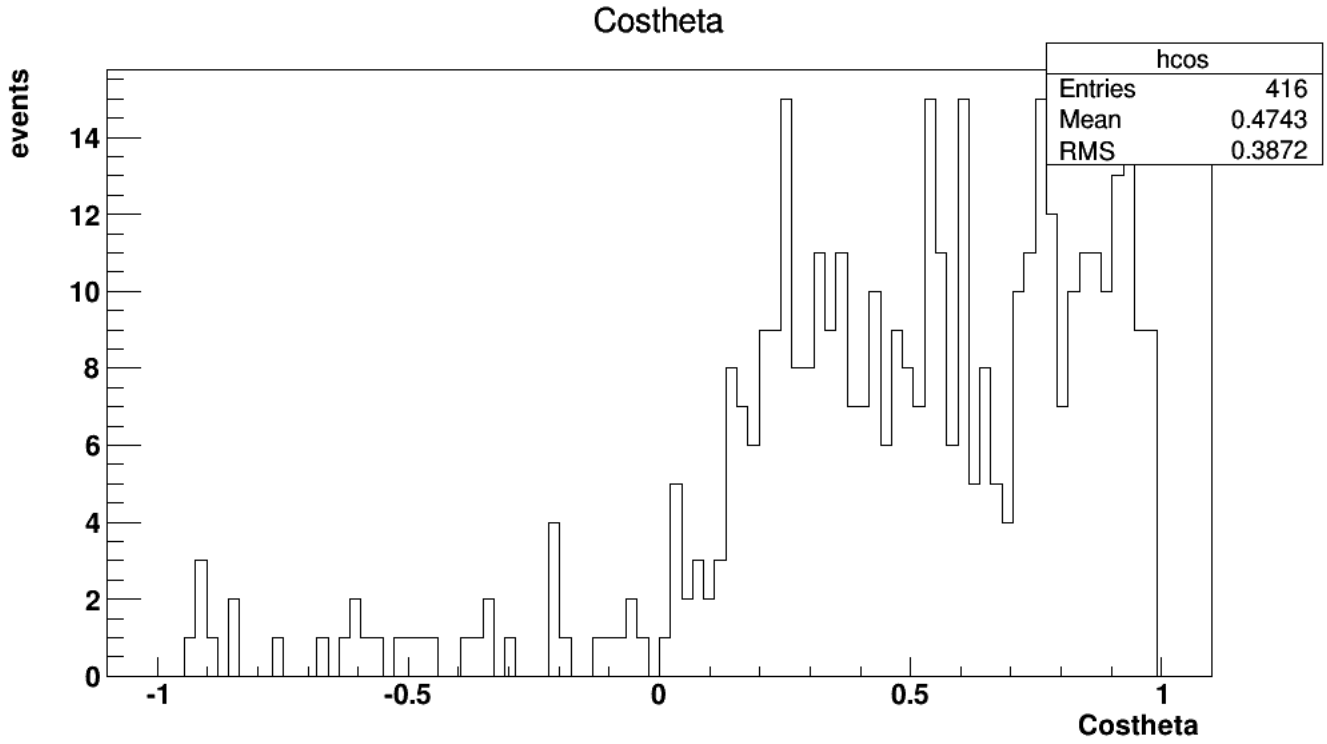


FIGURE 5.2: Of the events seen in the "hotspot" location, the vast majority of events have a positive $\cos\theta$, indicating the events are originating inside the detector.

and PSUP are seen in the cavity water unless it is recirculated through the water purification system to extract any contamination (see Chapter 3). This is shown in Figures 5.3 and 5.4, where high rates in the AV are linked to leaching from the acrylic vessel. In the top image of Figure 5.3, an overview of many events within the top quarter portion of the AV (denoted by an x-axis range of 0 m to 6 m) and PSUP (denoted by an x-axis range of 6 m to 8 m) can be seen without any energy cuts applied. The energy in the case of plots like this is represented by the term nhit, and is seen as a colour scale indicated on the right side of the plot. The higher the nhit value, the more energy there is. Computationally, nhits are calibrated to be associated with certain energies. Within an energy range of 3.5 MeV and 5.5 MeV, a high concentration of events can be seen on one side of the detector within the top of the PSUP, as seen in the bottom image. The colours here are are closer to a single colour as the energy range is small; there are not as many energies to depict with certain colours. It is possible that there are some RAT geometry issues closer to the AV, however it is still clear that there are high rates within the water. As the vessel has been exposed to the lab environment for many years since SNO, it has accumulated Rn daughters within its surface. Over time, the Rn daughters may be absorbed into the water. Another event rate contribution was due to a leaking pipe inside the neck of the detector, which has been fixed.

5.1.1 Cuts Applied

The general analysis cuts used in the "hotspot" analysis are as follows using the standard SNO+ package (RAT 6.3.1):

- fitValid == 1
- waterFit == 1

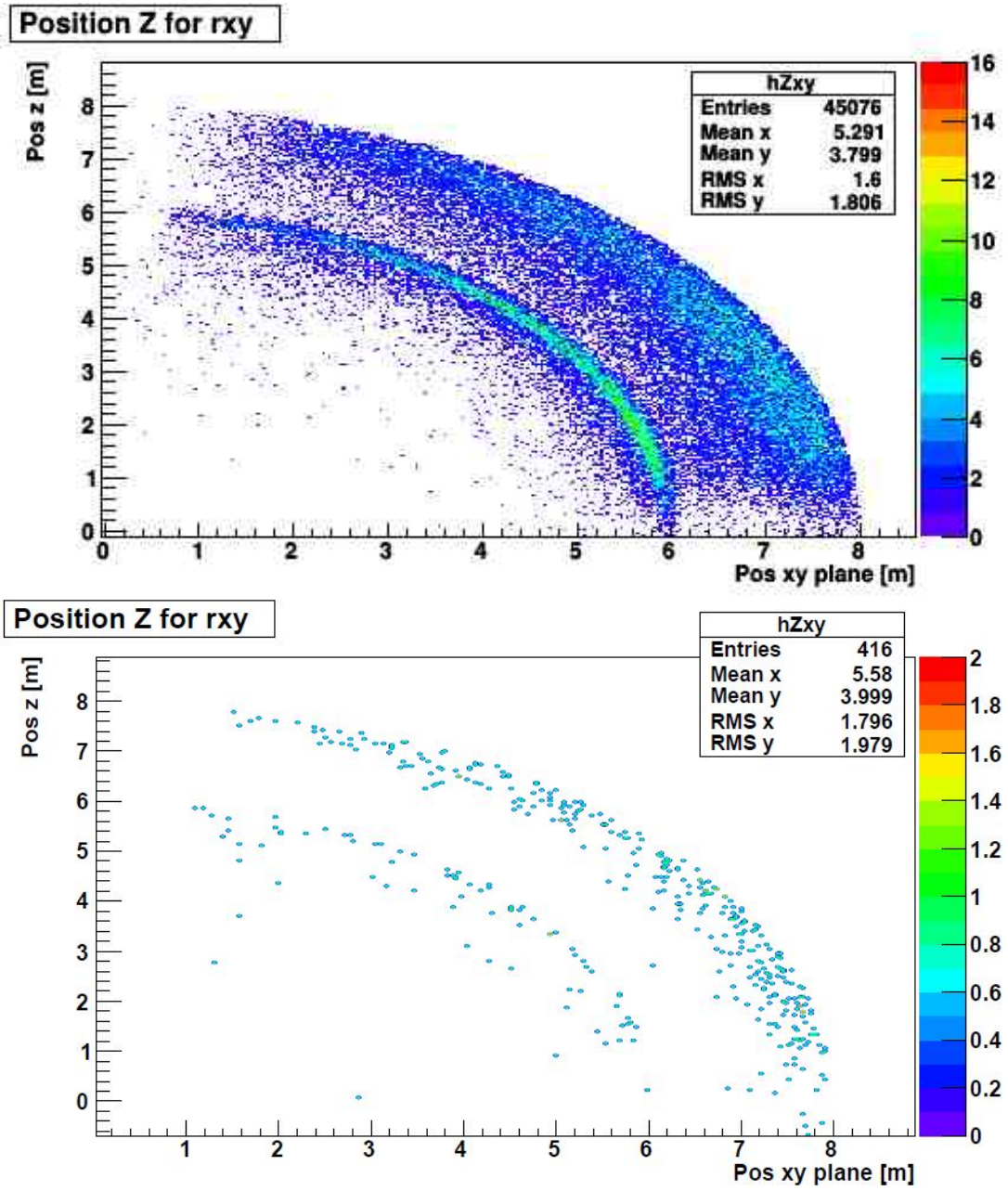


FIGURE 5.3: In the top image, an overview of many events within the detector can be seen without any energy cuts applied. Within an energy range of 3.5 MeV and 5.5 MeV, a high concentration of events can be seen on one side of the detector within the top of the PSUP, as seen in the bottom image. It is possible that there are some RAT geometry issues closer to the AV, however it is still clear that there are high rates within the water.

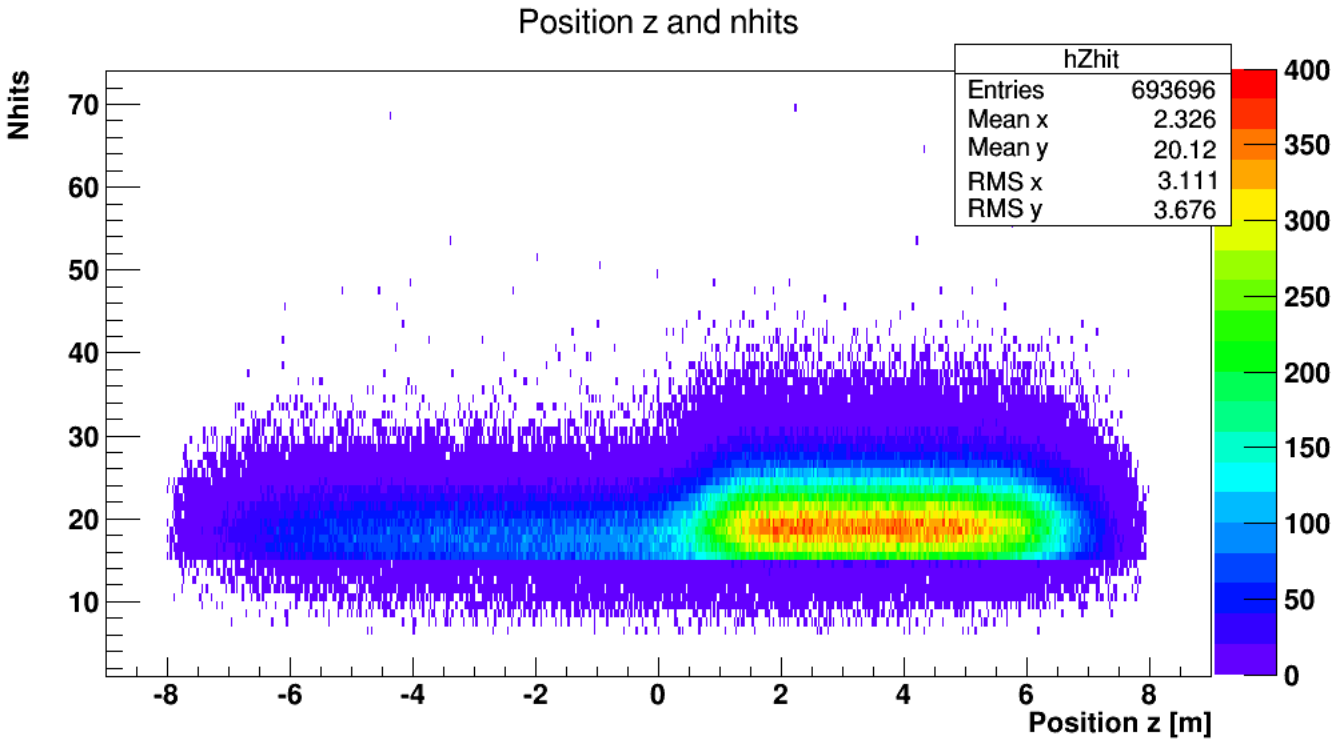


FIGURE 5.4: Similar to Figure 5.3, the NHits vs position z distribution shows a larger number of events at the top of the AV. This is likely due to the lack of water recirculation during the commissioning phase of the detector.

- nhitsCleaned > 15
- itr > 0.55
- nhits < 39
- -0.12 < β_{14} < 0.95

Essentially, the aim is to isolate regions with higher events that fall within the energy range expected for radon. This range is set between 3.5 MeV and 5.5 MeV as it is the range we expect to see ^{214}Bi. Alpha particles cannot scintillate in water, therefore we cannot detect Rn directly. We instead look for the beta decay from ^{214}Bi. The minimum energy range has been set with *nhitsCleaned > 15*, as anything below that nhit will be obscured by noise and is therefore difficult to analyze. An nhit is defined as the number of normal PMTs hit at least once in an event. An *nhitsCleaned* cut tracks the number of normal PMTs hit and passes the channel and hit cleaning cuts.

The other cuts such as *fitValid* and *waterFit* are booleans that indicate whether the full fit information being used is valid, and whether the fit information was stored in the ntuple, respectively. The ntuple is the condensed data format used in these types of analyses as they are simpler to use and smaller than their associated ROOT files. *Itr* is a classifier that denotes the number of hits falling within a defined time-frame to the total number of hits, and β_{14} is another classifier that identifies the anisotropy of events.

From these cuts, it can be seen in Figures 5.3 and 5.4 that there are regions with high event rates near the top of the cavity and AV, respectively. This is clearly seen in Figure **??** where the energies of the events (or nhits) are plotted against their location from the bottom of the PSUP (-8 m to -6 m) to the top of the PSUP (6 m to 8 m). The AV ranges from -6 m to 6 m, where 0 m is the equator of the detector. Given the bright colours and larger area of events from the

Isotope	Half-life (days)
$^{252}\mathrm{Fm}$	1.058
$^{160}\mathrm{Er}$	1.191
$^{239}\mathrm{Np}$	2.356
$^{198}\mathrm{Au}$	2.694
$^{253}\mathrm{Fm}$	3.000
$^{199}\mathrm{Au}$	3.139
$^{222}\mathrm{Rn}$	3.824
$^{47}\mathrm{Ca}$	4.536
$^{52}\mathrm{Mn}$	5.591

TABLE 5.1: Short-lived isotopes [55]

0 m to 8 m range, it is clear that the majority of events are occurring at the top of the detector. Analyzing these events over several weeks returns a decay curve, as seen in Figure 5.5. The curve is fitted with an exponential that returns a half-life value of 2.8 ± 0.1 days. Although it is not exact with the half-life of $^{222}\mathrm{Rn}$ (where $t_{1/2} = 3.82$ days), the value is small enough that it is unlikely to be any other isotope. To compare, a list of isotopes with a half-life of several days can be found in Table 5.1. Although an argument can be made that the half-life found in the data most resembles that of $^{198}\mathrm{Au}$ or $^{253}\mathrm{Fm}$, there are no indications of these isotopes within the detector, based on ongoing metals testing on water samples.

As the water recirculates, an uneven collection of events will be present when fitting a decay curve. This, and the convection due to temperature differentials inside the detector, and alter a decay curve, resulting in a slightly lower than expected half life.

As the detector continues to recirculate water, and prepare for the next phase, it is expected that the "hotspots" will be reduced as the water is constantly filtered for Rn daughters. It is a factor that requires continuous monitoring, as a build up of larger or greater quantities of "hotspots"

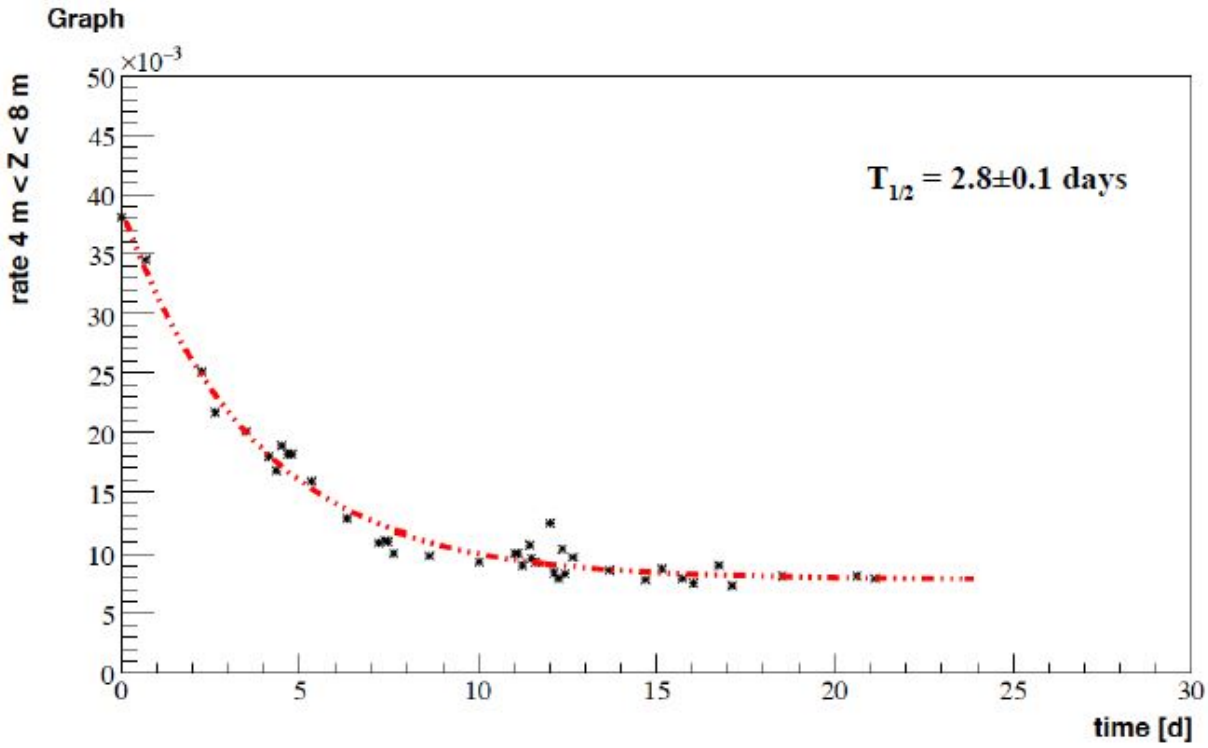


FIGURE 5.5: The "Hotspot" was analyzed over the course of several weeks, and fitted with a decay curve. The result is a halflife of 2.8 $\pm$ 0.1 days. Although not equivalent to radon's half life of 3.82 days, the rates in the decay curve are easily disturbed due to water recirculation and temperature gradients. [44].

will greatly affect the data collection required to observe rare physics interactions. The ideal is to have no "hotspots" present. However, as physics events are expected within the center of the AV, and outer perimeter cut has been applied in the analysis. This also cuts external events due to geometry and noise. Therefore "hotspots" lying on the outer edges of the AV will likely be a non issue. If the "hotspots" begin to grow and move with convection, then they will be a greater issue that must be dealt with immediately. Periods when water recirculation and purification, and water cooling continued for long lengths of time have helped diminish "hotspots" greatly, as well as implementing a cover gas system and fixing leaks. Current analyses are being done by a fellow collaborator, whose plots show that water recirculation and purification greatly diminishes the "hotspots". This can be seen in Figure 5.6, where without recirculation a "hotspot" can form. Within 24 hours of recirculation, that "hotspot" can then disappear, and also return quickly without continuous recirculation and purification. Small traces of water left after the filling of scintillator in the AV can contaminate the scintillator if there is higher than expected radon concentrations within the water. It is therefore crucial to understand these "hotspots" and work to reduce or eliminate them.

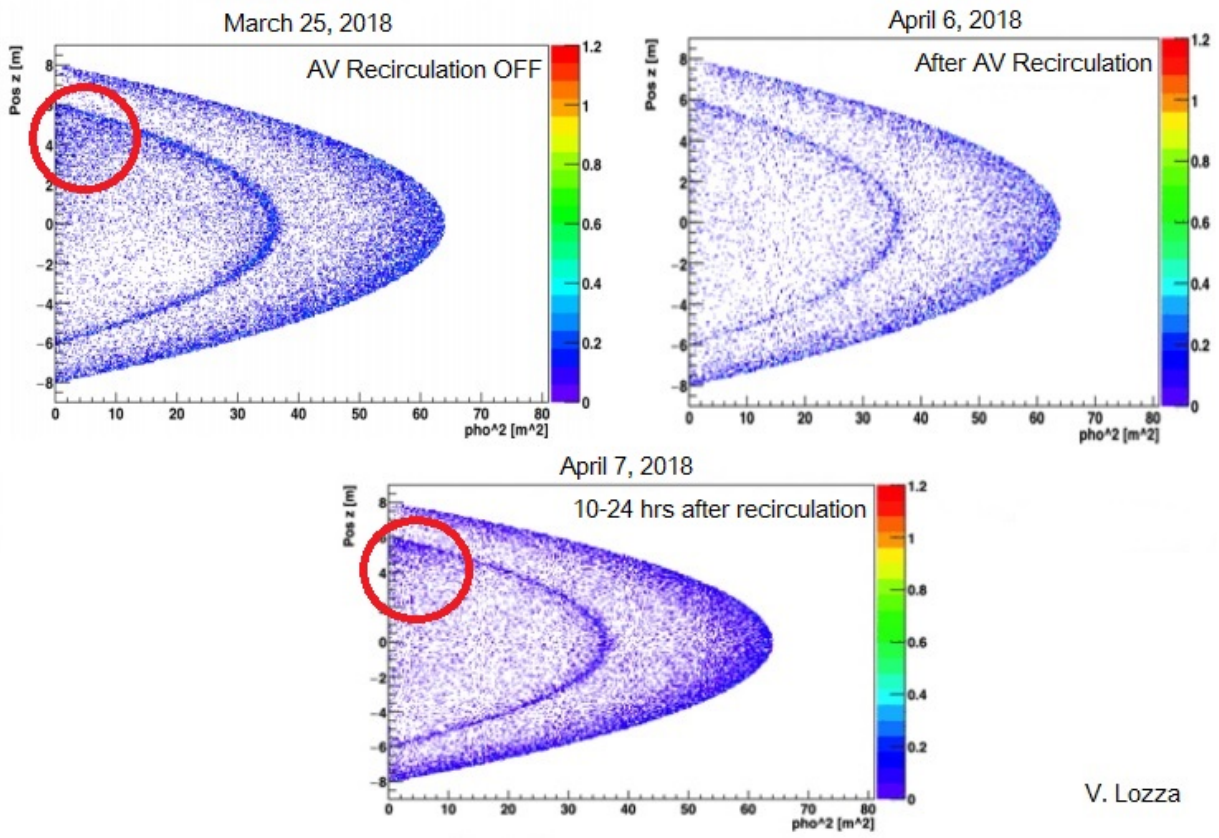


FIGURE 5.6: The "hotspot", which is circled in red in the above plots, can appear without consistent water recirculation and purification usually within 24 hours [45]. The inner oblong circle is half of the AV, and the outer oblong circle is half of the PSUP.

Chapter 6

Conclusion

> We have this one life to appreciate the grand design of the universe, and for that, I am extremely grateful.
>
> **Stephen Hawking**

Radon is naturally present every where on earth, and due do its long-lived daughter isotopes, is quite detrimental to particle physics experiments like SNO+. As discussed in Chapters 2 and 3, the mitigation of backgrounds can be done using several methods at the detector level such as employing a cover gas system. Monitoring can be done using *ex situ* methods such as radon assays, as discussed in Chapter 4 and at the analysis level such as applying fiducial volume cuts and analyzing areas with high event rates (also known as the "hotspot" analysis), as discussed in Chapter 5.

The radon assay system uses the water purification loops to extract samples using custom Lucas Cells. The procedures highlighted in Chapter 4, and further expanded in Appendices B and C, give insight into the complexities of extracting radon from water. The ground work for the radon assay system is well underway in SNO+'s analysis of *ex situ* measurements. The system procedures have been finalized, and all of the necessary components are in good working order asides

from the possibility of a leak. While not currently well understood, the background measurements of the system vary, and the results from previous measurements performed for the SNO experiment are not reproducible. The average measurement for the current system is 112.77 $\pm$ 5.07 counts per day, which does not differ greatly from SNO's report of an average of 92.5 cpd [24]. However further conversions into the number of radon atoms per day show drastic differences of two orders of magnitude when compared to the SNO result of 460 Rn atoms/day, where the average of the runs is 32930 Rn atoms/day. Further work must be done to return the system to optimal conditions to achieve SNO levels.

As SNO+ progresses into the scintillator phase of the experiment, more tests must be done on the radon assay system in order to set a baseline background count, and monitor the cavity radon levels. Current PSUP results of 3.68×10^{-14} gU/gH_2O (sampled on June 28, 2017) and 1.28×10^{-12} gU/gH_2O (sampled on May 30, 2018) are not consistent with each other, nor do they compare with the SNO result of 3.50×10^{-13} gU/gH_2O. Similarly, the AV water sample measured 2.89×10^{-11} gU/gH_2O on November 7, 2017 also does not compare to the internal SNO result of 6.63×10^{-15} gU/gH_2O. Current *in situ* analysis shows a magnitude of 10^{-13} gU/gH_2O, which is a good indication that as recirculation continues, water contamination will continue to be reduced.

The monitoring of the purification loop is essential, and more assays must be done in order to understand the radon rates. Continued monitoring and purification will also help reduce and/or eliminate the issue with the volumes of high event rates inside the detector. The next immediate steps will be to continue leak checking the system without running any water. Larger loops have already been done, therefore the smaller loops should be made by closing one valve at a time for each successive assay. It is clear from previous background assays that the MDG and FTS are not leaking. The vacuum pump and Vlad trap have also been checked, and hold good vacuum.

The leak is somewhere near or in the radon traps. Once it is found, it will be a matter of fixing the leak by tightening valves or replacing O-rings. From this point, background assays are expected to show levels around 460 Rn atoms/day because all leaks will have been fixed. The system will then be ready for continuous monitoring of the water levels with regular maintenance for the duration of the remaining SNO+ phases.

My contributions to this experiment include all of Chapter 4 and most components in Chapter 5. My focus has been monitoring the $^{222}\mathrm{Rn}$ levels in the water using *ex situ* analysis, and I have pursued that goal by performing all the 2016-2018 assays discussed in Chapter 4, and was aided in the analysis with the help of Dr R. Ford and Dr A. Wright. Much of the work in Chapter 5 has been done with the help of Dr V. Lozza as she continues to monitor "hotspots" within the detector. The remaining portions of the thesis have been developed by contributions within the SNO+ collaboration.

Appendix A

Lucas Cell Backgrounds

Lucas Cell	Status	Backgrounds (cpd)	Background 2017 (cpd)	file
7	Rm 115			
14	Spiked			
15	Leaks	41.97 $\pm$ 1.81		
16	Spiked			
A	Rm 115	658.17 $\pm$ 7.46		
B	Rm 115			
C	Rm 115	0.00 $\pm$ 0.00		
E	Rm 115	137.68 $\pm$ 3.53		
F	Rm 115	2478.23 $\pm$ 14.96		
A4	Rm 115	7.88 $\pm$ 0.78	75.63 $\pm$ 2.28	17030916.log
A12	Rm 115			
A14	Rm 115	99.43 $\pm$ 3.65	90.16 $\pm$ 1.69	17052614.log
A15	Rm 115			
H1	Rm 115	180.18 $\pm$ 4.03		
H2	Rm 115			
H4	Rm 115	342.65 $\pm$ 5.38		
H7	Rm 115	688.33 $\pm$ 10.12		
H9	Rm 115	321.17 $\pm$ 5.01		
H10	Rm 115			
H11	Rm 115	119.46 $\pm$ 3.28		
L12	Chris J. and Dimpal			
L11	In Use	0.25 $\pm$ 0.15		
L13	Chris J. and Dimpal			
L14	Nasim 24-June-14			

L15	Nasim 24-June-14			
L16	In Use	3.72 ± 0.56		
L17	Brand New			
L18	Brand New			
L19	Brand New			
L20	Brand New			
L21	Brand New			
L22	DEAP 3600			
L23	Brand New			
L24	Brand New			
L25	Brand New			
L26	Brand New			
L27	Brand New			
L28	Brand New			
L29	Brand New			
LCT 2	Rm 115			
LCT 4	Rm 115	25.13 ± 1.83		
LCT 5	Rm 115	134.32 ± 4.24	88.87 ± 2.75	17030915.log
LCT 6	Rm 115			
N8	Rm 115	24.46 ± 1.81		
N9	Rm 115	1007.57 ± 12.25	971.06 ± 16.25	17072614.log
N10	Rm 115	15.63 ± 1.52	160.00 ± 3.32	17032915.log
N19	Rm 115	13.10 ± 1.4		
Rexon 1 (R1)	Rm 115			
Rexon 2(R2)	Rm 115			
Rexon 4 (R4)	Rm 115			

TABLE A.1: Current and last known Lucas Cell backgrounds. The Lucas Cells were previously counted in 2014-2015. This table summarizes the known values for each Lucas Cell, as well as the current work done.

Appendix B

MDG Background Procedure

MDG Background Assay - No Water

Document Number: SL-OPS-PCS-30-351-P - rev1		**Revision Number: 1**
Document Owner: Allan Barr		
Reviewer: Sanford Clark		
Name:	**Signature:**	**Date:**
Approval Authority:		
Name:	**Signature:**	**Date:**

1. Scope

This procedure provides steps to perform a Radon (Rn) background assay on the MDG Rn skid. The Radon board traps radon from the monitor degasser into Lucas cells to be taken to the surface lab for counting. Before assaying, the FTS water trap is 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 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.

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 2.2.5 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 2.2.6 to flush air out of the N2 lines

2.2.7 Valve Open List

♦ Follow and fill in section 2.2.7 to open a path from the trap to the pressure gauge.

2.2.8 Pressurizing and Draining the Trap

♦ Follow and fill in section 2.2.8 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 2.2.9 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 2.2.10 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, Flushing Lucas Cells, 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, SL-OPS-PCS-10-010.

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 Evacuating Lucas Cells

♦ Follow and fill in section 2.3.5 to flush and evacuate Lucas cells.

2.3.6 Baking the Radon Board

♦ Follow and fill in section 2.3.6 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. UPW authorization is required before assay begins.

2.4.2 Confirm Closed Valves

♦ Follow and fill in section 2.4.2

2.4.3 Confirm Open Valve

♦ Follow and fill in section 2.4.3 to confirm the valve that is normally left open.

2.5 Assay Details

2.5.1 Running the Vacuum Degasser

♦ Follow and fill section 2.5.1 of the checklist to open the system to the MDG

2.6 Extraction from the Water

♦ Follow and fill out section 2.6.1-2.6.4 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 2.6.3 of the checklist during the extraction time. At the end of the assay follow and fill in section 2.6.5 to complete water extraction

2.7 Transfer of Radon

♦ Follow 2.7.1-2.7.5 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 A, the pressure in A may rise to greater than +200. If so, open the trap to vacuum. During the warming of Trap B, the pressure in B may rise off scale (> +600 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.

2.8 Bake Board again

♦ To prepare for the next assay follow section 2.8 to evacuate the traps.

2.9 System Shutdown at the End of All Assays

♦ Follow and fill in section 2.9.1 – 2.9.3 (checklist) 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.

2.10 Checklist Completion and Filing

♦ Follow and fill in section 2.10.1– 2.10.2 to prepare and file the checklist and complete the assay.

2.11 MDG Extraction Experiment Record Sheet

♦ Follow and fill in section 2.11 to record necessary data from the assay.

3. Potential Hazards and Risks

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

- 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.
- 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.

Notes:

4. Revision History

ORIGINATING DATE: 2013-08-01			
REV NO.	**EFFECTIVE DATE (YYYY-MM-DD)**	**AUTHOR**	**SUMMARY OF CHANGE**
0	2017-02-01	D. Chauhan, L.Anselmo, P. Woosaree, F. St Jacques J. Rumleskie	Developed a procedure based on SL-OPS-PCS-30-350-P-rev7 Added 2.3.4.1 –LC flushing and evacuation. Removed sections not needed for background Rn assay.
1	2018-05-15	P. Woosaree	Changed the LC flush procedure, updated the N2 access portion, reformatted text, updated Rn extraction sheet, added emergency shut down procedures. Changed document number from SL-OPS-PCS-30-350-P-rev7 to SL-OPS-PCS-30-351-P-rev1

SL-OPS-PCS-30-351-P Rev 1
MDG Background Run -
No Water

Personnel: _____

Day/Date: _____

Time: _____

2.1 Authorization to Implement (Explanation)

Note: UPWSS authorization is required in **2 places** for this procedure (2.2 - Draining the Trap, 2.10 - Checklist Completion and Filing).

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: section includes confirm closes and draining excess water from traps.	

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 °C. (if not done, enter NR)	

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	
N2 supply (beside MDG skid)	[Y]	V-668L	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

Ensure regulator is connected to the N2 cylinder, located on the first floor directly beneath the Rn skid				
Main N2 bottle supply valve			[Y] Lift red switch	
Regulator diaphragm valve (N2 cylinder - first floor)			[Y] OPEN P ~ 5 psi	
Needle valve on regulator (black circular valve)	[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 vacuum.				

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: mL				
NOTE: Mark the following 3 steps as "NR" if flushing Lucas Cells today:				
Main N2 bottle supply valve [Red Switch]	[Y]		CLOSE	
Regulator diaphragm valve	[Y]		BACK OFF	
Black valve	[Y]	V-660L	CLOSE	

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: mL				

Notes:

2.3 Pumping the Trap, Flushing Lucas Cells, and Baking the Radon Board

2.3.1 Authorization to implement

UPWSS initials to implement Section 2.3 Pumping the Trap, Flushing Lucas Cells, and Baking the Radon Board. Section includes turning on power, applying vacuum to traps, and cleaning traps.	

2.3.2 Initial Setup

Turn on Control Panel power				
Turn on FTS main power	FTS Panel, (**0/1**)		1	
Activate cooling cycle. Ensure the green light comes on	FTS Panel, (**Start/Stop**)		START	
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	
Make sure V_exhaust is open and confirm oil in the exhaust line of the vacuum pump	[Y]	V_Exhaust	Open	
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 SL-OPS-PCS-10-010 (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. Fill to black line on the blue zip tie next to the Vlad trap	
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	[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. Open in small increments	[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-222L	OPEN	
Vapour Trap outlet, beside FTS	[Y]	V-224L	OPEN	
* Radon Board bypass to Vlad trap and vacuum pump	[Y]	V-242L	OPEN Slowly	
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 and temperature is decreasing 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.				
LCID(s):				
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	
N2 Supply (side 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	
Relive pressure in lines, open V-745L	[Y]	V-745L	OPEN	
Close V-745L	[Y]	V-745L	CLOSE	
LC N2 Flush #1: Fill LC with N2				
RnBoard (Radon trap bypass) (~2sec)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
Let LC flush 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) (~2sec)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
Let LC flush 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) (~2sec)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
Let LC flush 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		[Y]	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	
Near Vlad trap	[Y]	V-247L	CLOSE	
Bring Lucas Cell(s) with you				

Notes: _____

2.4 Main Assay

2.4.1 Authorization to Implement

UPWSS initials to implement Section 2.4 – Main Assay. Section involved radon extraction from system	

2.4.2 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 (beside FTS)	[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	

2.4.3 Confirm Open Valve

Above Degasser, by PT-004 (normally left open)	[Y]	V-241L	Confirm Open	

Notes:

2.5 Assay Details

Lucas Cell Number LC #	**LC ID:**	

2.5.1 Running the Vacuum Degasser (311-DG01)

Confirm closed V-242L	[Y]	V-242L	Confirm Close	
Gradually open to MDG	[Y]	V-215L	Slowly OPEN	
Start time of flow			Time:	
Establish connection to MDG	[Y]	V-258L	Slowly OPEN	
Wait at least **25 minutes** for an accurate measurement				

2.6 Extraction from the Water

2.6.1 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.	

2.6.2 Trap A Extraction

CLOSE **V-258L**, quickly open **V-244L**, and turn **V-245L** downward	
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)	

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

2.6.3 Record Data

Temperature of MDG walls	^{o}C	
Thermometer (after 25 mins)	^{o}C	

2.6.4 Extraction Monitoring

Check the Vlad trap periodically and fill with LN_2 as required (every 30-40 min)	
Fill out the Rn extraction log sheet every **15 min**	

2.6.5 Water Extraction Completion [PROCEED QUICKLY]

Radon Board	[Y]	V-244L	CLOSE	
Rn Board, close when P<100 mTorr	[Y]	V-245L	CLOSE	
Record Time **Immediately (time of V-244L closure)**			Time:	
Record time on the Rn extraction log sheet as well				

2.7 Transfer of Radon

2.7.1 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 /or scissors jack	
Heat trap A: defrost and continue to heat until transfer is complete.	
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	

2.7.2 Transfer from Trap A to Trap B

Radon Board	[Y]	V-259L	OPEN	
Radon Board (**start of transfer**)	[Y]	V-245L	OPEN Upwards	
Allow the transfer to continue for **15 minutes** (meanwhile continue with 2.7.3)				

2.7.3 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 (watch PT007)	[Y]	V-261L	OPEN	
Radon Board (watch PT007)	[Y]	V-262L	OPEN	
Cell normally jumps to 20-100 mTorr on FTS and drops to stable pressure ~2-3 mTorr				
Record maximum pressure		Pmax: mTorr		
Record low stable pressure		Pstable: mTorr		
Radon Board	[Y]	V-261L	CLOSE	
Radon Board	[Y]	V-262L	CLOSE	

2.7.4 End of Transfer from Trap A to Trap B

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

2.7.5 Transfer from Trap B to the Lucas Cell

Remove the liquid Nitrogen from **Trap B**				
Heat Trap B: Defrost until trap is hot				
If pressure on gauge **B** goes above **+600**, open **V-260L** to relieve the pressure and allow the radon to flow into the Lucas cell.				
Record Pressure **B** on Extraction Sheet				
Start Transfer to Lucas Cell, continue heating Trap B	[Y]	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 bake) while Trap B to LC transfer is taking place	[Y]	Radon Board	Bake	
Close when P < 15 mTorr (end of bake)	[Y]	V-245L	CLOSE	
Note time: (**having allowed transfer to take place for 10 minutes**, continue heating Trap B otherwise)				
Before removing Lucas cell, note Pressure B	[Y]	Trap B		
Remove the Lucas cell and re-attach the blue caps				
Note Pressure B again	[Y]	Trap B		
Close (end of transfer)	[Y]	V-260L	CLOSE	
Extraction is now complete.				

2.8 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	[Y]	V-262L	OPEN	
Radon Board	[Y]	V-261L	OPEN	
Radon Board	[Y]	V-260L	OPEN	
Radon Board	[Y]	V-259L	OPEN	
Heat Trap B (~ 3 min)				
Rn Board Close when P <15 mTorr	[Y]	V-259L	CLOSE	
Radon Board	[Y]	V-260L	CLOSE	
Radon Board	[Y]	V-261L	CLOSE	
Radon Board	[Y]	V-262L	CLOSE	

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

IF YOU ARE RETURNING:				
Radon Board	[Y]	V-244L	CLOSE	
Rn Board	[Y]	V-245L	CLOSE	
IF YOU ARE NOT RETURNING (or unsure of your return):				
Radon Board	[Y]	V-244L	CLOSE	
Rn Board	[Y]	V-245L	CLOSE	
Valve on top of degasser	[Y]	V-215L	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, (S**tart/Stop)**	STOP	
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	
Near Vlad trap	[Y]	V-247L	CLOSE	
Bring Lucas Cell(s) with you				

2.9 System Shutdown at the End of All Assays

2.9.1 Degasser Shutdown

Valve on top of degasser	[Y]	V-215L	CLOSE	
Record Time	Time			hh:mm

2.9.2 Valve Close List

Confirm close possible return path valve	[Y]	V-550L	Confirm CLOSE	
Confirm close possible return path valve	[Y]	V-551L	Confirm CLOSE	
MDG Skid, above P26	[Y]	V-255L	Confirm CLOSE	
Confirm close possible skid inlet	[Y]	V-254L	Confirm CLOSE	

2.9.3 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, **(Start/Stop)**		STOP	
Turn off FTS	FTS Panel, **(0/l)**		0	
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	
Turn off Control Panel	Control Panel		OFF	
Unplug heat gun, meter for A/B and meter for MDG			Unplug	
Store liquid N2 (fill XRF detector in the junction if needed; ask operators)			Store	
Remove caution tape			Remove	

2.10 Checklist Completion and Filing

2.10.1 Ultrapure Water Systems Supervisors Review and Sign-off

Signature of the Ultrapure Water System Shift Supervisor; assay complete	

2.10.2 Copy and File Checklist, Report

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

2.11 MDG Extraction Experiment Record Sheet

DATE _____/_____/20_____
m d y

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: _____/_____/20____, _____ HV On ?? (Y/N) _____
m d y time

Delay time _____hrs (Hours between End of assay and Start of Counting)

Stop: _____/_____/20____, _____ File Name: _____
m d y time

Counts/ Live time:_____cpd

Bkg: _____ Net Counts/day _____

COMMENTS_____

_____

_____

_____

_____

_____

_____

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

EXTRACTION DETAILS

Extraction Start: _____ Stop: _____ Elapsed: _____

Lucas cell #:_____ MDG Temp (°C): _____

Time	MDG (°C)	Trap A	Alcatel Pressure (mTorr)	Trap Temp (°C)	Comments

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: _____ Transfer duration: _____

Stop time of transfer: _____

B reading with LC attached: _____

B reading with LC detached: _____

Appendix C

Updated Radon Assay Procedure

SNOLAB	**Radon Assay (DRAFT)**

Document Number: SL-OPS-PCS-30-350-P		**Revision Number: 8**
Document Owner: Allan Barr		
Reviewer: Sanford Clark		
Name:	**Signature:**	**Date: <YYYY-MM-DD>**
Approval Authority:		
Name:	**Signature:**	**Date: <YYYY-MM-DD>**

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.

2.2.4 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.

2.2.5 Flushing the Lines

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

2.2.6 Valve Open List

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

2.2.7 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.

2.2.8 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.

2.2.9 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, Flushing Lucas Cells, 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, SL-OPS-PCS-10-010.

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 Evacuating Lucas Cells

♦ Follow and fill in section 2.3.5 to flush and evacuate 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 Confirm Closed Valves

♦ Follow and fill in section 2.4.3

2.4.4 Confirm Open Valve

♦ Follow and fill in section 2.4.4 to confirm the valve that is normally left open.

2.4.5 Confirm/Establish Initial Set-up

♦ Follow and fill in section 2.4.5 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 Open Key Valves

♦ Follow and fill in section 2.5.2 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.

2.5.3 Notify Detector Operator and Confirm Closed Deck Valves

♦ Follow and fill in section 2.5.3 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.

2.5.4 Deck Considerations and Open Valves

♦ Follow and fill in section 2.5.4 to open the selected deck sample line valve.

2.5.6 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 Loop Sample Assay to Drain

2.7.1 and 2.7.2 Confirm Closed or Close Key Valves

♦ Follow and fill in section 2.7.1 and 2.7.2 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.

2.7.3 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.

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 – 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.

2.9 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

2.10 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 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.

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.

Notes:

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	2017-08-30	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.

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, Flushing Lucas Cells, 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: section includes confirm closes and draining excess water from traps.	

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 °C. (if not done, enter NR)	

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	
N2 supply (beside MDG skid)	[Y]	V-668L	Confirm Closed	

2.2.3 Preliminary Confirmed Open List

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

2.2.4 Preliminary Setup

Ensure regulator is connected to the N2 cylinder, located on the first floor directly beneath the Rn skid			
Main N2 bottle supply valve	[Y]	Lift red switch	
Regulator diaphragm valve (N2 cylinder - first floor)	[Y]	OPEN P ~ 5 psi	
Black valve	[Y]	V-660L	OPEN 1 Turn	

2.2.5 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	

2.2.6 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 vacuum.				

2.2.7 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					

2.2.8 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: mL				
NOTE: Mark the following 3 steps as "NR" if flushing Lucas Cells today:				
Main N2 bottle supply valve [Red Switch]	[Y]		CLOSE	
Regulator diaphragm valve	[Y]		BACK OFF	
Black valve	[Y]	V-660L	CLOSE	

2.2.9 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: mL				

Notes:

2.3 Pumping the Trap, Flushing Lucas Cells, and Baking the Radon Board

2.3.1 Authorization to implement

UPWSS initials to implement Section 2.3 Pumping the Trap, Flushing Lucas Cells, and Baking the Radon Board. Section includes turning on power, applying vacuum to traps, and cleaning traps.	

2.3.2 Initial Setup

Turn on Control Panel power				
Turn on FTS main power	FTS Panel, (**0/1**)		1	
Activate cooling cycle. Ensure the green light comes on	FTS Panel, (**Start/Stop**)		START	
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	
Make sure V_exhaust is open and confirm oil in the exhaust line of the vacuum pump	[Y]	V_Exhaust	Open	
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 SL-OPS-PCS-10-010 (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. Fill to black line on the blue zip tie next to the Vlad trap
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. Open in small increments	[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-222L	OPEN	
Vapour Trap outlet, beside FTS	[Y]	V-224L	OPEN	
* Radon Board bypass to Vlad trap and vacuum pump	[Y]	V-242L	OPEN Slowly	
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.				
LCID(s):				
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	
N2 Supply (side 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	
Relive pressure in lines, open V-745L	[Y]	V-745L	OPEN	
Close V-745L	[Y]	V-745L	CLOSE	
LC N2 Flush #1: Fill LC with N2				
RnBoard (Radon trap bypass) (~2sec)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
Let LC flush 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) (~2sec)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
Let LC flush 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) (~2sec)	[Y]	V-258L	OPEN	
Close Rn Board (radon trap bypass)	[Y]	V-258L	CLOSE	
Let LC flush 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		[Y]	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	
Near Vlad trap	[Y]	V-247L	CLOSE	
Bring Lucas Cell(s) with you				

Notes: _____

2.4 Main Assay

2.4.1 Authorization to Implement

UPWSS initials to implement Section 2.4 – Main Assay. Section involved radon extraction from system	

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

Run SL-OPS-PCS-30-403 to purge sample line if assay is following H_2O MnOx or HTiO assay	
Confirm that SL-OPS-PCS-30-200-P is running	
Record cavity level (LT-103)	
Make notes describing the current circulation & run plan, i.e.: - Is cavity automake-up active (checked in DeltaV)? 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? - Have there been any SDS trips in the last 24 hours? - Any other unusual circumstances?	

2.4.3 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 (beside FTS)	[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	

2.4.4 Confirm Open Valve

Above Degasser, by PT-004 (normally left open)	[Y]	V-241L	Confirm Open	

2.4.5 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)	[NN]	PCV-135	Set to 40 psi	
P05 inlet (PDG Pit)	[Y]	V-171L	OPEN	
Compressed air valve for P05 (PDG Pit)	[Y]	V-172L	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	

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 point(s)				
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)				
Open chosen sample valve	[Z]	V-	OPEN	

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 solenoid valve power for P26 (feed pump)		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	
P05 power (bottoms pump) (Assay Operator)		Control Panel	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 Skid)	[Y]	V-242L	OPEN Slow	
Skip the next page and move on to Section 2.7 (diaphragm pump adjustments to set flows)				

OPTION 2 – LOOP SAMPLE ASSAY

2.6 Flowpath Preparation

2.6.1 Confirm Close 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 the PDG inlet	
Loop adjustment(s) complete UPW's checkmark 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 eye on the MDG level.				
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):				
Slowly open H_2O sample valve	[V]	V-	Slowly OPEN	
Inlet to MDG (Assay Operator)	[Y]	V-248L	OPEN	
P05 power (bottoms pump) (Assay Operator)		Control Panel	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 Skid)	[Y]	V-242L	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	

Notes:

OPTION 3 – LOOP SAMPLE ASSAY to drain

2.7 Flowpath 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	

2.7.2 Confirm Close 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)	
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 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 the PDG inlet	
Loop adjustment(s) complete UPW's checkmark required here→	

2.7.4 Valve Open List

Open P05 outlet valve (PDG Pit)	[Y]	V-252L	OPEN	
To drain (PDG Pit)	[V]	V-471L	Slowly OPEN	
Indicate First Sample Valve Chosen (201, 202, 203, 204, 205, or 206):				
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 eye on the MDG level.				
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	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 Skid)	[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-248L	[Y]	V-248L	OPEN	

Notes:

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-137	Set to 50 psi	
Monitor the flow; should read about 24 lpm when stable	[Y]	FIT-121		lpm
Skip ahead to 2.8 Assay Details				

2.8.3 Note Diaphragm Pump Air Supply Pressures

Record P26 air supply pressure	[Y]	PCV-132	psi
Record P05 air supply pressure	[Y]	PCV-135	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	
Rn 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-294L	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	
Near Vlad trap		[Y]	V-247L	CLOSE	
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 valve	% 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've opened your sample valve and will be starting the sample line flow							

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 MDG	[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 ~ –453						
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 that 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

Turn on pump **stroke counter**					
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 PI-126A	Near P05	psi					
Bottoms Pump Air Pressure	PI-172 (maximum)	psi					
Strokes P05	Time per 20 strokes	sec					
Temperature of MDG walls	Thermometer (after 25 mins)	^{o}C					

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

2.10.4 Extraction Monitoring

	Sample Line Assays			Loop Sample Assays		
Check the Vlad trap periodically and fill with LN_2 as required (every 30-40 min)						
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 mTorr	V-245L	CLOSE						
Record Time **Immediately (time of V-244L closure)**		hh:mm						
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 transfer**)	V-245L	OPEN Upwards						
Allow the transfer to continue for **15 minutes** (meanwhile continue with 2.11.3)								

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 Assays			Loop Sample Assays		
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 Lucas cell.								
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 bake)	Radon Board	Bake						
Close when P < 15 mTorr (end of bake)	V-245L	CLOSE						
Note time: (having allowed transfer to take place for 10 minutes)								
Before removing Lucas cell, note Pressure	Trap B							
Remove the Lucas cell and re-attach the blue caps								
Note Pressure B again	Trap B							
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 <15mTorr	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 4 foot pipe section **above V-254L**	% 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 go to Section 2.13.							

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	
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-132	BACK OFF	
MDG Skid, by P26, compressed air to P26	[Y]	V-170L	CLOSE	
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-135	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 (downstairs)	[V]	V-544L	CLOSE (UPW)	
Confirm close or close loop sample return (downstairs)	[V]	V-470L	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	FTS Panel, **(0/I)**		0	
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	
Turn Control Panel off	Control Panel		OFF	
Unplug heat gun, meter for A/B and meter for MDG			Unplug	
Store liquid N2 (fill XRF detector in the junction if needed)			Store	
Remove caution tape			Remove	

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 _____/_____/20_____
m d y

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: _____/_____/20____, _____ HV On ?? (Y/N) _____
m d y time

Delay time _____hrs (Hours between End of assay and Start of Counting)

Stop: _____/_____/20____, _____ File Name: _____
m d y time

Counts/ Live time: _____ cpd

Bkg: _____ Net Counts/day _____

COMMENTS_____

_____

_____

_____

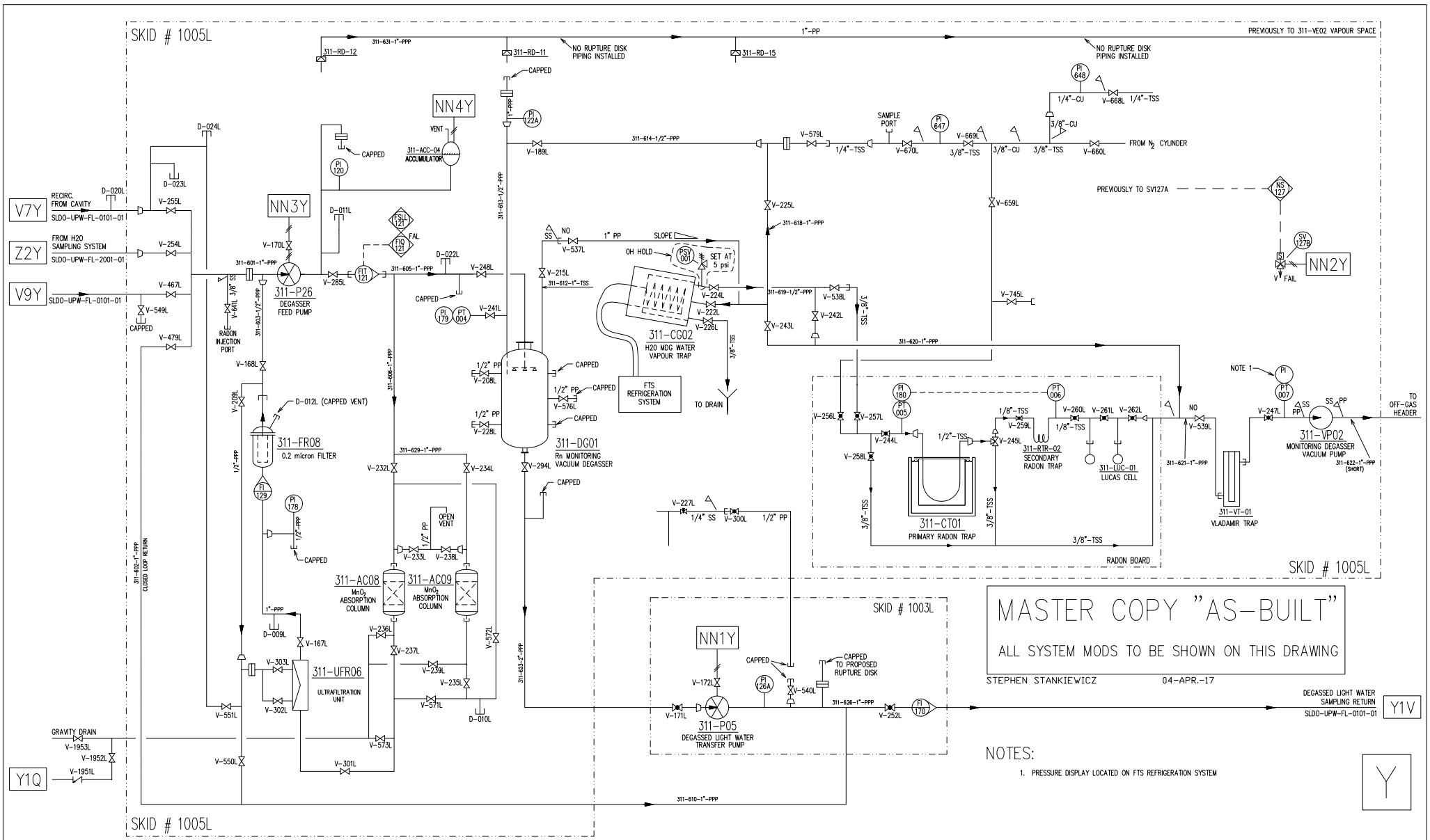
_____

_____

_____

Appendix D

Water Plant and Radon Skid System Flow Charts



DRAWN	S. STANKIEWICZ	SUBMITTED	A. BARR	APPROVED	M. HODAK
DATE	30-MAR-17	DATE	03-APR-17	DATE	04-APR-17

ISSUE	CHANGE	DATE
1	AS-BUILT	30-MAR-17
OB	ADDED EQUIPMENT PART NUMBERS AS PER MARK UPS FROM PETER L.	08-JUL-16
OA	AS PER MARKUPS FROM ALLAN BARR AND FIELD CHECKS BY STEPHEN S.	07-APR-16
0	DRAWING NUMBER CHANGED FROM SLDO-SNP-FL-7007-01	28-JAN-11
A	DRAWING NUMBER CHANGED FROM WPS-D-FL-1026	16-NOV-10

MATERIAL

DRAWN A. PINTO DATE 28-JAN-11 SUBMITTED APPD

ALL DIMENSIONS IN IMPERIAL UNITS

FINISH

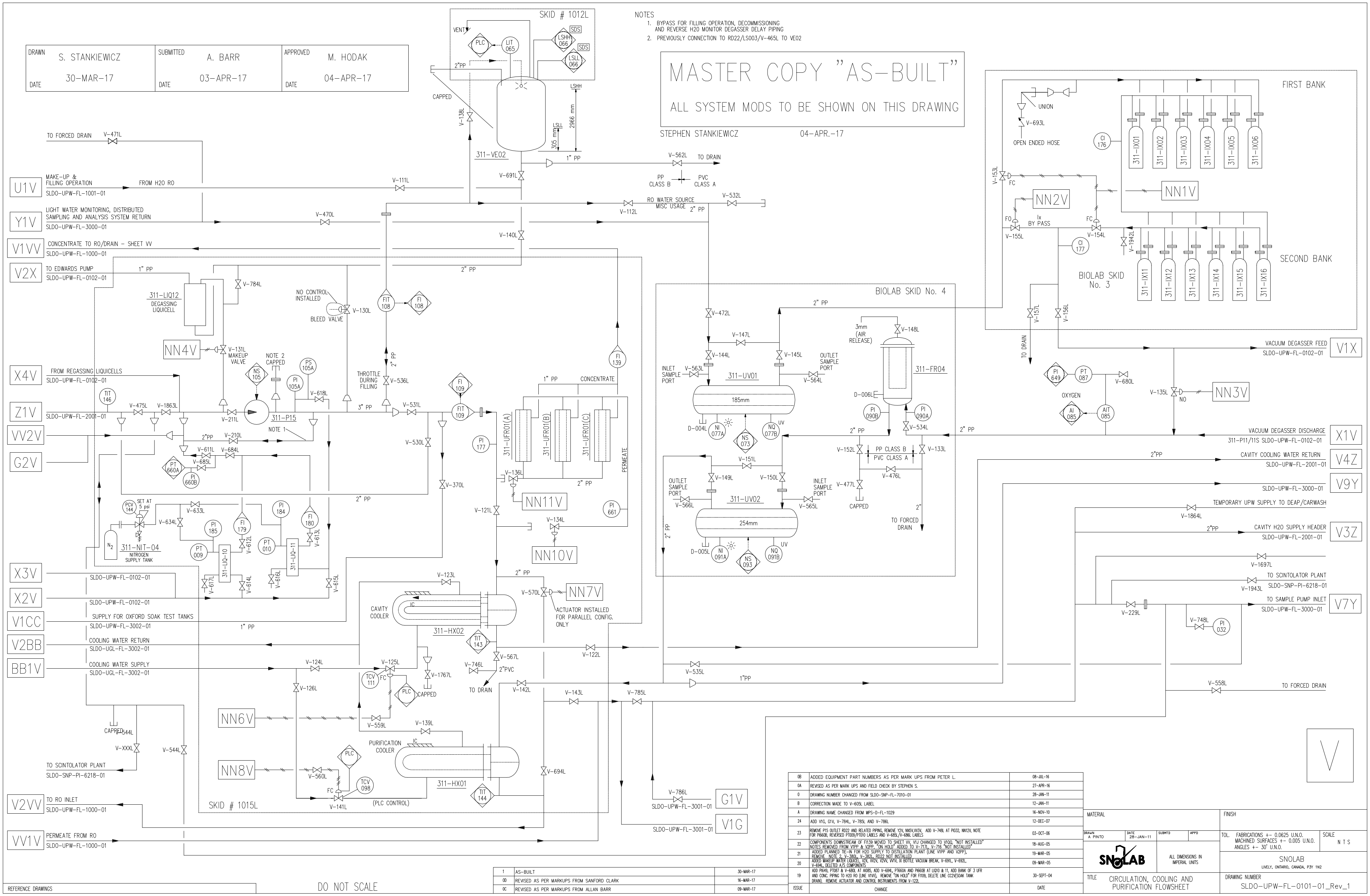
TOL. FABRICATIONS +- 0.0625 U.N.O. MACHINED SURFACES +- 0.005 U.N.O. ANGLES +- 30' U.N.O.

SCALE N T S

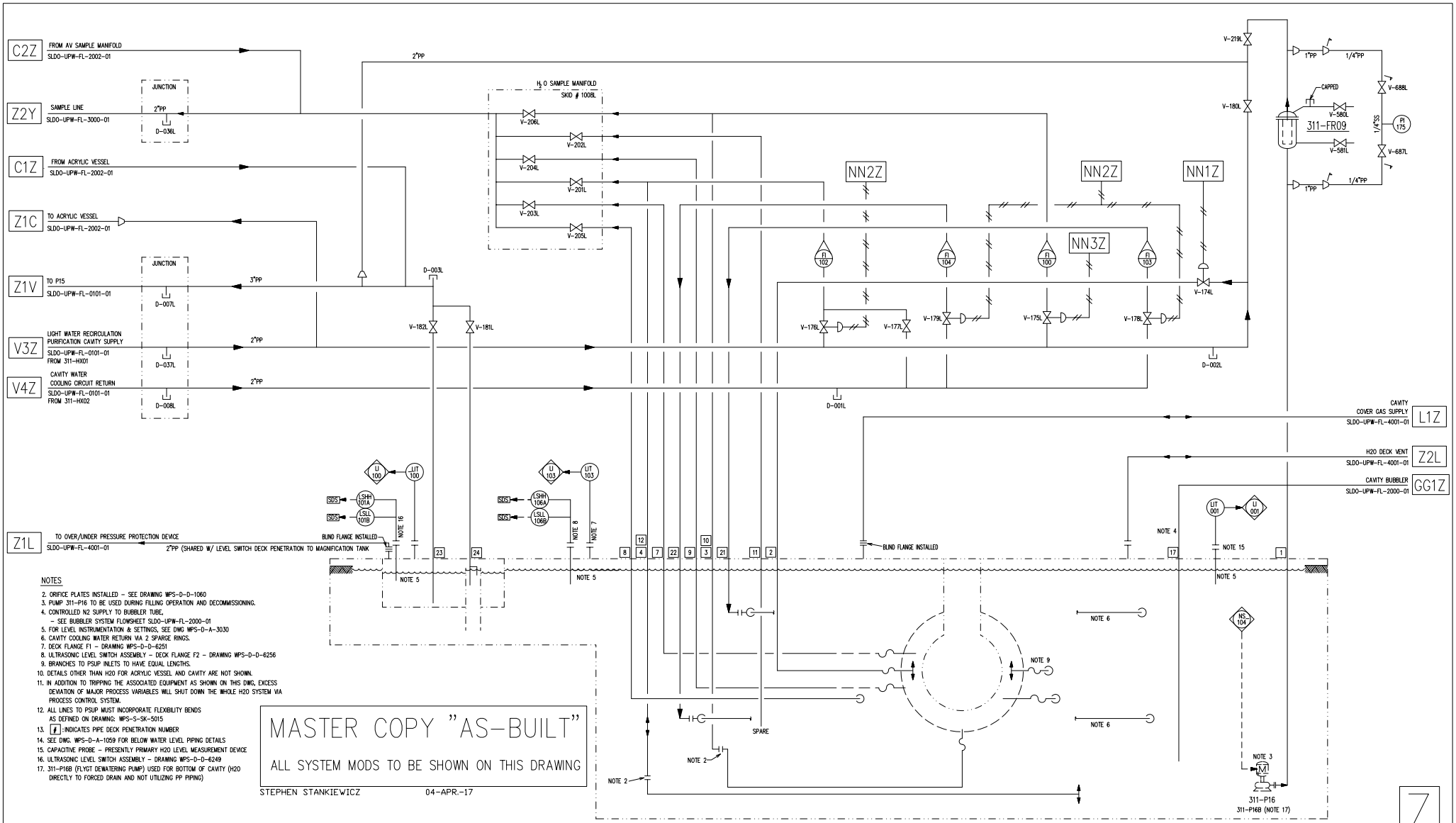
SNOLAB
LIVELY, ONTARIO, CANADA, P3Y 1N2

TITLE H2O MONITORING VACUUM DEGASSING SYSTEM FLOWSHEET

DRAWING NUMBER SLDO-UPW-FL-3000-01_Rev_1



DRAWN S. STANKIEWICZ DATE 30-MAR-17
SUBMITTED A. BARR DATE 03-APR-17
APPROVED M. HODAK DATE 04-APR-17
NOTES
1. BYPASS FOR FILLING OPERATION, DECOMMISSIONING AND REVERSE H2O MONITOR DEGASSER DELAY PIPING
2. PREVIOUSLY CONNECTION TO RD22/LS003/V-465L TO VE02
MASTER COPY "AS-BUILT"
ALL SYSTEM MODS TO BE SHOWN ON THIS DRAWING
STEPHEN STANKIEWICZ 04-APR.-17
SKID # 1012L
311-VE02
FIRST BANK
SECOND BANK
BIOLAB SKID No. 3
BIOLAB SKID No. 4
SKID # 1015L
311-LIQ12 DEGASSING LIQUICELL
311-P15
311-NIT-04 NITROGEN SUPPLY TANK
311-LIQ-10
311-LIQ-11
311-UFR01(A)
311-UFR01(B)
311-UFR01(C)
311-UV01
311-UV02
311-FR04
311-HX02 CAVITY COOLER
311-HX01 PURIFICATION COOLER
311-IX01 311-IX02 311-IX03 311-IX04 311-IX05 311-IX06
311-IX11 311-IX12 311-IX13 311-IX14 311-IX15 311-IX16
TO FORCED DRAIN
U1V MAKE-UP & FILLING OPERATION SLDO-UPW-FL-1001-01 FROM H2O RO
Y1V LIGHT WATER MONITORING, DISTRIBUTED SAMPLING AND ANALYSIS SYSTEM RETURN SLDO-UPW-FL-3000-01
V1VV CONCENTRATE TO RO/DRAIN - SHEET VV SLDO-UPW-FL-1000-01
V2X TO EDWARDS PUMP SLDO-UPW-FL-0102-01
X4V FROM REGASSING LIQUICELLS SLDO-UPW-FL-0102-01
Z1V SLDO-UPW-FL-2001-01
VV2V
G2V
X3V SLDO-UPW-FL-0102-01
X2V SLDO-UPW-FL-0102-01
V1CC SUPPLY FOR OXFORD SOAK TEST TANKS SLDO-UPW-FL-3002-01
V2BB COOLING WATER RETURN SLDO-UGL-FL-3002-01
BB1V COOLING WATER SUPPLY SLDO-UGL-FL-3002-01
TO SCINTOLATOR PLANT SLDO-SNP-PI-6218-01
V2VV TO RO INLET SLDO-UPW-FL-1000-01
VV1V PERMEATE FROM RO SLDO-UPW-FL-1000-01
V1X VACUUM DEGASSER FEED SLDO-UPW-FL-0102-01
X1V VACUUM DEGASSER DISCHARGE 311-P11/11S SLDO-UPW-FL-0102-01
V4Z CAVITY COOLING WATER RETURN SLDO-UPW-FL-2001-01
V9Y SLDO-UPW-FL-3000-01
TEMPORARY UPW SUPPLY TO DEAP/CARWASH
V3Z CAVITY H2O SUPPLY HEADER SLDO-UPW-FL-2001-01
TO SCINTOLATOR PLANT SLDO-SNP-PI-6218-01
V7Y TO SAMPLE PUMP INLET SLDO-UPW-FL-3000-01
G1V SLDO-UPW-FL-3001-01
V1G SLDO-UPW-FL-3001-01
NN1V NN2V NN3V NN4V NN6V NN7V NN8V NN10V NN11V
RO WATER SOURCE MISC USAGE
ACTUATOR INSTALLED FOR PARALLEL CONFIG. ONLY
(PLC CONTROL)
OPEN ENDED HOSE
OXYGEN
REFERENCE DRAWINGS
DO NOT SCALE
1 AS-BUILT 30-MAR-17
00 REVISED AS PER MARKUPS FROM SANFORD CLARK 16-MAR-17
0C REVISED AS PER MARKUPS FROM ALLAN BARR 09-MAR-17
0B ADDED EQUIPMENT PART NUMBERS AS PER MARK UPS FROM PETER L. 08-JUL-16
0A REVISED AS PER MARK UPS AND FIELD CHECK BY STEPHEN S. 27-APR-16
0 DRAWING NUMBER CHANGED FROM SLDO-SNP-FL-7010-01 28-JAN-11
B CORRECTION MADE TO V-605L LABEL 12-JAN-11
A DRAWING NAME CHANGED FROM WPS-D-FL-1029 16-NOV-10
24 ADD V1G, G1V, V-784L, V-785L AND V-786L 12-DEC-07
23 REMOVE P15 OUTLET RD22 AND RELATED PIPING, REMOVE Y2V, NN5V,VV3V, ADD V-748L AT PI032, NN12V, NOTE FOR PI660B, REVERSED PT009/PT010 LABELS AND V-685L/V-686L LABELS 03-OCT-06
22 COMPONENTS DOWNSTREAM OF FI139 MOVED TO SHEET VV, V1J CHANGED TO V1QQ, "NOT INSTALLED" NOTES REMOVED FROM V1PP & V2PP, "ON HOLD" ADDED TO V-717L, V-716 "NOT INSTALLED" 18-AUG-05
21 ADDED PLANNED TIE-IN FOR H2O SUPPLY TO DISTILLATION PLANT (LINE V1PP AND V2PP), REMOVE NOTE 2, V-380L, V-382L, RD22 NOT INSTALLED 19-MAR-05
20 ADDED MAKEUP WATER LIQUICEL, V2X, VV2V, V2VV, VV1V, IX BOTTLE VACUUM BREAK, V-691L, V-692L, V-694L, DELETED A/S COMPONENTS 09-MAR-05
19 ADD PI649, PT087 & V-680L AT AI085, ADD V-684L, PT660A AND PI660B AT LIQ10 & 11, ADD BANK OF 3 UFR AND CONC. PIPING TO H2O RO (LINE V1VV), REMOVE "ON HOLD" FOR FI109, DELETE LINE CC2V(SOAK TANK DRAIN). REMOVE ACTUATOR AND CONTROL INSTRUMENTS FROM V-122L 30-SEPT-04
ISSUE CHANGE DATE
MATERIAL
FINISH
DRAWN A PINTO DATE 28-JAN-11
ALL DIMENSIONS IN IMPERIAL UNITS
TOL. FABRICATIONS +- 0.0625 U.N.O. MACHINED SURFACES +- 0.005 U.N.O. ANGLES +- 30' U.N.O.
SCALE N T S
SNOLAB LIVELY, ONTARIO, CANADA, P3Y 1N2
TITLE CIRCULATION, COOLING AND PURIFICATION FLOWSHEET
DRAWING NUMBER SLDO-UPW-FL-0101-01_Rev_1
V



NOTES

2. ORIFICE PLATES INSTALLED – SEE DRAWING WPS-D-D-1060
3. PUMP 311-P16 TO BE USED DURING FILLING OPERATION AND DECOMMISSIONING.
4. CONTROLLED N2 SUPPLY TO BUBBLER TUBE.
   – SEE BUBBLER SYSTEM FLOWSHEET SLDO-UPW-FL-2000-01
5. FOR LEVEL INSTRUMENTATION & SETTINGS, SEE DWG WPS-D-A-3030
6. CAVITY COOLING WATER RETURN VIA 2 SPARGE RINGS.
7. DECK FLANGE F1 – DRAWING WPS-D-D-6251
8. ULTRASONIC LEVEL SWITCH ASSEMBLY – DECK FLANGE F2 – DRAWING WPS-D-D-6256
9. BRANCHES TO PSUP INLETS TO HAVE EQUAL LENGTHS.
10. DETAILS OTHER THAN H20 FOR ACRYLIC VESSEL AND CAVITY ARE NOT SHOWN.
11. IN ADDITION TO TRIPPING THE ASSOCIATED EQUIPMENT AS SHOWN ON THIS DWG, EXCESS DEVIATION OF MAJOR PROCESS VARIABLES WILL SHUT DOWN THE WHOLE H2O SYSTEM VIA PROCESS CONTROL SYSTEM.
12. ALL LINES TO PSUP MUST INCORPORATE FLEXIBILITY BENDS AS DEFINED ON DRAWING: WPS-S-SK-5015
13. [ℓ] :INDICATES PIPE DECK PENETRATION NUMBER
14. SEE DWG. WPS-D-A-1059 FOR BELOW WATER LEVEL PIPING DETAILS
15. CAPACITIVE PROBE – PRESENTLY PRIMARY H20 LEVEL MEASUREMENT DEVICE
16. ULTRASONIC LEVEL SWITCH ASSEMBLY – DRAWING WPS-D-D-6249
17. 311-P16B (FLYGT DEWATERING PUMP) USED FOR BOTTOM OF CAVITY (H20 DIRECTLY TO FORCED DRAIN AND NOT UTILIZING PP PIPING)

MASTER COPY "AS-BUILT"

ALL SYSTEM MODS TO BE SHOWN ON THIS DRAWING

STEPHEN STANKIEWICZ 04-APR.-17

DRAWN	SUBMITTED	APPROVED
S. STANKIEWICZ	A. BARR	M. HODAK
DATE 30-MAR-17	DATE 03-APR-17	DATE 04-APR-17

ISSUE	CHANGE	DATE
0A	AS PER MARKUPS FROM ALLAN BARR AND FIELD CHECKS BY STEPHEN S.	07-APR-16
0	DRAWING NUMBER CHANGED FROM SLDO-SNP-FL-7003-01	27-JAN-11
A	DRAWING NUMBER CHANGED FROM WPS-D-FL-1039	15-NOV-10
14	ADD ZIC, C1Z, C2Z AND NOTE17, NOTE 11 REFERS TO H20	12-DEC-07
13	CHANGE ZIG TO ZIC	25-SEPT-07
12	ADD LINES C1Z AND ZIG – MODIFICATION	07-AUG-07
11	ADD DRAINS D-036H AND D-037H IN JUNCTION	03-OCT-06
10	ADD NN1Z, NN2Z, V-687L & V-688L & RELATED LINES, DELETE PI176	09-MAR-05
9	ACTUATORS TO DECK VALVES, LINE GS1Z, DELETE LIT102	13-MAR-03
8	REISSUE, AS-BUILT	19-APR-01
1	AS-BUILT	30-MAR-17

MATERIAL	FINISH
DRAWN A. PINTO DATE 27-JAN-11 SUBMITTED APPD	TOL. FABRICATIONS +- 0.0625 U.N.O. MACHINED SURFACES +- 0.005 U.N.O. ANGLES +- 30' U.N.O.
SNOLAB	SCALE N T S
ALL DIMENSIONS IN IMPERIAL UNITS	SNOLAB LIVELY, ONTARIO, CANADA, P3Y 1N2
TITLE H2O CAVITY PIPING FLOWSHEET	DRAWING NUMBER SLDO-UPW-FL-2001-01_Rev_1

REFERENCE DRAWINGS

DO NOT SCALE

Bibliography

[1] 2012. URL: www.snolab.ca (visited on 01/23/2018).

[2] J. Bahcall. "Solar Models and Solar Neutrinos: Current Status". In: *Phys.Scripta T121* (2005), pp. 46–50.

[3] G. Benato. "Effective Majorana Mass and Neutrinoless Double Beta Decay". In: *The European Physical Journal C 75: 563* (2015). URL: https://doi.org/10.1140/epjc/s10052-015-3802-1.

[4] S. Biller. *Nucleon Decay*. URL: http://snoplus.phy.queensu.ca/Nucleon_Decay.html (visited on 03/31/2018).

[5] S. Biller and S. Manecki. "A New Technique to Load ^{130}Te in Liquid Scintillator for Neutrinoless Double Beta Decay Experiments". In: *Journal of Physics: Conference Series 888(1):12084* (2017).

[6] CERN. *Gargamelle*. URL: https://home.cern/about/experiments/gargamelle (visited on 05/28/2018).

[7] J. Chadwick. "Possible Existence of a Neutron". In: *Nature* 129.3252 (Feb. 1932), p. 312.

[8] M. Chen. "Neutrinoless Double Beta Decay Experiments". In: *J. Phys.: Conf. Ser.* 598 012008 (2015).

[9] M. Chen and H. M. O'Keefe. "Expected radioactive backgrounds in the SNO+ experiment". In: *SNO+ Internal Document: SNO+-doc-507-v37* (2010).

[10] B. T. Cleveland and I. T. Lawson. "Measurement of the γ activity of a Gd_2O_3 sample with the SNOLAB Ge detector". In: *SNO+ Internal Document: SNo+-doc-209-v1* (2008).

[11] Borexino Collaboration. "Improved Measurement of ^{8}B Solar Neutrinos with 1.5 kt·y of Borexino Exposure". In: *arXiv:1709.00756* (2017).

[12] EXO Collaboration. "Systematic study of trace radioactive impurities in candidate construction materials for EXO-200". In: *Nucl.Instrum.Meth. A591:490-509* (2008).

[13] KamLAND Collaboration. "Search for the Invisible Decay of Neutrons with KamLAND". In: *Phys.Rev.Lett.96:101802* (2006).

[14] SNO Collaboration. "The Sudbury Neutrino Observatory". In: *Nucl. Instr. Meth. A449* (2000).

[15] R. Eichler and M. Schädel. "Adsorption of Radon on Metal Surfaces: A Model Study for Chemical Investigations of Elements 112 and 114". In: *J. Phys. Chem. B* 106 (2002), pp. 5413–5420.

[16] C. Arpesella *et al*. "Direct Measurement of the ^{7}Be Solar Neutrino Flux with 192 Days of Borexino Data". In: *PRL 101:091302* (2008).

[17] C. Giganti *et al*. "Neutrino Oscillations: the rise of the PMNS paradigm". In: *Progress in Particle and Nuclear Physics* 98 (2018). arXiv:1710.00715 [hep-ex], pp. 1–54.

[18] C. Giunti *et al*. *Fundamentals of Neutrino Physics and Astrophysics*. OUP Oxford, 2007, pp. 245–252.

[19] C. Giunti *et al*. *Fundamentals of Neutrino Physics and Astrophysics*. OUP Oxford, 2007, p. 494.

[20] D. Cerdeno *et al*. "CNO Neutrino Grand Prix: The race to solve the solar metallicity problem". In: *Journal of Cosmology and Astroparticle Physics* (2018).

[21] D. Mei *et al*. "Muon-induced background study for underground laboratories". In: *Phys.Rev. D73 053004 astro-ph/0512125 LA-UP-05-3704* (2006).

[22] E. G. Adelberger *et al*. "Solar fusion cross sections II: the pp chain and CNO cycles". In: *Rev.Mod.Phys* 83, 195 (2011).

[23] G. Alimonte *et al*. "The liquid handling systems fr the Borexino solar neutrino detector". In: *Nucl. Instr. Meth. A 609* (2009), pp. 58–78.

[24] I. Blevis *et al*. "Measurement of $^{222}\mathrm{Rn}$ dissolved in water at at Sudbury Neutrino Observatory". In: *NIM A 517* (2004), pp. 139–153.

[25] I.Ogawa *et al*. "Search for neutrino-less double beta decay of $^{48}\mathrm{C}$ by CaF_2 scintillator". In: *Nucl. Phys.* A730 (2004), pp. 215–223.

[26] J. Albert *et al*. "Search for Majorana neutrinos with the first two years of EXO-200 data". In: *Nature* 510 (2014), pp. 229–234.

[27] J. Argyriades *et al*. "Measurement of the Double Beta Decay Half-life of 150-Nd and Search for Neutrinoless Decay Modes with the NEMO-3 Detector". In: *Phys. Rev. C.* 80 (2009). 032501 arXiv:0810.0248.

[28] K. Alfonso *et al*. "Search for Neutrinoless Double Beta Decay of $^{130}\mathrm{Te}$ with CUORE-0". In: *Phys. Rev. Lett.* 115 (2015). 102502 arXiv:1504.02454.

[29] K. Eguchi *et al*. "First Results from KamLAND: Evidence for reactor anti-neutrino disappearance". In: *PRL 90:021802* (2003).

[30] K. Kodama *et al*. "Observation of Tau Neutrino Interactions". In: *Phys.Lett.B504* (2001). arXiv: hep-ex/0012035, pp. 218–224.

[31] M. Agostini *et al*. “Results on neutrinoless double beta decay of 76Ge from GERDA Phase I”. In: *Phys. Rev. Lett.* 111 (2013). 122503 arXiv:1307.4720.

[32] M. L. Perl *et al*. “Evidence for Anomalous Lepton Production in e^+ - e^- Annihilation”. In: *Phys. Rev* 35 (1975), pp. 1489–1492.

[33] R. Arnold *et al*. “First results of the search of neutrinoless double beta decay with the NEMO 3 detector”. In: *Phys. Rev. Lett.* 95 (2005). 182302 arXiv:hep-ex/0507083.

[34] R. Arnold *et al*. “Search for Neutrinoless Double-Beta Decay of $^{100}\mathrm{Mo}$ with the NEMO-3 Detector”. In: *Phys. Rev. D.* 89 (2014). 111101 arXiv:1311.5695.

[35] S. N. Ahmed *et al*. “Constraints on Nucleon Decay via "Invisible" Modes from the Sudbury Neutrino Observatory”. In: *Phys.Rev.Lett.92:102004* (2004).

[36] *Enrico Fermi - Biographical*. Nobel Media 2018 AB. URL: https://www.nobelprize.org/prizes/physics/1938/fermi/biographical/ (visited on 11/28/2018).

[37] R. Henning. “Current status of neutrinoless double-beta decay searches”. In: *Reviews in Physics* 1 (2016), pp. 29–35.

[38] G. Heusser and H. Simgen. “The Gallex and GNO Experiments”. In: (2018). URL: https://www.mpi-hd.mpg.de/lin/research_history.en.html#gallex (visited on 12/08/2018).

[39] Y. Kishimoto. “Liquid Scintillator Purification”. In: *Proceedings from LRT* (2004).

[40] KM3NET. “Letter of Intent for ARCA and ORCA”. In: *Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001* (2016).

[41] Brookhaven National Laboratory. *Alternating Gradient Synchrotron*. URL: https://www.bnl.gov/rhic/AGS.asp (visited on 05/25/2018).

[42] Brookhaven National Laboratory. *Brookhaven and the Nobel Prize*. URL: https://www.bnl.gov/bnlweb/history/nobel/1988.php (visited on 05/25/2018).

[43] I. T. Lawson. "Performance of Radon-reduced air Supply". In: *Internal SNO+ Document: SNO+-doc-1604-v1* (2012).

[44] V. Lozza. "Hotspot Overview". In: *SNO+ Internal Document: SNO+-doc-4521-v1* (2018).

[45] V. Lozza. "Hotspot Summary". In: *SNO+ Internal Document: SNO+-doc-4386-v27* (2018).

[46] J. C. Maneira. "External Backgrounds in SNO+". In: *SNO+ Internal Document: SNO+-doc-43-v1* (2007).

[47] C. Miller. "Analysis of Cosmogenic Impurities in Tellurium and Development of Tellurium Loading for the SNO+ Experiment". In: *Master's Thesis* (2016).

[48] PBS NOVA. *The Elegant Universe*. 2003-2012. URL: http://www.pbs.org/wgbh/nova/physics/elegant-universe.html (visited on 03/30/2018).

[49] H. M. O'Keefe. "Low Energy Background in the NCD phase of the Sudbury Neutrino Observatory". In: *PhD Thesis, University of Oxford* (2008).

[50] W. Pauli. "Offener Brief en die Gruppe der Radioaktiven bei der GauverinsTagung zu Tubingen (German) [Open letter to the group of radioactive people at the Gauverein meeting in Tubingen]". In: *Symmetry Magazine* (1930). URL: http://symmetrymagazine.org/sites/default/files/legacy/pdfs/200703/logbook_letter.pdf (visited on 08/22/2017).

[51] X. Qian and P. Vogel. "Neutrino Mass Hierarchy". In: *Progress in Particle and Nuclear Physics (PPNP)* 83 (2015), pp. 1–30.

[52] F. Reines and C. L. Cowan Jr. "A Proposed Experiment to Detect the Free Neutrino". In: *Phys. Rev* 90 (1953), p. 492.

[53] J. Rumleskie. "Evaluating SNO+ Backgrounds Through ^{222}Rn Assays and the Simulation of ^{13}C$(\alpha, n)^{16}$O Reactions During Water Phase". In: *Master's Thesis* (2015).

[54] L. Sibley. "The SNO+ Liquid Scintillator Response to Low-Energy Electrons and its Effect on the Experiment's Sensitivity to a Future Neutrinoless Double Beta Decay Signal". In: *PhD Thesis* (2016).

[55] A. Sonzogni. *Chart of Nuclides*. URL: `https://www.nndc.bnl.gov/chart/chartNuc.jsp` (visited on 09/19/2018).

[56] 935 Mearns Rd Warminster PA 18974 USA SP Industries Inc. "FTS Titan-Trap, Refrigerated Cold Trap". In: *Cold Trap Operator's Manual* (2009).

[57] V. Takhistov. "Review of the Nucleon Decay Searches at Super-Kamiokande". In: *arXiv:1605.03235v1 [hep-ex]* (2016).

[58] *The Nobel Prize in Physics 2015 - Press Release*. 2015. URL: `https://www.nobelprize.org/nobel_prizes/physics/laureates/2015/press.html` (visited on 10/10/2017).

[59] M. Wurm. "Solar Neutrino Spectroscopy". In: *arXiv:1704.06331 [hep-ex]* (2017).