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A Process Degasser for the SNO Ultra-pure Light Water Facility

by

Alan T. DeKok

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
of the degree of Master of Science
Ottawa-Carleton Institute for Physics
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Ottawa, Ontario, Canada
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A Process Degasser for the SNO Ultra-pure Light Water Facility

submitted by Alan T. DeKok. B.Sc.,

in partial fulfillment of the requirements
for the degree of Master of Science

Thesis Supervisor

Chair, Department of Physics

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Abstract

A process degasser was built as part of the SNO ultra-pure light water facility. The design goal of the degasser was to remove ^{222}Rn from the light shielding water, and the degassing efficiency for Rn was measured to be $(98.0 \pm 0.7)\%$. The performance of the system was characterized over a number of different operating parameters, and found to behave as expected.

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Chapter 1

Introduction

The Sudbury Neutrino Observatory (SNO) was first discussed in 1987 in a paper entitled *A heavy water detector to resolve the solar neutrino problem*.^[1] In the paper, it was observed that a large heavy water Čerenkov detector would be sensitive to the flux of ^8B neutrinos from the sun. Today in 1996, the detector has been designed, funded, and construction is nearing completion.

As had been proposed, the detector is located in an artificial cavity 2070m underground at the Inco Limited Creighton Mine, near Sudbury Ontario. The detector consists of 1000 tonnes of 99.85% isotopically pure D_2O , with which neutrinos will interact. A transparent acrylic vessel contains the D_2O , and allows photons resulting from the neutrino interactions to be imaged by photomultiplier tubes (PMTs). Analysis of the data allows identification of a specific neutrino interaction, which may then be grouped collectively to statistically measure a neutrino spectrum.

The design goals of the SNO experiment are to measure the solar neutrino spectrum with high statistical accuracy, and to measure the total neutrino flux by the neutral-current process. Fulfilling these goals will allow SNO to determine whether or not neutrino oscillations exist, possibly solving the Solar Neutrino Problem (SNP).

Fulfilling these goals will also allow SNO to test solar models by determining the production rate of electron neutrinos in the solar core.[2]

What makes these neutrino spectrum measurements difficult to perform is the low signal rate of tens of events per day, combined with a large naturally occurring background radiation which mimics and masks these events. Requiring minimal background radiation in the detector leads inexorably to two further requirements: one, that naturally occurring background radiation be minimized; and two, that the amount of radioactive isotopes within the detector be minimized.

The first requirement is partially met by situating the detector deep underground, where the rock overburden will provide shielding against cosmic rays, but will contribute some small amount of radiation and radioactive isotopes itself. Shielding the detector from the background contributions of the rock is performed by surrounding the heavy water and PMTs with ultra pure light water.

The second requirement on background radiation is met by performing stringent materials analysis, and by selecting detector components with low naturally occurring radioactive impurities. As the bulk of the detector is water, the second requirement leads to the demand that an efficient water purification system be used which can control the amount of radioactive isotopes both in the D_2O and in the shielding H_2O .

One source of background contributed by the rock surrounding the detector is caused by the radioactive decay of ^{222}Rn and its daughters. We shall see below that ^{222}Rn is a mobile gas, and can penetrate the waterproof urylon lining between the detector and the rock. It's half life of 3.8d is sufficiently long for it to diffuse through much of the body of the detector, and to generate background noise when it decays. A component of the light water purification facility specifically designed to control and minimize the amount of ^{222}Rn in the light water is the process degasser.

Many of the design specifications of the process degasser had been completed

prior to the commencement of this thesis. These specifications included the physical size, structure, and geometry of the vessel and its associated plumbing. We are concerned here with finalizing the details of the design, constructing the degasser, and describing and analyzing its performance.

In this thesis, we describe the operation of the process degasser and develop a theory to predict degasser performance. In addition, we characterize the behavior of the process degasser by performing a number of experiments on it, and analyzing the results in light of our theory. Finally, we conclude that the degasser behaves as expected, and fulfills its operational requirements.

The following text in Chapter 1 describes the Sun and the Standard Solar Model (SSM), which is an attempt to model the processes occurring within the sun. Neutrino experiments performed in the past have shown a discrepancy between observation and theory, leading to a definition of the Solar Neutrino Problem (SNP). The SNO experiment is designed to solve the SNP, and we summarize the physics involved, and outline the design and operation of the detector. Describing the detector design leads naturally to an analysis of radioactive background, and to the necessity for ultra pure water, with the process degasser as a component of the water purification system.

In Chapter 2, we develop a theory to describe the physical processes involved in water absorbing and desorbing contaminant gases. Henry's Law and a simple model describing diffusion of gases are used to bound the design criteria of the degasser, and to come up with suggestions for its construction.

Chapter 3 describes the degasser as constructed, along with a summary of the H₂O water purification facility. The theory developed in Chapter 2 is coupled with the degasser physical parameters to describe its performance, and to make predictions about its response under different running conditions.

A series of experiments were performed with the process degasser, and are sum-

marized in Chapter 4. Instrument effects and errors due to increased ambient pressure at the experimental site, 2km underground are described. The experimental results are analyzed, and compared with the theoretical predictions.

Chapter 5 concludes that the degasser behaves as expected, and provides suggestions for the future. Finally, we conclude that the process degasser satisfies its operational requirements, and that it is an integral part of the light water purification facility.

1.1 The Sun and the Standard Solar Model

The most intense source of neutrinos near the Earth is the sun, which generates its energy through fusion in the proton-proton or *pp* chain. The reactions in this chain are shown schematically below in Fig. 1.1.

Figure 1.1: Nuclear reactions in the pp chain.

Initially, a Standard Solar Model (SSM) begins with a homogeneous main sequence star. It is assumed that the star condensed out of a gas cloud with some particular initial elemental abundancies, and that at a certain time energy generated through gravitational effects is sufficient to start fusion. After the initial light of the fusion flame, it is self sustaining, and energy within the star is generated through the fusion process. The rate of fusion depends on nuclear reaction cross sections, which are not precisely known, and which serve as additional input parameters.

Balancing the gravitational force is the pressure gradient due to high temperatures and radiation pressure. Radiation and convection transport energy from the core to the surface of the star, with stellar opacity limiting the transport of radiation through concentric spherical shells.

Intensive numerical calculations relate pressure, density and temperature at each point in the sun via an equation of state, and the star is allowed to evolve for 4.6×10^9 years. At this point, the properties of the simulated star must be identical to the properties of the Sun, within experimental and theoretical error.

The mass, luminosity, radius, surface temperature, surface elemental abundances, magnetic field, rotational speed, and age of the Sun have all been measured precisely, and impose severe constraints on the allowed final states of a SSM.

In addition to predicting the visible appearance of the sun, a SSM can be used to predict the solar neutrino spectrum. One such predicted solar neutrino spectrum is given below in Fig. 1.2.[3]

Reactions in the pp chain produce neutrinos at rates which depend on many input factors, with the production rate of ${}^8\text{B}$ strongly dependent on the core temperature of the sun. SNO proposes to specifically measure the spectrum of the ${}^8\text{B}$ neutrinos, which would allow a precise calculation of the solar core temperature. This measure-

ment is useful because unlike photons, neutrinos escape quickly from the sun and carry information about current events in the sun's core.

A photon produced in the core of the sun must perform a random walk, undergoing reactions such as Compton scattering, photo-ionization of an atom, or absorption by an orbital electron. As a result of these processes, approximately a million years pass before energy produced in the core of the sun is finally emitted in the form of photons. A secondary result is that these photons carry information mainly about the Sun's surface, and not about the core.

One other product of the pp chain that SNO is sensitive to are neutrinos from the fusion of ^3He and a proton (hep). While the flux of neutrinos from this reaction is expected to be much smaller than that from ^8B , it will give information on ^3He density and temperature. If the ^3He density is very different than expected, then the convection assumptions in the SSM must be reanalyzed.

The measurements of hep and ^8B neutrino flux may be performed independently, giving independent restrictions on the solar core temperature and the amount of convection in the sun. SNO will thus add further strong restrictions on SSMs.

Figure 1.2: The neutrino spectrum predicted by the Bahcall-Pinsonneault SSM

1.1.1 The Solar Neutrino Problem

The Solar Neutrino Problem (SNP) was defined originally in 1968, with the publication of results from the Homestake experiment.[4] The measured flux of ^8B neutrinos at the earth was found to be much smaller than the predicted counting rate, which is a problem that later experiments could not resolve.[5]

One of the suggested theories which could solve the SNP is called the MSW effect.[6, 7, 8] In this theory, at least one neutrino has nonzero mass, and the restrictions on lepton number conservation are removed. Calculations show that it becomes possible for neutrinos to undergo flavor oscillations in a variety of conditions, which would lower the flux seen by electron neutrino observatories and create the SNP. SNO will be sensitive to all neutrino flavors, and its observations may solve the SNP.

In a paper published in 1985, Herbert H. Chen proposed to use heavy water (D_2O) as a detection medium for neutrinos. Chen states “Measurement of the total neutrino flux tests the standard solar model independent of the neutrino-oscillation hypothesis and measurement of the ratio of the electron-neutrino flux to the total neutrino flux tests the neutrino-oscillation hypothesis independent of the standard solar model.”[9]

Following this paper, the proposal for the Sudbury Neutrino Observatory was published.[1] More detailed proposals followed, most notably the ‘White Book’.[2, 10, 11] These proposals summarized the physics and the detector design requirements for the experiment. A short summary of these discussions is given below.

1.2 The SNO Detector

The SNO experiment is being constructed in a barrel-shaped cavity at a depth of 2070m in the Inco Limited Creighton Mine near Sudbury, Ontario. The main body of the detector is 1000 tonnes of 99.85% pure D_2O contained in a thin-walled acrylic vessel, shown schematically in Fig. 1.3. The acrylic vessel is approximately 12 m in diameter, 5 cm in thickness, and is surrounded by 7300 tonnes of ultra pure H_2O .

Photon detection is performed by 9600 20 cm Hamamatsu R2080 PMT's, which are uniformly arranged on a physical support structure (PSUP) at a distance of 2.5m from the vessel. Each PMT has a multifilm coated aluminum reflector mounted in front of it in order to increase the efficiency of light collection, which gives an effective photocathode coverage of approximately 60%.

An array of magnetic field compensator coils is placed within the walls of the cavity. When the detector is in operation, current will be run through these coils to compensate for the magnetic field of the Earth, and minimize the impact it has on free electrons in the PMT's.

For a relativistic ($\beta = 1$) electron in the D_2O generating Čerenkov light, the electron will travel approximately 0.5cm, and yield 10 PMT hits, per MeV of electron energy. In addition to measuring the energy, the event vertex and momentum of the electron also need to be reconstructed. Analyzing the PMT hit location and photon time of arrival will give the event vertex, which is the point at which a source of light would generate the observed photon distribution. Computing a vector from the interaction vertex to the centroid of the PMT hit locations gives the direction the electron was traveling in, and along with the measurement of the energy of the electron, allows an accurate determination of the electrons 4-momentum.

Relativistic electrons may be generated through many processes. The SNO detector is designed to observe electrons from two of the neutrino interactions, but

other processes such as radioactive decay can also generate relativistic electrons. These extra processes will increase the background noise observed by the detector, and should be minimized in order to obtain the cleanest signal.

The water purification systems are designed to remove contaminated water from outside the PSUP, purify it, and return it inside the PSUP. The PSUP is 99% waterproof, ensuring that water flows only from inside to outside the support structure. This is expected to substantially reduce the background noise inside the PSUP observed by the PMTs.

Figure 1.3: Schematic design of the SNO detector.

1.2.1 The Process Degasser

The process degasser is one component of the light water purification facility, and is discussed in detail in § 3, below. It is useful to include here a short description of the degasser, as the description will clarify following discussion.

Fig. 1.4, below, is a simplified schematic diagram of the process degasser, which is designed to remove trapped gases from ultra-pure light water. Water enters the vessel at high pressure, and a number of spray nozzles distribute the water over the cross sectional area of the vessel in the form of droplets. Some of the water is vaporized, during which the initial stages of degassing occurs.

The center of the process degasser is filled with approximately 2.75 m^3 of a low volume, high surface area material called 'packing'. When water is sprayed onto this packing, it forms a thin surface film which allows trapped gases to easily diffuse through the water and into the surrounding vapor. The force of gravity causes the water to flow downwards to the bottom of the degasser, where it is collected in a liquid water reservoir.

After diffusing out of the water, the contaminant gases are removed from the vessel by a vacuum pump. The vacuum pump also removes water vapor from the vessel, and maintains the pressure inside the degasser near the vapor pressure of water. By keeping the partial pressures of the contaminant gases kept low, the vacuum pump ensures that the amount of contaminant gases trapped inside the vessel is small.

Also located inside the degasser is a set of heating and cooling coils. When operating, the heaters vaporize part of the water which flows past them, and the cooling coils condense water vapor which comes into contact with them. The net effect the heating and cooling coils have is that they drive a flow of rising water vapor. This vapor flow carries contaminant gases along with it to the top of the

vessel, where they can be removed by the vacuum pump.

Finally, a clean pump not shown in Fig. 1.4 pulls the degassed water from the bottom of the vessel, and circulates it to the rest of the purification system.

Figure 1.4: Schematic design of the process degasser.

1.3 SNO Physics

The solar neutrino energy spectrum predicted by the Bahcall-Pinsonneault Standard Solar Model (SSM) is shown above in Fig. 1.2.[3] Part of this spectrum will be observed by SNO, which is sensitive to the flux of ${}^8\text{B}$ neutrinos above an energy of 6 MeV. SNO is also sensitive to the ${}^3\text{He} + \text{p}$ (hep) neutrinos, but these have a flux three orders of magnitude smaller than that from ${}^8\text{B}$, and will thus be observed at

correspondingly smaller rates.

The SNO detector is designed to observe neutrinos via three reactions, electron scattering (ES), charged-current (CC), and neutral current (NC). These measurements will return information about the electron neutrino (ν_e) flux, energy spectrum and direction, and the total neutrino flux independent of neutrino type.

Neutrino-electron elastic scattering (ES) occurs as follows.

$$\nu_e + e^- \rightarrow \nu_e + e^-. \quad (1.1)$$

The ES reaction is most sensitive to the ν_e flux, as the scattering cross section for the ν_e is 6 times larger than that for the other neutrino flavors.[12, 13] The relativistic free electrons produced from this reaction generate Čerenkov radiation, which is detected by the PMTs. The electrons have a strong forward peak in their spatial distribution due to kinematic constraints, and thus provide excellent directional information.

A background measurement for the ES reaction may be performed during the normal run of the experiment using events observed in the light water surrounding the acrylic. Additionally, any event which does not appear to be in line with the Earth-Sun vector can be tagged as background.

The rate for the ES process, however, is very low at about 1 count/day.

The charged-current (CC) reaction is mediated by $W^\pm$ vector bosons, and is

$$\nu_e + d \rightarrow p + p + e^- \quad (Q = -1.44 \text{ MeV}). \quad (1.2)$$

To a first approximation, neutrinos of energy E_ν produce electrons of energy $E_e = E_\nu - 1.44\text{MeV}$. These electrons are seen by observing the Čerenkov light they generate, which allows a measurement of their flux and energy spectrum. The ν_e flux, energy spectrum, and direction can be directly determined from the flux and energy spectrum of electrons.

The angular distribution of the electrons is related to the angular distribution of the neutrinos by the function $W(\theta) = 1 - \frac{1}{3} \cos \theta$, where θ is defined to be the angle between the incoming neutrino and the outgoing electron.

Counting rates for the CC reaction are expected to be about 7 counts/day.

Other detectors use the ES and CC processes to observe neutrinos, but only SNO will be sensitive to the neutral current process.

The neutral current (NC) reaction is mediated by the Z^0 boson, and is

$$\nu_x + d \rightarrow \nu_x + p + n \quad (Q = -2.2 \text{ MeV}). \quad (1.3)$$

The NC reaction provides a measurement of the total neutrino flux, with a threshold of about 2.2 MeV. The proton from the NC vertex is stopped immediately, and does not produce Čerenkov light. The neutron scatters, and reaches thermal equilibrium with its surroundings before being captured by an atomic nucleus. Capturing of the neutron causes the nucleus to enter an excited state, and to release high energy γ 's when it relaxes to its ground state. These photons will Compton scatter to produce relativistic electrons, whose Čerenkov light will be detected by the PMT's.

The counting rate for the NC reaction is expected to be about 12 counts/day, with a significant source of background with the NC reaction due to photodisintegration of deuterons. Minimizing the number of high energy photons with $E_\gamma > 2.2 \text{ MeV}$ will minimize the background for this process.

The D_2O and H_2O purification plants described below are designed to manufacture water with a low concentration of radioactive impurities, which will minimize background high energy photons. Many stages of purification are used in order to remove contaminants from the input water, with ultra pure water exiting from the plants for use in the detector.

One component of the light water purification facility is a process degasser. The design of the degasser allows it to selectively remove ^{222}Rn gas from light water,

which will lower the rate of photodisintegration of deuterons, and help to minimize the background for the NC process.

1.4 Radioactive Background and Shielding

In practice, controlling the background means controlling the purity of the materials used to construct the detector. For most of the components of the detector, screening is performed by radiometric counting of component samples. Low radioactivity materials can be identified and selected for use in the detector.[11, p.50]

The background noise in the SNO detector must be kept as low as possible due to the extremely low solar neutrino signal rate of a few tens of events per day. The sources of background noise we must concern ourselves with are cosmic rays and radiation produced by naturally occurring radionuclides.

1.4.1 Cosmic Ray Background

At a depth of 2070 m, the cosmic ray background is greatly reduced due to the shielding effect of the overlaying rock. Any surviving radiation is composed of muons and neutrinos.

Cosmic or atmospheric neutrinos will have a flux much smaller than the solar neutrino flux, and will generate a nearly isotropic background for the NC and CC processes. Background for the ES process can be determined by marking the interactions with neutrinos whose directions do not point away from the sun.

Atmospheric neutrinos can be further identified by their energy spectrum, which peaks in the multi-GeV range.[14] As the solar neutrino ^8B and *hep* spectra end below 20 MeV, a cut in reconstructed neutrino energy will eliminate most of the atmospheric neutrino background.

Part of the background from muons is estimated to be $1.5 \text{ }^{16}\text{O}$ spallation events per day.[10, p.58] These events may be identified by looking for a high energy muon signal followed by a β decay signal.

In addition to generating spallation events, relativistic muons may pass through the detector without interacting. Muons surviving at a depth of 2km are much more energetic than the electrons produced by the three reactions of interest, and the Čerenkov light they generate can be used as a tag to signal muon background. The high energy muon signal results from the muon traveling much further in the D_2O before thermalizing, and it will produce more light than an electron by the ratio of 18 m to typically 0.05 m.

The detector includes outward looking PMTs, which will detect muons and further restrict the background. The one surviving background from muon events is events where the path of a muon falls across a small arc of the active detector volume. Despite the muon having high energy, the small fraction of this energy deposited in the detector volume will give a low-energy electron signal. An event cut on radial distance from the center of the detector will lower this background.

1.4.2 Radionuclide Background

The background from radionuclides is much larger than the background from cosmic rays, and is dominated by the ^{232}Th and ^{238}U decay chains, given respectively in Fig. 1.5 and Fig. 1.6. Simplified decay schemes for ^{212}Bi and ^{214}Bi are shown at the bottom of the respective figures, highlighting the photons with $E_\gamma > 2.2 \text{ MeV}$.

Radionuclides are the source of three different kinds of radiation, α particles, β particles, and γ rays. Within the SNO detector, α 's will not contribute to the background, as they are non-relativistic and will thermalize immediately.

The low energy β 's and γ 's generated by radioactive decays will for the most

part be of insufficient energy to cross the trigger threshold of 4 MeV. Signals from coincident events may possess sufficient energy to trigger the detector, and will contribute to the background. The background at low energies increases significantly because of these radioactive decay byproducts.

Directional cuts will be used to partially remove the background from high energy γ events. Many γ 's are generated in the light water shielding the detector and in the PMT's, and these photons will be reconstructed to be outside the D_2O , or directed radially into the center of the detector. These reconstructed photons may be removed with high efficiency.

High energy photons of $E_\gamma > 2.2$ MeV have sufficient energy to break apart a deuteron, mimicking the NC reaction, and creating unwanted background signals. Removing radionuclides preceding Bi from the water will minimize the number of Bi atoms which decay inside the detector body, and lower the background due to these photons. Of the radiation produced by radionuclides, high energy photons will be the largest source of background, and limiting the quantity of radionuclides in the detector will strongly limit the background.

Due to the large backgrounds introduced by radioactive decays, close attention has to be paid to lowering the amounts of impurities in the detector components, most notably ^{232}Th and ^{238}U . Minimizing the level of impurities in the acrylic, PSUP, and instruments involves careful analysis and selection of the materials with the best mechanical properties and low concentrations of radioactive isotopes.

If we require that the ^{232}Th and ^{238}U decay chains produce a NC background of one event per day per chain, we must limit the contamination to $2.2 \times 10^{-14}\text{g/g}$ for ^{232}Th , and $1.5 \times 10^{-14}\text{g/g}$ for ^{238}U in the light water.[10, p.76] These results, along with tolerable levels of contamination in other detector components are summarized in Table 1.1, below.

The norite rock surrounding the detector contains trace levels of Thorium and

Material	gU/g	gTh/g
D ₂ O	3.8×10^{-14}	4.0×10^{-15}
H ₂ O (inside PSUP)	1.5×10^{-14}	2.2×10^{-14}
H ₂ O (outside PSUP)	1.0×10^{-12}	1.3×10^{-13}
Acrylic	3.6×10^{-12}	1.9×10^{-12}
Norite	1.2×10^{-6}	1.0×10^{-12}

Table 1.1: Tolerable levels for ^{238}U and ^{232}Th in the SNO detector.

Uranium, so light water is placed between the rock and the PMT's to shield the detector from background γ 's and neutrons. This shielding water introduces impurities of its own, which will be removed by the H₂O purification system, to be discussed in the following chapter.

Out of necessity, the tolerable contaminant levels inside and outside the PSUP are different. The reason behind this variation is that the shielding water inside the PSUP is within the field of view of the PMTs, while the PSUP shields the PMTs from decays in the surrounding light water. The PSUP is 99% waterproof, with the water purification system removing water from outside the PSUP, cleaning it, and returning the water inside the PSUP. This flow pattern ensures that the water in the fiducial volume of the detector is as pure as possible.

As mentioned above, our goal in this project is to remove radioactive Rn gas from the shielding light water. We will not closely analyze Rn in the thorium decay chain, as the half life of ^{220}Rn is very short, preventing a water purification facility from efficiently removing the Rn before it decays. Much work has been performed elsewhere to develop techniques to remove radioactive daughters of ^{232}Th from light water, and to monitor the purity of the light water.[15]

In the ^{238}U decay chain, however, ^{222}Rn is a radioactive gas, with a half life of 3.8 days. A process degasser can be built to remove ^{222}Rn from the light shielding water at high efficiency, and perform this task before the Rn decays.

Degassing the water will have the added benefit of removing other gases from the light shielding water, which will remove oxygen and inhibit biological activity in the detector.

1.4.3 ^{222}Rn Emanation

There are many sources of ^{222}Rn in addition to the norite rock. Component cleanliness control can only ensure minimum radioactive content, and cannot eliminate radioactivity altogether. Many studies have been done which analyze Radon emanation into vacuum or water, so that the Rn load in the light water can be understood, and the contribution from various parts analyzed.[16] Some results from these studies are summarized in Table 1.2, below.

Material	Emanation rate	Rn load [atoms]
Urylon lining	$12 \text{ m}^{-2} \text{ hr}^{-1}$	3.2×10^6
PMT	$< 20 \text{ PMT}^{-1} \text{ hr}^{-1}$	$< 2.6 \times 10^7$
Omega reflector	$< 1.5 \text{ m}^{-2} \text{ hr}^{-1}$	$< 1.9 \times 10^6$
Acrylic	$< 0.1 \text{ m}^{-2} \text{ hr}^{-1}$	$< 7.9 \times 10^3$
Coax cable 9067	$< 0.6 \text{ m}^{-1} \text{ hr}^{-1}$	$< 1.2 \times 10^7$

Table 1.2: ^{222}Rn Emanation rates and supported Rn load.

The original SNO proposal uses a limit of $1.5 \times 10^{-14} \text{ gU/gH}_2\text{O}$ to calculate predicted background. Later work indicated that the detector sensitivity to decays in the ^{238}U chain is such that a level of $1 \times 10^{-13} \text{ gU/gH}_2\text{O}$ would not seriously

compromise the experiment.[17]

Within the critical region between the acrylic and PMT's, a level of 10^{-13} gU/gH₂O would give 2×10^6 Rn atoms in the 1670 tonnes of water. This radioactivity would be left from imperfect purification of the water. With a Rn load in the water outside the PSUP of approximately $< 4.3 \times 10^7$ atoms, we require that the purification system degas the water at $> 95\%$ efficiency. It is critical that the purification system degasses the water with an efficiency of at least 95% in order for the background to be low.

Materials inside the detector emanate radon and support it at a total level of approximately 5×10^5 Rn atoms inside the PSUP. Most materials tested emanate radon at a level of tenths to tens of Rn atoms per square meter per hour. The majority of these radon emanation measurements were performed for emanation into vacuum, with one report studying radon emanation into water. The conclusions of these reports were that the emanation changed by a factor of three higher or lower, depending on the material.[18] For simplicity, we will use the vacuum emanation results, and assume that they are accurate within an order of magnitude.

During construction and fill of the detector, the ambient air at 2070m underground carries a radon load of approximately 3 pCi/l. Radon from the air will diffuse into the water during the fill, with most of these atoms decaying before the experiment starts. Waiting a period of 38 days after completing the fill will cause the amount of radon left over from being absorbed from the air to fall by a factor of 1000.

The components of the detector contribute equally to the radon load, within an order of magnitude. The urylon supports a level of 10^{-13} gU/gH₂O, emanation into the outer water accounts for another 1.5×10^{-13} gU/gH₂O, mainly from dust and cabling. The inner water load is approximately 0.7×10^{-13} gU/gH₂O, resulting from emanation from dust and the PMT's.

Figure 1.6: The ^{238}U decay chain, and simplified decay scheme for ^{214}Bi .

Chapter 2

A Simple Degassing Model

The role of the process degasser is to remove absorbed contaminant gases from water. In this chapter, we will examine the physical effects controlling gas flow through water, and discover which parameters may be optimized to yield efficient degassing.

We will concentrate here on describing and analyzing the physics of gas transfer through a thin water film. This film is supported by the packing described above, with a more detailed description of the packing material given below in § 3.1.2.

The model we use describes bulk volumes of liquid and gas, and the phase boundary between these two regions. We assume that the majority of the bulk gas is the vapor phase of the liquid in question, and mass transfer of the contaminant gas between bulk liquid and gas is driven by differences in the concentrations of the unwanted gas .

We consider a two layer model, which focuses on the gas and liquid regions of interest near the phase boundary, called the transition layer. The model predicts a simple analytic form for the degassing efficiency of our system.

Next, we consider the flow of masses of liquid and gas inside the degasser, and

develop an alternative method of predicting degassing efficiency. This alternative prediction depends on large-scale effects inside the degasser, and not on molecular effects.

Finally, we describe a method for measuring the flow of mass to the vacuum pump, and show how this measurement allows us to further characterise the system.

2.1 Henry's Law

Henry's law describes the equilibrium condition between a gas and a liquid. The partial pressure P_x of a gas determines the mole fraction X_x of that gas dissolved in a liquid, subject to a proportionality constant H . The exact value of H depends on the specific liquid and gas in question.

$$P_x = H X_x \quad (2.1)$$

Henry's law relates the partial pressure of a gas with its concentration in a particular liquid, leading us to conclude that we may degas a liquid by ensuring that the partial pressure of an unwanted gas is very small. Minimizing the total pressure the degasser experiences will allow the partial pressure of a particular gas to be controlled, limited by the vapor pressure of water.

In practice, the partial pressure of a gas in a complex system is difficult to measure, so we develop an equivalent form for Henry's Law in terms of concentration. These concentrations can easily be measured either at the intake or out take of the process degasser. The gas and liquid concentrations are written respectively as C_{sg} and C_{sl} , with the units of concentration given by $[\text{mol}/\text{m}^3]$. Under Henry's Law, the gas and liquid concentrations are related by

$$C_{sg} = H' C_{sl} \quad (2.2)$$

Here H' is the new Henry's law constant, and can be calculated by converting H to the new units.

$$H' = \frac{18 \times 10^{-6}(\text{m}^3/\text{mol H}_2\text{O})}{RT} H = \frac{18 \times 10^{-6}(\text{m}^3/\text{mol H}_2\text{O})}{0.024(\text{atm m}^3/\text{mol gas})} H. = 7.5 \times 10^{-4}/\text{atm} H \quad (2.3)$$

For the gases of interest here, H' may be found in standard references such as the CRC handbook. Values of H' are listed below in Table 2.1, for the gases of interest.[19]

Gas	H'_{CRC}	H'
N ₂	2.33	1.04
O ₂	4.89	2.18
Rn	51.0	22.8

Table 2.1: Values of H' for various gases. Values of H'_{CRC} are given as cc gas dissolved per 100cc of water at STP, and H' is given as mol gas/m³ vapor, per mol gas/m³ water.

2.2 The Two-layer Model

For any degassing to occur, contaminant gases absorbed in the water must be able to travel from the water to gas phase, crossing a phase boundary.

The model we use to describe gas transfer between the liquid and gas phase is a two-layer model.[20] This model focuses on the liquid-gas transition layers and the phase boundary between these layers. To a first approximation, the gas concentrations in the bulk volumes of liquid and gas are considered to be uniform. That is,

the main bodies of liquid and gas are well mixed. Turbulent regions on opposite sides of the phase boundary feed gas and liquid to the transition regions, as shown schematically in Fig. 2.1.

Figure 2.1: Two layer model for Radon transfer

In addition to defining C_{sl} and C_{sg} in § 2.1 above, we now define C_l and C_g to be the concentration in the bulk volumes of liquid and gas. Mass transfer from the bulk volume to the transition layer is driven by the differences in these concentrations.

Across the transition layer, the rate of mass transfer is described by the mass flux. Mass flux depends on D , the coefficient of molecular diffusion for the gas in a liquid; z , the coordinate perpendicular to the interface; and $c(z)$, the gas concentration as a function of z .

$$F = -D \frac{\partial c(z)}{\partial z} \quad (2.4)$$

The functional form of $c(z)$ is in general unknown and unmeasurable. The only restrictions on $c(z)$ are that it monotonically decreases from C_l to C_{sl} , from C_{sg} to C_g , and that $C_{sg} = H' C_{sl}$. The simplest assumption to make is that the change in

concentration is linear with z , allowing us to rewrite the above equation as

$$F = D \frac{\Delta C}{\Delta z} = k \Delta C \quad (2.5)$$

where ΔC is the concentration difference across the layer of thickness Δz , and is a concentration per unit volume. The term k is the exchange constant, with dimensions of velocity.

Conservation of mass forces the mass flux from the bulk volume of liquid to the transition layer to be equal to the flux from the transition layer to the bulk volume of gas. We define k_l and k_g as the exchange constants for the liquid and gas phases, and our mass flux equation can now be written as

$$F = -k_l(C_l - C_{sl}) = k_g(C_g - C_{sg}). \quad (2.6)$$

Across the phase boundary, the concentrations C_{sg} and C_{sl} are related by Henry's law (Eq. 2.2). We cannot measure these concentrations experimentally, but we can use this relationship to eliminate them from Eq. 2.6. To simplify the form of the mass flux equation, new exchange constants are defined to be

$$1/K_G = 1/k_g + H'/k_l \quad (2.7)$$

to be the overall gas phase transfer coefficient, and

$$1/K_L = 1/k_l + 1/(H'k_g) \quad (2.8)$$

to be the overall liquid phase transfer coefficient.

The mass flux from Eq. 2.6 can then be written,

$$F = -K_L(C_l - C_g/H') = K_G(C_g - H'C_l) \quad (2.9)$$

The terms K_L and K_G depend on many factors, including the temperature, water viscosity, diffusibility of the gas in the liquid, water drop size, and degree of

turbulence in the fluid. While these parameters can be calculated from the known physical properties of the gas and liquid in question, any such calculation includes large, unknown errors. The parameters C_g and C_l , however, can easily be measured, as we shall see below.

2.2.1 Calculating K_L and K_G

The values of k_l and k_g must be calculated from empirical data, as they depend on the unknown quantity Δz . In general, k_g is approximately 1×10^{-2} m/s, and k_l is 3×10^{-5} m/s for gases such as O_2 , and N_2 . [21] We may calculate K_L and K_G using Eq. 2.8, Eq. 2.7, and the values for k_l , k_g , and H' given above.

In order to calculate k_g and k_l for Rn, we must take into account the differences in diffusion between Rn and O_2 . For diffusion D_g in a gas, and D_l in a liquid, we have

$$k_{(g/l)} = \frac{D_{(g/l)}}{\Delta z} \quad (2.10)$$

The diffusion parameter $D_{(g/l)}$ varies as $1/\sqrt{M}$. Knowing k_g and k_l for O_2 , we can then calculate the corresponding values for Rn by

$$k_{(g/l),Rn} \simeq k_{(g/l),O_2} \sqrt{\frac{M_{O_2}}{M_{Rn}}} \quad (2.11)$$

This assumes that the strongest effect is the differing $\bar{c}$, the mean molecular speed, and that the mean free path ℓ is the same for all gas species. As the system is dominated by water, we believe this assumption to be reasonable.

We may then use the k_g and k_l values for Rn in order to calculate K_L and K_G . The results for O_2 , N_2 , and Rn are summarized in Table 2.2, below.

Gas	H'	K_L [m/]	K_G [m/s]
N ₂	1.04	2.99×10^{-5}	2.88×10^{-5}
O ₂	2.18	2.99×10^{-5}	1.37×10^{-5}
Rn	22.8	1.14×10^{-5}	5.00×10^{-7}

Table 2.2: Calculated values of K_L and K_G for various gases, with H' as above.

2.3 Degassing Efficiency

Degassing efficiency k_d is defined to be the difference between inlet and exit gas concentrations $C_i - C_e$ in the degasser, divided by the inlet concentration C_i , or

$$k_d = \frac{C_i - C_e}{C_i} \quad (2.12)$$

We can calculate k_d analytically by writing the mass flux F as a function of mass flow rate dW per time dt , through an area A enclosing a volume V . We then relate this flux to the flux calculated above in Eq. 2.9, and integrate to find the time evolution of C_l .

$$F = \frac{dW}{Adt} = \frac{dC_l(t) \cdot V}{Adt} = -K_L(C_l(t) - C_g(t)/H'). \quad (2.13)$$

We assume $C_g(t) = C_g(0) = C_g$, as the contaminant gas concentration in the bulk gas is kept constant by continually pumping away the contaminant gas. This assumption will not be initially true, as our experimental system will normally be kept filled with N₂ at atmospheric pressure when not in operation.

In normal operation, the gas concentrations in the system will be in quasi-static equilibrium, where the preceding assumption will hold true.

Rewriting Eq. 2.13 in terms of $C_l(t)$.

$$\frac{dC_l(t)}{dt} = \frac{-K_L \cdot A}{V} \cdot (C_l(t) - C_g/H') \quad (2.14)$$

which integrates to

$$C_l(t) = (C_l(0) - C_g/H') \exp \left[- \int_0^t K_L \frac{A}{V} dt' \right] \quad (2.15)$$

and gives us the time evolution of C_l .

To simplify our model, we make some reasonable assumptions. First, we assume that $C_l \gg (C_g/H')$ when the pressure is near the vapor pressure of water. Second, we consider that the water takes a time Δt to pass through the degassing region, and that degassing takes place in this region only.

Therefore, with $C_e = C_l(t = \Delta t)$, $C_i = C_l(t = 0)$, and neglecting the terms containing C_g , we have

$$C_e = C_i \exp \left[- \int_0^{\Delta t} K_L \frac{A}{V} dt' \right] \quad (2.16)$$

which enables us to write the overall degassing efficiency from Eq. 2.12 as

$$k_d = 1 - \exp \left[- \int_0^{\Delta t} K_L \frac{A}{V} dt' \right]. \quad (2.17)$$

If steady-state conditions hold true, the parameters K_L , A , and V will be constant throughout the degassing period, and the above equation becomes

$$k_d = 1 - \exp \left[- K_L \frac{A}{V} \Delta t \right]. \quad (2.18)$$

In general, K_L , A , and V are slightly time dependent and Eq. 2.18 will not be correct. To first order, however, we should still be able to characterize the degassing efficiency in this way. The parameter K_L will be nearly constant throughout the degasser, and we can characterize unknown physical parameters A and V in different regions of the degasser by overall theoretical parameters A and V . The transfer time Δt is physically measurable, but cannot be directly controlled, as it is dictated by specifics of the apparatus components, their geometries, and water flow through the system.

The three free parameters A , V , and Δt in Eq. 2.18 are reduced to two by the limited control on transfer time Δt , and to one by the steady-state condition that the volume of water V inside the degasser remain constant. We may maximize the degassing efficiency k_d , therefore, by maximizing the surface area over which degassing occurs.

Material called 'packing' may be used to increase the reaction surface area, and will be discussed in detail below. In short, the ideal packing has the physical properties of zero volume and infinite surface area, along with mechanical properties which cause it to be self supporting when large packing heights are required.

Besides providing a large surface area, the packing has other effects on degasser performance. One large effect is to maximize the path followed by the water through the packing, which maximizes time available for transfer. With the careful selection of a packing material, it may be possible to use secondary effects to achieve finer control on degassing efficiency.

2.3.1 Relating k_d for O_2 to Rn

We shall see below that many measurements of k_d for O_2 were performed, and only a few for Rn . We wish to be able to relate the degassing efficiencies for these two gases in a simple manner, so we may compare the results, and make predictions from O_2 measurements for Rn .

Eq. 2.18 above has the form

$$k_d = 1 - \exp \left[-K_L \frac{A}{V} \Delta t \right]. \quad (2.19)$$

for some unmeasurable physical A , V , and known Δt . The parameter Δt is measured by observing the water flow through the degasser, and will be described in detail below.

The only parameter which changes for R_n is K_L , and we can thus make a prediction for $k_{d,Rn}$ from a measured k_{d,O_2} , via

$$k_{d,Rn} = 1 - \exp \left[\frac{K_{L,Rn}}{K_{L,O_2}} \ln(1 - k_{d,O_2}) \right] \quad (2.20)$$

2.4 Mass Flow in the Process Degasser

Table 2.3, below, lists the parameters we use to describe the system inside of the process degasser, and Figure 2.2 shows a schematic of how these parameters interact in the degasser.

Term	Definition	Term	Definition
$\dot{m}_1$	liquid flow into degasser	P_1	pressure below packing
$\dot{m}_2$	vapor flow out of degasser	P_2	pressure above packing a
$\dot{m}_3$	liquid flow out of degasser	T_1	temperature 1
$\dot{m}_4$	vapor flow upwards from feed	T_2	temperature 2
$\dot{m}_5$	liquid flow downwards from feed	T_3	temperature 3
$\dot{m}_6$	vapor flow up from packing	T_4	temperature 4
$\dot{m}_7$	liquid flow from cooling coils	T_7	coolant intake temperature
$\dot{m}_8$	vapor flow from heaters	T_8	coolant exhaust temperature
$\dot{m}_9$	liquid flow from packing	c_w	coolant water flow rate
$\dot{q}_1$	power added by heaters	$\dot{q}_2$	coolant heat removal rate
h_{1v}	water vapor enthalpy at P_1	h_{1l}	liquid water enthalpy at P_1
h_{2v}	water vapor enthalpy at P_2	h_{2l}	liquid water enthalpy at P_2

Table 2.3: Degasser internal parameters

From conservation of energy and mass, we can arrive at the following equations.

Conservation of mass flow through the system.

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \quad (2.21)$$

Conservation of mass flow through the packing.

$$\dot{m}_5 - \dot{m}_6 + \dot{m}_7 = \dot{m}_9 - \dot{m}_8 \quad (2.22)$$

Conservation of mass flow out the bottom of the degasser.

$$\dot{m}_3 = \dot{m}_9 - \dot{m}_8 = \dot{m}_1 - \dot{m}_2 \quad (2.23)$$

Conservation of mass flow out the top of the degasser.

$$\dot{m}_2 = \dot{m}_4 + \dot{m}_6 - \dot{m}_7 \quad (2.24)$$

Fraction of mass which vaporizes on entry to the degasser, due to expansion,

$$\dot{m}_4 = \dot{m}_1 \frac{0.893}{h_{2v} - h_{2l}} \quad (2.25)$$

The parameter 0.893 J/s°C is a function of the inlet pressure.[22]

Fraction of mass which does not vaporize,

$$\dot{m}_5 = \dot{m}_1 - \dot{m}_4 = \dot{m}_1 \frac{0.107}{h_{2v} - h_{2l}} \quad (2.26)$$

Vapor mass flow rate up from the packing,

$$\dot{m}_6 = \dot{m}_2 - \dot{m}_4 + \dot{m}_7 \quad (2.27)$$

Vapor to liquid mass flow from power removed by coolant,

$$\dot{m}_7 = \frac{\dot{q}_2}{h_{2v} - h_{2l}} \quad (2.28)$$

Liquid to vapor mass flow from power added by heaters,

$$\dot{m}_8 = \frac{\dot{q}_1}{h_{1v} - h_{1l}} \quad (2.29)$$

Liquid water flow from the bottom of the packing,

$$\dot{m}_9 = \dot{m}_3 + \dot{m}_8 = \dot{m}_1 - \dot{m}_2 + \frac{\dot{q}_1}{h_{1v} - h_{1l}} \quad (2.30)$$

Power removed by the coolant water,

$$\dot{q}_2 = 4.186 \times 10^3 \cdot c_w \cdot (T_7 - T_8) \quad (2.31)$$

where 4.186 kJ/ (°C litre) is the energy required to raise or lower the temperature of one litre of water by one degree Centigrade.

These calculations ignore the effects of heat transport through the walls of the vessel.

When the degasser is in normal operation, we will be able to measure $\dot{m}_1$, $\dot{m}_2$, P_2 , $\dot{q}_1$, $\dot{q}_2$, which will completely characterize our system.

Figure 2.2: Mass flow and internal parameters. Lengths are not to scale, and are taken from the degasser blueprints stored on-site.

2.4.1 Degassing Efficiency and Mass Flow

Detailed analysis of degassing indicates that for gases such as O_2 with a large Henry's law constant, the practical limit on degassing efficiency is $k_d \simeq 0.9999$. [23, p.246] This limit may be used as a starting point to calculate mass flow parameters which would be otherwise unquantifiable.

With a 1.7m high liquid water level, the volume of gas inside the degasser is at the most $(2.4 \pm 0.2) \text{ m}^3$. We use the design specification that the water flow rate into the degasser is 120 l/min, or $\dot{m}_1 = 2 \text{ kg/s}$, and assume that O_2 , N_2 , and Rn are absorbed in the incoming water at some initial concentration. Dr. Henry Lee has performed experiments measuring the gas concentrations in the water we will use, and has measured 0.03 litres of dissolved gas per litre of water at STP. [24] The level of dissolved Rn in the water underground is high when compared to water at ground level, but negligible when compared to O_2 and N_2 .

With 30cc of gas at STP, we have 6.28 cc of O_2 , and 23.4 cc of N_2 per litre of water, with the mass ratio $O_2/H_2O = 8.9 \text{ ppm}$. Table 2.4 shows the calculated C_L for the four main gas fractions of the atmosphere, and for Rn. [25]

We are not degassing the water with 100% efficiency, so there must be a constant background C_G in the degasser, or

$$C_e = (1 - k_d)C_i$$

and

$$C_{G_e} = H'C_{L_e} = (1 - k_d)H'C_L$$

These results are summarized in Table 2.5 below.

We can now characterize the rate of change of gas concentration in the degasser volume V_G by knowing the initial gas concentrations in the liquid, the mass flow rate

Gas	H'	Atmospheric %	C_L [mol/m ³]	ppm
N ₂	1.04	78.084 ± 0.004	1.04	29.3
O ₂	2.18	20.946 ± 0.002	0.280	8.98
Ar	2.5	0.394 ± 0.001	1.25 × 10 ⁻²	0.500
CO ₂	76.5	0.033 ± 0.001	4.42 × 10 ⁻⁴	0.019
Rn	22.8	$C_G = 4.72 \times 10^{-18}$	2.07 × 10 ⁻¹⁹	4.60 × 10 ⁻¹⁷

Table 2.4: Equilibrium liquid concentrations for the most four main constituent gases of the atmosphere. In the analysis below, only N₂ and O₂ and Rn will be considered significant. The value of C_G for Rn is calculated from measurements performed on-site.

into the degasser, and the practical limit on degassing efficiency.

$$\dot{C}_G = \frac{k_d \dot{m}_1 C_L}{V_G} \quad (2.32)$$

or in terms of pressure, the rate of increase of pressure of a gas is given by

$$\dot{P}_G = \frac{k_d \dot{m}_1 C_L R T}{V_G} \quad (2.33)$$

In order to maintain a steady-state pressure inside the degasser, the vacuum pump must remove gas at the same rate at which gas is introduced, or $\dot{P}_G$.

The lower limit for the Rn concentration in the exhaust water at $k_d = 0.9999$ is $C_L = 12$ atoms/m³, or 2.0×10^4 Rn atoms in the 1670 tonnes of light shielding water inside the PSUP. This level of purity is well below the cleanliness requirements described above.

We will be operating near the vapor pressure of water, where for water $C_G = 1.09$ mol/m³. If the vacuum pump is in continuous operation, the fraction of contaminant gases is small compared to the total amount of water vapor.

Gas	C_G [mol/m ³]	P_G [Pa]	$\dot{C}_G$ [mol/m ³ s]	$\dot{P}_G$ [Pa/s]	$\dot{m}$ [kg/hr]
N ₂	1.09×10^{-4}	0.264	8.71×10^{-2}	2.12	0.210
O ₂	6.12×10^{-5}	0.149	2.34×10^{-4}	0.569	0.0646
Rn	4.15×10^{-21}	1.01×10^{-17}	1.73×10^{-22}	4.21×10^{-19}	9.20×10^{-23}

Table 2.5: Static background and rate of increase of gas concentrations and pressures in the degasser for k_d , T , $\dot{m}_1$, and C_L mentioned above. Gas partial pressures are negligible with respect to the vapor pressure of water, 2.7 kPa at 293K.

2.4.2 Predictions for k_d

To predict k_d , we take a simple ratio of the total mass flowing upwards in the degasser to the mass flow rate $\dot{m}_2$ to the vacuum pump, and assume that increases in the upwards vapor flow translate directly into increases in degassing efficiency.

Using our simple model, we may calculate the theoretical degassing efficiency, and the results for heating and cooling parameters are summarized in Table 2.6, below. The results are based on the experimental measurement of $k_d = (99.75 \pm 0.05)\%$ with no heating or cooling, and the predicted values are extrapolated from this initial measurement.

$$k_d = 0.9975 + 0.0025 \left(1 - \frac{\dot{m}_2}{\dot{m}_4 + \dot{m}_6 + \dot{m}_8} \right) \quad (2.34)$$

2.4.3 Mass flow rate $\dot{m}_2$

The mass flow rate $\dot{m}_2$ describes mass removed from the degasser by the operation of a vacuum pump, which we desire to measure experimentally. No commercial mass flow meters were available which were designed to operate at the conditions

		Heating				
		0 kW	2 kW	4 kW	6 kW	8kW
Cooling	10 kW	99.98	99.99	99.99	99.99	99.99
	5 kW	99.97	99.98	99.98	99.99	99.99
	0 kW	99.75	-	-	-	-

Table 2.6: Theoretical values for k_d in percent under different conditions. All errors are $\pm 0.05\%$. The value for no heating or cooling was measured experimentally, and all others calculated from it.

the degasser is operated in, so it was necessary to develop our own method.

The theory of gas flow tells us that a constriction in a pipe causes a differential pressure ΔP to be generated. An orifice plate may be used, such as seen below in Fig. 2.3.

Figure 2.3: Schematic diagram of an orifice plate. $\Delta P = P_2 - P_3$
 $d_o = (0.500 \pm 0.005)\text{in}$, $d_1 \simeq 7.5\text{cm}$.

We may calculate the maximum value for $\dot{m}_2$ from mass flow through the orifice plate, assuming one side of the orifice plate is at vacuum ($P_3 = 0$), and the other at $P_2 = P_w = 2600\text{Pa}$, the vapor pressure of water at 20°C , with molecular mass

$M = 18\text{g/mol}$, $T = 293\text{K}$, $V_G = (2.4 \pm 0.2) \text{ m}^3$, $A_o = \pi/4 d_o^2$, and $v_{rms} = 588\text{m/s}$.

$$\dot{m}_2 = M\dot{n} = M \frac{\dot{P}V_G}{RT} = \frac{M A_o v_{rms} P_w}{RT} = 5.86 \times 10^{-3} \text{ kg/s} = 21.1 \text{ kg/hr} \quad (2.35)$$

Engineering handbooks tell us that the mass flow through an orifice depends on the diameter d_o of the orifice, the differential pressure ΔP across the orifice, and the pressure P_2 on the high pressure side of the orifice according to the following relation,[26]

$$\dot{m}_2 = 0.0109 d_o^2 \sqrt{P_2 \Delta P} \quad (2.36)$$

with $\dot{m}_2$ in kg/s. We assume here that $P_2 = P_G$, the pressure inside the degasser.

This equation assumes the flow of gas through the orifice is not choked, or that the gas flow through the orifice is smooth and not turbulent. We define the choke status for a diatomic gas such as N_2 to be

$$choke = \frac{P_2 - P_3}{P_2} - 0.5283 = \frac{\Delta P}{P_2} - 0.5283 \quad (2.37)$$

If $choke > 0$, then Eq. 2.36 holds true.[26] In physical terms, a large value for $choke$ means that gas flow through the orifice plate is not limited or affected by the compressibility of that gas. The simplistic choke model described above is not very accurate, however, as we shall see below that larger $choke$ values lead to better agreement of Eq. 2.36 with Eq. 2.38, below.

If we pump down the degasser from high to low pressure, and measure the absolute pressure with time, we have the change of pressure P_G in the degasser with respect to time, $\dot{P}_G$, which can be related to the mass flow using Eq. 2.35. If we also measure the differential pressure across the orifice while this is happening, we can calibrate the ΔP measured by the flow meter, and use P to give us $\dot{m}_2$. We know

$\dot{m}_1$ by observing it at the RO, and these measurements let us fully characterize the system.

The ideal gas law gives

$$\dot{m}_2 = M\dot{n} = \frac{MV_G}{RT}\dot{P}_G = 0.2456\dot{P}_G \quad (2.38)$$

with $\dot{P}_G$ in psi, as that is the unit used by the instruments.

We can relate this equation which is dependent on $\dot{P}_G$, to Eq. 2.36, above, which is dependent on P_G and ΔP .

Chapter 3

The Process Degasser

The process degasser is a component of the light water purification facility. The H₂O System is required to perform the following functions: [11, p.51][10, p.76]

- Purify the mine water on initial fill.
- Maintain water purity and radioactivity at acceptable levels, 2.2×10^{-14} g/g (130 atoms/ton) in the ²³²Th chain, and 1.5×10^{-14} g/g (90 atoms/ton) in the ²³⁸U chain. Removing Ra and Th from the water should achieve these limits.
- Maintain optical purity.
- Allow monitoring of the water purity.
- Cool the detector to 10°C, which will reduce PMT noise rates and help control biological activity.

3.0.4 The H₂O System

A functional diagram of the H₂O system is given in Fig. 3.1, below. An independent purification system exists for the D₂O which is similar in design to the H₂O

system. The D_2O purification systems have been separated in order to limit H_2O contamination of the D_2O .

Water enters the system from an Inco supply line during the initial fill, and passes through the pretreatment charcoal filter which removes gross impurities such as organics and chlorine. Next, the water softeners remove calcium, magnesium, and dissolved iron from water. The next component that the pretreated water enters is the Reverse Osmosis (RO) unit. A semipermeable membrane concentrates >99% of the contaminants and discards the dirty concentrate water, while the clean permeate water is passed to the next component.[11, p.52]

Further purification occurs in a ultraviolet (UV) sterilizer, which serves to break up large organic compounds into their constituent elements. Ion exchange columns remove the contaminant elements, and the water is passed on to the process degasser.

Water enters the process degasser at a rate of approximately 120 litres per minute. At this stage the water is degassed with a design goal of > 95% efficiency. Degassing removes O_2 and ^{222}Rn from the water, limiting the growth of aerobic bacteria, minimizing corrosion within the detector, and lowering the level of radioactive isotopes within the detector. A final stage of UV light and filtering occurs before the water is chilled and allowed to enter the detector. The final chill stage ensures that the detector operates at the design goal of 10 C, slowing anaerobic bacterial growth, and removing heat produced by the PMTs and the surrounding rock.

In normal operation, the water purification system continuously circulates the light water from the detector through the later stages of purification. Water is taken from outside of the PSUP, cleaned, and returned inside the PSUP. Any trapped gases, biological contaminants, and ions are removed before the purified water is allowed to reenter the detector. Circulating the water in this way ensures that the fiducial volume of the detector is as radioactively clean as possible.

As outlined here, the H_2O system performs four of the five required functions.

The fifth, monitoring of the water purity, is performed by a monitor degasser as described in a previous M.Sc. thesis.[27]

Figure 3.1: A functional diagram of the H₂O purification system. (RO= Reverse Osmosis; DI=deionization; UV=Ultraviolet)

Figure 3.2: Simplified schematic diagram of 311-DG02 and associated plumbing

3.1 Process Degasser Subsystems

The operation of the process degasser is summarized here, with a more detailed theoretical analysis given above in § 2.

A schematic of the components surrounding the degasser is shown in Fig. 3.2. The figure has been simplified slightly in order to describe the system more clearly. As a result, the following descriptions of subsystems and operating modes are for informational purposes only. Complete blueprints along with the proper operational procedures can be found on the SNO site, in the reference cabinet of the Utility room.

3.1.1 Subsystems and Instrumentation

When the water enters the degasser, it passes through seven spray nozzles, which causes the water to form mist and small droplets. The spray nozzles spray water over the entire cross section of the degasser and are located approximately 10 cm above the surface of the packing.

The packing chosen for the degasser was Fabco TRI-PACK NO.1/2, and is described in detail below. In short, the packing fills the middle of the vessel and has a large surface area on which liquid water films can form.[28] Water transport through the packing is performed by the flow of water film and drops, during which the contaminant gases diffuse into the bulk vapor.

A heater element is located below the packing, but above the liquid water level in order to provide an upwards flow of radon-free water vapor. The upward flowing water vapor provides a carrier medium to strip the degassing column of contaminant gases, and carry them out to the vacuum pump. The flow of water vapor also helps ensure that the concentration of contaminant gases is low in the vapor surrounding the packing. A cooling element at the top of the vessel condenses much of the water

vapor, reducing the load on the vacuum pump.

Differential pressure (DP) cells monitor the water level inside the vessel, and a clean pump 311-P11 in the pit at the bottom of the degasser is computer controlled in order to keep the liquid water level stable within a small range.

The O₂ meter AIT085 measures the oxygen level of the degasser intake or exit water, FT145 measured the mass flow to the vacuum pump, and PT086A measures the pressure inside of the degasser.

Temperatures inside and near the degasser are monitored manually using differential temperature indicators DTI158 B through H. Temperatures T_2 through T_8 are calculated from these differential readings by referencing them from the absolute temperature sensor TI158A.

The flow of water into the degasser can be measured by observing the permeate flow meter on the RO unit. In all of the operating modes of the degasser, water is taken from the RO which is upstream of V154L, processed, and sent either to drain or to the monitor degasser.

V162L controls the rate of coolant water flow, which is measured by flow meter FI149, in litres per minute. HTR01 controls the heaters, allowing the selection of heating from no heating to an upper limit of 8kW.

3.1.2 Packing in the Process Degasser

The purpose of the packing is to ideally provide an infinite surface area, zero volume structure on which thin water films may form. This thin water film ensures that contaminant gases have minimal distance to diffuse before entering the bulk gas, increasing degassing efficiency.

In reality, the packing has a finite, though large surface area, and a small volume. The geometric surface area is 85 ft²/ft³, or 279 m²/m³, with a 91% void space.

The design of packing may be considered to be a 'black art', as it is not fully understood. For example, packing with identical surface areas and different physical shapes yield different results when placed inside a packed tower. The only apparent reason for the difference is that the *wetted* or *active* surface area of a packing is also dependent on the physical shape, and not solely on the physical surface area.

The manufacturer of the packing used here claims that the active surface area is higher than the geometric surface area, but we shall use only the geometric area in the following analyses.

The packing is nominally one inch (1") in size, hollow, with a spherical shape, and pack 92 elements per meter vertically. The shape and structure of the packing results in there being no direct path for water to fall through the vessel, which maximizes transit time and the time available for degassing. The packing possesses many of the characteristics of an ideal packing, which include geometric symmetry, structural uniformity, and high void space.[28]

The volume of the packing used is $(1.80 \pm 0.03) \text{ m}^3$, for a total surface area of $(5.0 \pm 0.1) \times 10^2 \text{ m}^2$. Including the walls of the vessel, the total surface area available for degassing is $A = (5.2 \pm 0.1) \times 10^2 \text{ m}^2$.

3.1.3 Vacuum Subsystem

The vacuum pump 311-VP02 is an Edwards EH500A mechanical booster pump, with a QDP80 backing pump. At 60Hz and 460V, the pump can reach a limit of $5 \times 10^{-3} \text{ mbar}$, or 0.5Pa, with a maximum volumetric pumping speed of $95 \text{ m}^3/\text{hr}$ at one to 10 mbar. At the process degasser operating pressure of 20 to 30 mbar, the volumetric pumping speed is 90 to $95 \text{ m}^3/\text{hr}$, with a pressure differential of 0 to 90 mbar across the booster pump.[29]

When in operation, the vacuum pump lowers the pressure inside the degasser to

the vapor pressure of water, and maintains it there while the water is degassed.

We wish to measure the mass flow rate to the vacuum pump, to quantify the amount of mass removed, and to better understand degassing efficiency. The flow meter FT145 measures the pressure drop across an orifice plate located on the pipe to 311-VP02. We saw above that the mass flow per unit time through the orifice plate can be calculated from the differential pressure across the plate, giving us a good measurement of the mass flow rate to the vacuum pump.

The flow meter FT145 has physical limitations on the differential pressure it can accurately measure, so V095L may be partially closed in order to limit the mass flow to 311-VP02.

When initially pumping down from atmospheric pressure to the operating pressure, V468L is opened in order to bypass the orifice plate. The pipe on which V468L is situated is physically larger than the pipe V095L is on. Fully opening V468L allows the pressure inside the degasser to be quickly reduced to the operating range.

When not in use, the degasser is maintained at atmospheric pressure by the flow of clean, dry nitrogen from nitrogen bottles through V295L. Automatic circuitry ensures that the valve is opened whenever the vacuum pump is not running.

3.1.4 Circulation system

V102L, 311-P11, DPT082, LCV082, and V299L comprise the main body of the circulation system. Water exits from the bottom of the degasser, and is pumped away by 311-P11. The liquid water level is monitored by a differential pressure transducer DPT082, and a computer controls the position of the level control valve LCV082 in order to maintain a stable water level in 311-DG02.

V299L allows 311-P11 to be isolated when the entire degasser is bypassed.

3.2 Quantifying k_d

Now that we have described our experimental setup in some detail, we can begin to quantify degassing efficiency. The initial stage of degassing is performed when the water enters the degasser, is partially vaporized, and largely transformed into droplets. These droplets are small, with a diameter d of approximately 0.1 mm to 1.0 mm, and are sprayed under pressure onto the packing.

With a fall time of approximately $\Delta t = 0.1$ s, and using $A/V = 6/d$, we can calculate initial degassing efficiencies. Using the numbers mentioned above, and $K_L = 3 \times 10^{-5}$ m/s, we see that $(0.018 \leq k_d \leq 0.16)$ is the minimum degassing efficiency we can achieve solely due to the droplets exiting from the spray nozzles. The addition of packing effects will greatly increase k_d by increasing the time available for transfer, and by greatly decreasing the thickness Δz of water contaminant gases must diffuse through.

Chapter 4

Experiments

This chapter discusses the various experiments which have been performed, and compares experimental and theoretical results.

The first set of measurements which were performed were calibrations of the instruments used in the following experiments, in order to quantify instrument behavior at high ambient pressure.

Degassing efficiency k_d was measured for O_2 , as the measurements could be performed quickly and reliably. Many experimental runs were taken over a variety of operating conditions, which allows a determination of the response and behavior of the degasser.

Radon measurements were performed using the Monitor degasser, which was not fully operational until the later stages of this experiment. The oxygen degassing efficiency measurements which were performed previously could be related to the efficiency for degassing Radon, and the few Radon measurements served as a check on the accuracy of the extrapolation.

The degasser is designed to be used in a number of different operational modes. The configuration of valves allow it to be bypassed completely, filled with water, run

normally, isolated to recirculate the water inside the degasser, or shut down completely. Fig. 3.2 shows a simplified schematic of the plumbing and valves associated with operation of the degasser.

We start with the degasser dry, leak checked, filled with dry N_2 to ambient pressure.

4.1 Instrument Calibrations

The main data collection instruments used were a pressure gauge labeled here as PT086A, and a DP cell labeled FT145.[30], [31]

No commercial mass flow meter was found to be suitable for the planned operating conditions of the degasser. Theoretical analysis showed that it was possible to use an orifice plate to constrict the flow through a pipe, and to measure the differential pressure (ΔP) across the orifice plate. This ΔP would scale in a well understood way with the mass flow rate, but it was necessary to first calibrate it to our operating conditions.

Both gauges were calibrated for instrument noise and zero scale, as the manufacturers calibrations were specified for atmospheric pressure, and the pressure underground was approximately 30% higher than this.

FT145 was found to be non-linear in its response to absolute pressure, so it was necessary to analyze its output over a variety of pressures when both sides of the flowmeter saw the same absolute pressure.

Once that was done, a cross-calibration of PT086A and FT145 was performed, in order to calibrate the output of FT145 with the differential pressure seen across two legs.

4.1.1 Gauge Noise and Zero Calibrations

Instrument manufacturers supplied calibration certificates which consisted of tests performed on surface, at atmospheric pressure. The pressure 2080m underground is significantly higher than atmospheric at 124 kPa, and this pressure increase may modify the instruments response. In order to account for possible atmospheric effects, a series of gauge noise observations and zero offset calibrations were performed.

The degasser 311-DG02 was pumped down for one hour, and isolated by closing valves V102L, V095L, V468L, and V165L. A helium leak checker was used to measure the pressure to be $(1.7 \pm 0.1) \times 10^{-2}$ mbar, or (17 ± 1) Pa. The output of instruments PT086A and FT145 was recorded for 25 minutes. Both instruments were observed to have an noise of less than $\sigma = 0.2$ mA, which is the manufacturers specification.

Figure 4.1: Gauge noise for FT145. $\bar{x} = (2.92123 \pm 0.00009)$ mA, $\sigma = 0.003$ mA.

Dropouts in the figure are due to the limits of digitization.

The zero calibration of PT086A was performed at the same time as the gauge noise calibration described above. Fig. 4.2 shows that the zero reading of $(4.5167 \pm 0.00004)\text{mA}$ is slightly higher than the manufacturers calibration data of 4.45 mA at 0.0 psi, but well within specified accuracy of the device.[30] We will therefore use the manufacturers calibration data for PT086A in the following experiments.

Performing a zero calibration of the dP cell FT145 was slightly more complicated. Initial observations indicated that the zero reading depended on the absolute pressure experienced by FT145, and the differential pressure reading varied on top of this zero. A series of calibration runs were performed in order to quantify this behavior.

Figure 4.2: Zero calibration for PT086A. $\bar{x} = (4.5167 \pm 0.00004)\text{mA}$, $\sigma = 0.001\text{mA}$.

An orifice plate of inside diameter (0.500 ± 0.005) in. was placed in the system by FT145, and V102L and V165L were closed. The N₂ fill bottles were used to ensure the degasser contained only dry nitrogen, and 311-VP02 was run until the pressure observed by PT086A was near 2.5psi.

The valves V095L and V468L were closed, and the system allowed to stabilize at the chosen pressure for thirty seconds. A further ten minutes of data were taken at this pressure, in order to observe the reading FT145 gave when both legs were at the same pressure.

Valve V095L was then opened, and the pressure allowed to drop slightly. In all, the pressure was varied in twelve steps from approximately 2.5 psi to near 0.0psi, as seen in Fig. 4.3.

A fit to the data was performed, of the form $f(P) = a \exp(-bP) + c$, with P being the pressure in psi measured by PT086A. This functional form was chosen because it was simple, and because it fit the data closely at the low pressures where the experiments would be performed.

The raw reading from FT145 could then be corrected at various pressures with this fit, to give a true zero reading when the differential pressure across the legs of FT145 was zero.

Figure 4.3: Zero calibration for FT145. The fit used was of the form $f(P) = a \exp(-bP) + c$, with $a = (-2.904 \pm 0.004)$ mA, $b = (1.913 \pm 0.08)$ psi^{-1} , and $c = (3.185 \pm 0.004)$ mA, with $\chi^2/\text{d.f} = 0.135$.

4.1.2 Calibrating the flow meter FT145

A metal disk, or blank orifice plate was placed in the system by FT145, and V468L was closed, with V095L open. The vacuum pump 311-VP02 was allowed to run for 15 minutes, and V095L was closed. This procedure caused one leg of FT145 to be at the lowest pressure 311-VP02 was capable of reaching, 0.5 Pa or 7×10^{-5} psia. The pressure in the degasser was varied in nine steps from high to low pressure, limited by the range of differential pressures measured by FT145.

At each pressure P , ten minutes of measurements were taken using PT086A and FT145, and the results plotted in Fig. 4.4 after performing a zero correction for

absolute pressures experienced by FT145 as discussed above. A linear fit to the data yielded a calibration of FT145 from instrument current output to differential pressure across the orifice plate.

For the measurements performed below using this calibration of FT145, we take the y-intercept of Fig. 4.4 to be zero as shown. We then fold in the stability error for PT086A of $\sigma = 7 \times 10^{-2}$ psi in order to calculate the conversion error.

Figure 4.4: FT145 mA to psi calibration. The fit is linear, with slope $m = (2.15 \pm 0.04) \times 10^{-3}$ psi/mA, y-intercept $b = (0.0 \pm 0.2) \times 10^{-4}$ psi, and $\chi^2/\text{d.f.} = 0.5005$.

4.1.3 Water Film Thickness

The purpose for this experiment was to discover the approximate thickness of the film of water covering surfaces inside the degasser. The first run was done with the

degasser dry, and a water flow rate of (32 ± 1) GPM, or (121 ± 4) litres/minute.

Time was recorded starting when water was first observed to emerge from the spray nozzles, and stopped when a steady flow of was observed through the bottom viewport. The water film thickness can then be calculated from the known surface area of the degasser, and the volume of water which wets that surface. The degasser has a nominal surface area of $A = (5.2 \pm 0.1) \times 10^2 \text{ m}^2$, and the volume of trapped water can be calculated from the known flow rate and transit time.

Table 4.1 records the delays observed and the film thickness associated with that delay. As expected, an already wetted surface will adsorb less water than a dry surface, resulting in shorter delays before the extra water is shed.

	Δt (s)	V/A (m)
dry	40 ± 10	$(1.5 \pm 0.4) \times 10^{-4}$
wet 1	23 ± 2	$(8.9 \pm 0.8) \times 10^{-5}$
wet 2	23 ± 2	$(6.9 \pm 0.8) \times 10^{-5}$

Table 4.1: Run times and water film thickness.

The value for film thickness we will use later in this report is the second one, $(8.9 \pm 0.8) \times 10^{-5} \text{ m}$. The transit time of water in the system was taken to be (23 ± 2) s. In choosing which values to use, we have assumed that we may ignore any static water film trapped on surfaces inside the degasser.

4.1.4 Mass flow using dry N_2

§ 2.4.3 developed the theory of measuring mass flow using a differential pressure gauge, and this section describes experiments which attempt to verify that theory, and to calibrate our instruments.

Gas	K_L [m/s]	k_d [%]
N ₂	2.99×10^{-5}	99.95
O ₂	2.99×10^{-5}	99.95
Rn	1.14×10^{-5}	94.74

Table 4.2: Predicted degassing efficiencies using $V/A = (8.9 \pm 0.8) \times 10^{-5}$ m, and $\Delta t = (23 \pm 2)$ s. Errors on k_d scale as $e^{-7} K_L k_d$, and are neglected.

These calibrations were necessary, as no commercial mass flow meter was found to be suitable for the planned operating conditions of the degasser.

A series of experimental runs were performed in order to calibrate the mass flow meter. For each run, the degasser was set to some initial pressure P , and then pumped down from P to vacuum through the orifice plate. At each second, readings of pressure P from PT086A, ΔP from FT145, and time were recorded. The mass flow through the orifice plate was calculated using the two methods, and the results compared.

Using Eq. 2.36, which is given as

$$\dot{m}_2 = 0.0109 d_o^2 \sqrt{P_2 \Delta P},$$

we may use the calibrated ΔP and P readings to calculate $\dot{m}_2$, and the results for the experimental runs are summarized below in Fig. 4.5.

Figure 4.5: Measured mass flows for various P and ΔP settings

We may perform a similar calculation using the known rate of change of P , $\dot{P}$, and Eq. 2.38, given as

$$\dot{m}_2 = M \frac{\dot{P} V_G}{RT}.$$

We may generate a surface from this equation by relating $\dot{m}_2$, and $\dot{P}$ to the known ΔP at each point, and interpolating between points. The surface generated by this method is shown below in Fig. 4.6.

Figure 4.6: Measured mass flow using interpolated surface from $\dot{P}$ and ΔP .

We may combine the above two figures into one in order to be able to quickly compare the methods of calculating $\dot{m}_2$. Fig. 4.7, below, shows the combination. For low P and high ΔP , the methods are not in good agreement. However, the process degasser will normally be running in the range of $P = (0.4 \pm 0.1)\text{psi}$, where the methods are in good agreement. We can therefore conclude that Eq. 2.36 accurately and precisely describes mass flow through the orifice plate, and that it may be used to experimentally measure $\dot{m}_2$.

Figure 4.7: Mass flows for various P and ΔP settings, combined from the previous two figures.

4.2 O₂ Assay

Prior to performing radon degassing measurements, we first performed the same experiments measuring oxygen degassing efficiency. We concentrated on oxygen rather than radon because oxygen removal efficiency depends on the same parameters as Radon removal, and would follow the same trends. We could also perform measurements in real time, which allowing us to vary control settings and to observe the change in oxygen levels from one stable regime to another.

V154L, V156L, and V157L control the flow of the water to the upper level of the utility room. These valves allow the RO permeate to be sent to the mezzanine level, and controlled from there, as they are physically closer to the rest of the system. For

the following descriptions of operational modes, we assume that V154L and V156L are open, and V157L and any other valve not specifically mentioned is closed.

4.2.1 Intake O₂

For each experiment outlined below, we assume that prior to performing the experiment, an initial measurement of trapped Oxygen in the intake water was made. The initial Oxygen levels in the RO intake water was measured in the O₂ monitoring mode. Water was taken from the RO through valves V154L, V156L, V135L, and past V133L to drain. All other valves were closed.

Once an O₂ measurement was recorded, the system was modified to run in another operational mode. The initial intake O₂ measurements varied from 6 ppm to 8 ppm, with these measurements folded into the results on degassing efficiency, below.

4.2.2 Initial O₂ removal

After recording an initial O₂ measurement, the degasser was filled with water, and the heaters and coolant set off.

After a short period of time the degasser reached pressure and temperature equilibrium. The oxygen readings from AIT085 were recorded approximately every ten minutes as the vessel was pumped down to the vapor pressure of water, and the measured oxygen degassing efficiency is shown graphically in Fig. 4.8, with detail in Fig. 4.9.

We can see immediately from the figures that an efficiency of $k_d = (99.75 \pm 0.05)\%$ was reached without the benefit of an upwards flow of water vapor. We expect therefore, that the efficiency will change as heating and cooling parameters are adjusted, and that we will be able to find some combination of controls that maximizes k_d .

An additional O_2 degassing run was performed, with $\dot{q}_1 = 6kW$, and $\dot{q}_2 = 9.7kW$, with $c_w = (50 \pm 1)$ LPM. The results are plotted in Fig. 4.10, with detail in Fig. 4.11.

These plots show us that k_d has been substantially increased over the previous runs, and that high k_d is achieved much more quickly than before. These changes lead us to conclude that as expected, modifying the heating and cooling parameters allow us to control k_d , and that the vessel had absorbed large amounts of O_2 . Repeated runs of degassing had the side benefit that the vessel itself had trapped gases removed, allowing it to more quickly reach equilibrium.

Figure 4.8: Initial O_2 degassing run.

Figure 4.9: Detail of initial O_2 degassing run.

Figure 4.10: Second O_2 degassing run.

Figure 4.11: Detail of second O_2 degassing run.

4.2.3 Heating and Cooling Parameters

A number of experimental runs were performed under different conditions of heating and cooling. The results are summarized below in Table 4.3, with the heater settings on the horizontal axis, and the coolant water flow in litres per minute on the vertical axis. The heating power was calculated from measurements of voltage and current to the heaters, and the coolant power was calculated from the flow and the measured temperature differential $T_7 - T_8$. For all of the runs summarized here, the degasser was at a uniform temperature within 0.1°C , and the coolant water temperature differential was roughly constant at $(2.6 \pm 0.2)^\circ\text{C}$.

We see that increasing the amount of heat added to the system, or increasing the coolant water flow increases the degassing efficiency.

The initial mass flow to the vacuum pump for these experiments was set at $\dot{m}_2 = (1.1 \pm 0.2) \text{ kg/hr}$, but it was found that with a coolant flow of 25 LPM, the

degassing efficiency dropped steadily during the course of one run. Accordingly, the recorded values for k_d at a coolant water flow of $c_w = (25 \pm 1)$ LPM were made with the 3in valve V468L fully open, and $\dot{m}_2 > 20$ kg/hr.

	Heating	0	60	120	180	240	$\dot{m}_2$
Cooling		0 kW	2 kW	4 kW	6 kW	8kW	[kg/hr]
50 LPM	9.7 kW	99.73	99.80	99.86	99.90	99.96	1.1 ± 0.1
25 LPM	4.8 kW	99.62	99.79	99.86	99.91	99.96	> 20
0 LPM	0 kW	99.60	-	-	-	-	1.1 ± 0.1

Table 4.3: Experimentally measured k_d in percent for different heating and cooling parameters. Errors are ± 0.05 %

4.2.4 Vacuum pumping Rates

The theoretical model for mass flow and degassing efficiency developed above in § 2.4.1 tells us that that the larger $\dot{m}_2$ is, the better the degassing efficiency k_d becomes.

Practical limitations in the operation of the system prevent us from controlling $\dot{m}_2$ by more than 10% near the low range of $\dot{m}_2 = 1$ kg/hr, and allow only one other unmeasurable range of $\dot{m}_2 > 20$ kg/hr with the current 0.5in orifice plate. Using a different orifice plate may allow better control, and would have to be determined with further experiments. Despite these limitations, we can see that changes in $\dot{m}_2$ have a large effect on the degassing efficiency.

The experimental runs summarized in Table 4.3 above indicate that large amounts of cooling are required to get good k_d when $\dot{m}_2 \simeq 1$ kg/hr. With lower settings of coolant flow, it was impossible to achieve good k_d until $\dot{m}_2$ was greatly increased.

We may conclude then, that the good k_d may be achieved while minimizing the load on the vacuum pump 311-VP02, by optimizing the heating and cooling parameters.

4.2.5 Recirculation Measurements

Recirculation occurs because we want to discover the limits of degassing efficiency, and to see what gas background is sustained by the degasser.

Recirculation mode was entered after the degasser was filled with water, and an initial O_2 measurement recorded. V135L and V157L were opened, and V156L was closed. This change forces the RO permeate to flow to the drain, while the degasser exit water is recirculated to the entrance.

In order to record O_2 measurements, V151L or V133L were opened, which allows a small fraction of the recirculating water to flow out of the system past the O_2 meter. Readings were recorded, and the valves closed again.

One problem with recirculation mode was that a 'dead' leg existed to the oxygen meter AIT085. The water in this section of pipe was not degassed, but instead fed liquid with a higher gas content back into the system. As the diffusion rates of the contaminant gases in water are small and turbulence was low, we expect that a sufficiently long period of time spent in recirculation mode will negate the effect of the dead leg.

The measured degassing efficiency for the recirculation mode was poor, at $k_d = (99.83 \pm 0.05)\%$. This low efficiency is due to the dead leg mentioned above, and not to any inherent flaws in the system.

As stated above in § 2.4.1, degassing efficiency has upper bounds.[23, p.246] The highest measured k_d above was $k_d = (99.96 \pm 0.05)\%$, which is within experimental error of the theoretical limit $k_d = 99.99\%$. At very high efficiencies, the factors lim-

iting k_d include outgassing from the packing and walls of the degasser, and diffusion through degasser components.

In order to achieve the best possible k_d , we must first outgassing from the degasser, by maintaining it at vacuum for an extended period of time, or by flushing it before circulating the water back to the detector.

4.3 ^{222}Rn Assay

While it was useful to measure the O_2 degassing efficiency of our system, the purpose of the process degasser is to remove ^{222}Rn from the light water with high efficiency.[10] Using O_2 initially allowed a number of runs to be performed quickly, as the O_2 meter AIT085 gave current measurements of oxygen levels, and the experiments could be performed by one individual.

Measuring k_d for ^{222}Rn was much more time consuming, as each run required the participation of many individuals on different pieces of apparatus. In addition, the ^{222}Rn measurements required most of one shift underground to set up the monitor degasser, to perform background measurements on the RO permeate water and the degasser, and to run the system for the experiment in question.

The few ^{222}Rn measurements which were performed serve as a check on the O_2 measurements, and as a verification that the process degasser is fulfilling its design goals.

4.3.1 ^{222}Rn Background

There are many sources of ^{222}Rn background within the experiment. As mentioned above, all materials have trace contaminations of ^{232}Th and ^{238}U , and the degasser is no exception. In addition to radioactive background, diffusion of ^{222}Rn through

the polypropylene pipes occurs at some small rate.

Prior to installing the apparatus, Dr. Henry Lee performed some background ^{222}Rn measurements, which are summarized in Table 4.4, below.[24]

	rate [atoms/hour]
Packing	$< (41.5 \pm 0.7)$
Vessel	22.9
In Situ	32 ± 4

Table 4.4: Background counting rates for ^{222}Rn . The In Situ data is from tests performed on the installed degasser.

The background of the degasser vessel was initially measured without any components installed, and is for the pressure vessel only. As installed, the degasser includes copper heating coils, stainless steel thermowells, acrylic viewports, plastic o-rings, vacuum grease, and stainless steel cooling coils. All of these components will increase the background.

It should also be noted that the packing and vessel backgrounds were measured without rigorously cleaning the components, and therefore include large components from surface dust. Prior to measuring the installed background, the degasser was operated for many hours to supply pure water for the underground fire system. It would be expected that most of the surface dust would be removed after 100,000 litres of water passed through the system.

As we can see from the last line of Table 4.4, the background for the system as installed is not substantially larger than what we would expect from the initial background measurements. The degassing efficiency may be limited by the emanation rates, and not by the theoretical limits on k_d .

4.3.2 ^{222}Rn Degassing efficiency

Two runs were performed, under different conditions.

Parameter	Run 1	Run 2
RO permeate flow (GPM)	32 ± 2	22 ± 2
c_w (lpm)	50 ± 1	50 ± 1
$T_7 - T_8$ ($^{\circ}\text{C}$)	0.17 ± 0.05	0.1 ± 0.1
T_1 ($^{\circ}\text{C}$)	17.01 ± 0.05	17.52 ± 0.05
P_2 (psi)	0.42 ± 0.2	0.44 ± 0.1
$\dot{m}_2$ (kg/hr)	1.1 ± 0.2	1.1 ± 0.2
Heating (kW)	8 ± 1	4 ± 1
$k_d \text{ O}_2$ (%)	99.96 ± 0.05	99.28 ± 0.03
$k_d \text{ Rn}$ (%)	98.0 ± 0.7	97.7 ± 0.9

Table 4.5: Experimental settings and measured k_d for O_2 and ^{222}Rn for two runs.

At an initial $C_L = 2.07 \times 10^{-19}$ mol Rn/ m^3 , with $k_d = (98.0 \pm 0.7)\%$, we have the Rn concentration in the water at $C_L = (4.2 \pm 0.3) \times 10^{-21}$ mol Rn/ m^3 , or $(2.5 \pm 0.9) \times 10^3$ Rn atoms/ m^3 .

4.4 Extrapolating from O_2 to ^{222}Rn

Eq. 2.20, above, enables us to extrapolate from a measured k_d for O_2 , and make a prediction for k_d for Rn under the same operating conditions. Table 4.6 below summarizes these predictions.

We may note that the measured k_d for Rn at 8kW of heating and 9.7kW of cooling is $(98.0 \pm 0.7)\%$, which is not in agreement with the corresponding prediction

	Heating	0	60	120	180	240
Cooling		0 kW	2 kW	4 kW	6 kW	8kW
50 LPM	9.7 kW	89.51	90.64	91.83	92.82	94.94
25 LPM	4.8 kW	88.05	90.47	91.83	93.10	94.94
0 LPM	0 kW	87.82		-	-	-

Table 4.6: Predicted k_d in percent for Rn, extrapolated from the results for O_2 summarized above. Errors are $\pm 0.05\%$

in Table 4.6. Table 4.7 below compares the measured and predicted values of k_d for O_2 and Rn for different experimental runs summarized above in Table 4.5.

Parameter	k_d Run 1 (%)	k_d Run 2 (%)
O_2 (measured)	99.96 ± 0.05	99.28 ± 0.03
O_2 (predicted)	99.95	-
Rn (measured)	98.0 ± 0.7	97.7 ± 0.9
Rn (predicted)	94.94 ± 0.05	84.76 ± 0.05

Table 4.7: Comparisons of measured and predicted degassing efficiencies for O_2 and Rn.

The differences in predicted and measured k_d for Rn shown in Table 4.7, above, are significant, and cannot be ignored. Recent runs of the system have indicated that the O_2 degassing efficiencies measured by AIT085 are lower than the real efficiencies. Specifically, transitions between operating modes cause very low O_2 readings to be observed for a short period of time, after which the readings slowly rise and stabilize at a higher level.

The reason for the rise from a low to high O_2 reading is most likely suction effects in the pipes. Different conditions inside the degasser can cause the pressure of the outlet water to vary drastically. If the pressure is lower than the back pressure of the water in the drain, dirty drain water will be brought back into the system near AIT085, causing the oxygen meter to give anomalously high readings..[32]

We believe that the Rn degassing efficiency measurements are correct, as the different experimental configuration for sampling Rn minimizes the possibility of this suction occurring.

The variation and uncertainty in the preceding calculations are due to the simplicity of the model used, to the measurement errors described above, and to the lack of quantitative data about the internal behavior of the degasser. Despite these uncertainties, we have shown that the model is a good predictor of the behavior of O_2 in the system, but poor for Rn . The lack of accuracy in the degassing efficiency predictions for Rn is probably due to the anomalously low measured degassing efficiency for O_2 . With these considerations taken into account, we believe that this model should be used as a basis for future analysis of the process degasser.

Chapter 5

Conclusions

We have shown above that the operation of the degasser is well understood, and that the experimentally measured ^{222}Rn degassing efficiency is $> 97\%$. The minimum required degassing efficiency, as presented in § 1.4.3, was 95%, which we have exceeded. Therefore we can conclude that the system fulfills its design requirements.

5.1 Suggestions for the Future

The greatest weaknesses in the experiments described here is the few experimental measurements performed. Now that the system has been described and verified to work as designed, many more experiments can be done to further quantify the behavior of the process degasser under a number of different conditions.

5.1.1 Long Term Recirculation Tests

In § 4.2.5, we described recirculation experiments which were run under sub-optimal conditions. After those experiments had been performed, construction of the 60 ton tanks was completed, and plumbing installed to connect them with the rest of the

water purification system.

The purpose of these tanks is to serve as holding tanks for D_2O , in order to allow radioactive nuclides to decay away before the D_2O is used to fill the acrylic vessel. As the D_2O will not be underground in the near future, it becomes possible to use the tanks for other purposes.

Specifically, we would like to have a determination of the absolute levels of degassing using a long-term run. An experiment may be performed where one of the 60 ton tanks is filled with purified light water, and this water is circulated between the two tanks via the process degasser.

A cover gas supply is required for the tanks to minimize contamination of the water with O_2 and ^{222}Rn . Initially, one tank would be filled with purified water, and the other tank left empty. Water would circulate through the process degasser, and be pumped to the second tank, and the role of the tanks would be reversed when all of the water had been removed from one tank. This circulation pattern would allow the stage N purified water to remain isolated from the stage $N - 1$ water.

Performing this test would allow a precise determination of the background emanation rates of the purification system, and also serve to remove most of the trapped gases from the system.

5.1.2 Degassing Water with Low Gas Concentration

We would expect that the degassing efficiency k_d would decrease as the gas load of the intake water decreased. This is of interest, as the tests performed here were with high contaminant gas concentration. When the SNO experiment is in operation, the light shielding water will be continuously recirculated through the purification system, and will have very low contaminant gas concentrations.

The recirculation experiment described above will help to quantify the behavior

of the degasser at low gas loads, which is the regime it will normally be operating in.

Without doing much more analysis, it is difficult to quantitatively describe the behavior of the process degasser under extremely low gas loads. We see from the experiments performed above that very low contaminant gas concentrations are possible, and that we have measured $> 90\%$ degassing efficiency for Rn, at an initial concentration of $C_L = 2.07 \times 10^{-19} \text{ mol/m}^3$, and $> 99.9\%$ degassing efficiency for O_2 at an initial concentration of $C_L = 1.04 \text{ mol/m}^3$.

From these widely differing initial gas concentrations, both with high degassing efficiency, we can say that the process degasser will most likely operate at $k_d > 97\%$ efficiency for all initial gas concentrations $C_L > 10^{-19} \text{ mol/m}^3$.

5.1.3 D_2O Process Degasser

One of the intentions behind building the light water process degasser was to see if similar apparatus could be used to degas the heavy water. The requirements for degassing heavy water are slightly different than those for light water, with the most strict being the desire to not lose any of the heavy water.

With the light water process degasser, any water $\dot{m}_2$ that flows to the vacuum pump is thrown away. A heavy water process degasser must scavenge the water from the vacuum pump exhaust, condense it, and return it to the degasser intake for a second stage of degassing. More studies are required before the optimal design of a condensation and recirculation system are decided on.

In addition to the recirculation requirement, heavy water poses its own unique problems. The thermophysical properties of D_2O are slightly different than those of H_2O , and these differences must be taken into account in the design of a heavy water degasser.[33].

To first order, we can assume the properties are the same, and conclude that heavy water may be degassed at $> 95\%$ efficiency, similarly to light water.

5.2 Comments on the Operation of the Process Degasser

Once the degasser is at its operating temperature and pressure, with the heating and cooling parameters set as desired, the degassing efficiency stabilizes with a few minutes. The system can then be run for many hours with only minor variations in k_d .

The temperature within the degasser is uniform throughout to about 0.1°C , and only changes when the heating or cooling parameters have been modified. Within about 20 minutes of changing a parameter, the degasser returns to equilibrium.

One condition which must be watched carefully is the amount of contaminant gases left in the degasser over long periods of time. If ambient air is allowed to enter the vessel, oxygen and radon will diffuse into the packing, and will take a long time to be removed.

This effect was seen in the first few experiments performed, as the vessel had been sitting at ambient pressure, filled with mine air for months before being operated. When it was used, the oxygen level was observed to fall very slowly, and many hours of operation passed before a stable low oxygen level was reached.

After these first runs, a set of dry nitrogen tanks were used to back fill the degasser with pure nitrogen after every experiment, preventing more oxygen or radon from entering the system. With each additional experimental run, this low oxygen level was attained more quickly. The time required to reach equilibrium was then controlled simply by the time required to pump the vessel down from atmospheric

pressure to operating pressure.

5.3 Satisfying Design Goals

The original design goals for the light water process degasser were laid out in the MarkII description. Specifically, the objective to

- Develop full scale, high efficiency ($>99\%$) Rn removal from water and low background counting of ^{222}Rn . [11, p.58]

We have shown here that the the degasser as described above has achieved a maximum value of k_d for Rn of $k_d = 98.0 \pm 0.7\%$, which is within experimental error of the original goals, as specified in the design description for the detector. The degassing efficiency also exceeds the minimum required to have a neutral current background of less than 1n/day in the fiducial volume of the detector. Therefore we can conclude that the behavior of the degasser is reasonably well understood, and that it exceeds its design requirements.

Appendix A

Symbols and Definitions

A Surface area of the degassing region.

A_o Cross-sectional area of the orifice in the orifice plate.

c_w Coolant water flow rate.

choke Status of the gas flow through an orifice plate, smooth or turbulent.

CC Charged Current neutrino reaction.

C_e Radon concentration in exit (degassed) water.

C_g Concentration in the bulk gas.

C_i Radon concentration in input (undegassed) water.

C_l Concentration in the bulk liquid.

C_{sg} Concentration in the gas at the phase interface.

C_{sl} Concentration in the liquid at the phase interface.

D Diffusion coefficient for a contaminant gas.

DP Differential pressure cell.

ES Electron Scattering neutrino reaction.

F Flux of contaminant gases through a phase interphase.

h_{1v} Water vapor enthalpy at P_1 .

h_{1l} Liquid water enthalpy at P_1 .

h_{2v} Water vapor enthalpy at P_2 .

h_{2l} Liquid water enthalpy at P_2 .

H Henry's law constant for the gas and liquid in question.

H' Henry's law constant for the gas and liquid in question, concentration units.

k_d Degassing efficiency. Defined as $(C_i - C_e)/C_i$.

k_g Exchange constant for gas phase.

K_G Overall gas phase transfer coefficient.

k_l Exchange constant for liquid phase.

K_L Overall liquid phase transfer coefficient.

$\dot{m}_1$ Liquid flow into degasser.

$\dot{m}_2$ Vapor flow out of degasser.

$\dot{m}_3$ Liquid flow out of degasser.

$\dot{m}_4$ Vapor flow upwards from feed.

$\dot{m}_5$ Liquid flow downwards from feed.

$\dot{m}_6$ Vapor flow up from packing.

$\dot{m}_7$ Liquid flow from cooling coils.

$\dot{m}_8$ Vapor flow from heaters.

$\dot{m}_9$ Liquid flow from packing.

M Molecular mass.

NC Neutral Current neutrino reaction.

pp Proton-Proton fusion chain.

PMT Photomultiplier tube.

P_1 Pressure below packing.

P_2 Pressure above packing.

P_3 Pressure after orifice plate.

ΔP Pressure differential across the orifice plate.

P_G Pressure in the degasser.

P_x Partial pressure of gas x .

PSUP Physical support structure for the photomultiplier tubes.

$\dot{q}_1$ Power added by heaters.

$\dot{q}_2$ Power removed by coolant.

RO Reverse-osmosis unit.

SNO Sudbury Neutrino Observatory.

SNP Solar Neutrino Problem.

SSM Standard Solar Model.

T_1 Temperature 1.

T_2 Temperature 2.

T_3 Temperature 3.

T_4 Temperature 4.

T_7 Coolant intake temperature.

T_8 Coolant exhaust temperature.

UV Ultra-violet sterilizers.

V Volume of the degasser.

V_G Volume of gas inside the degasser.

X_x mole fraction of the gas x dissolved in the liquid (Henry's law).

z coordinate perpendicular to liquid-gas phase interface

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PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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PRECISIONSM RESOLUTION TARGETS

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