DESIGN AND IMPLEMENTATION OF AN AUTOMATED GAMMA PROBE FOR JET BORING URANIUM MINING

by

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THE UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

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Abstract

A proof-of-concept detector prototype capable of collecting and storing radiometric data in Jet Boring System (JBS) pilot holes at the Cigar Lake uranium mine is presented. Variant design is used to design, develop, test and implement the detector’s hardware, firmware and software. The battery powered detector is attached inside a JBS drill rod to collect radiometric data through the drilling cycle. A readout box is used to initiate the detector, recharge the battery and download radiometric data after a pilot hole drilling cycle is complete.

Functional testing results are presented and comparative test results between the JBS gamma probe and the AlphaNUCLEAR Hi-Flux probe are evaluated. Field data collected from three pilot holes is plotted against each pilot hole’s driving layout and jetting recipe. Future work is discussed for use of Monte Carlo modelling and a high activity source to characterize the JBS gamma probe and achieve conversion of gamma counts into $U_3O_8$ grade.

Cigar Lake is the second highest known grade uranium mine in the world. The mine is located in northern Saskatchewan, Canada. Project engineers during the 2000 JBS proof-of-concept tests suggested that jetting parameters for extracting cavities at full production may be more effective if selected based on gamma logs and experience from adjacent cavities instead of using pre-set recipes and interim surveys during jetting. Moreover, in-situ pilot hole radiometric data may also be useful for grade control and grade reconciliation from a cavity-to-cavity basis. At present, there is no method available to efficiently and effectively obtain gamma logs from pilot holes, this project is a major first step to address this issue.
Dedication

In memory of my late mother Nadyisaba Marie Consolate.
Acknowledgements

A thousand times thank you to my advisor Scott Nokleby without whom this project would not have been possible. Thank you to Andre Boucher for his guidance and giving me a place to work in the alphaNUCLEAR lab. Thank you to Terry Onda, Brody Mykytyzyn, Derrick Harper and Baomin Qiao for help populating circuit boards, brainstorming ideas and fabricating hardware. Thank you to Tyler Mathieson for the opportunity to experiment with high activity sources and for his work developing the Monte Carlo Uranium Equivalence Scheme (MCUES) which is the best candidate for characterizing high flux gamma probes. Thank you to Cliff Revering and Lloyd Rowson for their help defining customer requirements and discussing project needs. Thank you to Vince Marshall, Mark Georget and the JBS crew for help fabricating the probe bracket, modifying an old JBS drill rod, setting up field tests and carrying out troubleshooting. Thank you to Michael Bonnell, Adam Gobeil, Carolyn Ingram, Kelsey McKee, Murray Dunn, Stephanie Mawson, Rachel Major and Bradley Harris for their support during the project. Thank you to Scott Bishop, Noel Voykin, Mike Murchie, Ghislain Jouband and Imre Bartha for backing the project and helping me receive the Natural Science and Engineering Research Council of Canada (NSERC) Industrial Partnership Scholarship to fund my studies.
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Chapter 1

Introduction

1.1 Thesis Objective

A proof-of-concept for an automated radiometric probe to determine $U_3O_8$ grade in Jet Boring System (JBS) pilot holes at the Cigar Lake uranium mine with no cycle time impact is presented. Data collected from each pilot hole will be used for grade reconciliation on a cavity-per-cavity basis and to augment the current geological model for increased forecasting ability. Detector characterization will be required for conversion of radiation counts to equivalent $U_3O_8$ grade. This project was identified during Professor Scott Nokleby’s site visit at Cigar Lake in 2012 as a collaboration between the University of Ontario Institute of Technologies (UOIT) and Cameco Corporation, henceforth referred to as Cameco. Gamma flux in JBS pilot holes was originally collected in the four ore test holes excavated during the 2000 JBS testing. Each pilot was logged manually at 10 cm intervals with gamma counts integrated over a 10 s period and total counts standardized to 50 cm length samples to determine equivalent $U_3O_8$ grades using a high flux probe [1].

In 2011, Cameco initiated a request for proposals for a project with the primary objective of determining uranium grade boundaries within the host rock and a secondary
Objective of accurately logging the entire ore zone for equivalent $U_3O_8$ grades. Unfortunately, funding was cut shortly after the proposal was finalized and the project got shelved. Cameco is working on preliminary plans to implement physical assaying sampling downstream from the pilot hole for deleterious elements concentration characterization and determining average grades per cavity. The penetrative nature of gamma radiation makes it possible to sample rock masses larger than the drill hole itself; leading to a more accurate uranium content characterization and yielding much faster results than chemical assaying [2]. Moreover, an automated radiometric data acquisition system has applications at other Cameco mining operations such as McArthur River where it can collect in-situ data for grade control on a raise-by-raise basis. The automated system acquires data from a fixed position within a drill rod and therefore does not suffer from the same limitations associated with manual logging from within drill rods where the steel attenuation changes with variations in cross-section at the drill rod threads.

Cigar Lake is the second highest known grade uranium mine in the world, over 100 times the world’s average for uranium deposits. The mine has 108.4 million pounds $U_3O_8$ proven and probable reserves at an average grade of 18.3% [3]. The mine is owned by Cameco (50.025%), AREVA Resources Canada Inc. (AREVA) (37.1%), Idemitsu Canada Resources Ltd. (Idemitsu) (7.875%), and TEPCO Resources Inc. (TEPCO) (5.0%). The mine site is operated by Cameco as the majority shareholder. The mine is located approximately 660 km north of Saskatoon as depicted in Figure 1.1.

1.2 Format of Thesis

The next chapter provides an introduction to the Cigar Lake mine, an overview of the JBS and the motivation for the project.
Chapter 3 reviews the project needs and specifications. The project mission statement is defined as well as customer needs and product design specifications. A functional decomposition is presented to divide the JBS gamma probe in simpler subsystems. In Chapter 4, secular equilibrium, Z-effect and dead time are reviewed in the radiation interaction with matter section. Gas-filled detectors, scintillation detectors and semiconductor detectors are reviewed in the radiation measurement technologies section. Commercial probe examples are provided for each type of detector.

In Chapter 5, concept generation for each subsystem is presented and concept scoring matrices are compiled. A morphological table is presented at the end of the chapter to show the selected design option for each subsystem.

In Chapter 6, the JBS gamma probe implementation is summarized. Details are provided on the construction and design of the detector’s circuit board hardware, firmware and software. Form generation is reviewed for the detector box design, readout box design and the connection termination module. Finally, the configuration
for the Cigar Lake alpha test is presented. In Chapter 7, prototype functional tests are summarized and laboratory testing results conducted before the Cigar Lake in-situ test are presented. Lab testing was conducted on an 81 kBq and a 15 MBq natural uranium source. The chapter concludes with a discussion on the results.

Chapter 8 presents results from the JBS pilot hole field testing from cavities 765_025_E_CV, 765_030_E_CV and 765_030_B_CV. The water damage failure of the first pilot hole test, in 781_021_A_CV, is reviewed along with the design improvements it engendered. Numerical modelling options using Monte Carlo Equivalence Scheme (MCUES) is proposed for conversion of detector counts to equivalent $U_3O_8$ grade.

Finally, Chapter 9 summarizes the results and provides conclusions. Future refinement and development options for the JBS gamma probe are proposed. Development of wireless technologies is proposed to increase the capabilities of the gamma detector with live readings.
Chapter 2

Cigar Lake Mine

2.1 Background

Cigar Lake is a tabular unconformity style deposit 1,950 m long situated between 410 and 450 m below surface. The orebody thickness varies between 0.4 m and 13.5 m with average thickness of 5.4 m. Known mineralization is divided into Phase 1, east of mine 10405 E (mine coordinates) and Phase 2 west of 10405 E. The Phase 1/Phase 2 mineral resource and reserve estimates are based on 310 mineralized drill holes. The only economical portion of the Cigar Lake orebody is the high grade mineralization at the unconformity. The cut-off grade used for defining the limits of the mineralization of the model is 1.0% $U_3O_8$ at a 1 m minimum thickness vertically and 0.1% $U_3O_8$ horizontally. It was proven using uranium decay series measurements that bulk dissolution of uranium is not occurring and that the unconformity mineralization exists at equilibrium. $^{235}U$ isotope ratio is determined to be the naturally occurring value of 0.71% [3].

In 2011, Cameco’s Mineral Resource Management (MRM) department developed conversion coefficients for determining percentage $U_3O_8$ grade using assays and bore-
hole radiometric data. The deposit is in secular equilibrium as proven by the correlation between borehole gamma log uranium grade estimates and chemical assay results. The mineral resource and mineral reserve geological interpretation model is the basis for the JBS cavity grades estimates and contains a combination of chemically assayed drill holes and borehole radiometric data as shown in Figure 2.1 [4].

![Figure 2.1: Cigar Lake Mine Orebody Grades](image)

### 2.2 Mining Method

The Jet Boring System (JBS) is a new mining method specifically developed for the Cigar Lake deposit. It is a non-entry mining method capable of adequately tackling challenges associated with ground water control, weak to heavily altered rock formations, radiation control and water inflow [3]. The JBS mining method consists of extracting cavities in previously frozen ore, approximately 4.5 m in diameter, with a 15,000 PSI high pressure water jet. Each cavity produces approximately 230 t of ore.
for a typical 6.0 m ore thickness as depicted in Figure 2.2. The Cigar Lake orebody is highly altered with a high clay content therefore the ground must be frozen prior to mining to eliminate risks due to water inflow from the saturated sandstone above the deposit and to increase ground competency. The frozen ground criteria for any cavity is:

- Minimum of 10 m frozen ground cap above the cavity;
- Minimum of 5 m of frozen ground at -10 °C, or
- 10 m of frozen ground at -5 °C in all directions horizontally around the cavity.

Figure 2.2: Cigar Lake Jet Boring Mining General Arrangement [3]

Figure 2.3 shows the cavities extracted from the 465 level during the 2000 JBS proof of concept test. During the 2000 JBS proof of concept test, the production tunnels were on 465 L; in 2006 this level was abandoned and backfilled due to water inflow and all production tunnels had to be planned from the 480 L [3]. This change adds extra distance and steeper angles to each pilot hole.
2.2.1 Jet Boring Mining Method

The JBS mining machine is a five car train as shown in Figure 2.4. The shuttle car transfers materials between the tunnel entrance and the rod car. This distance can reach up to 140 m when the JBS is positioned on a cavity at the south end of a production tunnel. There are two rod cars that store and deliver pilot hole drill rods, jet rods and backfill pipes to the drill car. This transfer is accomplished using mechanized chains capable of bringing the cassettes to the drill car’s loading position. Loading each 456.2 lbs, 1 m long, drill rods from the loading position to the hydraulic drill rod handler is done with an electromagnetic crane. The drill car
houses a powerful hydraulic drill, hydraulic stabilizers and the preventer assembly that controls dust while drilling and directs cuttings to the slurry car. The slurry car has a large container in which drill cutting and slurry are stored. The contents of the slurry car are pumped to the Run-Of-Mine (ROMs) holding tanks before going though the underground grinding circuit.

The cavities are jetted with a rotating 15,000 PSI water jet from the nozzle sub that pulverizes the ore [1]. The ore cuttings mix with water to create a slurry that is directed out of the cavity through a blade screen and travels between the jet rod outer pipe and the pilot hole casing at a rate of 2,500 l/min. The jet string tools are depicted in Figure 2.5.

Jet boring consists of a series of four main steps:

1. Drilling of pilot hole;
Figure 2.5: JBS Jet String Assembly [1]

2. Deployment of jet string in cased pilot;

3. Start jetting cycle; and

4. Scan and backfill final cavity.

The pilot hole drilling cycle starts with drilling a 16\(\frac{1}{2}\) in primary hole to install a primary casing insert that attaches to a preventer. The rest of the pilot hole is drilled with a 14\(\frac{3}{4}\) in tri-cone drill bit as depicted in Figure 2.6 and the hole is surveyed with a gyroscope [5].

Next in the cycle is to install fibreglass casing in the ore zone and threaded steel casing in the waste rock. In the 2000 tests, gamma probing was completed at this stage by pushing the probe with an aluminium rod inside the cased hole with a stabilizer to keep the probe centred.

Before a cavity can be extracted, the jet rods are inserted in the cased pilot hole as depicted in Figure 2.7 and the jetting sequence is initiated following a jetting recipe.
Figure 2.6: Pilot Hole Drilling [5]
that details the jetting duration and number of high pressure pumps to use at 10 cm intervals.

Figure 2.7: Jetting Rods in Position in Previously Cased Pilot Hole [5]

12
Once jetting is complete, the jet rods are removed and replaced by backfill rods. A three dimensional laser cavity scan is conducted before backfilling begins as depicted in Figure 2.8. The results from the scan provide the shape and dimensions of the cavity. These scans are used to determine backfill volume requirements, cavity reconciliation and to design neighbouring cavities [5].

Figure 2.8: 3D Laser Scan and Backfill After Cavity Completion [5]
2.2.2 Project Motivation

Despite the fact that Cameco has successfully demonstrated the JBS mining method in 2000, the method has not been proven at full production [3]. Uranium grades at the Cigar Lake mine are extremely variable and have been found to range from hundreds of ppm to more than 80% $U_3O_8$ over a standard sample width [4]. Metallurgical test work has been completed on samples collected during exploration and delineation. However, it is possible that the samples may not be representative of the deposit as a whole [3]. Additional sampling and metallurgical test work will be required to verify the consistency of recoveries at the mill and to address the potential impacts of ore variability.

The automated JBS radiometric probe described in this thesis will be a key candidate for an investigative tool for reconciliation and analysis. Sampling information from every pilot hole collected by the JBS gamma probe will be a major first step to help bridge this gap.
Chapter 3

Project Needs and Specifications

3.1 Project Planning

3.1.1 Opportunity Identification

As mentioned in Chapter 1, the gamma logs collected on the four ore cavities excavated in 2000 were used to determine equivalent ore grades for the cavity. Figure 3.1 shows the gamma log drawing produced from ore cavity #1 excavated in September 2000. The project engineers on the JBS test suggested that jetting parameters for cavities at full production would be more effective if selected based on gamma logs and experience from adjacent cavities instead of a pre-set jetting recipes or interim surveys [1]. However, at present, there is no method available to efficiently and effectively obtain gamma logs from pilot hole drilling.

 Cameco’s 2011 request for proposals sent to alphaNUCLEAR requesting development of radiometric scanning equipment, software and a tool for use in the JBS drill rods annulus did not proceed due to a lack of funding. When production commissioning started in December 2013, gamma logs were not part of the JBS cycle because they are time consuming to perform and no appropriate tools were available.

Cigar Lake relies heavily on the geological model for estimating cavity grade and even
though this model is accurate, coupling it with in-situ data would provide an increased level of confidence and grade control in outgoing slurry shipments.

The value of this project is the ability to collect accurate in-situ radiometric data from the pilot hole of each cavity without adding to the cycle time. This radiometric information is particularly important for Cigar Lake due to the complex and discontinuous nature of the orebody. Radiometric data is useful for refining the jetting recipe, grade control and grade reconciliation on a cavity-by-cavity basis.

![Diagram of Cavity #1 Gamma Logs](image1.png)

**Figure 3.1: 2000 JBS Test: Cavity #1 Gamma Logs [1]**

### 3.1.2 Mission Statement

The mission statement for the JBS gamma probe project, summarized in Table 3.1, was subdivided into product description, benefit proposition and assumptions [6].
Table 3.1: JBS Gamma Probe Mission Statement

<table>
<thead>
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<th>Mission Statement: JBS Gamma Probe</th>
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<tr>
<td><strong>Product Description</strong></td>
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<tr>
<td><strong>Benefit Proposition</strong></td>
</tr>
<tr>
<td><strong>Assumptions</strong></td>
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3.2 Costumer Need Identification

3.2.1 Costumer Needs Lists Identification and Weighting

Project needs were identified in collaboration with the Chief Mine Geologist and the Mine Superintendent to represent the interests of the geology department and mine operations. Ten design needs were identified and listed in Table 3.2 with corresponding 1-3-5 weighting where 1 is least important to the customer and 5 is most important.

3.3 Product Specifications

Project specifications targets and marginal values were determined in collaboration with the Manager of AlphaNUCLEAR based on the project needs identified in Table 3.2. The project specifications are summarized in Table 3.3.
Table 3.2: Project Needs List

<table>
<thead>
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<th>Need. ID</th>
<th>Need</th>
<th>Imp.</th>
</tr>
</thead>
<tbody>
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<td>N1</td>
<td>JBS Gamma Probe can be used to determine $U_3O_8$ grade in the ore zone</td>
<td>5</td>
</tr>
<tr>
<td>N2</td>
<td>JBS Gamma Probe operates normally in the JBS pilot hole rough environment</td>
<td>3</td>
</tr>
<tr>
<td>N3</td>
<td>JBS Gamma Probe sustains power through the full pilot hole drilling cycle</td>
<td>5</td>
</tr>
<tr>
<td>N4</td>
<td>JBS Gamma Probe can be checked for calibration before use</td>
<td>3</td>
</tr>
<tr>
<td>N5</td>
<td>JBS Gamma Probe has no impact on cycle time</td>
<td>5</td>
</tr>
<tr>
<td>N6</td>
<td>JBS Gamma Probe can be maintained and supported in-house through alphaNUCLEAR</td>
<td>5</td>
</tr>
<tr>
<td>N7</td>
<td>JBS Gamma Probe data can be retrieved from the device</td>
<td>5</td>
</tr>
<tr>
<td>N8</td>
<td>JBS Gamma Probe assembly can be mounted in the JBS pilot hole drill rod</td>
<td>5</td>
</tr>
<tr>
<td>N9</td>
<td>JBS Gamma Probe device is in compliance with Cameco’s safety, health, environment and quality (SHEQ) standards</td>
<td>5</td>
</tr>
<tr>
<td>N10</td>
<td>JBS Gamma Probe is easy to deploy and initialize</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 3.3: Project Specifications List

<table>
<thead>
<tr>
<th>Spec. ID</th>
<th>Need IDs</th>
<th>Metric</th>
<th>Imp.</th>
<th>Units</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>N1 N4 N7</td>
<td>Report gamma flux measurement in cps</td>
<td>5</td>
<td>Binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>S2</td>
<td>N1</td>
<td>Maximum $U_3O_8$ grade detection</td>
<td>3</td>
<td>%</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>S3</td>
<td>N1</td>
<td>Dead time</td>
<td>3</td>
<td>$\mu$s</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>S4</td>
<td>N1</td>
<td>Recovery time</td>
<td>3</td>
<td>$\mu$s</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>S5</td>
<td>N1</td>
<td>Low amplitude noise pulse rejection</td>
<td>3</td>
<td>mV</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>S6</td>
<td>N1</td>
<td>Pulse rise time</td>
<td>5</td>
<td>$\mu$s</td>
<td>5</td>
<td>.5</td>
</tr>
<tr>
<td>S7</td>
<td>N2</td>
<td>Temperature range</td>
<td>5</td>
<td>°C</td>
<td>-20 to 60</td>
<td>-30 to 60</td>
</tr>
<tr>
<td>S8</td>
<td>N1</td>
<td>Time-keeping slip</td>
<td>5</td>
<td>s/mth</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>S10</td>
<td>N4 N9 N10</td>
<td>User inputs for detector</td>
<td>1</td>
<td>Inputs</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>S11</td>
<td>N3</td>
<td>On-board power duration</td>
<td>5</td>
<td>hrs</td>
<td>48</td>
<td>72</td>
</tr>
<tr>
<td>S12</td>
<td>N7</td>
<td>Universal Serial Bus connectivity</td>
<td>5</td>
<td>Binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>S13</td>
<td>N9 N10</td>
<td>Modular controls</td>
<td>5</td>
<td>Binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>S14</td>
<td>N7</td>
<td>Gamma probe data retrieval</td>
<td>5</td>
<td>Inputs</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>S15</td>
<td>N1 N10</td>
<td>Time synchronization error with computer</td>
<td>3</td>
<td>s</td>
<td>± 2</td>
<td>0</td>
</tr>
<tr>
<td>S16</td>
<td>N2 N8</td>
<td>Probe form factor fits in drill rod</td>
<td>5</td>
<td>Binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>S17</td>
<td>N3 N5</td>
<td>Power consumption</td>
<td>5</td>
<td>mAh</td>
<td>1000</td>
<td>≤100</td>
</tr>
<tr>
<td>S18</td>
<td>N6</td>
<td>Use of standard components</td>
<td>3</td>
<td>%</td>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>S19</td>
<td>N2</td>
<td>Ingress progression rating</td>
<td>5</td>
<td>IP</td>
<td>67</td>
<td>68</td>
</tr>
<tr>
<td>S20</td>
<td>N1</td>
<td>Synchronization error with JBS rod position</td>
<td>5</td>
<td>cm</td>
<td>100</td>
<td>5</td>
</tr>
</tbody>
</table>
3.4 Technical Feasibility

Before starting the project, an experiment was conducted to verify that orebody radiation could be picked up from inside a JBS pilot hole drill rod. The testing, as depicted in Figure 3.2, was conducted on Cigar Lake ore in containment barrels using a standard AlphaNUCLEAR Hi-Flux gamma probe SN# : AN03 and an Automess detector for cross-comparison with gamma results. Results indicated that there was sufficient sensitivity and the project could move on to the development stage [7].

![Figure 3.2: Experimental Setup for Gamma Detection from JBS Drill Rod Annulus](image)

3.5 Functional Decomposition

The functional decomposition flowchart in Figure 3.3 simplifies the JBS gamma probe problem into smaller subsystems with respect to flow of energy, materials and information [8].
Figure 3.3: JBS Pilot Hole Gamma Probe Functional Decomposition Diagram
Chapter 4

Literature Review - Radiometric Measurements Methods

4.1 Radiation Measurement

This section is a literature review on radiation interaction with matter, radiometric measurement technologies and other considerations to designing the JBS radiometric probe such as equilibrium, Z-effect and dead time.

4.1.1 Radiation Interaction with Matter

Radiation energy exists as waves or particle streams occurring over a large spectrum divided into ionizing and non-ionizing radiation as shown in Figure 4.1. This thesis will only concentrate on ionizing radiation; the portion of the spectrum carrying enough energy to result in radiolysis and the creation of free radicals. Beta and gamma decays will be the focus of the section with a short overview on neutrons.

Beta radiation results from quark transformation in which a neutron’s down quark transforms into an up quark via weak interaction [10]. The result is a proton and emission of a positron and neutrino pair or emission of an electron and antineutrino
pair. Radiation decay has to interact with matter in order to be detected. Beta radiation interaction with matter mainly consists of inelastic collisions between positrons and electrons resulting in electronic excitation and ionization [10]. Pair production is the interaction between a positron and an electron which causes annihilation of both the electron and positron and creates two photons with identical energy quanta of 511 keV, emitted in opposite directions.

Photon radiation is classified as X-ray when originating outside the nucleus and gamma ray when originating from the nucleus. High-speed charged particles from nuclear scattering passing through a medium can also emit continuous electromagnetic energy in the range of X-rays called Bremsstrahlung [11].

Gamma rays can interact with matter by transferring energy to an atomic electron, ejecting it from the atom with energy equal of the gamma ray minus the binding energy $E_b$ as:
where $h$ is Planck’s constant of $6.626 \times 10^{-34}$ Js, $\nu$ is the electromagnetic wave frequency and $E_{e^{-}}$ is the ejected electron’s energy.

This is the photoelectric effect, first described by Einstein when describing the quantized nature of light. The majority of intermediate gamma energies interact with matter through Compton scattering which is the interaction between a gamma photon and an electron causing an increase in the electron’s energy. The electron’s energy after Compton scattering is characterized as a function of the scattering angle of the gamma ray $\theta$:

$$E_{e^{-}} = h\nu \left[ \alpha (1 - \cos \theta) \right] \left[ \frac{1}{1 + \left[ \alpha (1 - \cos \theta) \right]} \right];$$

where

$$\alpha = \frac{h\nu}{m_{0}c^2};$$

and $m_{0}c^2$ is the electron rest energy 0.511 MeV; and, $h\nu$ is the incoming photon energy.

Pair production is the process by which a photon enters matter with energy in excess of 1.022 MeV and is subjected to strong field effects when passing near a nucleus. The photon is annihilated through energy/mass conversion to produce an electron and a positron that share the energy of the gamma ray. If the positron is stationary, it will interact with an electron creating two gamma rays with energies of 511 keV each. The energy of the electron-positron pair resulting from pair production is:

$$E_{e^{+}} + E_{e^{-}} = h\nu - 1.022 \ (MeV)$$

where $E_{e^{+}}$ is the energy of the positron; $E_{e^{-}}$ is the energy of the electron; and, $h\nu$ is the photon energy.
Interaction probability of a photon $\mu$ can be calculated as a sum of the three possible interaction mechanisms as shown in Figure 4.2.

$$\mu = \kappa + \sigma + \tau \quad (4.5)$$

where $\tau$ is the photoelectric effect interaction probability; $\sigma$ is the Compton scattering interaction probability; and, $\kappa$ is the pair production interaction probability.

![Figure 4.2: Total Probability of Ionizing Radiation Interaction [10]](image)

### 4.1.2 Equilibrium

$^{238}U$ does not emit characteristic gamma rays used to measure its concentration, it is measured from its X-rays or indirectly from the gamma emission of its decay nuclide [4]. The important high-energy gamma emitters in the uranium series, $^{214}Pb$ and $^{214}Bi$, are decay products of radon. While these gamma rays are relatively intense and easy to measure, equilibrium must exist between the decay product and the parent uranium them for estimating uranium concentration.
4.1.3 $Z$-effect

Elements with high atomic number, $Z$, will absorb low energy photons due to the photoelectric effect and emit photoelectrons [12]. Uranium has a high atomic number, $Z=92$, and is self-shielding. That is, uranium will absorb a large portion of the low energy photons it emits [13]. This makes it challenging to accurately measure uranium at high concentrations.

Figure 4.3 shows the mass attenuation coefficients for lead [12] and Figures 4.4 and 4.5 show the mass attenuation plots for carbon and uranium, respectively. The difference in mass attenuation at low energies is considerable for uranium and lead compared to a lower $Z$ element such as carbon.

Figure 4.3: Mass Attenuation Coefficients for Lead ($Z=82$, $\rho = 11.35 \times 10^3 \text{ kg/m}^3$) [12]

In Figure 4.6, the $Z$-effect from uranium concentration follows a log function with the high end of the plot at 6% $U_3O_8$. Australian researcher Dickson indicated that grades
at Cameco mines can reach up to 60% $U_3O_8$ and that there are no calibration pits to perform $Z$-effect calibration for such high grades [13]. A new calibration method is proposed, the Monte Carlo Uranium Equivalence Scheme (MCUES) in which Monte Carlo modelling is coupled with measurements of a high activity source to characterize the behaviour of a high flux probe without requiring calibration pits [15].
Figure 4.5: Uranium Mass Attenuation Coefficients Where $\mu/\rho$ is the Mass Attenuation Coefficient, and $\mu_{en}/\rho$ is the Mass Energy-Absorption Coefficient [14]

Figure 4.6: Radiation Counts Versus Energy for Uranium Concentrations of 0.06% U, 0.6% U and 6% U versus background [16]
4.1.4 Dead Time

The dead time of a detector is the time during which a detector is insensitive to another incoming photon when processing a previous ionization event. This leads to an overall reduction of the true count in a high-count environment [17]. The equation for dead time for non-paralyzable systems is:

\[ N = \frac{M}{1 - tM} \] (4.6)

where \( N \) is the actual number of events, \( M \) is the recorded count and \( t \) is a unique dead time constant for each detector.

The dead time constant can be characterized by logging known high uranium concentration samples and iteratively finding a value for \( t \). The \( t \) value is calculated using a least-square fit or a second order polynomial to ensure that the correction does not incidentally include Z-effect in the correction [18]. Figure 4.7 illustrates the dead time and recovery time based on the discriminator level. Each ionization event causes the voltage to drop below the discriminator threshold. Dead time is the time elapsed before the detector is able to detect a second instance of radiation. Recovery time is the time elapsed before the detector produces a signal with high enough amplitude to create a count from the discriminator [19].

Detectors with relatively long dead times also experience pulse pile-up where two or more photons deposit their energies in the detector in a time shorter than the resolution of the system and the combined pulse induces a false reading [20]. This is particularly important when using a spectrometer. Pulse pile-up may cause counts to be discarded as noise and may decreases the overall peak intensities.
4.2 Radiation Measurement Technologies

4.2.1 Radiation Detectors Basics

Radiation detectors require high voltage power to operate, ranging from 100 V DC for surface barrier semiconductors to 4,500 V DC for hyper-pure germanium semiconductors [18]. A pre-amplifier is often needed to boost the signal from the detector by two or three orders of magnitude before it is used by the amplifier. The amplifier is sized to work with the maximum signal from the pre-amplifier to avoid data truncation. Pre-amplifiers can also be used with a gain of 1 for the main purpose of impedance matching with the amplifier. The detector assembly varies and may include accessories such as oscilloscopes, multichannel analysers, single channel analysers, scalers and timers [12].

In non-destructive assay (NDA) of nuclear materials there are three main types of detectors: gas filled detectors, scintillation detectors and semi-conductor detectors [2,13]. The detection resolution comparison provided in Figure 4.8 shows that scintillation
detectors have high detection efficiencies but poor resolution. Proportional gas filled detectors have a higher degree of precision and semiconductor detectors have the best detection resolution [12].

Figure 4.8: Gamma Detection Resolution Between \textit{NaI} Scintillation Detector, Gas Filled Proportional Detector and \textit{Si(Li)} Semiconductor Detector for Primary X-rays of Silver [21]

\section*{4.2.2 Gas Filled Detectors}

\subsection*{4.2.2.1 Background}

There are two types of gas filled detectors based on how the ionization events are reported. Integrating chambers, as shown in Figure 4.9, measure the current induced by the movement of electron-ion pairs under the influence of an electric field. Pulse chambers, as shown in Figure 4.10, use electronic pulse shaping to output a digital count.

The gas filled detectors work as follows [12]:

1. Ionizing radiation passing through the detector with high voltage potential transfers all or part of its energy to the gas to generate electron-ion pairs [18];
2. The detector produces a pulse, or reports a change in amperage, by measuring the current produced from movement of electron-ion pairs to the cathode and anode under the influence of an electric field.

4.2.2.2 Gas Filled Detectors High Voltage Regions

Theoretically, increasing the high voltage of any gas filled detector will yield five distinct regions with specific characteristics. Each type of gas filled detector is designed to work in a specific region. The five gas filled detector high voltage regions are depicted in Figure 4.11.

Region I in Figure 4.11 is the recombination region:

- Electrons and ions move too slowly and high instances of recombination occur. No sufficient charge can be collected. Gas molecules dissociated during radiolysis from incoming ionizing radiation will mostly recombine without causing a change...
in the detector voltage; and,

- No detectors can be made for this region.

Region II in Figure 4.11 is the ionization region:

- No recombination and no secondary ionization;

- Secondary ionization occurs when primary ionization acquires sufficiently high kinematic energy to create further ionization [12]; and,

- Ionization chamber detectors measure the energies from strongly ionized particles such as alphas, protons and fission particles.

Region III in Figure 4.11 is the proportional region:

- Increased secondary ionization; and,

- Proportional counters measure the energy from any charged particle.

Region IV in Figure 4.11 is the Geiger Müller (GM) region:
• A single electron pair generates a chain reaction detected as a distinct pulse;

• The shape of the signal is only dependent on the electronics of the detector, Typically at TTL levels, and cannot provide energy discrimination [22];

• GM counters produce a signal large enough to detect without using a pre-amplifier [12];

• GM detectors are less complex and more rugged than any other gas-filled detectors; and,

• The trade-off for this simplicity is a long dead-time of 200-300 ms [23].

Region V in Figure 4.11 is the self-sustaining ionization region:

• Electric field is too high and a single ionization start a self-sustaining chain reaction;

• No gas filled detectors can operate in this region; and,

• Any ionization event saturates the instrument causing an infinite dead time.

Gas filled detectors are manufactured in three different geometries: parallel plate, cylindrical, and spherical as represented in Table 4.1.

4.2.2.3 High Voltage Plateau

As can be seen in Figure 4.12, a detector’s count rate increases as the pulse height rises. Once the pulse height goes above the discriminator level, the counting rate increases with the pulse height between $V_A$ and $V_B$. However, between $V_B$ and $V_C$, the height of the pulses increases but the pulse count does not. This is the high voltage plateau in which a detector is operated to output stable counts despite inevitable small changes
<table>
<thead>
<tr>
<th>Gas-filled detector geometry</th>
<th>![Parallel plate diagram]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel plate</td>
<td>$V = 0$</td>
</tr>
<tr>
<td></td>
<td>$V = V_e$</td>
</tr>
<tr>
<td>![Cylindrical diagram]</td>
<td>$V = V_e$</td>
</tr>
<tr>
<td>Cylindrical</td>
<td></td>
</tr>
<tr>
<td>![Spherical diagram]</td>
<td>$V = V_e$</td>
</tr>
<tr>
<td>Spherical</td>
<td></td>
</tr>
</tbody>
</table>
in voltage. Above $V_C$, the voltage level is too high and no detectors operate in this region.

The high voltage plateau slope is defined as:

$$\text{Plateau slope} = \frac{\Delta r / r}{\Delta V}$$  \hspace{1cm} (4.7)

where $r / r$ is the relative change of the counting rate $r$ for the corresponding change in voltage.

There will always be a slight positive slope associated with the high voltage plateau and its slope contributes to increased efficiency in proportional detectors and false counts for GM counters [12].

### 4.2.2.4 Commercial Probe Example

AlphaNUCLEAR manufactures the Hi-Flux probe with two LND$^{TM}$ detectors equivalent to ZP 1320 Geiger Müller (GM) counters coupled to an anti-coincidence circuitry
capable of detecting uranium ore grades from 0.1% to 70% $U_3O_8$ [24]. This probe has many advantages due to its miniature high voltage power supply capable of supplying 500-600 $V_{DC}$ reliably and without large thermal emissions unlike the cascading diode power supply from competitor companies such as Mount Sopris.

The ANHF gamma probes can be seen in Figure 4.13; specifications are as follows [24]:

- Two $ZP\, 1320$ GM counters;
  Halogen quenched GM probes;
  Able to detect ore grades between 0.1% and 70%;
  Able to register a maximum of 40,000 $CPS$;

- Dead time of 20 $\mu s$;

- Able to operate from -40 $^\circ C$ up to +65 $^\circ C$;

- Housing pressures of up to 150 Bar; and,

- Maximum cable length of 1,500 m.
Figure 4.13: AlphaNUCLEAR hi-Flux Gamma Probe [24]
4.2.3 Scintillation Detectors

4.2.3.1 Background

There are three categories of scintillation detectors: inorganic, organic and plastic. Scintillators were discovered in 1903 by William Crookes, the first person to note that alpha particles leave imprints on a zinc sulphide film [18]. Scintillations are small emissions of visible photons caused by interaction of the crystal structure with ionizing radiation. At its onset, scintillation was time consuming, ineffective and contained a great amount of human error. Scintillation has had a pseudo renaissance with the rise of electronics since computers allow real-time readings, no human error and an increase in precision [18]. An overview of the assembly is depicted in Figure 4.14.

![Diagram of a scintillation detector](image)

Figure 4.14: Diagram of a scintillation detector [12]

4.2.3.2 Scintillation Detector Photomultiplier Tube

The photomultiplier tube, or phototube, may multiply photons emitted by a scintillator by a factor of $10^6$ [18]. If a scintillation probe is chosen for the JBS gamma probe, it must be appropriately matched to the right phototube. Each phototube works optimally at discrete wavelength ranges. The two most commonly utilized photocathode materials are cesium-antimony ($Cs - Sb$) and silver-magnesium ($Ag - Mg$) [12].

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Cs – Sb has a maximum sensitivity of 440 ηm and are adequate for NaI(Tl) scintillators with a maximum wavelength in 410 ηm but will not capture all the scintillations from a CsI(Tl) crystal with a maximum wavelength of 565 ηm [12].

4.2.3.3 Working Principle

Scintillators work by excitation and de-excitation of electrons moving from the valence and conduction energy bands in a crystal. Similarly to the discrete electronic energy states of an atom, a crystal has discrete energy bands as represented in Figure 4.19. Electrons may only occupy allowable discrete bands as well as free electronic bands of the activator.

Figure 4.15: Discrete Energy Bands in Typical Scintillator [12]

In Figure 4.19, the valence band is completely occupied and the conduction band is empty at ground state. Given enough energy, electrons may move from the valence band to the conduction band separated by an energy difference in the order of 8 eV [18]. If the electron is not given quite enough energy, it will rise up to the exciton state below the conduction band. This electron remains electrostatically bound to the unoccupied electron space in the valence band, or hole. This electron-hole pair
is an exciton. The exciton band is the energy state higher than the valance band that spans an energy band of approximately 1 eV directly below the conduction band [12]. Doped crystals scintillators have more energy bands between the valence and conduction bands. Thallium energy state changes are in the order of $10^{-8}$ s and release photons of known energies.

4.2.3.4 Inorganic Scintillators

Inorganic scintillators are typically alkali metal crystals doped with small concentrations of impurities. Common crystal are $NaI(Tl)$, $CsI(Tl)$ and $CaI(No)$ where the element in parentheses is the activator or impurity [12]. In $NaI(Tl)$, discovered by Hofstatder in 1948, the crystal only contains $10^{-3}$ of Thallium on a per mole basis but this element is responsible for the majority of the scintillation emitted.

4.2.3.5 Organic Scintillators

Organic scintillators are aromatic compounds mostly consisting of benzenoid rings as solvents or solutes. Organic scintillators may contain nitrogen and oxygen groups, usually for secondary solvents. Their photon production is due to molecular transitions. They can also be made into plastic scintillators using the right combination of solvents and solutes [12]. This class of scintillators is not elaborated any further since they are not typically used for uranium detection and because they are ill-suited for the mining industry due to their high susceptibility to mechanical and thermal shock.

4.2.3.6 Commercial Probe Example

Terraplus manufactures the $2GHF - 1000$, a probe represented in Figure 4.16 designed and marketed directly for uranium exploration. This radiometric probe utilizes a gas filled GM probe as well as a 3800 $NaI$ crystal scintillator. The features of $2GHF - 1000$ are as follows [25]:

41
• Utilizes a 3800 NaI crystal scintillator and two Geiger Müller probes ZP 1320 and ZP 1200;

• Operation temperature -10 °C to +50 °C; and,

• Able to detect ore grades between .01% and 20% $U_3O_8$.

Figure 4.16: Terraplus’s 2GHF-1000 Probe Section [25]

4.2.4 Semiconductor Detectors

4.2.4.1 Background

The working principle of semiconductor detectors is comparable to gas filled ionizing chambers with a few notable differences:

• Semiconductor detectors are solid-state devices;

• Higher density increases the instances of energy deposition from ionizing radiation particles making semiconductor detectors more sensitive [19];

• Current created in semiconductor detectors is caused by electrons-holes pairs instead of electron-ion pairs resulting in increases in processing speed and reduced dead time;

• Excitons move as fast as electrons as opposed to electron-ion pairs. In gas-filled detectors, electrons will reach the cathode before the ions have barely moved [12]; and,

• Semiconductor detectors have a superior energy resolution, no geometric limitations for detector shape, fast pulse rise time and insensitivity to magnetic fields [18].
Silicon and germanium are the most successful detectors but there are other compounds such as cadmium telluride ($CdTe$), cadmium zinc telluride ($CdZnTe$), cesium iodide ($CsI$), and mercuric iodine ($HgI_2$) that are gaining in popularity [12].

### 4.2.4.2 Semiconductors Characteristics

Semiconductors are materials that, for any current, do not allow electron movement when the temperature is close to absolute zero. Semiconductors allow a certain amount of electron movement as the temperature increases and become conductive to a certain degree. Electrons in solids may only exist in discrete bands as discussed earlier for crystals. In the solid depicted in Figure 4.19, electrons may only occupy bands 1, 2 and 5; bands 2 and 4 are forbidden.

![Figure 4.17: Discrete Energy Bands Allowed for Solids][12]

The probability $P(E)$ that a state of energy $E$ is occupied is defined as:

$$P(E) = \frac{1}{1 + e^{(E - E_f)/kT}} \quad (4.8)$$

where $k$ is the Boltzmann constant, $E_f$ is the Fermi energy, and $T$ is the Temperature in Kelvins.
If an electron acquires enough energy, $E_g$, it may jump from ground state to an excited state. The distribution of the electronic states is dictated by the Fermi distribution function, $P(E)$ in Equation (4.8) and illustrated in Figure 4.18. $P(E)$ is dependent on the temperature and the Fermi energy $E_f$ which relates to the purity of the solid.

The Fermi function is defined such that, at absolute zero, all energy states below $E_f$ are fully occupied and energy states above the Fermi energy cannot be occupied. At any other temperature, the probability density at an energy state equal to the Fermi energy are 0.5 as shown in Equations (4.9 - 4.11).

![Figure 4.18: Fermi Probability Density Function for Solids][12]

At $T=0$, the Fermi probability density function is:

$$ P(E) = 1 \quad E < E_f \quad (4.9) $$

$$ P(E) = 0 \quad E > E_f \quad (4.10) $$

At any $T$, the probability density at the Fermi energy is:

$$ P(E_f) = \frac{1}{2} \quad (4.11) $$

For $T > 0$, the function $P(E)$ extends beyond $E_f$. If $E - E_f > kT$, $P(E)$ takes the form:

$$ P(E) = \frac{1}{1 + e^{(E - E_f)/kT}} \quad (4.12) $$

$$ = \frac{1}{e^{(E - E_f)/kT} + 1} = e^{-(E - E_f)/kT} $$

$$ \exp\left(-\frac{E - E_f}{kT}\right) $$

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Figures 4.19 to 4.21 represent the difference between insulators, conductors and semiconductors, where $S(E)$ is the distribution of allowed electronic energy states and $N(E)$ is the distribution of occupied energy levels.

4.2.4.3 Semiconductor Compounds

Arsenic has five valence electrons but, when silicon is doped with arsenic, only four of the five valence electrons are required to form covalent bonds with surrounding silicon atoms. The fifth electron is loosely bound to the arsenic atom and requires very little energy to move to the excited state, introducing the donor level depicted in Figure
4.22.

Arsenic doping in silicon creates a donor level energy state whose conductivity is due to electrons, creating \( n \)-type semiconductors. Conversely, doping elements such as gallium only have three valence electrons but being more electronegative than silicon, attract one of the silicon’s valence electrons [12]. The electron may attach itself to the gallium leaving behind a hole very close to the valence energy band. Gallium becomes an acceptor atom and its conductivity is mainly due to holes. Semiconductor compounds made with acceptors are positively charged; \( p \)-type semiconductors.
4.2.4.4 Advantages and Limitations

The great advantage of semiconductor detectors is the low dead time since the electron-hole excitation/de-excitation cycle happens in the order of $10^{-12}$ s; four orders of magnitude faster than for scintillation detectors and six orders of magnitude faster than gas filled detectors [19]. Similarly to scintillating detectors, semiconductor detectors are doped with impurities that introduce donor or acceptor states. There are no intrinsic semiconductor detectors, made from one pure crystal, all detectors are extrinsic [26]. However, even if a detector starts off as a pure crystal, semiconductor detectors experience radiation damage in the crystal structure over time. The ionization radiation deposition impact may displace an atom and cause interstitial vacancy pairs know as Frenkel defects [12]. Recoiling atoms are also known to cause other atoms to shift in the crystal causing further Frenkel defects [12].

Semiconductor detectors experience shorter dead time and offer higher efficiencies comparative to gas-filled and scintillation detectors. However, they are less resilient in harsh environments and will loose performance over time due to Frenkel defects. The change in conductivity for a semiconductor is a function of the concentration of charge carriers and the mobility of electrons and holes which, in turn is dependent on temperature. Semiconductor detector’s temperature dependency disqualifies some
Figure 4.24: Interaction with Ionizing Radiation Raises Electrons to Conduction Bands in (a) and After a De-excitation in the Order of $10^{-12}$ s, in (b), Electrons Congregate at Upper Portion of Valence Band and Holes at Lower Portion of Conduction Band [12]

semiconductor detectors from the mining industry because they require liquid nitrogen cooling.

4.2.4.5 Working Principle

The exact process by which ionizing radiation transfers its energy to semiconductors is a complex process. The scientific community has not yet agreed on a single common model to describe it. Figure 4.24 shows a simplified explanation of one of the schools of thought. An energetic particle collides with an electron and transfers its energy. If this energy is sufficient, the electron leaves its valance band or other deeper electronic band and may rise to an excited energy state creating an exciton that is influenced by electric fields [19].

The energy needed to create electron-hole pairs must be larger or equal to the energy ($E_g$) required for an electron to cross the gap between the valance band and the conduction band for any element. Electron-hole pair creation energies and gap energies
will vary with respect to temperature.

When p and n type semiconductors are put in contact. Electrons will diffuse from the n-type semiconductor to the p type to fill all the holes and concurrently creating a disequilibrium in the overall charge of the two semiconductors [18]. A reverse bias is established by applying an external voltage with the positive pole on the n side and the negative pole on the p side. This makes movement of the electrons more difficult in towards to n-type semiconductor. In Figure 4.25, a p-n junction is illustrated in (a) with its associated voltage $v_o$ due to electron diffusion and depletion depth, $x_o$ along which there is an electric field. in (b), an external voltage $v_b$ is applied and the voltage across the p-n junction becomes $v_o + v_b$. This causes the electric field across $x_o$ to become significantly stronger and wider.

![Figure 4.25: P-n junction in (a) and p-n junction with reverse bias in (b) [12]](image)

Incoming radiation striking the detector at the p – n junction creates electron-hole pairs, which are promptly dissipated by the electric field $x_o$ causing a current that can be measured using a similar $RC$ circuit as for gas-filled detectors [12]. Capacitance $C$, is characterized by the following equation:

$$C = \frac{\varepsilon(a)}{4\pi \times x_o} \quad (4.13)$$
where $\epsilon$ is the dielectric constant of the material; and, $a$ is the surface area of the detector.

### 4.2.4.6 Commercial Probe Example

Canberra, part of the Areva Corporation family of companies, manufactures the *STHF – R* Ultra High Flux gamma probe as shown in Figure 4.26. This probe uses an energy compensated silicon diode semiconductor detector to detect high gamma dose-equivalent rates up to 1,000 $Sv/h$ [27]. The energy compensation consists of shielding that allows a flatter energy response over the spectrum of energies measured by the detector.

![Canberra’s STHF-R Gamma High Flux Detector](image)

**Figure 4.26: Canberra’s STHF-R Gamma High Flux Detector [27]**

The STHF-R high flux gamma probe has the following features [27]:

- Energy compensated silicon diode semiconductor detector;
• Measurement range of 1 $mSv/h$ to 1000 $mSv/h$. A separate conversion is required to change $mSv$ to grade;

• Sensitivity of 60 counts per $\mu Sv$;

• Cable reel up to 50 $m$;

• Dead time 45 $\eta s$;

• Operating temperature between -30 °C to +50 °C;

• Canberra also offers the $EM78468$ calibration/setup software for the probes; and,

• 40 hours battery life with a Radiagem system;

Concept generation and selection for the five subsystems of the JBS gamma probe are described in Chapter 5.

### 4.3 Existing Patents

A review of existing patents shows that there are several gamma radiation detector designs intended for measurement while drilling. The majority of the designs encountered are designed for the oil and gas industry. Halliburton Energy Services holds a patent on a gamma radiation detector for use while drilling that provides directional data but has to be installed in a non-rotating section of the drill rod [28].

US8803076 is a patent for gamma logging that presents a device with built in memory. However, the gamma logger requires connection to the gamma detector with a cable. The multiple gamma controller assembly is a data acquisition and processing system that can analyse gamma data from multiple boreholes but requires a physical input [29].
US 7253401 B2 presents a spectral gamma ray logging-while-drilling system for down-hole gamma ray detection. In this system, the detectors are embedded in the periphery of the drill bit to maximize sensitivity. There are no indications that the device would be suitable for the high flux environment present in the Cigar Lake mine ore-body. Moreover, this system requires pre-existing telemetry to transfer information to surface equipment for further processing [30].
Chapter 5

Concept Generation and Selection

5.1 Concept Generation

Concept generation for the JBS gamma detector starts with radiation detector selection since it drives the requirements for all other downstream systems. The concept classification tree in Figure 5.1 represents the detectors presented in the literature review and the grey circles represent hardware considered for inclusion in design selection. For brevity, no classification trees are presented for the other subsystems. An overview of the selected designs is presented before each concept scoring matrix.
Figure 5.1: Detector Classification Tree
5.1.1 Radiation Detector Concepts

Table 5.1 shows the scoring matrix for the radiation detector, associated scores and rankings. In each table, the datum design is identified and given a neutral score. Datum gets a multiplier of 3 for each of the applicable system specifications. Other designs are compared to the datum and receive a multiplier of 5 if they are better, 3 if they are the same and 1 if they are worse. The top two designs are considered for further development or combination. Refer to Table 3.3 in Section 3 for specifications metric descriptions.

Below are the designs evaluated for radiation detection concepts:

- The AlphaNUCLEAR Hi-Flux gamma probe is selected as datum for three reasons:

  1. The Hi-Flux probe is already in use at the Cigar Lake mine;
  2. Cameco owns AlphaNUCLEAR therefore engineering detailed drawings and technical information on this probe are readily available for this project; and,
  3. The Hi-Flux probe has high grade capabilities and an anti-coincidence circuitry [24].

- 2GHF-1000 probe also utilizes two ZP1320 GM counters and a 13 mm diameter by 28 mm long NaI scintillation probe coupled by an anti-coincidence circuitry that provides three gamma logs recorded simultaneously [31]. This arrangement provides very accurate readings at low grade with the scintillation detector and uses the ZP1320 to characterize high $U_3O_8$ concentrations where the NaI detector is normally saturated;

- The Canberra STHF-R Ultra High Flux gamma probe is a silicon diode semiconductor detector with data digitization occurring directly in the probe [27]. This
fully integrated instrument has the lowest dead time of all probes evaluated, the lowest power consumption and is capable of collecting spectral data;

- The 2SNA-1000-S DX series spectral gamma probe has a temperature compensated BGO detector for high energy gamma able to provide spectral data. This probe is part of the Mont Sopris DX series and can be coupled with many other accessories. The probe is rated to work from -40 °C to +70 °C [32]. Drill rods get magnetized during the pilot hole drilling cycle, this is expected to cause problems with scintillation probes. Magnetic fields will interact with the photomultiplier and may interfere with the photo tube, occasionally causing the detector to not register counts at all; and,

- The last detector evaluated is the Smart Gamma Probe by IMS. This probe is capable of fast accurate detection, built-in ability for historical data registration using a patented filtering algorithm and optional Bluetooth connectivity. The probe can be programmed using any PC or with the Android platform [33]. The detector is rated to work at temperatures from -25 °C to +50 °C, the enclosure is IP67 rated and the detector is only 3.54 inches long with a 1.26 inches diameter.
Table 5.1: Ionizing Radiation Detector: Concept Scoring Matrix

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<th>Spec. ID.</th>
<th>Rating</th>
<th>Weight</th>
<th>AlphaNuclear Hi-Flux (datum)</th>
<th>MountSopris 2GHF-1000</th>
<th>Canberra STHF-R</th>
<th>TerraPlus 2SNA-1000SB</th>
<th>IMS Bluetooth SGP</th>
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Total Score: 141, 95, 165, 123, 125
Rank: 2, 5, 1, 4, 3
Continue?: Yes, No, Yes, No, No
5.1.2 High Voltage Power Supply Concepts

- The datum for the high flux detector was the HVM ECHV0510. This regulated miniature high voltage DC to DC converter weighs 15 grams and is 1.8 inches long by 1.0 inches wide by 0.4 inches high. It is capable of converting 5 V DC input to 1,000 VDC output at 1 mA with an output ripple of less than 0.1% with an operating range from -55 °C to +70 °C [34];

- The hvBase-N was considered if a photo tube is required. It is a voltage divider for 10 stage photomultiplier tubes that outputs from 550 V DC up to 1,500 V DC from 3.3 to 5.5 V DC input. At 1,000 V DC the power supply draws 21 mA [35]. The biggest drawback of this power supply is that it is only rated to operate from 0 °C to +70 °C;

- The third high voltage power supply analysed is the HMA 0.5 W Series 0.6x0.8-5P capable of outputting 600 V DC at 0.8 mA with a typical ripple at <10 mVpp from an 4.5 to 5.5 V DC input [36]. The power supply measures 15.7 mm wide by 39.6 mm long and also operates from 0 °C to +40 °C;

- Next was the EMCO Q-Series Q06, a proportional high voltage power supply that can output up to 600 V DC at 0.833 mA with a ripple of 0.1% [37]. The power supply is a 0.5 inches cube and operates at temperatures ranging from -55 °C to +75 °C; and,

- The last power supply analysed was the Matsusada TR Series TR-0.7P, a temperature compensated high voltage power supply capable of supplying up to 700 V DC with a ripple of <20 mVpp from an 4.75 to 5.25 V DC input. The unit is 2 inches long by 1.4 inches wide by 0.6 inches high, weighs 60 grams and operates in temperatures ranging from -10 °C to +60 °C [38].

Table 5.2 shows the scoring matrix for the high voltage power supply.
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Table 5.2: High Voltage Power Supply: Concept Scoring Matrix
5.1.3 Controller Concepts

- The matrix logger was chosen as the datum because it is already used at the Cigar Lake mine for logging boreholes. Different systems were evaluated for their ability to integrate a remote gamma probe and it is assumed that the final control system will be developed using variant design. The matrix logger is manufactured by Mount Sopris and uses ultra fast high resolution converters to log detector counts. The logger requires a 60-240 V AC input and may be supplied up to 300 V DC at 500 mA [39]. Connection to a computer may be established via USB;

- The Udoo board was also explored as a novel alternative to traditional borehole loggers. The Udoo board is a mini PC that runs Android or Linux OS with an embedded Arduino board. The Udoo is based on the ARM iMX6 Freelance processor and the Arduino DUE ATMEAL SAM3X processor on a single board [40]. This board connects to other peripherals via USB, Ethernet and WiFi. The board uses a 6 to 15 V DC power supply and requires 3 W to operate without peripherals;

- The next board analysed was the AlphaNUCLEAR 597-PX3 logic board. This board is designed in-house by alphaNUCLEAR for the PRISM Alpha monitoring system and is an area monitoring device for radon progeny built for the rough underground mining environment. The board is powered by a 6 V DC battery and consumes 30mA without the microdiaphram air pump. The board is based on a PIC18F67J50 controller, has 2 GB internal memory and up to USB 3 connectivity [41]; and,

- The last controller analysed was the Beaglebone Black microboard. The board is based on a Sitara AM3359AZCZ100 processor and also has 2 GB onboard flash [42]. It is powered by 5 V DC, is compatible to USB, has HDMI output
and can connect to peripherals using Wifi and Bluetooth.

Table 5.3 shows the scoring matrix for the controller.

Table 5.3: Controller : Concept Scoring Matrix

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5.1.4 Battery Concepts

- The PowerSonic 6 V DC 7,000 mAh valve regulated acid lead battery was chosen as the datum because it is cheap and readily available for early testing. However, this battery has very low energy density and a long recharge time. The battery is 151 mm long by 94 mm wide by 100 mm high and weighs 1,100 grams. It operates at a temperature range from -40 °C to +60 °C [43];

- The second battery investigated was a NiMH battery pack. The pack is made of 1.2 V DC nominal voltage NiMH battery cells at 1,000 mAh [44]. These cells measure 30.0 mm diameter by 60.5 mm in height and can operate at temperatures from -20 °C to +50 °C;

- The VDC LiFePO$_4$ battery pack is made of LFP-26650-3300 cylindrical Lithium Iron Phosphate battery cells with nominal capacity of 3,300 mAh at 3.2 V DC and a discharge cutoff at 2.5 V DC [45]. The battery measures 26.1 ±0.11 mm diameter and 65.15 ±0.51 mm in height with operating temperatures from -20 °C to +60 °C; and,

- The LiNiMnCo battery pack is made from ICR26650C1 Lithium-ion battery cells with a 4,000 mAh nominal capacity, working voltage of 3.6 V and discharge cutoff at 3.0 V DC [46]. The battery measures 26.30 mm diameter and 65.8 mm height and is designed to operate at temperatures from -10 °C to +60 °C.

Table 5.4 shows the scoring matrix for the battery.
Table 5.4: Battery: Concept Scoring Matrix

<table>
<thead>
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<th>Spec Weight ID.</th>
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<th>Scaled Score</th>
<th>Rating</th>
<th>Scaled Score</th>
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</tbody>
</table>

**Rating**

▼ = 1
■ = 3 (Ref.)
▲ = 5

**Battery**

- **PowerSonic VRLA 6 V 7.0 Ah (datum)**
- **NiMH 6.0 V 10 Ah Battery pack**
- **LiFePO4 6.4 V 6.6 Ah Battery pack**
- **LiNiMnCo 7.2 V 8 Ah Battery pack**
5.1.5 Enclosure Concepts

- The Pentair EXE22012090, an IP66 rated box, was selected as the datum because it is manufactured by Haffman, a company highly recommended by the JBS project engineers. This enclosure is specifically made for hazardous environments with compression moulded, high-impact and high temperature fiberglass with added agents to prevent static charge build up. This box is 260 mm long by 160 mm wide by 90 mm high, has 6 internal mounting points and service temperature from $-50^\circ$C to $+100^\circ$C [47];

- The Bud Industries AN1322 is an IP66 rated box made of ADC12 aluminium alloy that is 200 mm long by 113.99 mm wide by 75 mm high [48]. This box also offers four convenient mounting points on the back of the box and 12 mounting points inside the box;

- The BOPLA 221306 ABS 70424 is an IP67 made of ABS plastic. The box measures 231 mm by 125 mm by with a height of 60 mm [49]. The enclosure operating temperature ranges from $-60^\circ$C to $+200^\circ$C when used with the Bopla silicon seal [50]; and,

- The last enclosure analyzed is the Hammond R190112-000 with captive stainless steel screws cover [51]. It is an IP67 box made from die-cast aluminium and is 200 mm long by 106.00 mm wide by 60 mm high.

Table 5.5 shows the scoring matrix for the enclosure.
Table 5.5: Enclosure: Concept Scoring Matrix

<table>
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<th>Spec Weight ID.</th>
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</tbody>
</table>

Rating ▼=1
■=3(Ref.)
▲=5
5.2 Concept Selection

Ideally, combining the AlphaNUCLEAR Hi-Flux Probe with the Canberra STHF-R probe would create a detector that can handle extremely high count environment and provide spectral information. This goal is unrealistic given the effort required to develop an entirely new detector and the time constraints of the project. Only one probe can be chosen to continue the design. The STHF-R is the superior probe as shown in the scoring matrix in Table 5.1. Unfortunately, no information on the probe was publicly available, the detectors are expensive and developing an entirely new circuit board for this application requires a lot of resources but lacks credibility to the customer when compared to using a commercially available design. Even though the STHF-R scored the highest, because of the reasons above, the AlphaNUCLEAR Hi-Flux probe was chosen for development for the following reasons:

- Very little information is publicly available on the STHF-R probe’s working principle;

- AlphaNUCLEAR expressed interest to be involved with the project and wanted to be able to fully support the JBS gamma probe final product. It was very unlikely that Canberra, owned by Cameco’s joint venture partner Areva would supply technical drawings and parts lists for their flagship product to a direct competitor; and,

- The Cigar Lake mine is already using the AlphaNUCLEAR Hi-Flux probe and the nature of the mining industry is very resistant to changes and technological leaps. Using the Hi-Flux probe would give the project better chances of integration while providing a level of accuracy that is already endorsed in the company.

With the AlphaNUCLEAR Hi-Flux probe in mind, the next challenge was to figure out a high voltage power supply. The EMCO Q06 power supply was chosen because
of its quality as outlined in the concept selection matrix and because it was currently use with the AlphaNUCLEAR probes.

The next step after selecting the radiation detector was selecting a compatible controller. The AlphaNUCLEAR 597-PX3 logic board was selected as the controller because it was the highest ranked device from Table 5.3. however, this controller required lots of modifications to switch from being an alpha particle detector to a gamma counter. The Udoo board was a very close second but also would have required modifications to turn it into a gamma reader. However, the Udoo board’s high energy consumption makes it a less desirable platform for this project since the detector has to be autonomous for 72 hours. Further details on the 597-PX3 logic board modifications are discussed in Chapter 6.

Once the probe, power supply and controller are selected, the system’s power requirements were estimated and this information was used as an input for battery selection. The $LiFePO_4$ battery pack was chosen because it was identified as the best design in Table 5.4. This was the battery pack used in the extended life PRISM units manufactured by AlphaNUCLEAR.

Lastly, once the above electronics were selected, the size required for an enclosure was estimated. The decision matrix in Table 5.5 designated the Hammond R190-112-000 box as the best suited to meet the customer requirements. It was found that the Hammond box is three times more expensive that the Bud Industries AN1322 enclosure and it requires more machining for fabricating a bracket. The Hammond box is more compact and coincidently requires use of more expensive bulkhead connectors, and ribbon cables inside the box to fit all of the detector components. Keeping in mind that this project is a proof-of-concept, requiring iterative design, the cheaper AN1322 box was selected for development.

The morphological table in Table 5.6 shows the selected designs for each system in grey. Chapter 6 provides further information on the design and implementation of
the five systems. Test results from the design will be discussed further in Chapter 7 for lab testing and Chapter 8 for JBS pilot hole probe tests conducted at the Cigar Lake mine.

Table 5.6: Concept Selection Morphological Table

<table>
<thead>
<tr>
<th>Radiation Detector</th>
<th>HV Power Supply</th>
<th>Control System</th>
<th>Battery Pack</th>
<th>Enclosure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha Nuclear Hi-Flux Probe</td>
<td>HMV ECHV0510</td>
<td>Alpha Nuclear 597-PX3 Logic Board</td>
<td>NIMH 6.0 V 10,000 mAh</td>
<td>Hammond R190-112-000</td>
</tr>
<tr>
<td>Canberra STHF-R Probe</td>
<td>EMCO Q-Series Q06</td>
<td>Udoo board</td>
<td>LiFePO4 6.4 V 6,600 mAh</td>
<td>Bud Industries AN1322</td>
</tr>
</tbody>
</table>
Chapter 6

Product Design and Implementation

6.1 Implementation

The JBS gamma probe proof-of-concept collects data required to create a gamma profile for a JBS pilot hole. Successful implementation of the JBS gamma probe was achieved through a combination of hardware, firmware and software. The gamma detector is mounted inside a JBS drill rod. The detector continuously collects gamma radiation data though the drilling cycle and records a time stamped log on an internal SD card. Before drilling starts, the detector is initialized using the readout box and an AlphaNUCLEAR start/stop dongle. Time synchronization and data downloading is done using a rugged Xplore IX 104C4 rugged PC via USB connection. Pilot hole gamma logs and JBS drill logs are correlated to determine the location of the JBS gamma probe in the pilot hole with respect to time.

The JBS probe data acquisition unit is located in an old zero rod outfitted with a bracket, 1.5 meters away from the end of the pilot hole. Zero rods have a blanked off inner conduit that allow pressurization of packer rods to prevent water inflows
in an emergency. The JBS probe is originally designed for installation in the zero rod directly behind the drill bit. This configuration gathers data as close to the end of the hole as possible. Unfortunately, all the zero rods available at the mine site have a welded stabilizer that blocks access to the centre of the rod. Acquiring a custom zero rod is beyond the budget of this proof-of-concept project. An old zero rod with a stabilizer held in place by a snap ring was therefore located and outfitted with a custom bracket to hold the JBS gamma probe in place as shown in Figure 6.1. The current configuration is a good compromise that provides information along the entirety ore zone because the pilot hole extends 2 meters beyond the top of any planned cavity extents to make room for the instrumentation in the jet string situated above the JBS jet nozzle.

![Figure 6.1: JBS Gamma Probe and Bracket General Arrangement in Modified Zero Rod](image)

6.1.1 **Hardware**

The JBS gamma probe circuit board is designed to incorporate all the components required for initialization, radiation detection, data storage, connection to a computer for data upload and time synchronization. The JBS gamma probe circuit board was developed using variant design to combine as many modules as possible from the AlphaNUCLEAR PRISM depicted in Appendix A.1 and the Hi-Flux probe circuit
shown in Appendix A.2 on a single circuit board that also incorporated a high voltage power supply and GM tubes to satisfy all customer requirements.

The final JBS gamma probe prototype circuit board layout is represented in Figure 6.2. The circuit board is designed using PCB Express. Two prototype boards were ordered and populated at the AlphaNUCLEAR laboratory. Figure 6.3 shows both sides of the first populated circuit board. In order to keep radiation exposure As Low As Reasonably Achievable (ALARA), the first prototype is kept at the mine site for data collection once the Cigar Lake alpha test started and the other detector is used at the laboratory in Saskatoon for firmware refinements and characterization experiments. The PRISM board components used on the JBS gamma probe board keep the original names. Components from the Hi-Flux probe board have the suffix “A” added to distinguish them.

![Figure 6.2: JBS Gamma Probe Circuit Board Layout](image)

The JBS gamma probe radiation detection circuit is based on the original Hi-Flux probe shown in Appendix A.2. The output signal from the gamma detection circuit is fed directly to the PIC microprocessor resulting in a better signal quality and lower
power consumption compared to the original Hi-Flux probe which drives counts as superimposed pulses on the power line.

When powered, the gamma radiation integrated circuits start automatically analysing output current from the Gieger Muller counters (GM1 and GM2). Signals from GM1 and GM2 are amplified by two 4.5 MHz internally phase compensated BiMOS operational amplifiers at U1A and U2A [52]. The amplified output signals are fed to a dual precision voltage comparator U3A that acts as a discriminator to discard all voltage changes lower than 100 mV [53]. U3A is connected to a pull up resistor that produces a high output signal sent to U4A when the offset voltage is below 100 mV. U3A outputs a low signal when the offset voltage is larger than 100 mV. U4A marks the beginning of the anti-coincidence circuitry that uses logic gates and pulse shaping to only register a single count per ionization event.

The anti-coincidence circuitry is made of four integrated circuits, U4A to U7A. It is responsible for accuracy and reliability of the gamma probe counts. U4A has six inverting buffers used for high-to-low level logic conversion, U5A is an integrated
circuit with four separate dual input NAND logic gates, U6A has four dual input OR logic gates, and finally U7A is a resettable, retriggerable dual multivibrator that produces precise pulse widths outputs when triggered [54–57]. The circuit is better explained as a whole in the flowchart in Figure 6.4 where U5A and U6A are at the core of the anti-coincidence logic. The NAND gates at U5A both output a trigger signal when the lockout pulse is off and ionizing radiation above the discriminator level is reported by a Geiger Muller counter. The OR gate at U6A compares the incoming signals from both U5A logic gates and outputs a single signal to U7A. The rising edge of the U6A triggers both U7A multivibrators. The first multivibrator creates a 5 $\mu$s trigger pulse fed to the microprocessor detector interrupt pin to register a count and the second multivibrator creates a 20 $\mu$s lockout pulse fed back to both U5A gates to disable triggering of another gamma count. The lockout provides time for quenching of the GM detectors, ensuring that secondary and tertiary ionization from a single event are not counted multiple times. Furthermore, counts triggered by both detectors at the same time are only registered once. In high count environments, the anti-coincidence circuitry makes it possible to have less missed counts due to dead time.

Figure 6.4: Anti-coincidence Circuitry Logic Gate Layout
6.1.2 Firmware

The JBS gamma probe firmware V0.6 is based on the AlphaNUCLEAR prism board and fulfils all customer requirement with regards to gamma counts recoding, power management, connectivity, ease of use and in house support by AlphaNUCLEAR. The firmware is developed using MPLAB IDE V8.92 and the same compiler as the PRISM to maximize troubleshooting and maintainability. The PRISM firmware code is proprietary and is not included in this document. Descriptions of the modified code used for the JBS gamma probe is kept at a high level to protect sensitive information.

The JBS gamma probe radiation measurement logging, USB connection, memory disc drive and power management are based on the original PRISM firmware and all functions related to radon measurement and run modes are replaced with gamma radiation detection. Helper routines are modified to incorporate and manage gamma radiation counts and the CSV file logging is modified with the calibration data in the header and all subsequent entries listed as separate rows. The high level structure of the firmware is shown in Figure 6.5 in three separate function groups. ON/OFF and power management function group is represented in red, the initiation sequence function group is in yellow and the gamma radiation detection function group is in green.

Efficient power utilization is required to fulfil customer need N3 for sustained power through the entire pilot hole drilling cycle. The JBS gamma board consumes approximately 70 mA at full load and has a 6,600 mA battery. The probe has a constant 3.3 V supply to the microprocessor and, in turn, the microprocessor can switch off the power regulators to the gamma detection circuit, LCD screen and SD card to save power when entering sleep mode.
Figure 6.5: JBS Gamma Probe Firmware Flowchart (The processes in red are basic function groups for powering the board and power saving, in yellow are initialization function groups and in green are the gamma counting function groups.)
6.1.3 Software

The JBS gamma probe firmware reverts back to a default date and time at first initialization of the microprocessor. The JBS gamma probe utility accurately synchronizes the microprocessor to system time to correlate gamma counts to pilot hole depths. The JBS gamma probe configuration utility was developed in C# using Microsoft Visual Studio Professional 2013 to modify the original PRISM utility represented in Appendix A.3. Only the serial number, firmware version, system time syncing and manual clock setup are required to fulfil specification S15 (time synchronization). The user interface of the JBS gamma probe utility is shown in Figure 6.6 and connects to the JBS gamma probe via USB. Once connected, the microprocessor settings are downloaded and the date and time can be replaced by the system time or a manual date.

![JBS Gamma Probe Configuration Utility](image)

Figure 6.6: JBS Gamma Probe Utility Interface
6.2 Form Generation

6.2.1 Detector Box Design

Form design of the JBS gamma detector was driven by constraints from the pilot hole drilling cycle’s harsh environment and the presence of radioactive materials. The detector box was designed for high ingress protection and minimal moving parts. This design had increased survivability and decreased failure modes.

The detector box configuration in Figure 6.7 shows the location and orientation of the circuit board, rechargeable battery, connection module and two Anphenol bulkhead connectors used to connect to the readout box. Both bulkhead connectors have 18 pins and are of identical size. For error proofing, the first bulkhead connectors is male and the other female. Two $\frac{3}{4}$ in holes were punched to accommodate the bulkhead connectors and each connector has four $\frac{1}{8}$ in bolt holes. A bulkhead connector gasket was used to provide a good seal. Additionally, thread locker was applied to each bolt and a lock washer, double nuts and room temperature vulcanization silicone were used with each bolt to ensure a tight seal.

The circuit board was mounted using 4/40 machine screws and risers attached to two perpendicular din rails to minimize material and decrease attenuation. The largest contributors for attenuation are the drill rod steel followed by the battery.

The detector was tapped out to $\frac{1}{4}$ in fine thread to securely attach to the mounting bracket with four machine bolts.

6.2.2 Readout Box Design

The readout box has an LCD screen, a battery charger module and an RJ45 plug used for USB connectivity and for turning the detector ON or OFF. The readout box internal configuration is depicted in Figure 6.8. LED lights are used to visually communicate the state of the detector. Amber and blue LEDs are used when the
charger is plugged in to indicate that the battery is charging or done charging respectively. Red, yellow and green LEDs are used to indicate if the detector is ready for deployment.

The LCD screen provides information on system time, battery life and provides instructions during initialization.

Two cable glands were used to connect to the detector box in order to distance the operator from the detector for radiation protection.

The RJ45 plug is used for all functions that require transfer of information to and from the microprocessor. This setup minimizes cost and provides a simple system for operators.

The battery charger circuit board is located in the readout box. The circuit board is a modified 1.2 A Smart Fast Charger where the fuse is replaced with a box mounted fuse for easy replacement and AC connections are replaced by more rugged cables. The LEDs from the detectors were also removed and replaced with the readout box charger LEDs.
6.2.3 Connection Terminal Module

The connection terminal module depicted in Figure 6.9 was developed for ease of maintainability and fast reliable termination of pins shared between the detector box and the readout box. FCI headers and crimp contacts were used due to their resistance to vibrations, ease of installation and troubleshooting.

The connection terminal module for the detector and the readout box were designed as a single board to reduce cost. Perforated holes were aligned in the middle to allow splitting of the two sides before populating them. A terminal block was kept on the readout box terminal module to separate the charger AC current from the DC current on the rest of the circuit board.

The first iteration of the JBS gamma probe had terminal blocks to connect each of the thirty six cables from the detector box to the readout box. In that configuration, seventy two continuity checks are required to reconnect all the cables when they are disconnected for troubleshooting. Moreover, detailed drawings are required to determine where each cable goes. This process was time consuming and did not allow troubleshooting in the field. The connection terminal module addressed these
problems with an elegant, user friendly and compact solution. Each system had a specific header where pin 1 was identified. It becomes possible to change out a full detector and reconnect all the cables without requiring soldering, continuity checks or detailed drawings. The connection terminal module is illustrated in Figure 6.10 where the “Before” picture is the old terminal block design.

Figure 6.9: JBS Gamma Detector Before and After the Connection Module

Figure 6.10: JBS Gamma Detector Before and After the Connection Module
6.3 Cigar Lake Alpha Testing Configuration

Figure 6.11 shows the JBS gamma probe charging before deployment. The detector box is installed in the detector rod and all other required rods are loaded on the JBS rod car before drilling begins. Once the primary insert is secured, the detector is initialized, connector plugs are securely tightened and the detector rod is deployed. The drilling rods arrangement for the JBS gamma probe alpha tests is shown in Figure 6.12. Pilot hole drilling typically takes 24 hours but times vary depending on ground conditions. At end-of-hole, a gyroscope survey (gyro) is used in the drill rod annulus to get the pilot hole as-built orientation. After the gyro, the pilot hole cleaning cycle begins. All the drill rods and tripping out of the hole. To ensure a clean hole before casing starts, all the drill holes are tripped back in and out of the pilot hole once more. The cleaning cycle providing an extra set of radiometric data for the JBS gamma probe.

Figure 6.11: Gamma Probe on The JBS Before Pilot Hole Drilling

Test data is collected through the full drilling cycle but due to limited drill log information, only data collected during the initial pilot hole drilling is used to determine
the radiometric profile of a pilot hole. The initial drilling cycle is the only time when drill logs are kept and the detector can be situated in the cavity. Data from the cleaning cycle cannot be used because there are no drill logs recorded. This issue has been identified and will be addressed in due time by a previous shelved project that uses the JBS drill table height and drill clamp position to determine the position of the drill head through the full drilling and cleaning cycle. Once position of the drill rods is tracked through the full drilling cycle, at least four data points will be available for each 10 cm interval to increase confidence in the measurements.

The following chapter summarizes the lab tests conducted on the JBS gamma probe and results from the Cigar Lake alpha tests are presented in Chapter 8.
Figure 6.12: Pilot Hole Drilling with JBS Gamma Probe General Arrangement
Chapter 7

Laboratory Testing and Discussion

7.1 Prototype Test Results

JBS gamma probe functionality, ruggedness and quality were tested before the tool was considered ready for alpha testing. The prototype test plan and associated test procedures are listed in Appendix B. The tests were developed to systematically confirm that the probe was fabricated properly, produces results comparable to the Hi-Flux probe and can survive the JBS pilot hole drilling cycle.

Circuit board population was tested by completing probe functionality Tests 1.1 to 1.7, and power consumption Tests 2.1 and 2.2.

Successful implementation of the firmware was determined by completing probe functionality Tests 1.8, 1.9, 1.11 to 1.13 and calibration routine Test 5.1.

The configuration utility was tested by completing probe functionality Test 1.10.

Detector box fabrication quality and effectiveness was measured by completing enclosure performance Tests 3.1 and 3.2 and cold weather Test 6.1.

The readout box functions were tested by completing modular controls Tests 4.1 and 4.2.

Finally, field testing of the JBS gamma probe was conducted by determining the
Localization of the detector in the pilot hole using Test 7.1 and the JBS pilot hole alpha Test 8.1.

Results from the aforementioned testing are summarized in Table 7.1. Detector 1 is the original detector built for the alpha test. The first alpha test was not successful. Detector 1 sustained water damage and was rebuilt into Detector 1.1 with better ingress protection. Detector 2 is a fully functional detector built for testing improvements when Detector 1.1 is in the field.

Detector 1 passed all the tests except for time synchronization, submersion test and the Cigar Lake alpha test. Submersion testing was done on Detector 1 when it still had cable glands as seen in Appendix A.4 and Appendix A.5. The design was changed shortly thereafter to bulkhead connectors to reduce moving parts but the submersion test was not repeated before the alpha test.

Detector 1 failed the time synchronization test. The JBS gamma probe configuration utility was not yet developed. For testing purposes, approximate time was programmed in the firmware as a temporary measure and had to be updated every time the microprocessor lost power.

Detector 2 was not intended for use in a rough environment. No submersion or cold weather testing was conducted on this detector. Moreover, there was no need for localizing the detector in the JBS pilot hole or getting it ready for the alpha testing.

### 7.2 Laboratory Test Results

Laboratory bench tests were conducted to verify the performance of the JBS gamma probe against a Hi-Flux probe at various gamma energy levels and shielding. This experiment was intended to prove that the JBS gamma probe outputs readings similar in magnitude and consistency to the Hi-Flux probe. It was expected that readings from the two probes would be similar without shielding and a slight difference was
expected when the probes are in their respective enclosures due to thickness and material differences. The mean and standard deviation for each trial were compiled and compared. A two tailed independent multivariate t-test was conducted using the Microsoft Excel statistical package for each experiment with the null hypothesis that both detectors produced similar readings.

Gamma counts from the JBS gamma probe and the Hi-Flux probe were measured.
using a Philips PM 6612 high resolution counter with the gate set to average counts every 10 seconds. Sixty readings were recorded for each experiment to obtain a representative sample twice as large as the minimum sample size required by the central limit theorem.

The first set of readings, Experiment I, were conducted by placing a weak gamma source (81 kBq natural uranium) in direct contact with the two Geiger counters on both probes to compare their reading ability without shielding. Results from this experiment are summarized in Table 7.2. The p-value of 0.1274 is too large to reject the null hypothesis. The results from this experiment support the fact that the detectors have identical reading ability with no shielding.

Table 7.3 shows the results from Experiment II conducted on a high activity source (15 MBq natural uranium) on both probes without enclosures. The p-value $5.3 \times 10^{-35}$ indicates that there is very strong evidence that the two probes have different readings, most likely due to a systematic error. However, readings are tightly grouped and the JBS gamma probe has consistently higher readings than the Hi-Flux Probe. There was plexiglass between the bottom of the High flux probes and source which was not the case for the JBS gamma probe.

The third sets of readings were conducted by placing both detectors in their respective enclosures to determine the enclosure shielding differences. An experiment was conducted on both probes by placing the weak gamma source at 120 mm away to determine the difference introduced by the probe’s enclosures without additional shielding from the zero rod drill steel. Results from Experiment III are summarized in Table 7.4. The low p-value of 0.0034 indicates that there is very strong evidence to reject the null hypothesis and suggests that the probes produce different readings in these testing conditions. Once again, the readings are closely grouped with similar standard deviations.

The fourth experiment was performed on both probes in their enclosures, placed
Table 7.2: JBS Gamma Probe and Hi-Flux Probe Comparative Test Experiment I: 81 kBq Source, Probes Without Enclosures

<table>
<thead>
<tr>
<th></th>
<th>JBS gamma probe</th>
<th>Hi-Flux probe</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. count (cps)</td>
<td>126.89</td>
<td>128.10</td>
<td>1.0%</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>3.84</td>
<td>4.69</td>
<td></td>
</tr>
<tr>
<td>St. Dev. %</td>
<td>3.0%</td>
<td>3.7%</td>
<td></td>
</tr>
</tbody>
</table>

Null hypothesis: There is no significant difference between the two detector measurements

P-value = 0.1274
Table 7.3: JBS Gamma Probe and Hi-Flux Probe Comparative Test Experiment II: 15 MBq Source, Probes Without Enclosures

<table>
<thead>
<tr>
<th></th>
<th>JBS gamma probe</th>
<th>Hi-Flux probe</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. count (cps)</td>
<td>114.33</td>
<td>104.33</td>
<td>8.8%</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>2.93</td>
<td>3.23</td>
<td></td>
</tr>
<tr>
<td>St. Dev. %</td>
<td>2.6%</td>
<td>3.1%</td>
<td></td>
</tr>
</tbody>
</table>

Null hypothesis: There is no significant difference between the two detector measurements

P-value = $5.3 \times 10^{-35}$
Table 7.4: JBS Gamma Probe and Hi-Flux Probe Comparative Test Experiment III: 81 kBq Source at 120 mm, Probes With Enclosures

<table>
<thead>
<tr>
<th></th>
<th>JBS gamma probe</th>
<th>Hi-Flux probe</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. count (cps)</td>
<td>8.62</td>
<td>8.10</td>
<td>6.1%</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.97</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>St. Dev. %</td>
<td>11.3%</td>
<td>11.6%</td>
<td></td>
</tr>
</tbody>
</table>

Null hypothesis: There is no significant difference between the two detector measurements

P-value = 0.0034
on top of the high activity gamma source to determine the difference in enclosure shielding. Results from Experiment IV are summarized in Table 7.5. The low p-value of 0.0134 indicates that there is very strong evidence to reject the null hypothesis and suggests that there is a difference from the shielding differences. Once again, the readings are closely grouped with similar standard deviations with less consistency in the Hi-Flux probe readings.

The fifth experiment was conducted by placing the weak gamma source inside a zero rod and placing the detectors on top of the rod to evaluate the difference from the combined effect of the zero rod and the detector enclosures. Results from Experiment V are summarized in Table 7.6. The low p-value of $3.3 \times 10^{-6}$ indicates that there is very strong evidence to suggest that the probes produce different readings on a high activity source in these testing conditions. Once more, the readings are closely grouped with similar standard deviations but this time, the JBS gamma probe readings are less consistent.

The sixth set of readings was conducted using a high activity source. The zero rod drill pipe was placed directly on top of the high activity source to mimic drilling in the ore body. Readings were taken by placing the detectors 5.5 inches inside the drill rod. Results from Experiment VI are summarized in Table 7.7. The high p-value of 0.0667 indicates that there is no sufficient evidence to support the fact that the probes produce different readings across the JBS rods on a high activity source. The readings are very closely grouped, statistically identical and with the same standard deviation.
Table 7.5: JBS Gamma Probe and Hi-Flux Probe Comparative Test Experiment IV: 15 MBq Source, Probes With Enclosures

<table>
<thead>
<tr>
<th></th>
<th>JBS gamma probe</th>
<th>Hi-Flux probe</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. count (cps)</td>
<td>78.15</td>
<td>76.68</td>
<td>1.9%</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>2.56</td>
<td>3.75</td>
<td></td>
</tr>
<tr>
<td>St. Dev. %</td>
<td>3.3%</td>
<td>4.9%</td>
<td></td>
</tr>
</tbody>
</table>

Null hypothesis: There is no significant difference between the two detector measurements

P-value = 0.0134
### Table 7.6: JBS Gamma Probe and Hi-Flux Probe Comparative Test Experiment V: 81 kBq Source Inside Drill Rod, Probes With Enclosures

<table>
<thead>
<tr>
<th></th>
<th>JBS gamma probe</th>
<th>Hi-Flux probe</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. count (cps)</td>
<td>6.35</td>
<td>5.64</td>
<td>11.1%</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.88</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>St. Dev. %</td>
<td>13.8%</td>
<td>12.3%</td>
<td></td>
</tr>
</tbody>
</table>

Null hypothesis: There is no significant difference between the two detector measurements

P-value = $3.3 \times 10^{-6}$

![Graph showing count vs time for 81 kBq source inside drill rod, probes with enclosures](image1.png)

![Image of JBS Gamma Probe](image2.png)

![Image of Hi-Flux Probe](image3.png)
Table 7.7: JBS Gamma Probe and Hi-Flux Probe Comparative Test Experiment VI: 15 MBq Source Across Drill Rod, Probes With Enclosures

<table>
<thead>
<tr>
<th></th>
<th>JBS gamma probe</th>
<th>Hi-Flux probe</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. count (cps)</td>
<td>11.08</td>
<td>10.61</td>
<td>4.2%</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.99</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>St. Dev. %</td>
<td>8.9%</td>
<td>8.9%</td>
<td></td>
</tr>
</tbody>
</table>

Null hypothesis: There is no significant difference between the two detector measurements

P-value = 0.0667
7.3 Discussion

This project creates a gamma logger capable of determining ore grades and ore/waste contacts while drilling the JBS pilot hole without affecting the JBS cycle time. Lab experiments were conducted to tackle the first portion of the mission statement, namely proving that the JBS gamma probe is capable of gathering data that can be used to determine ore grades and ore/waste contacts. Converting counts to grade was not part of the project scope but significant steps were taken to arrange the testing to allow this conversion.

7.3.1 Circuit Board Testing

The micro-controller can work with voltages from 2 to 3.6 V DC. In this particular instance, the test requires exactly 3.3 V DC because the battery cut-off circuit, fed by the same voltage, requires this input for the analogue battery level circuit to work properly. The sensor power supply test sets the supply voltage to the microprocessor to 3.3 V DC using the variable resistor VR1. The same voltage regulation can be achieved using an LM1117 3.3 V regulator with a simpler circuit. However, the output from simpler regulators will vary more significantly as the battery gets depleted. This project uses a MAX882ESA linear regulator to take advantage of the ultra low supply current, low dropout voltage, and a low battery detection comparator to obtain a steady 3.3 V output. A test circuit was developed by alphaNUCLEAR to confirm that the circuit board enters sleep mode when the battery voltage drops below 5.4 V. Though variable resistors are practical, they loose their setting over time and vibrations may accelerate this process. Variable resistor VR1 is fixed in place using a soluble glue to prevent accidental changes. The same voltage regulation can be achieved using high precision resistors but that option is much more expensive and was not used for this project. The SD, LCD and gamma detection circuit power...
supplies were checked using Test 1.3. An LM1117 - 3.3 V DC at U5 power supply was used for the SD card, an LM1117- 5 V DC at U6 was used for the LCD screen and the last LM1117- 5 V DC at U8 power regulator was used for the gamma detector circuit. Confirming the outputs from the power supplies confirmed that the circuit was populated properly.

Establishing connection to the micro-controller with the PIC in-Circuit Debugger (ICD 3) confirmed that the PIC 18F67J50 microprocessor was soldered properly on the circuit board. Being able to program the microprocessor confirmed that the In-Circuit-Serial-Programming (ICSP) circuit was populated correctly and that the 12 MHz primary oscillator was working properly. Being able to see the instructions on the LCD screen confirmed that the LCD header J5 was properly soldered and that the LCD initiation code was working as designed. Confirming that the micro-controller worked properly was an important step towards constructing the automated gamma detector.

Setting the high voltage power supply output in the GM counter high voltage plateau was critical for proper operation of the gamma counter as explained earlier in Chapter 4. The high voltage plateau of the ZP1320 is 575 V DC as specified by the manufacturer [58]. AlphaNUCLEAR uses the LND713 Thin Wall Beta-gamma Detector equivalent to the ZP1320. The LND GM counters have a wide high voltage plateau from 450 to 650 V DC with a recommended operating point of 500 V DC [59]. A high impedance voltmeter must be used to measure the current produced by the high voltage power supply. Theoretically, the output must be exactly 575 V DC for the ZP1320 and 500 V DC for the LND713. In practice, the voltage is set slightly higher because carbon resistors slip over time and the high voltage plateau spans a large voltage range, allowing for this practice to be used without affecting the count rate. AlphaNUCLEAR sets the LND713 operating voltage at 575 V DC as a legacy from the ZP1320. Setting the high voltage is a tedious task when choosing an appropriate
resistor within the 5% design limit. However, this method is cheaper than getting high precision resistors and much more effective than using variable resistors known to drift normally but more so under load. The test concluded with another test on the high voltage power supply under load. There should be no appreciable difference between the high voltage power supply with and without the sources. Faulty high voltage power supplies were identified at this point and changed out. EMCO tests all power supplies before delivery, finding a faulty power supply is rare. It was found that the high power supply in Detector 1 was water damaged. During this test, the output voltage would not go over approximately 380 V DC and had to be replaced. The miniature high voltage power supply is the most expensive component on the JBS gamma probe. It would be worthwhile to look into a potting method to make it watertight and avoid having to replace the unit if the enclosure is breached. Detectors 1 (before water damage from the alpha test), 1.1 and 2 passed the high voltage power supply test and showed negligible changes in the high voltage when measuring radiation from a 81 kBq natural uranium source.

Setting the discriminator level was an integral part of the gamma detection circuit. Setting it too high may discard counts for noise and setting it too low may include noise in the gamma counts. Variable resistors VR1A and VR2A were used to set both the discriminators in U3A. Signals from the GM counters are treated independently from each other before the anti-coincidence circuity. The same arguments for and against using high precision resistors presented above holds true in this instance as well. Using this style of discriminator creates a pulse chamber type detector as described in Section 4.2.2. GM counters cannot distinguish the energy of the incident radiation so using a pulse chamber circuit does not diminish the input data. The pulse chamber will, however, simplify the downstream processing because complicated analogue circuits can be replaced with binary logic. The output pulse was set to 5 µs as legacy from the Hi-Flux probe but it could be significantly reduced without affecting efficiency for
the JBS gamma probe because this signal is fed directly to the microprocessor. In the Hi-Flux probe, the signal is driven through a logging line, introducing limitations on the minimum width of a pulse that still allows the line to recover between counts. In this regard, the JBS gamma probe is a superior probe. On-board signal processing is used by many high resolution detectors including the STHF-R ultra high flux detector to avoid dropped counts which would happen if the pulses were driven in the logging line.

The lockout pulse is particularly important in GM counters where a single energy deposition triggers primary, secondary and tertiary ionization because it stops the counter from registering additional counts before the detector is quenched. It is suspected that a semiconductor detector, for example, would not necessarily require an anti-coincidence circuitry because the event occurs and dissipates very rapidly. This is not the case for GM counters. 20 µs is an adequate lockout pulse because it allows quenching below the discriminator level. But suppose ionizing radiation is deposited in GM 1, triggering the lockout pulse and a second event happens 10 µs after in GM 2. At first, only the event from GM 1 will be registered. After 20 µs, the lockout is off and the count from GM 2 may be registered, lowering dead time, provided quenching has not yet brought the voltage in GM 2 below the discriminator level.

Power consumption was determined using Test 2.1. Most elements on the JBS gamma probe are low energy consumers with the exception of the LCD screen and LEDs which are not attached to the detector during drilling. It was expected that the power consumption would increase by up to 25% in high counts but little change in current was observed (less than 5V). It was not possible to measure the exact increase in amperage draw from the detector because no very high activity sources were available (≥ 7.9 GBq). A Low energy Bluetooth module could be used in the detector box to further decrease power consumption due to the LED lights and the LCD screen without losing functionality. Adding a second battery to the readout
box and removing cables would not only increase power efficiency in the probe box but would also contribute in radiation protection. Induction charging could also be developed for the detector box to further improve the design.

A 1.2 A Smart Charge was used to charge the battery, which is really 1 A charger when assuming 20% inefficiency.

7.3.2 Firmware Testing

Firmware tests were conducted after establishing that the micro-controller, radiation detection and power distribution circuits were working properly.

The detector sleep mode was tested by Test 1.8. This test confirmed that the detector enters sleep mode properly. This simultaneously tested the firmware, power supplies shut-off and the 32.768 kHz secondary oscillator. Sleep mode is very power efficient. Detector 1 kept a charge for 25 days underground in sleep mode before the first alpha test. Sleep mode is essential to keep the clock going while saving power. The detector is less efficient at time keeping in sleep mode because there are less machine cycles to update the clock. It was observed experimentally that in the sleep mode, the detector time keeping will slip by 9 seconds every month. This can be remedied by reprogramming the detector before deploying it in a cavity. When the detector is logging, it uses the 12 MHz, 366 times faster than when in sleep mode, which does not have any appreciable time slip.

The detector USB connection was tested for connectivity with a computer via Test 1.9. The JBS gamma probe, like the AlphaNUCLEAR PRISM, follows the Universal Serial Bus Implementers’ Forum (USB-IF) protocols for USB Mass Storage Device class (UMS) and USB Human Interface Device class (USB HID). Test 1.9 only tested the UMS portion where the device’s internal memory can be accessed and modified from a computer. There were no modifications required to the original PRISM code to meet the customer demands with regards to USB connectivity.
Test 1.11 was used for testing the CSV file creation and Test 1.13 tested the CSV file upload onto a computer. The CSV file data fields were broken down into the date and time, counts and errors encountered. The CSV file format is compatible with all operating systems and the file size is compact, allowing for more data to be stored on the 2 GB internal SD card. Adding a battery level field to the data already recorded in the CSV file could prove beneficial for post-cavity analysis and refining the low battery limit. Logging systems may store logging data using proprietary file extensions and unique tool configuration files containing a plethora of parameters. For this project, the CSV file is the better choice because of its simplicity, compact size and multi platform ability.

The gamma field is averaged every minute. Test 1.12 verified that this convention was observed. Loading data every minute was determined from the 6 m per hour JBS max drilling rate in order to get data every 10 cm as requested by the Cigar Lake geology department. Once position data of the JBS drill rods can be obtained during the cleaning cycle, the recording frequency will be modified accordingly to obtain a reading every 10 cm using the maximum travel speed of the drill rods during the cleaning cycle.

The calibration routine in Test 5.1 was built into the initialization routine. When the detector turns on, it will automatically prompt the user to get the calibration check source and place it on the detector rod. This is not an actual calibration, it is a calibration check intended to identify if the detector is working as intended. If the calibration check numbers seem off, data from the particular run are discarded and the probe is sent in for calibration. GM counters are less likely to fail than scintillation or semiconductor detectors. The calibration checks are especially important in scintillation probes where a deformation or a crack in the crystal will decrease the detector sensitivity. Similarly, Frenkel defects in semiconductor detectors will also influence the reading ability of the detector. The JBS gamma probe always starts with the
calibration routine. The yellow and red LEDs are on for 15 seconds, allowing time for
the user to place the calibration source into position on the JBS gamma rod. The red
LED turns off and the yellow LED remains on for 1 minute to collect the calibration
check sample. Once the sample is complete, the calibration screen is replaced by the
date, time and battery level. The yellow LED turns off and the green LED turns on
with a screen message indicating that the probe is ready.

7.3.3 JBS Gamma Probe Configuration Utility

The JBS gamma probe configuration utility uses the HID protocol to upload micro-
processor data such as the serial number, firmware number and the date to a computer
and to allow a user to change time parameters. The HID, debugging and device man-
agement code from the PRISM were used without modifications in the JBS gamma
probe utility. The file input/output declarations code from the PRISM utility was
truncated to only include the probe serial number, firmware and ability to change
the date. Handles were matched between the JBS gamma probe firmware and the
configuration utility to allow overwriting of the date and time data.

7.3.4 Detector Box Testing

The submersion Test 3.1 was designed to identify flaws in the detector box construc-
tion so they could be fixed before the gamma detector was installed. Detector 1 was
not tested for water tightness after the box design changed to a bulkhead connec-
tor. During the first alpha test, two bulkhead connector bolts failed and water was
introduced in the detector. Success of the JBS gamma probe is dependant on the
integrity of the detector box. Every pilot hole will have a certain amount of water
before entering the frozen ground. The detector box could be potted with epoxy to
further protect the electronics from ground water and also dampen the vibrations
from drilling. This option was not explored further because it makes maintenance
very challenging.
Enclosure mounting Test 3.2 ensured that the detector was securely mounted at a fixed position in the gamma probe drill rod. Before the detector box design was changed to a bulkhead connector, the detector was designed to be accessed from the bottom of the drill rod by cables going through the drill rod stabilizer as shown in Appendix A.5. The configuration was abandoned because it was found that the cables would be crushed by the drill chuck during the drilling cycle. The detector box design was therefore changed to a bulkhead connector with no moving parts and access from the top of the drill. Many designs can be used for the bracket. Angle iron was used for the prototype to save on cost. Machining a circular suspension bracket held in place with a snap ring would be a more efficient design. The most effective design would be to design a custom rod to house the detector directly behind the drill bit to collect gamma data as far up the pilot hole as possible. A bulkhead connection extension would be required to access to sensor.

The cold weather testing in Test 6.1 was an extreme case but served as re-assurance that the detector could function in the rough, frozen environment of the ore body. During the drilling cycle, heat is created as the tricone bit grinds away the rock. Moreover, the detector is inside a drill rod that is not in direct contact with the surrounding rock. The only time when the drill is expected to cool substantially is at the end of the drilling cycle while waiting for the gyroscope survey. This would be the only time where the detector is suspected to work in frozen conditions. The main concern in this state is rapid depletion of the battery in cool temperatures. This did not prove to be a problem in the field tests.

7.3.5 Readout Box Testing

The readout box functions were tested by completing modular controls Tests 4.1 and 4.2. The LCD screen provides useful information to the user during initialization
and before deploying the gamma probe. However, because the readout box has no independent power, a major design limitation is that the LCD screen loses its initial configuration as soon as the readout box is disconnected from the detector box. When reconnected, the detector must be restarted for the screen to work properly again. The green LED light is used to communicate that the detector is on even when the LCD screen is not working properly. A button can be developed to reinitialize the detector LCD screen when it is reconnected to make it work when reconnected. Field experience shows that the LCD screen is not required post cavity because data downloading can still occur through the RJ45 socket and the detector is shut off and put on charge. Turning the detector back on will re-initialize the LCD screen.

7.3.6 Field Testing

Field testing of the JBS gamma probe was conducted by determining the location of the detector in the pilot hole using Test 7.1. An Excel spreadsheet was developed to correlate gamma logs to the JBS operator drill logs to determine the depth of the detector with respect to time. Drill log data is copied into a dedicated sheet with the depths of the JBS drill rods and the time when each drill rod length was started and when it finished. A forecasting function is used in conjunction with the offset and match functions to match every gamma log entry with the closest drill log depth. Once the closest match is found, the forecasting function interpolates between the two closest known drill depths to determine where the JBS gamma probe was located at the time the gamma entry was logged. The forecast function assumes a linear drill rate, which in reality would vary with ground competency. Matching each gamma entry with the closest known drill logs improves the forecasting ability on a rod-by-rod basis. Until such time that the actual depth of the JBS drill rods is estimated using the machine’s encoders and drill table height, this forecasting method is an effective alternative for determining the location of the gamma probe in the pilot hole.
respect to time.

Test 8.1 is the alpha test which is discussed in more detail in Chapter 8.

7.3.7 Lab Testing

The laboratory test results were completed on Detector 1 at the AlphaNUCLEAR facility in Saskatoon. A representative sample of the JBS drill rod was procured from Venables Machine Works Limited to test the characteristic shielding from within a JBS pilot hole. The drill steel was a rejected piece where the threads were machined in the wrong direction. The piece was 16 inches long, made of AISI 4140 high tensile strength steel with 26 cm outer diameter and 3.66 cm wall thickness.

The results from Experiment I confirm that the JBS gamma probe has the same reading ability as the Hi-flux probe. It was expected that the same results would be observed with Experiment II but the experimental setup suggests that the 8.8% difference is due to the fact that the sources were placed side by side, not at the same spot, introducing a systemic error resulting in the extremely low p-value. Placement of the detector is important on a natural uranium source such as the one used in this experiment because the grade distribution inside the source is not uniform. Therefore, it is important that both detectors be placed at the same spot to report similar counts. Furthermore, the GM counters on the JBS gamma probe are located facing down on the source, but the Hi-Flux probe’s GM counters have a thin piece of plexi-glass below on which they are attached; a small amount of shielding is introduced. Despite this fact, the readings are closely grouped and would not translate in a significant grade difference. In Experiment VI, where both detectors were placed at the exact same spot in their respective enclosures, readings from both detectors were statistical identical. The results are a little surprising because they suggest that the shielding from the drill steel is so large that the probes enclosures have little effect on the
readings. However, more experiments on higher energy sources would have to be conducted to substantiate this claim.

Experiments III to V were all closely grouped and no significant departure in the datasets could be observed. All experiments were satisfactory to prove that the JBS gamma probe has the precision and resolution to determine $U_3O_8$ grade through a JBS drill rod. The data also suggests that the JBS gamma probe must be characterized to normalize its count rate. The full series of experiments proved that the probe is able to report consistent counts with adequate resolution.

None of these experiments saturated the probe, and none introduced dead time errors because the count rates were too low. In an experiment conducted with the Hi-Flux probe in 2013, it was found that, at a minimum, a 7.9 GBq $^{137}$Cs source at 12 cm is required to bring the detector close to its 40,000 counts per second limit. Cameco does not currently have the license or facilities to store and operate such a high activity source. A request for quote has been sent to the Saskatchewan Research Council (SRC) to conduct further experiments on their high activity sources but that work is not part of the scope of this project.

Since the probe characterization was not completed, experiments at Cigar Lake mine only provided gamma counts per second. The magnitudes of the counts were proportional to the grade and follow the same trends but could not be translated into equivalent $U_3O_8$ grade.
Chapter 8

JBS Field Testing Results and Discussion

8.1 Results

8.1.1 765_025_ E_ CV Pilot Hole Test

The first successful pilot hole radiometric characterization was done on 765_025_ E_ CV. This cavity had an average grade of 4.62% $U_3O_8$ and measured 42 meters long at 83.7° dip or inclination to the East. The ore was expected between 33.7 and 39.2 meters. The full set of results from the JBS gamma probe are represented below in Figure 8.1.

The numbered regions represent readings taken in the orebody. Readings from Region “1” are taken when the drill bit first goes through the ore zone during the drilling cycle. Once at the end of the pilot hole, the drilling operation stops and the hole is surveyed for orientation. Once the survey is complete, the JBS crew retrieves all the drill strings from the pilot hole. During the retrieval process, the detector will go through the orebody once more, but this time from the top down, these readings are represented by Region “2”. All JBS holes are cased with steel in the waste rock.
and fiberglass in the ore zone. The pilot hole must be as clean as possible to make the installation of the casing successful. To make casing installation easier, the JBS crew will complete a cleaning cycle in which they will run all the drill strings back in the hole for the full length of the pilot hole. Readings from the cleaning cycle are represented in Region “3” on the way up and Region “4” on the way down. As discussed previously, only readings in the blue region currently have drill log data that can be used to correlate the location of the JBS gamma probe in the pilot hole using timestamps. Region “2” was found to be variable depending on the cleanliness of the drill bit. Due to the long period of inactivity before the hole survey is complete, mud can accumulated on the outside of the drill bit and shield the detector. The best set of readings are from the cleaning cycle where there is very minimal debris falling passed the drill rod.

The radiometric profile was plotted along the cavity on the driving layout in Figure 8.2. The general trend of the JBS gamma probe is consistent with diamond drill hole SF771_03 and the spike at the top of the cavity is consistent with SF766_04 as shown in Figure 8.3.

The radiometric profile was plotted along the pilot hole on the jetting recipe layout in Figure 8.4. The majority of the counts are around 10 to 20 cps which is consistent with the low grade expected in the cavity. The 220 cps spike is not in the planned
Figure 8.2: 765_025_E_CV Driving Layout Gamma Profile Overlay on Pilot Hole

Figure 8.3: 765_025_E_CV Section View Looking East With Diamond Drill Holes $U_3O_8$ Grades (Courtesy of Cameco)
cavity but is expected to be excavated according to the jetting recipe.
Figure 8.4: 765_025_E CV Jetting Recipe Gamma Profile Overlay
8.1.2 765_030_E_CV Pilot Hole Test

The 765_030_E_CV cavity had an average grade of 13.4% $U_3O_8$, the highest grade of all the cavities tested with the JBS gamma probe. The pilot hole was 45 meters long, dipping 84.4° East and the ore zone was expected between 34.4 and 43.1 meters. The full set of results from the JBS gamma probe are represented below in Figure 8.5.

![Gamma Counts](image)

Figure 8.5: 765_030_E_CV Gamma Counts. Drill Location Data is Collected in Blue Zones. Rods Pulled Out in First Red Zone to Allow Ground Relaxation And Second Red Zone is During the Cleaning Cycle

The radiometric profile was plotted along the cavity on the driving layout in Figure 8.6. The results indicate that the ore is concentrated towards the middle of the cavity. The radiometric profile was plotted along the cavity on the driving layout in Figure 8.2. The radiometric profile from the JBS gamma probe matches the diamond drill hole SF771_04 and SF766_04 by showing that the majority of the high grade ore is near the top of the cavity. The pilot hole profile is a good intermediate between SF771_04 and SF766_04 as shown in Figure 8.7.

The radiometric profile was plotted along the pilot hole on the jetting recipe layout in Figure 8.8. As expected, the average count of the cavity was significantly higher than 765_025_E_CV. The gamma profile fit in the confines of the geological model perfectly. Counts started to increase at the lower contact with the unconformity and tapered back down at the top of the cavity at the orebody outline.
Figure 8.6: 765_030_E_CV Driving Layout Gamma Profile Overlay on Pilot Hole

Figure 8.7: 765_030_E_CV Section View Looking East With Diamond Drill Holes U₃O₈ Grades (Courtesy of Cameco)
Figure 8.8: 765_030_E.CV Jetting Recipe Gamma Profile Overlay
8.1.3 765_030_B.CV Pilot Hole test

The 765_030_B.CV JBS gamma probe readings are represented below in Figure 8.9. The detector entered sleep mode in the second pass in the orebody. Further investigation in the gamma logs showed that the detector had collected data for a full day before starting this cavity and might have been deployed in 765_030_B.CV without a full charge. This cavity pilot hole was 43.1 meters long, dip of 82° West, average grade of 6.56% $U_3O_8$ and the ore zone was expected between 35.1 and 41.2 meters.

![765_030_B.CV PH Gamma Counts With Respect to Time](image)

Figure 8.9: 765_030_B JBS Gamma Counts During Drilling Cycle

The radiometric profile was plotted along the cavity on the driving layout in Figure 8.10. Data from the JBS gamma probe is as expected in this cavity with three distinct peaks similar to diamond drill hole F749_046 as shown in Figure 8.11. U085 is a good example of the rapid changes that can occur over short distances. In this case, U085 did not see any high grade at the top of the cavity but both F749_046 and the JBS gamma probe picked up on this feature. The radiometric profile was plotted along the pilot hole on the jetting recipe layout in Figure 8.12. The JBG gamma probe readings indicate that the highest grade material in the cavity was located at the top of the cavity. The relative magnitude of the counts was between 765_025_A.CV and 765_030_E.CV, consistent with the grade of the cavity. There was a sharp increase in gamma counts when the detector breached...
Figure 8.10: 765_030_B CV Driving Layout Gamma Profile Overlay on Pilot Hole

Figure 8.11: 765_030_B CV Section View Looking East With Diamond Drill Holes U₃O₈ Grades (Courtesy of Cameco)
the unconformity at 36 meters, and the counts taper down at 41 meters, above the geological model orebody’s outline at 40.6 meters.

Figure 8.12: 765_030_B_CV Jetting Recipe Gamma Profile Overlay
8.1.4 781_021_ A_ CV Pilot Hole Test

The first trial of the JBS gamma probe, conducted in 781_021_A.CV, was not successful. Two bolts were dislodged as shown in Figure 8.13 and water was introduced in the detector box causing a short circuit, water damage and corrosion. The gamma logs showed that the detector stopped recording at 9:34 PM, only an hour after the pilot hole had started. Upon review of the driller logs, it was found that hard ground was encountered at 9:22 PM and bit pressure was increased to 16,000 kN. This was suspected to have rattled the two bolts off and water was introduced in the detector while another rod was installed between 9:30 PM and 9:40 PM. With the drill rods stationary, water from the formation was allowed to seep into the open holes in the enclosure and cause the detector to fail.

Figure 8.13: 781_021_A_CV Bulkhead Connector Screws Failure

Figure 8.14 shows the components that were redesigned or replaced due to this incident. The RJ45 plug in the bottom left was removed and replaced with FCI connectors. It was found that the RJ45 connection was not secure enough to resist the vibrations during the drilling cycle and became disconnected. Without this connec-
tion, data cannot be retrieved from the detector and the ON/OFF dongle cannot work. The microchip, high voltage power supply and SD card holders were removed and replaced with new components because they had sustained water damage. Corroded traces were replaced with jumpers or wires to re-establish the electrical connections. Ground water in the mine has a high mineral content that rapidly corrodes electronics. The detector was washed in clean water after this incident to stop corrosion from spreading any further. The design of the bulkhead connector was revisited and reinforced to provide four layers of protection with thread locker, lock washers, double nutting and room temperature vulcanization silicone.

Figure 8.14: 781_021_A.CV Water Damage To Circuit Board Components. Circled Elements Were Removed or Replaced

8.2 Discussion

Results collected by the JBS gamma probe demonstrate the potential of this tool for characterizing the gamma profile of each cavity. Once the JBS gamma probe is characterized and counts can be converted to grade, radiometric information will be
included in the Acquire\textsuperscript{TM} database and will augment the current pool of radiometric data available for jetting recipe design, grade control and grade reconciliation from a cavity-to-cavity basis. It was found the JBS gamma probe provided data at 4 cm on average during the drilling cycle, two and a half times more granularity than the required data at 10 cm. During the drilling cycle, the maximum observed distance between counts was 7 cm. Furthermore, analysis of the counts reported while the detector was stationary were very consistent with average standard deviation less than 5\% of the mean similar to the readings obtained during the lab testing on a single point source.

The JBS gamma probe can only detect radiation around the pilot hole, typically up to 40 cm. This limitation will have to be taken into consideration when using detector data to refine a jetting recipe. Augmenting the JBS gamma probe data with neighbouring diamond drill hole and experience from nearby previously mined cavities will be beneficial to interpret the most likely geology and grade distribution in a cavity.

JBS gamma probe data correlates very consistently with the ore contacts at the unconformity and on top of the orebody. In 765\_025\_E\_CV, the two count peaks observed by the detector are consistent with the radiometric data obtained from diamond drill hole SF771\_03. The large count intersection, is also consistent with the high counts encountered by diamond Drill hole SF766\_04. This correlation further increases confidence in the data from the detector.

765\_030\_E\_CV was the highest grade cavity tested with the JBS gamma probe and the counts were proportionally higher compared to the other two tests. 765\_030\_B\_CV had the sharpest transition in counts at the unconformity as seen in Figure 8.12. Once the probe has been characterized, it will be possible to make comparisons between the grade prediction from the pilot hole gamma profile and the diamond drill holes on a cavity-by-cavity basis. Mill assays can also be used on a monthly basis but
because the ore is blended in the Run-Of-Mine holding tanks, it would be challenging to reconcile the assays back to a particular cavity, let alone a particular location in a cavity.

Passes 3 and 4 in 765_025_E_CV and 765_030_E_CV are speculated to have the best radiometric information. This was not proven because there is no drill log data to situate the detector inside the pilot hole. The cleaning cycle is thought to have no drill cuttings falling past the detector, therefore introducing a minimum amount of discrepancies in the readings. Data from the second, third and fourth pass will be used in the future to get a better average count but it currently cannot be used because there are no drill logs to correlate counts to a location in the pilot hole using timestamps.

8.2.0.1 Problems Encountered

Two problems were encountered since the 781_021_A_CV water damage. The first problem was encountered before drilling 765_039_E_CV where the detector battery was not charging. Troubleshooting instructions were sent up to the mine site to help fix the issue. It was found that the charger pin had not been secured on the connection module and the issue was fixed by reconnecting it.

The second issue was encountered with the 765_029_A_CV. The detector showed a “No SD card” error suggesting that the SD card was dislodged from the socket due to vibrations. Troubleshooting instructions were sent to the mine site to fix this problem successfully. In the future, the SD card will be epoxied in place to avoid this problem from happening again. The 2 GB card can hold enough information to log 30 years worth of continuous gamma data so there is no need to ever have to replace it or readily have access to it. In upset conditions, having the option to remove the SD card is helpful. Even though the detector might not be working, data can still be retrieved and it is easy to identify the time at which the failure occurred.
8.2.1 Numerical Modelling

Characterization of the JBS gamma probe is required to convert gamma counts with regards to time to equivalent percentage $U_3O_8$. A project proposal was compiled to arrange a pit-less probe characterization using a high activity $^{137}Cs$ source from SRC and Monte Carlo modelling to derive the factors necessary to convert counts to grade. SRC has the licence and facilities required to store and operate high intensity radioactive sources. It was demonstrated that the Monte Carlo Uranium Equivalence Scheme (MCUES) method yields better results at high uranium grades (higher then 4%) as compared to traditional pit based calibration [15].

![Figure 8.15: Comparision on Pitless and Traditional Method on Well Q8-110 Versus Chemical Assaying at 2MGA 1000 SN4395 [15].](image)

Using the MCUES method proposed by the Cameco exploration department, the JBS gamma probe’s reading inefficiency are characterized by comparing experimental results from a high activity $^{137}Cs$ at varying distances with the ideal counts modelled via Monte Carlo Modelling for the same configuration [60]. A second Monte Carlo model is prepared to characterize the ideal detector readings with varying uranium grades [60]. The model is constructed with the JBS Gamma probe inside a JBS drill rod to account for the steel and enclosure attenuations. Success of this method is largely dependant on the accuracy of the Monte Carlo models compared to field observations. Arrangements for probe characterization were not yet completed at the
time this thesis was written and will not be part of the scope of the project.

Figure 8.16: Pitless Characterization Process Flow Chart For Count Rate Conversion to Equivalent $U_3O_8$ Grade [60]
Chapter 9

Conclusions and Recommendations for Future Work

9.1 Summary and Contributions

A prototype for an automated JBS pilot hole radiometric probe with no impact to overall cycle time was presented and tested at the Cigar Lake uranium mine. Detector characterization was out of the scope of the thesis and has not yet been completed. Conversion of gamma counts rates from the detector to equivalent $U_3O_8$ grade is not possible at this stage. Successful testing of the prototype is a major step towards designing jetting parameters for extracting cavities more effectively based on gamma logs and experience from adjacent cavities instead of using pre-set recipes and interim surveys during jetting. In-situ pilot hole radiometric data may also be useful for grade control and grade reconciliation from a cavity-to-cavity basis. Once the probe is characterized, this technology could be applications at Cameco’s McArthur River and Rabbit Lake uranium mines. A miniaturized version of this technology would also have applications in uranium exploration diamond drilling where mineralized intersections could be identified and logged automatically.
A background of the Cigar Lake mine was provided with a review of the mine’s unique challenges and a review of the Jet Boring mining method was presented. The JBS mining sequence was presented in detail along with the opportunity for radiometric logging of pilot holes. A formal engineering design was utilized where the first steps identified the project customer needs, specifications and functional decomposition for the pilot hole radiometric probe.

A review of radiation measurement was presented with a review of radiation interaction with matter, equilibrium, Z-effect and dead time. Radiation measurement technologies were reviewed with a particular focus on gas filled detectors, scintillation detectors and semiconductor detectors.

The JBS gamma probe concept generation process was presented with selection matrices for the radiation detector, high voltage power supply, controller and enclosure selection. A morphological table summarized the options chosen to build the proof of concept prototype for each of the five subsystems.

The prototype was presented and discussion focused on the prototype circuit board design and presentation of the critical circuits for gamma detection. The firmware architecture was presented with an overview of the programming logic. The design of the JBS gamma probe configuration utility was presented. The detector box design was presented as part of the detector form design, followed by the readout box design. The form function concluded with a presentation of the connection terminal module which greatly simplified the design for the detector and readout box and allowed for troubleshooting without special tools. The alpha testing configuration for the JBS gamma probe was presented.

Laboratory test results were presented for the circuit board components, configuration utility, detector box fabrication, readout box functions and the JBS pilot hole alpha test. The JBS gamma probe was also tested against a Hi-Flux probe in the laboratory and comparative tests results were presented and discussed. Test results from the JBS...
gamma test on three cavity pilot holes were presented and mapped against the pilot hole driving layout and jetting recipe.

The following is an itemized list of the contributions made by this research:

- Formal engineering design process documentation;
- Design and population of two tested JBS gamma probe circuit boards;
- Design of the connector terminal circuit board;
- Fabrication of four bulkhead connector and four cable assemblies with FCI connector blocks to connect the terminal board;
- Fabrication of two JBS gamma probe detector boxes and readout boxes;
- JBS gamma probe firmware and installation package; JBS gamma probe utility for time synchronization;
- JBS gamma probe test plan;
- JBS gamma probe comparative lab testing with the Hi-Flux probe;
- JBS gamma rod made from a modified zero rod with a bracket to hold the probe in position;
- JBS gamma probe troubleshooting instructions for SD card error and no charge error;
- Template spreadsheets for extrapolating drill position in the pilot hole using operators drill logs; and,
- Pilot hole gamma count rate profiles.
9.2 Future Work

Building the gamma detector and proving its ability to survive in the hostile environment of the JBS pilot holes is an important first step to being able to produce the gamma profile for a pilot hole. The most important work required to bring the technology on-line will be a characterization of the detector to allow conversion of radiation count rate to $U_3O_8$ grade. The MCUE method is the recommended method because of the high grades encountered at the Cigar Lake mine. Moreover, there are no calibration pits big enough to accommodate the physical size of the JBS gamma probe. A calibration schedule will be developed for the final version of the probe to ensure that the electronics and the detector are certified bi-annually.

Revising the bracket design will yield a more rugged product where the GM sensors are perfectly centred in the cavity. Redesigning the detector box to separate the sensors from the circuit board will lead to less attenuation from the battery and lesser from the electronic components. A redesign of the JBS zero rod to include the gamma detector will allow for more data collection along the pilot hole. Working with the JBS engineers to develop a system capable of using the JBS sensors to determine the exact location of the JBS drill rods with respect to time will allow the use of the second, third and forth pass data. Alternatively, localization using an inertial measurement system coupled with a known start and end point could be used to determine the location of the JBS gamma probe in time independently from the JBS system.

Development of near field radio or other wireless communication that connects to the detector during the drilling cycle to collect live data would create new opportunities for the JBS gamma probe. Development of dedicated software to generate gamma profiles during the drilling cycle using the live data could also allow modification of the pilot hole length during the drilling cycle to optimize ore recovery and minimize dilution.
References


[57] ON Semiconductor, *Data Sheet: MC14528B*, ON Semiconductor, May 2013, MC14528B/D.


Appendix A

Original Designs
Figure A.1: Original Prism Utility Interface.

Figure A.2: Hi-Flux Circuit Board Layout
Figure A.3: Original Prism Utility Interface.

Figure A.4: Original Detector Box Layout
Figure A.5: JBS Bracket in Original Detector Configuration
Appendix B

Prototype Test Plan
Table 1 provides a summary with the description and objective of all the tests that will be conducted.

<table>
<thead>
<tr>
<th>Category ID</th>
<th>Description</th>
<th>Test case</th>
<th>Description</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Probe functionality</td>
<td>1.1</td>
<td>Micro-controller power supply calibration</td>
<td>Set the power supply to the PIC controller and USB connection to 3.3V</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.2</td>
<td>Initialize PIC controller</td>
<td>Verify that PIC controller is working properly and initialize</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.3</td>
<td>SD, LCD and Gamma probe power supplies</td>
<td>Verify that power regulation to SD card is set at 3.3 volts and LCD and gamma probe circuitry are set to 5V.</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.4</td>
<td>High voltage power supply</td>
<td>Set high voltage power supply to 575Vdc</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.5</td>
<td>Discriminator adjustment</td>
<td>Set discriminator level to 100mV to filter out noise from real radiation events</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.6</td>
<td>Adjust pulse width for radiation event</td>
<td>Set event pulse to 5 microseconds</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.7</td>
<td>Adjust lockout pulse</td>
<td>Set lockout pulse to 20 microseconds</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.8</td>
<td>ON-OFF dongle</td>
<td>Test that OFF-ON dongle puts device in sleep mode and wakes it up</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.9</td>
<td>Computer connection test</td>
<td>Verify that computer recognized probe via USB</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.10</td>
<td>Device clock setup test</td>
<td>Set current time on the device to record gamma readings in real time</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.11</td>
<td>CSV file creation test</td>
<td>Create CSV file with time-stamped gamma counts</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.12</td>
<td>Average gamma counts every minute</td>
<td>Verify that the probe can make gamma readings every 10cm at JBS' maximum drilling rate (6meters/hour)</td>
</tr>
<tr>
<td>T1</td>
<td></td>
<td>1.13</td>
<td>CSV import test</td>
<td>Import CSV file on</td>
</tr>
<tr>
<td>T2</td>
<td>Power consumption</td>
<td>2.1</td>
<td>Power consumption</td>
<td>Verify probe’s power consumption under normal operation</td>
</tr>
<tr>
<td>T2</td>
<td></td>
<td>2.2</td>
<td>Battery charging</td>
<td>Determine battery charging time</td>
</tr>
<tr>
<td>T3</td>
<td>Enclosure performance</td>
<td>3.1</td>
<td>Waterproof enclosure test</td>
<td>Determine if enclosure is adequately waterproof to house the probe</td>
</tr>
<tr>
<td>T3</td>
<td></td>
<td>3.2</td>
<td>Enclosure mounting</td>
<td>Verify that enclosure can be securely mounted inside JBS rod</td>
</tr>
<tr>
<td>T4</td>
<td>Modular controls</td>
<td>4.1</td>
<td>Display test</td>
<td>Verify that modular display is functional</td>
</tr>
<tr>
<td>T4</td>
<td></td>
<td>4.2</td>
<td>Modular controls</td>
<td>Verify that modular controls work as per design</td>
</tr>
<tr>
<td>T5</td>
<td>Calibration routine</td>
<td>5.1</td>
<td>Calibration routine</td>
<td>Verify that calibration routine works properly</td>
</tr>
<tr>
<td>T6</td>
<td>Cold weather testing</td>
<td>6.1</td>
<td>Cold weather testing</td>
<td>Verify that sensor can operate in frozen ground</td>
</tr>
<tr>
<td>T7</td>
<td>Time-stamped JBS pilot hole position</td>
<td>7.1</td>
<td>Logging JBS pilot hole position with respect to time</td>
<td>Verify acquisition of time-stamped position data for the JBS pilot hole drilling</td>
</tr>
<tr>
<td>T8</td>
<td>JBS pilot hole alpha test</td>
<td>8.1</td>
<td>Pilot hole alpha test</td>
<td>Verify that probe will be able function normally in its intended environment</td>
</tr>
</tbody>
</table>
TEST SCHEDULE

The JBS pilot hole gamma probe prototype will be tested in accordance to the schedule in Table 2.

### Table 2. JBS Pilot Hole Gamma Probe Prototype Test Schedule

<table>
<thead>
<tr>
<th>Test objective</th>
<th>Test case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe functionality</td>
<td>1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 1.10, 1.11, 1.12, 1.13</td>
</tr>
<tr>
<td>Sensor power consumption</td>
<td>2.1, 2.2</td>
</tr>
<tr>
<td>Enclosure performance</td>
<td>3.1, 3.2</td>
</tr>
<tr>
<td>Modular controls and display</td>
<td>4.1, 4.2</td>
</tr>
<tr>
<td>Calibration routine check</td>
<td>5.1</td>
</tr>
<tr>
<td>Cold weather testing</td>
<td>6.1</td>
</tr>
<tr>
<td>Time-stamped JBS pilot hole position</td>
<td>7.1</td>
</tr>
<tr>
<td>JBS pilot hole alpha test</td>
<td>8.1</td>
</tr>
</tbody>
</table>

TEST PROCEDURES

This section provides the detailed procedures for conducting the tests in Table 1. Each test case details the customer specification it addresses, the necessary initialization steps, inputs, procedures and expected results. This thorough approach will confirm that all customer requirements met and that the device’s individual components and the system as whole are tested and proven to work within specifications.

CUSTOMER REQUIREMENTS

Table 3 provides a summary of the customer’s requirements for the JBS pilot hole radiometric probe as they are referenced in the test procedures.

### Table 3. Client Requirements Summary

<table>
<thead>
<tr>
<th>Need ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N2</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N3</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N4</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N5</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N6</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N7</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N8</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N9</td>
<td>JBS gamma probe</td>
</tr>
<tr>
<td>N10</td>
<td>JBS gamma probe</td>
</tr>
</tbody>
</table>
SENSOR FUNCTIONALITY

TEST CASE 1.1 – SENSOR POWER SUPPLIES CALIBRATION

Need Reference(s): N1

Test Level: Component

Test Type: Functional

Test Description: This test verifies that the power supply to the PIC controller and USB connection is set to 3.3 volts.

Initialization:
1. Before energizing the board for the first time, all components are properly soldered and the circuit is checked for shorts and cold solder joints; and,
2. Connect power cable.

Test Inputs:
1. N/A.

Test Procedure:
1. With a multimeter, confirm there is power across the fuse J2;
2. Place multimeter on pin 2 of J8. Measure input power to PIC controller; and,
3. Adjust variable resistor VR1 using set screw until voltage at J8, pin 2 is 3.30Volts.

Expected Test Results:
1. Power supply output voltage to microcontroller is set at 3.3 volts; and,
2. Microprocessor is detectable from the ICD3 programmer using MPLAB.

Special Instructions: None.
TEST CASE 1.2 – INITIALIZE PIC CONTROLLER

Need Reference(s): N1

Test Level: System

Test Type: Functional

Test Description: Verify PIC controller is working properly.

Initialization:
1. Compile PIC controller Firmware code;
2. Connect ICD3 debugger to computer via MPLAB; and,
3. Powered on the gamma probe.

Test Inputs:
1. MPLAB Firmware.

Test Procedure:
1. Connect J8 to ICD 3 debugger using ICSP standards and verify the micro-controller is detected;
2. Load probe code onto microprocessor; and,
3. Check LCD screen for startup routine.

Expected Test Results:
1. Successful program the microprocessor; and,
2. LCD screen instructions to indicate proper startup routine.

Special Instructions: None.
TEST CASE 1.3 – SD, LCD AND GAMMA PROBE POWER SUPPLIES

Need Reference(s): N1

Test Level: System

Test Type: Functional

Test Description: Verify voltage regulator to SD card (U5) is set at 3.3 volts and voltage regulators for the LCD (U6) and gamma detectors (U8) are set to 5V.

Initialization:
1. Device has power

Test Inputs:
1. MPLAB Firmware.

Test Procedure:
1. Using a multimeter, connect to the SD card voltage regulator at pin 4 of U5 to check to voltage output; and,
2. Repeat step 2 for the LCD voltage regulator by checking pin4 of U6 and for the gamma detectors’ voltage revelators by checking pin 4 of U8.

Expected Test Results:
1. Successful programming of microprocessor; and,
2. LCD screen instructions to indicate proper startup routine.

Special Instructions: None.
Need Reference(s): N1

Test Level: Component

Test Type: Functional

Test Description: Set miniature high voltage power supply to approximately 575V DC.

Initialization:
1. Firmware is uploaded;
2. Power up the detector; and,
3. Get gamma radiation source.

Test Inputs:
1. MPLAB Firmware.

Test Procedure:
1. Confirm that GM counters are installed properly;
2. Place 31 ohms 5% resistor in R23A;
3. With high impedance voltmeter, measure current on the high voltage side of the power supply;
4. Repeat steps 2 and 3 until a resistor is found that provides between 575.0 and 578.0 V DC. Due to the 5% tolerance, every 31 ohm resistor produces a different high voltage output;
5. Place a gamma radiation source 2 cm from GM counters and take another measurement on the high voltage side of the power supply;
6. Confirm that there is no significant voltage and no sudden voltage changes;
7. If step 7 is unsuccessful, discard resistor and start over from step 2;
8. Once the proper resistor is selected, solder it in place; and,
9. Return radiation source to storage.
Expected Test Results:
1. Successful selection of resistor that provides between 575 and 578 VDC at high voltage end of high voltage power supply; and,
2. Voltage will decrease slightly when Geiger counters are active.

Special Instructions:
1. DO NOT TOUCH THE HIGH VOLTAGE TRACES; and,
2. Always use As Low As Reasonably Achievable (ALARA) principles when working with gamma radiation sources. Return sources to locked storage directly after use.
TEST CASE 1.5 – DISCRIMINATOR ADJUSTMENT

Need Reference(s): N1

Test Level: Component

Test Type: Functional

Test Description: Set discriminator level to

Initialization:
1. Powered up the device.

Test Inputs:
1. N/A.

Test Procedure:
1. Measure voltage at inverting input A at pin2 of U3A;
2. Set non-inverting input A at pin 3 to 100mV above the reference reading from pin 2 by changing the variable resistor at VR2A;
3. Measure voltage at Inverting Input B at pin6 of U3A; and,
4. Set non-inverting input B at pin 5 to 100mV above the reference reading from pin 6 by changing the variable resistor at VR1A.

Expected Test Results:
3. Adjusting VR2A and VR1A achieves set points for pins 3 and 5 of 100mV above pins 2 and 6 respectively.

Special Instructions: None.
Need Reference(s): N1

Test Level: Component

Test Type: Functional

Test Description: Set event pulse to 5 microseconds.

Initialization:
1. Ensure device is powered on;
2. Will require gamma radiation source; and,
3. Will require oscilloscope.

Test Inputs:
1. N/A.

Test Procedure:
1. Put gamma radiation source at 5 cm of the Geiger Muller counters;
2. Make sure oscilloscope negative lead is grounded;
3. Attach oscilloscope positive probe securely to non-inverted output of the dual the monostable multivibrator at pin 10 of U7A;
4. Adjust variable resistor at VR3A by turning the setscrew until the pulse width from pin 10 is at exactly 5 microseconds; and,
5. Store gamma radiation source appropriately.

Expected Test Results:
1. Pulse width from pin 10 is at exactly 5 microseconds when reporting an instance of radiation.

Special Instructions: Always use ALARA principles when working with gamma radiation sources. Return source to locked storage directly after use.
TEST CASE 1.7 – ADJUST LOCKOUT PULSE

Need Reference(s): N1
Test Level: Component
Test Type: Functional
Test Description: Set lockout pulse to 20 microseconds.

Initialization:

1. Ensure device is powered on;
2. Will require gamma radiation source; and,
3. Have oscilloscope ready.

Test Inputs:

1. N/A.

Test Procedure:

1. Put gamma radiation source at 5 cm of the GM counters;
2. Make sure oscilloscope negative lead is grounded;
3. Latch Oscilloscope positive probe securely to non-inverting output of the dual the monostable multivibrator at pin 6 of U7A;
4. Adjust the variable resistor at VR4A by turning the setscrew until the pulse width from pin 6 is at exactly 20 microseconds; and,
1. Store gamma radiation source appropriately.

Expected Test Results:

1. Pulse width from pin 6 is at exactly 20 microseconds when reporting an instance of radiation.

Special Instructions: None.
Need Reference(s): N1, N10

Test Level: System

Test Type: Functional

Test Description: Test verifies that ON/OFF dongle puts the detector in sleep mode and wakes it up.

Initialization:
1. Ensure device is powered on.

Test Inputs:
1. N/A.

Test Procedure:
1. Attach LCD display;
2. Place "off" side of the ON/OFF dongle in RJ45 Socket;
3. Check that device goes through shutdown routine;
4. Use voltmeter to verify that the U5, U6 and U8 power supplies are off by checking pin 2 or 4;
5. Place "on" side of the ON/OFF dongle in RJ45 socket; and,
6. check LCD screen for initialization to confirm device is no longer in sleep mode.

Expected Test Results:
1. When inserted in the RJ45 Socket, the "OFF" side of the dongle puts device in sleep mode, and the "ON side" wakes up the detector.

Special Instructions: None.
TEST CASE 1.9 – COMPUTER CONNECTION TEST

Need Reference(s): N7
Test Level: System
Test Type: Functional
Test Description: This test verifies that computer recognized probe via USB.

Initialization:
1. N/A.

Test Inputs:
1. N/A.

Test Procedure:
1. Connect probe to PC using the RJ45 to USB cable;
2. Wait for computer to detect device; and,
3. Disconnect device.

Expected Test Results:
1. Successful detection of probe as mass storage device.

Special Instructions: None.
TEST CASE 1.10 – DEVICE CLOCK SETUP TEST

Need Reference(s): N1

Test Level: System

Test Type: Functional

Test Description: This test verifies that the JBS gamma probe clock can be synchronized by the configuration utility.

Initialization:
1. Install JBS gamma probe configuration utility on computer.

Test Inputs:

Test Procedure:
1. Connect probe device to computer;
2. Click "Connect" in the AN utility to connect with the probe;
3. In "Clock Setup" select "Sync. To System Time";
4. Click on "Apply Changes" and wait for changes to be applied; and,
5. Check device LCD screen to verify time has been updated to computer system time.

Expected Test Results:
1. Detection of device as human interface device; and,
2. Device time gets updated to computer system time.

Special Instructions: None.
TEST CASE 1.11– CSV FILE CREATION TEST

Need Reference(s): N1, N7

Test Level: System

Test Type: Functional

Test Description: Create CSV file with time-stamped gamma counts.

Initialization:
1. Make sure SD card is write enabled and is inserted in SD slot.

Test Inputs:
1. This test can be conducted with or without a gamma source.

Test Procedure:
1. Power-up detector;
2. Wait for device to initialize (1 minute);
3. Allow device to take at least a couple readings;
4. Plug device in a computer using adapter cable or remove SD card and place it in a computer; and,
5. Check the latest CSV file to verify that the probe recorded gamma counts and appropriate date and time. (Note that the CSV files will be named with regards to the date and time on the device at the time it was created, this time may not be accurate if the device was reset).

Expected Test Results:
1. CSV files will contain the exact sensor date and time of readings.

Special Instructions: None.
TEST CASE 1.12 – AVERAGE GAMMA COUNTS EVERY MINUTE

Need Reference(s): N1

Test Level: System

Test Type: Functional

Test Description: Verify that the probe can make gamma readings every 10cm at JBS’ maximum drilling rate (6 meters/hour).

Initialization:

1. Make sure SD card is write enabled and is inserted in SD slot.

Test Inputs:

1. This test can be conducted with or without a gamma source.

Test Procedure:

1. Turn on detector and wait for at least 6 minutes (1 minute for initialization and five 1 minute runs);

2. Plug device in a computer using adapter cable or remove SD card and place it in a computer; and

3. Verify that the readings are taken at 1 minute interval.

Expected Test Results:

2. Readings are taken every minute.

Special Instructions: None.
Need Reference(s): N7

Test Level: System

Test Type: Functional

Test Description: This test will verify the Import CSV file on a computer

Initialization:
1. Make sure SD card is read/write enabled and is inserted in SD slot.

Test Inputs:
1. SD card data.

Test Procedure:
1. Plug probe device in a computer using adapter cable;
2. From the computer, select a CSV file on the probe and upload it onto the computer; and
3. Confirm that upload is done successfully by opening the imported file to ensure it is not corrupt.

Expected Test Results:

Special Instructions: None.
POWER CONSUMPTION

TEST CASE 2.1 – POWER CONSUMPTION

Need Reference(s): N3, N5

Test Level: System

Test Type: Performance

Test Description: This test verifies the sensor power consumption under normal operation.

Initialization:
1. N/A.

Test Inputs:
1. N/A.

Test Procedure:
1. Disconnect the positive battery from probe;
2. Set multimeter to measure current, the expected value around 80 mA;
3. Connect the battery negative lead to the probe ground;
4. Connect battery positive lead through the multimeter and to probe's positive power input at pin 1 on J4;
5. Measure current consumption every minute for 5 minutes with the LCD Screen attached;
6. Measure current consumption every minute for 5 minutes without the LCD screen;
7. Place gamma radiation source at 5cm of sensor and repeat steps 5 and 6; and,
8. Compute average for power consumption each set of measurements.

Expected Test Results:
1. Power consumption lower without LCD screen; and,
2. Power consumption while probes active less than 100 mA.

Special Instructions: Always use ALARA principles when working with gamma radiation sources. Return source to locked storage directly after use.
TEST CASE 2.2 – BATTERY CHARGING

Need Reference(s): N5, N10

Test Level: Component

Test Type: Performance

Test Description: This test verifies battery recharge time.

Initialization:
1. Deplete sensor battery; and
2. Timer.

Test Inputs:
1. N/A.

Test Procedure:
1. Connect battery charger to probe and start timer;
2. Wait until charger indicator turns blue;
3. Record recharge time; and,
4. Test failed if detector charge time is over 6.5 hours.

Expected Test Results:
1. 6.6A battery fully charged in 6.5 hours.

Special Instructions: None.
ENCLOSURE PERFORMANCE

TEST CASE 3.1 – WATERPROOF ENCLOSURE TEST

Need Reference(s): N2, N8

Test Level: Component

Test Type: Functional

Test Description: This test will determine if enclosure is adequately waterproof to house the JBS gamma probe.

Initialization:
1. Place 3M (TM) water contact indicator tape inside the enclosure on all facets;
2. Filled up sink with enough water to fully submerge the detector; and,
3. Submersible weight to keep detector from floating (a 2 L water bottle works fine).

Test Inputs:
1. N/A.

Test Procedure:
1. Remove probe from enclosure and set in safe place;
2. Securely close the detector box;
3. Make there is a good seal;
4. Submerge in sink and place weight on top for 4 hours;
5. Remove detector box from sink, carefully dry the outside; and,
6. Open the enclosure and assess if any water was introduced.

Expected Test Results:
1. All water contact indicators tapes inside the enclosure remain unchanged.

Special Instructions: Do not place probe in the enclosure during this test.
Need Reference(s): N8

Test Level: Component

Test Type: Functional

Test Description: This test will sets up and verifies that the detector box securely mounts inside JBS drill rod.

Initialization:

1. Arrange experiment with JBS team well in advance (30 days) to ensure operator and material availability.

Test Inputs:

1. N/A.

Test Procedure:

1. Remove old zero stabilizer and snap ring;
2. Fabricate mounting bracket;
3. Mount enclosure on bracket;
4. Mount Bracket on stabilizer using thread locker and 5/8” bolt;
5. Place assembly inside old zero rod; and,
6. Assess enclosure fit and robustness though normal handling.

Expected Test Results:

1. Enclosure securely mounted inside zero rod and bulkhead connectors are accessible though the top of the zero rod.

Special Instructions: None.
Need Reference(s): N4, N9, N10

Test Level: Component

Test Type: Functional

Test Description: This test will verify that modular display is functional.

Initialization:
1. N/A.

Test Inputs:
1. N/A.

Test Procedure:
1. Connect readout box to Detector box via the bulkhead connectors;
2. Turn probe on with the dongle from the modular controls RJ45 socket; and,
3. Visually check if LCD display is functional.

Expected Test Results:
1. LCD screen and modular controls works normally.

Special Instructions: None.
TEST CASE 4.2 – MODULAR CONTROLS

Need Reference(s): N4, N5, N7, N9, N10

Test Level: Component

Test Type: Functional

Test Description: This test will verify that modular controls work as per design.

Initialization:
1. N/A.

Test Inputs:
1. N/A.

Test Procedure:
1. Connect modular controls to umbilical cord;
2. Turn probe on with the dongle from the modular controls RJ45 socket;
3. Check that indicator lights are functional during initialization; and,
4. Verify that the LCD screen works properly.

Expected Test Results:
1. Indicator lights functional; and,
2. Calibration test lights functional.

Special Instructions: None.
Need Reference(s): N4, N10
Test Level: System
Test Type: Functional
Test Description: This test will verify that calibration check routine is functional.

Initialization:
1. Gamma radiation source.

Test Inputs:
1. N/A.

Test Procedure:
1. Connect modular controls to readout box;
2. Turn probe on with the dongle from the modular control RJ45 socket;
3. LEDs go from yellow and red to just yellow. Follow screen prompts; and,
4. Yellow LED shuts off, green LED switched on to indicate instrument is ready for use.

Expected Test Results:
1. Calibration check routine executes normally.

Special Instructions: None.
COLD WEATHER TESTING

TEST CASE 6.1 – COLD WEATHER TESTING

Need Reference(s): N2, N3

Test Level: System

Test Type: Functional

Test Description: This test will verify that calibration the sensor can operate in frozen ground.

Initialization:
1. Deep freezer; and,
2. Fully charged battery.

Test Inputs:
1. N/A.

Test Procedure:
1. Initialize probe device;
2. Double check enclosure is securely closed and place in deep freezer for 12 hours;
3. Connect device to computer and retrieve CSV file; and,
4. Analyze CSV file to identify if there were anomalies in the probe during cold run.

Expected Test Results:
1. Probe works normally in cold weather.

Special Instructions: None.
Need Reference(s): N1

Test Level: Component

Test Type: Functional

Test Description: This test will verify acquisition of time-stamped position data for the JBS pilot hole drilling.

Initialization:
1. Coordination with JBS Foreman.

Test Inputs:
1. JBS operators drill logs; and,
2. JBS gamma probe spreadsheet.

Test Procedure:
1. Collect life data during JBS pilot hole drilling;
2. Get a copy of the JBS drill logs;
3. Export JBS gamma probe data and enter the timestamped values in the JBS gamma probe excel spreadsheet in "Raw data;"
4. Plug JBS drill log depths and times in JBS Gamma probe excel spreadsheet in "Operator logs;"
5. Adjust distance extrapolation formula extents to fit the data available; and,
6. Plot gamma counts against the pilot hole driving layout and the jetting recipe.

Expected Test Results:
1. Counts are relative to the cavity grade and are distributed in the orebody.

Special Instructions: None.
JBS PILOT HOLE ALPHA TEST

TEST CASE 8.1 – PILOT HOLE ALPHA TEST

Need Reference(s): N1, N2, N3, N5, N7, N8, N9, N10

Test Level: System

Test Type: Functional

Test Description: This test verifies that the probe is able to function normally in its intended environment.

Initialization:

1. Install probe enclosure in JBS gamma probe rod, directly behind the Zero rod; and,
2. Fully charged Battery.

Test Inputs:

1. N/A.

Test Procedure:

1. Connect to probe to readout box and initialize it;
2. Secure bulkhead connectors caps;
3. Deploy gamma rod directly behind the zero rod;
4. Once pilot hole drilling is complete, connect probe to computer and retrieve CSV file;
5. Plug data in JBS gamma probe spreadsheet and correlate depths using driller logs;
6. Export spreadsheet with counts Vs depth in the pilot hole;
7. Give data to the geology department for further analysis; and,
8. Re-charge sensor to get it ready for the next pilot hole.

Expected Test Results:

1. Sensor performs normally through full JBS the cavity pilot hole drilling with no cycle time impact.

Special Instructions: None.