Technology roadmap for improvement of the North-West University neutron monitor system of the Centre for Space Research

Dissertation Submitted as fulfillment of the requirements for the degree

Magister Ingeneriae

In Electronic Engineering

By

Erick F. Minnie

supervised by

Prof. J.E.W. (Johann) Holm

with co-supervisor

Prof. H. (Harm) Moraal

19 November 2010

Acknowledgements

I would like to thank the following people and institutions for making this project possible.

God Almighty – For the ability to learn, think and work and the numerous opportunities He provided to me.

My Fiancé – For her endless love and support throughout the development and creation of this project.

My Parents – Who taught me the values of life and living, and the courage to take on a challenge.

My Supervisors – For their technical and skilled support and granting me the chance of learning from them.

The Centre for Space Research – Who made this project possible through their field of research and the equipment they use.

What I learned through working on this project will most definitely shine through in my current position as engineer. But the method of systems engineering will also shine through in my walk of life and the way I pursue my future. It gave me the key to think differently about the world, realizing that the Perfect Bigger Picture can be built by well-defining the smallest and seemingly most insignificant bits and pieces, these pieces that can easily lead to destruction if neglected.

Abstract

The Centre for Space Research (formerly known as the Unit for Space Physics) at the North-West University manages the operation, maintenance and data gathering of four neutron monitors. This is done in order to indirectly study the patterns and reactivity of the Sun. Some of these neutron monitors have been operating from the late 1950's while not receiving much attention regarding technology upgrades, but were kept alive by merely maintaining the bits and pieces that started giving problems.

This is all about to change due to this thesis that will serve as a Technological Roadmap for the Improvement of the North-West University Neutron Monitor System of the Centre for Space Research. It begins by looking at the essential parts needed to count cosmic rays – the primary particles that are affected by the Sun's intensity and reactivity – and register their collision-products, neutrons. Then it covers the Centre for Space Research's neutron monitor systems as a whole, including the physical locations up to the logistics needed to change a part.

The systems analysis of the neutron monitor operation was done in order to determine the current neutron monitor operational functions and to determine the system's risk profile. A complete FMECA breakdown of worst-case scenarios and their impact on the system was done, and the mitigating actions were discussed in order to minimize the effect a specific failure mode will have.

The project ends by giving a couple of technological and design suggestions in order to maintain and upgrade the system.

Uittreksel

Die Sentrum vir Ruimtenavorsing (voorheen bekend as die Eenheid vir Ruimtefisika) aan die Noordwes-Universiteit handhaaf die bestuur, bedryf, instandhouding en data-insameling van vier neutron monitors in die Suidelike Halfrond. Dit word gedoen om indirek die reaktiwiteit en siklusse van die son te bestudeer deur kosmiese strale te tel. Sommige van hierdie neutron monitors is in bedryf sedert die laat 1950's, en sedertdien is daar nie daadwerklike tegnologiese opgraderings aan die stelsels gedoen nie. Hul is aan die lewe gehou deur foutiewe komponente en gebreke te vervang soos nodig.

Die doel van hierdie verhandeling is om ‘n Tegnologiese Padkaart vir die verbetering van die Noordwes-Universiteit Neutron Monitor Stelsel van die Sentrum vir Ruimtenavorsing daar te stel om die voortgesette, betroubare werking van die neutronmonitors te verseker. Dit skop af deur die primêre dele van ‘n neutronmonitor te beskou wat noodsaaklik is om kosmiese strale te tel - die primêre deeltjies wat indirek deur die son se intensiteit en reaktiwiteit geraak word – en hul neweprodukte (neutrone) as gevolg van botsings met deeltjies in ons atmosfeer op aardoppervlak te registreer en te tel.

Dit dek dan ook die Sentrum vir Ruimtewetenskap se hele neutronmonitor stelsel en program, van die fisiese plekke waar die Sentrum se neutronmonitors bedryf word, tot die logistieke paaie wat gevolg moet word om ‘n neutronmonitor onderdeel te vervang.

Die neutronmonitor stelsel ondergaan dan ook ‘n volledige stelselanalise om die werking en prosesse van die huidige NM opset te verstaan en op die uiteinde daarvan die risiko profiel van elke hulpbron en funksionele eenheid te bepaal.

‘n Volledige FMECA-analise van falingstoestande is gedoen om te bepaal waar die stelsel mees vatbaar is vir ‘n kritieke faling, en voorkomende optredes vir verminderde waarskynlikheid dat die spesifieke funksie of hulpbron sal faal, word uit die hulpbron-toedeling en oorbelaaide analise afgelei. Die verhandeling kom tot ‘n einde in die vorm van ‘n paar belangrike tegniese en ontwerpsvoorstelle om die toekoms en betroubare werking van die neutronmonitors te verseker.

Key terms used

CSR – Centre for Space Research

NM – Neutron Monitor

UPS – Uninterrupted Power Supply

HV – High Voltage

LV – Low Voltage

xR – Resource(s)

xI – Interface(s)

BF3 – Boron-Trifluoride

He – Helium

NMDB – Neutron Monitor Database (International Database)

FMECA – Failure mode, effects and criticality analysis

Table of Contents

Chapter 1 Background information and literature study

1.1 Introduction

The act and science of counting neutrons has been a new thing during the early 1950's and it has been going on ever since. Although modern scientists prefer to look at data from neutron monitors in outer space to try and determine the origin of cosmic rays more directly, the neutron monitors based on earth still generate invaluable information about our Sun and the space surrounding us here on earth.

In particular, the four neutron monitors controlled and owned by the Centre for Space Research at the North-West University add a significant amount of earth-based cosmic ray data due to them being four of the 10 or so neutron monitors in the Southern Hemisphere. This is one reason why the continued operation of the CSR's neutron monitors is so important. Together they span more than 5000 kilometres, reaching from close to the South Pole to near the Equator. This also means that the atmosphere above each neutron monitor differs not only in molecular composition, but also in magnetic rigidity.

As the North-West University's Centre for Space Research focuses on academic quality of its research output s, human resources have been available to maintain the research programme. Recently, the need was identified to investigate the current status of the overall neutron monitor system and to propose a technology plan (road map) that will reduce risk and ensure sustainability of the system from a technical point of view. However, it was realized that the technical effort required a review and a technology plan to reduce the dependency of the system on scarce resources and introduce business continuity – this is the underlying rationale of the research documented in this thesis.

In order to propose a technology roadmap, it was necessary to do the following:

1. Document the existing system "as is". That is, visit the system's facilities, as remote as Antarctica, and document the existing physical configuration of the system;
2. Perform a literature study in order to understand the system as a whole, as well as techniques for analyzing risk;

3. Understand the technical functions of the system through a preliminary operational and technical analysis;
4. Perform a functional analysis and deduce an abstraction of the system to eliminate the technology-specific functional definition of the system and introduce a technology independent configuration of the system (function-based);
5. Perform a risk analysis to identify specific technical and operational risks, including a process for the identification of critical items (resources and functions that form the core of the functionality, with their dependencies);
6. Propose mitigating action, in the form of a technology roadmap, to reduce future risk and to guide the acquisition of new technology.

By doing a thorough investigation and analysis, mitigating actions become apparent as solutions to the identified shortfalls. By analyzing the risk prior to mitigation, as well as the mitigated risk, one can qualitatively show a relative reduction in risk.

The validation of the study lies in the method of analysis that was followed. That is, when a systems engineering approach is followed, all risks are identified and mitigating actions are taken - this in itself is in an engineering sense a scientific method. External factors are considered in combination with risk controls in order to provide a road map that is comprehensive in terms of its scope.

Results were validated by following a systematic approach. This was done by firstly introducing the reader to the system and its functionality, followed by an analysis of the existing system at operational level, and finally performing a risk analysis (FMECA). The risk analysis includes identified mitigating factors based on the FMECA study - hence the critical system components could be identified. The study ends with conclusions drawn from the system analysis and provides recommendations toward the design of a new system. Therefore, the validation of the results lies in the correctness and comprehensiveness of the method that was followed - if the method is systematic in nature, the results will be valid.

Detail design and implementation does not form part of this thesis and will be performed by researchers and developers by using the output of this work as input requirements. That is, the scope if this work is limited to operational analysis, technical analysis, and risk analysis and mitigation at this high level.

While development, operational, and maintenance and support costs are not ignored, the focus is simply on technical aspects so that the analysis is not cluttered with project management issues. Cost will be considered in future research and development as part of cost-effective development and design.

This thesis is presented as described in the following section.

Chapter 1 is the introduction which describes the basic functionality of a neutron monitor, and provides a basis for further analysis.

Chapter 2 provides a level 1 and level 2 operational analyses of the overall system and the four stations. Logistics, energy and data transmission are analyzed and presented, together with an "as is" analysis of each station. A logical abstraction is done to give both architectural (form) and operational flow (function) definition to the system. Finally, a link is established between functions and resources to be used in a later risk analysis.

Chapter 3 gives a risk analysis of the system by using a failure mode, effects and criticality analysis (FMECA). The system resources are intentionally "broken", compromised or removed, including human failure, in order to identify all critical elements of the system.

Chapter 4 provides a conclusion and recommendation based on the critical elements that were identified in the risk analysis. External and internal factors are considered and a list of specific and general design guidelines is provided.

The contribution of this research and development includes the following:

1. An "as is" analysis of existing operations with a physical configuration that is documented. This is the result of a time-consuming effort including a year-long visit to SANAE in Antarctica;
2. A logical / functional abstraction, also documented, to be used in the upgrading of the existing equipment and other system elements. This is a critical output since this affords developers and analysts a basis for future development;
3. A comprehensive risk analysis in the form of a FMECA. A list of critical components and mitigating actions resulting from the risk analysis is presented;
4. A recommendation for future development is given as part of the technology roadmap for the planned upgrade.

1.2 Overview of core functionality

Neutron monitors are used to count the number of neutrons that enter our atmosphere and (for the ground-based stations like those covered by this project) reach the earth's surface. By counting the number of neutrons, an indication of the intensity and number of cosmic rays entering the earth's atmosphere is obtained, which in turn gives indirect information regarding the sun's reactivity. The number of neutrons counted on the earth's surface, along with the number of cosmic rays entering the earth's atmosphere, is indirectly related to the sun's cycles and activities. The more reactive the sun, the less neutrons are counted due to less cosmic rays colliding with atmospheric particles, and vice versa.

Counting of neutrons is achieved when a small pulse – the result of a collision between thermal neutrons and boron-tri-fluoride or helium atoms – gets recorded each time a cosmic ray manages to enter our atmosphere, collides with an oxygen molecule and releases a high-energy neutron. These high-energy neutrons then result in thermal neutrons mentioned above as explained in more detail later on in this paper.

A basic neutron monitor consists of either a boron-tri-fluoride or helium-filled tube (it can vary from one tube to multiple tubes) with a high-voltage energy field set up inside it (Dighe 2007). This energy field causes a certain amplification effect, called *gas amplification*, when a thermal neutron collides with the tube's gas atoms. The amplification effect results in a small voltage pulse that is carried by the tube's centre wire to a pre-amplifier to boost the pulse's size in order for it to be counted. From here on electronic devices shape the pulse in order to be counted and recorded on a per-minute base.

Figure 1 Neutron monitor proportional tube with (out-dated) electronics

There are a number of factors to keep in mind when counting cosmic rays. One of the major factors is the atmospheric pressure at the site where the neutron monitor is operated. This is because this atmospheric pressure is directly related to the amount of air directly above the neutron monitor, and this value has a significant impact on the velocity of the inbound neutrons than should be counted by the neutron monitor. Another factor is the ambient temperature of the neutron monitor. The ambient temperature of the neutron monitor affects the density of the gas inside the tubes – therefore, the temperature should stay as constant as possible.

Specific primary and support tasks have to be performed on the neutron monitor at regular intervals. Checks to assure that everything is in perfect order including calibration of the pressure sensors are done on a daily basis. Monthly data processing and sharing is done to make the neutron monitor data available to everyone interested in cosmic ray numbers. This forms part of an international effort that generates useful information to determine sun activity cycles as well as space weather warnings for possible sunspot eruptions.

1.3 Neutron tube and pulse generation

The fundamentals as well as the operation of a neutron tube and pulse generation form the heart of the neutron monitor and are explained here. The physics behind the chain reaction to create thermal neutrons to be counted by the neutron monitor is described, followed by the electronics involved in counting cosmic rays. The basic signal path and setup of each neutron monitor proportional tube are shown in Figure 2

The current neutron monitor architecture (not showing the $230V_{AC}$ power connections to all the systems) is shown in Figure 1. This section continues the operation and peripheral connection from after the pulse to be counted is given by the logic level converter.

It also discusses the other peripherals connected to the neutron monitor, not actively used for counting cosmic rays, but also playing a crucial part in the neutron monitor operations or just monitoring environmental variables that influence the reliable counting of the cosmic rays.

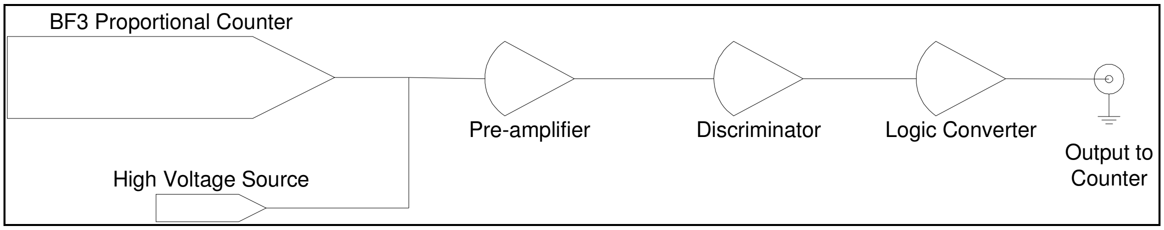

Figure 2 Basic operational structure of a neutron monitor counter

1.3.1 BF_3 Proportional counter tube

At the heart of the neutron monitor is the proportional counter tube filled with boron tri-fluoride, a toxic gas that has been enriched with the Boron-10 isotope with a high reaction cross-section to be excited by thermal neutrons. When a neutron reacts with the B^{10} nucleus, the following reaction occurs:

$$B^{10} + n^{1}(thermal) \rightarrow Li^{7} + He^{4} + 5MeV\ Kinetic\ Energy$$

The 5MeV kinetic energy resulting from the reaction (collision) between thermal neutrons and the boron nucleus causes a small voltage spike on the anode (centre wire) of the tube. This impulse is very small and can be detected by using sensitive electronic equipment.

When a positive high voltage is applied to the anode (as in the case with the International Geophysical Year tubes being used – referred to as IGY tubes), a very strong electric field between the anode (centre wire) and the cathode is created (the tube itself is the cathode, connected to ground). The force that the electric field exerts on an electron is directly proportional to the distance between the electron and the anode, decreasing as *1/r*. This means that an electron will be gradually accelerated from where initial ionization occurred (right after the neutron-Boron collision) to a distance *xr* from the anode where additional ionization as described in **section 1.3.2**, will take place.

In doing this, the electrons released by the 5MeV kinetic energy, cause ionization of other boron nuclei, resulting in them losing electrons, and supplying the anode with a "cloud of electrons" from this multiplication effect. This creates a larger, more detectable pulse. This is termed the gas amplification effect and is directly proportional to the original number of electrons released by the 5MeV kinetic energy.

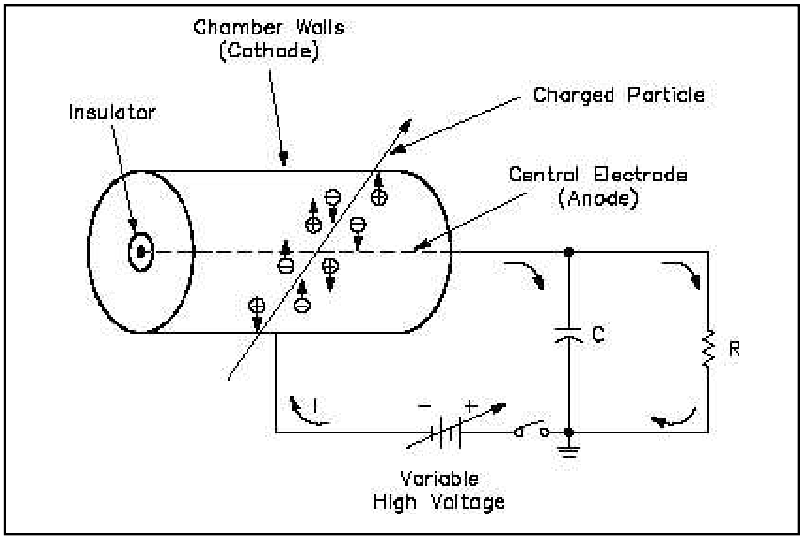

Figure 3 Gas amplification inside the proportional tube, with high voltage applied (Integrated Publishing 2003b)

1.3.2 High voltage DC supply

The avalanche (cloud) of electrons in the counter relies on the value of the supplied high voltage. In this particular case, making use of IGY tubes, the voltage must be kept at 3.6kV.

There are six basic voltage regions which produce different types of pulses and energy levels. The following graph represents these regions (using a tube filled with Argon gas, explaining the lower-than-mentioned voltage levels for each region).

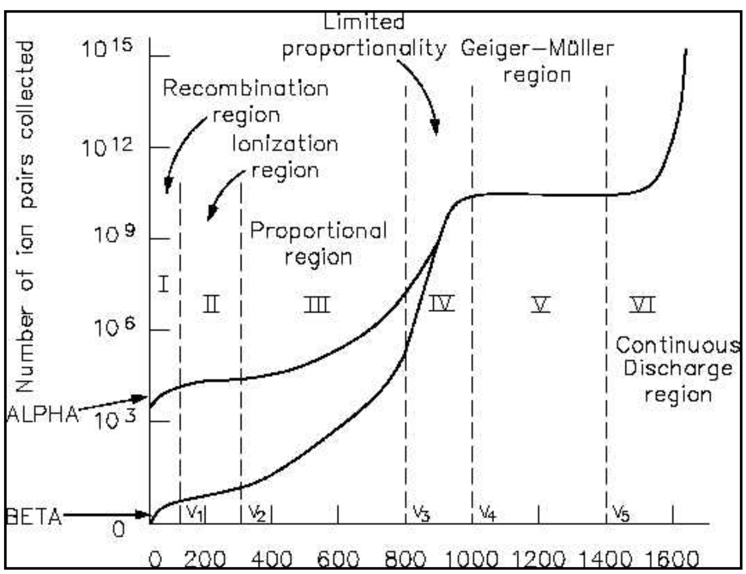

Figure 4 Applied detector voltage: Ion pairs collected vs applied voltage (Integrated Publishing 2003a)

1. In the Recombination Region (I) the applied voltage does not accelerate the electrons sufficiently quick for all of them to be detected because some of electrons recombine with free ions, resulting in neutral atoms and an insignificant pulse height;
2. In the Ionization Region (II) the applied voltage is strong enough to accelerate all the electrons released by the 5MeV kinetic energy and prevent recombination, but no gas amplification takes place, resulting in a very small pulse;
3. In the Proportional Region (III) the gas amplification factor A is proportional to the applied voltage, and the pulse height increases as the applied voltage increases. This means that more electrons are produced than the amount initially ionized;
4. In the Limited Proportional Region (IV) the applied voltage is of such a magnitude that ionization takes place very rapidly, with every released electron capable of "releasing" many more electrons. Due to the much higher mass of the positive ions and them being more inert than the electrons, they remain close to the point where ionization occurred, reducing the electric field to a point where further avalanches (Townsend avalanche) are impossible;
5. In the Geiger-Müller Region (V) the pulse height is independent of the number of electrons released by the radiation causing the initial ionization and the pulses are usually in the order of several volts. The field strength is so great that once the discharge/ionization is started, it continues to spread until further ionization is impossible due to the barrier of positive ions. The pulse height is relatively independent of the original number of electrons released by the radiation and the gas amplification factor is independent of the specific type of radiation to be detected;
6. In the Continuous Discharge Region (VI) the applied voltage is so high that any high-energy particles (n, $\mu^{+/-}$, $e^{+/-}$, p^+, γ) cause ionization that saturates the anode and delivers the same amplitude pulses. This renders the detector basically useless to specific radiation detection.

Should voltage levels higher than that defined for the Continuous Discharge Region be applied, it will cause sparking (corona) between the anode and cathode inside the tube, damaging both the tube itself and decreasing the concentration of the gas used inside the tube. It is therefore important to design a HV supply unit that will not be able to exceed the HV rating for the tubes (Integrated Publishing 2003a).

The tubes are designed to draw very little current, as the anode and cathode are not connected via conducting materials like copper or gold. The only medium that connects the anode and cathode is the Boron-Tri-Fluoride gas inside the tube. The only current that will be drawn by the tube is when the tube is set up by the correct HV applied to get it into the proportional region of operation and the gas amplification factor starts playing a role. The current drawn in this state is also assumed to be in the order of of microamperes, but an effort will be made to accurately measure / determine the current.

1.3.3 Pre-amplifier

The pulses created by ionization in the Geiger-Müller Region are fairly large, typically in the range of one Volt. This is definitely not the case in the Proportional Region, using BF_3 or the new ^3He gas-filled tubes. The amplitude of the pulses for a Proportional Counter using BF_3 is typically in the millivolt range, and perhaps 10 times smaller for ^3He.

Therefore, a pre-amplifier is used to enlarge the pulses that are created on the anode wire. In the case of ^3He being used, the pre-amplifier is connected directly to the anode wire - with no extra wiring in between - to overcome the transmission losses.

1.3.4 Discriminator

After the pulses have been amplified by the pre-amplifier, it is necessary to determine which pulses are relevant to the direct study of cosmic rays. Due to the physical construction of the Proportional Counter tube, some of the neutrons that enter the tube are not moderated (slowed down) enough by the surrounding polyethylene or wax, and continue their way through the tube, while causing ionization along the way, only to be reflected by structures surrounding the tube. The second time around these neutrons will be further moderated by the polyethylene/wax, but will still cause ionization inside the tube. The pulse resulting from this “secondary ionization” will also be amplified by the pre-amplifier, but does not have to be counted (Stoker 8 June 2000, 4-19).

Another important reason for using discrimination levels is to ensure that only one kind of radiation is measured. Although the Proportional Counter operates on one specific kind of radiation, other forms of radiation like muons (μ), gamma's (γ) and particularly photons can have an impact on the final count of the monitor when no control over the pulses to be counted is applied. The neutrons caused by photons usually have much less energy than the neutrons produced by the intergalactic cosmic rays. The photons, however, have the tendency to produce single neutrons with each collision and these slower neutrons can cause pulses that are thus not relevant to cosmic rays and should not be counted.

The discriminator therefore sets up a threshold value to define which pulses will get counted and which pulses will be ignored. Although the discrimination level is predetermined based on the reaction properties of the tube (either BF_3 or ^3He) with a thermal neutron, the purpose of a discriminator or discriminating device is to create a dynamic discrimination level in order to study a broader spectrum of cosmic ray intensity and particle composition, and to be able to determine the effect of ambient radiation on the monitor itself (Stoker 8 June 2000, 9).

1.3.5 Logic level converter

After the pulses have been discriminated and only those that are relevant to the study on cosmic rays have been permitted to pass, the pulses (quite often with very short pulse width of a few microseconds) are converted to a more manageable level for the counter system to interpret. Each pulse is converted to a pulse with width of at least 20μs to enable the slower counter to record all pulses.

In the present neutron monitor counter, this amplified and shaped pulse is the only output from the tube to the computer.The dynamic discrimination level, as described above, gives a pulse together with its associated discrimination level and shape.

1.3.6 Additional measurements

Additional measurements that are required for accurate counting include the following:

- **Time and location**: The current neutron monitor setup mainly uses GPS units for timing, but the exact neutron monitor location is also used when the data coming from the neutron monitor is integrated in other reference systems and research resources. This data forms part of the global neutron monitor and geophysical / space weather research community. Data on different cosmic ray intensities at different neutron monitor locations can then be used to support other projects like geomagnetism and ionospheric research. For neutron monitor counting purposes only the GMT-time factor of the GPS signal is extracted and used to synchronise the computer clocks used to capture and store the data. This is done to ease the comparison of different neutron monitors' data and eliminates the adjustmend of the time scales for major events that are of importance to the client;
- **Pressure**: The atmospheric pressure measured at a neutron monitor is directly related to the density of air particles above it. This "column" of air should be brought into consideration when counting the neutrons caused by cosmic particles as it determines the velocity with which the neutrons will hit the monitor tubes. As described in **section 1.3.1**, the velocity of the inbound neutron will determine how many thermal neutrons will be released by the lead that surrounds the proportional tubes, thus determining the number of chain reactions inside the tube and the size of the pulses that emanate from the tube (Stoker 8 June 2000, 2). All of the neutron monitors under the CSR's control make use of Digiquartz Paroscientific Pressure Standard devices that are returned to the manufacturer at regular intervals for calibration inspection purposes. They are manufactured to give an accuracy of 0.0001% and a guaranteed minimum pressure drift (error) of 1hPa (hektopascal, 1 hPa = 100 Pa) over 3 years;
- **Temperature**: The ambient temperature of the neutron monitor is also important because reaction of the Boron-gas gets affected by extreme temperature variations. The consistency of the gas in the tube (as with any other gas) changes as its temperature changes, and because the tube is operated at high DC voltage levels, the desired region of operation of the tubes might be compromised. This can lead to a tube with little or no response due to extreme

cold or internal sparking that shortens the tube's life due to extreme heat. In certain instances the temperature can be controlled using air conditioners and heaters but the tubes' response to the ambient temperature as measured by its own temperature sensors, describes a capacitive temperature value. This means that the tube temperature takes much longer to change than the ambient temperature.

1.4 Summary

In summary, the functionality of the core of the neutron monitor system was described in this chapter. It is evident that, apart from the complexity of a neutron counter unit, external factors play a significant role in the accuracy of measurements. In addition to fundamental neutron detection and pulse generation, the supporting measurement functions must be provided, supported and maintained – this is achieved by a rather complicated system of facilities, equipment, human resources, logistics, and communication.

The overall system that counts, processes, stores, and communicates neutron counter data is very important and is the subject of the following chapter. The complexity of the overall system is easily overlooked when only the core functionality of the neutron monitor is considered, ie the detector and counter. The value of a proper system analysis will become evident once the system has been presented in a comprehensive manner in the following chapters.

Chapter 2 Operational analysis of existing neutron monitor system

2.1 Introduction

The analysis of the overall system proceeds in this chapter with an analysis at the highest operational level (level 1) with a focus on the overall system in terms of the system deployment, logistics, energy supply, human resourcs, and data communications. This analysis is later conducted at a deeper level, level 2, where individual stations are analyzed in more detail.

Each neutron monitor is situated at a different location because the earth's magnetic field line density is not the same for every location on earth, and therefore the cosmic particles at one monitor have different characteristics than others. As a result, the system requires different transportation methods (logistics), different support structures and different maintenance strategies to keep the monitors running smoothly. If, for example, the Potchefstroom or Hermanus monitor requires a new PC immediately, then one can be bought, set up and installed in a matter of hours. But should the SANAE (Antarctica) monitor suddenly need a new UPS or even just a ream of paper to print the monthly data images, then it has to be cleared by customs, either flown out to SANAE from Cape Town using a special airplane (permitting that it is in the Antarctica summer period) or shipped with an ice-breaker or shipped with ice-breaking and ice-strengthened capabilities (permitting that it is still within the Antarctic summer period).

So, each monitor has its own unique logistics requirements, data retrieval, energy supply, and support personnel and it was very important to keep these issues in mind when an analysis for this project was done.

2.2 System life cycle

The functional flow analysis of the neutron monitor system begins with a full life cycle flow. This is done by taking into consideration that the neutron monitors have been operating for the best part of 60 years and that immediate upgrading and planning for future maintenance is imminent. In addition, a detailed maintenance and scheduled upgrade plan must be designed in order to ensure the reliable operation of the neutron monitors in future.

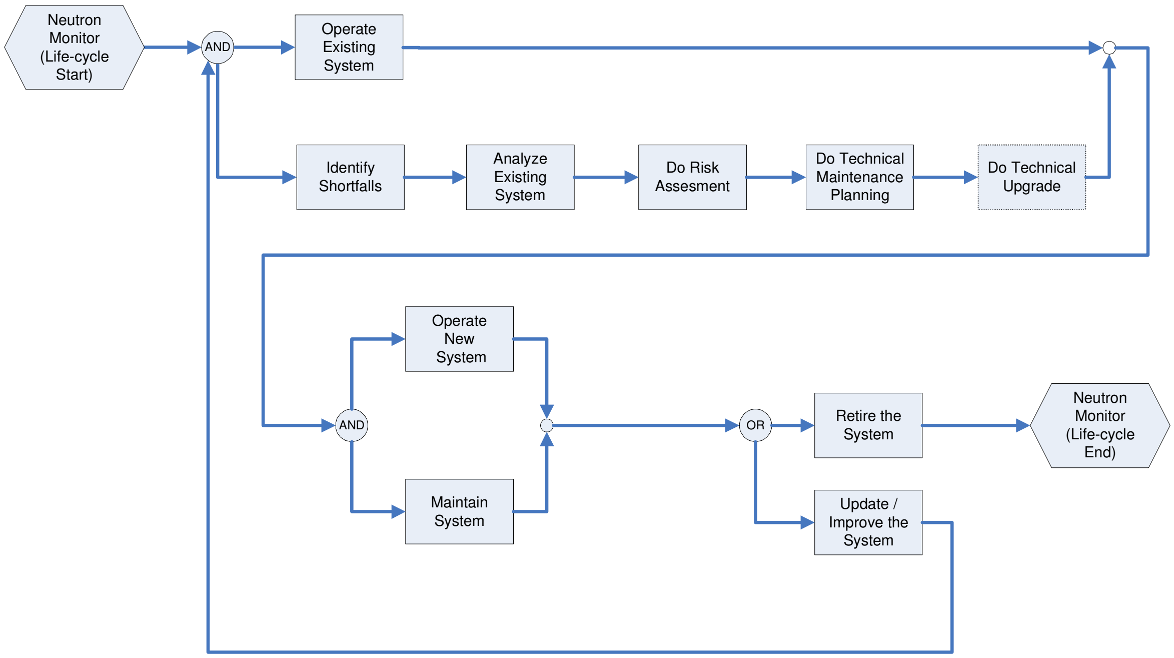

Figure 5 Neutron monitor life cycle with current and ongoing operation

The detail design and implementation of the upgrade and maintenance functions and resources for the neutron monitor system do not form part of the scope of this work. This work includes operational requirements, high-level design requirements, and a failure mode and resulting risk analysis.

Documenting a development and design is an integral part (and almost inevitably, a major risk) of each step of the entire system life cycle and must be performed throughout if a system is to be sustainable. A major shortfall of the existing neutron monitor system is the lack of documentation (technical data and user data), almost inevitably requiring the “reinvention of the wheel” in a manner of speaking. This document thus forms the input document to the remainder of upgrade / development work that will result from a high-level risk analysis – a classical case of an incremental innovation where new technology and associated processes are improved in an existing system.

The complete life cycle of the neutron monitor systems for the CSR is shown in Figure 5 with the start of the life cycle being the current neutron monitor system with its current technologies, components and peripherals used, and its end being the neutron monitor setup after the upgrade has been done and the decision that neutron monitor techniques are obsolete has been made.

The detail design and implementation (the technical upgrade) are not part of the scope and are therefore enclosed in dotted blocks. Also, the description of the current neutron monitor setup as starting point for the system life cycle was done in the previous sections, so the operational analysis of the system life cycle begins with identification of the shortfalls of the current system, followed by analysis of the existing system, risk assessment on the critical parts and a technical maintenance plan.

2.3 Deployment and logistics of the neutron monitor system

Should anything go wrong with the neutron monitors and someone from the head office in Potchefstroom had to visit the remote stations, or if any spares had to be sent to one of the stations, an established logistics path must be used in order to ensure that the spares get there on time, or that the person responsible for checking the system can get there as quick as possible and do repairs, modifications or verifications.

Therefore, the logistics paths were analyzed and recorded for comprehensiveness.

2.3.1 Potchefstroom NM

As the CSR head office is in Potchefstroom it is not a problem to access this monitor should anything go wrong. The Potchefstroom NM is connected to the University's local ICT data network, so the NM data can be accessed either through the network or by visiting the NM itself and physically copying the data to HDD or flash drive.

Potchefstroom has its own business community and computer support and both general and specialised electronic equipment can be bought with limited uncertainty. Should other specialised equipment be needed, either new, replacements or to be repaired, Potchefstroom is close enough to big centres like Gauteng to order equipment from abroad to be couriered to Potch.

Potchefstroom also has – because of the university – a good knowledge-base and should specific knowledge be needed, the Faculty of Engineering or IT support can provide support (and have done so in the past).

2.3.2 Hermanus NM

The Hermanus neutron monitor is situated in an old building on the premises of the Hermanus Magnetic Observatory (HMO). Logistically it is two hours' drive from Cape Town International Airport (keeping in mind that Potchefstroom is about two hours' by car from OR Tambo International Airport) and therefore relatively close to a major centre should replacement parts for the NM be needed. The downside, however, is that all major maintenance is performed by personnel travelling from Potchefstroom to Hermanus. The personnel used from the HMO to monitor the NM are not trained to perform maintenance.

When one of the Hermanus PC's has to be replaced, all the necessary software is installed and the PC gets tested in Potchefstroom (because all the NMs essentially have the same hardware setup) after which the PC is flown to Hermanus to be installed.

These maintenance and checking operations can be done throughout the year and represents the primary logistics effort travelling to and from Hermanus.

From the above it is obvious that remote management is a requirement. That is, diagnostics and built-in test capabilities are critical to succes.

2.3.3 Tsumeb NM

The Tsumeb neutron monitor is situated in an old Alfred Wegener Institüt (AWI) building that was transferred to the CSR for operation. It is more or less two hours' drive from Tsumeb and it has basically the same logistical requirements as the Hermanus NM. Although all major technical alterations or repairs must be done by someone from the Potchefstroom NM, minor checks and operations are performed by local personnel.

Like with the Hermanus NM, if a PC or other equipment should be replaced at the Tsumeb monitor, it is assembled and tested in Potchefstroom and then transported to be installed by one of the CSR personnel. The Tsumeb NM can be reached throughout the year and again the inconvenience and cost are from travelling between Potchefstroom and Tsumeb.

The above analysis motivates the requirement for a modular design that supports testability (remote, to be specific).

2.3.4 SANAE neutron monitor, Antarctica

With geographical coordinates 71°40"S 2°51"W the SANAE neutron monitor is the southern-most and most secluded NM in operation for the CSR. Here the logistics become very challenging and logistics planning becomes crucial, as the station can only be reached once a year, for a total period of 3 months by sea, or at most 6 months by air.

Part of this investigation was to visit the SANAE station in order to do a physical audit on the SANAE neutron monitor. This is done on an annual basis where a person is located at the base for a period of one year.

The SANAE station is located in a harsh environment that can be very strenuous on both electronic equipment and the personnel responsible for the base and its science projects. Spare parts that are sent from Potchefstroom to SANAE will at times comprise complete computer and electronic systems. These systems are not necessarily interchangeable and modular, and the person responsible for the NM throughout the year should be able to do routine maintenance as well as upgrades as necessary. This individual should place orders at Potchefstroom for spare parts and components regarding the NM and other science projects under the CSR's control.

So logistically speaking, the team member stationed for a specific year at SANAE is responsible for ordering most of the spare parts for the following year's team member. These orders can then only be shipped to SANAE every year-end, or if it is of critical importance, it can be flown in between October and March. Those are the only times and mechanisms for transporting supplies to Antarctica and SANAE.

SANAE, as well as the islands that are of scientific interest for South Africa, Marion and Gough, are all serviced at least once a year by the multi-purpose vessel, the SA Agulhas. The islands can be visited more regularly should the need arise, because they are in unfrozen (albeit stormy) seas. During winter months the sea ice forms and extends for hundreds of kilometres around Antarctica, making it impossible for the ship to deliver supplies to SANAE. As said, the same ship also services the two islands, which increases the risk of sinking and not being able to service the NM at SANAE.

There is, however, collaboration between RSA and the other Antarctic beneficiaries, and ships like the Polarstern (German) and the Naya Arktika (Russian) may be used in special events.

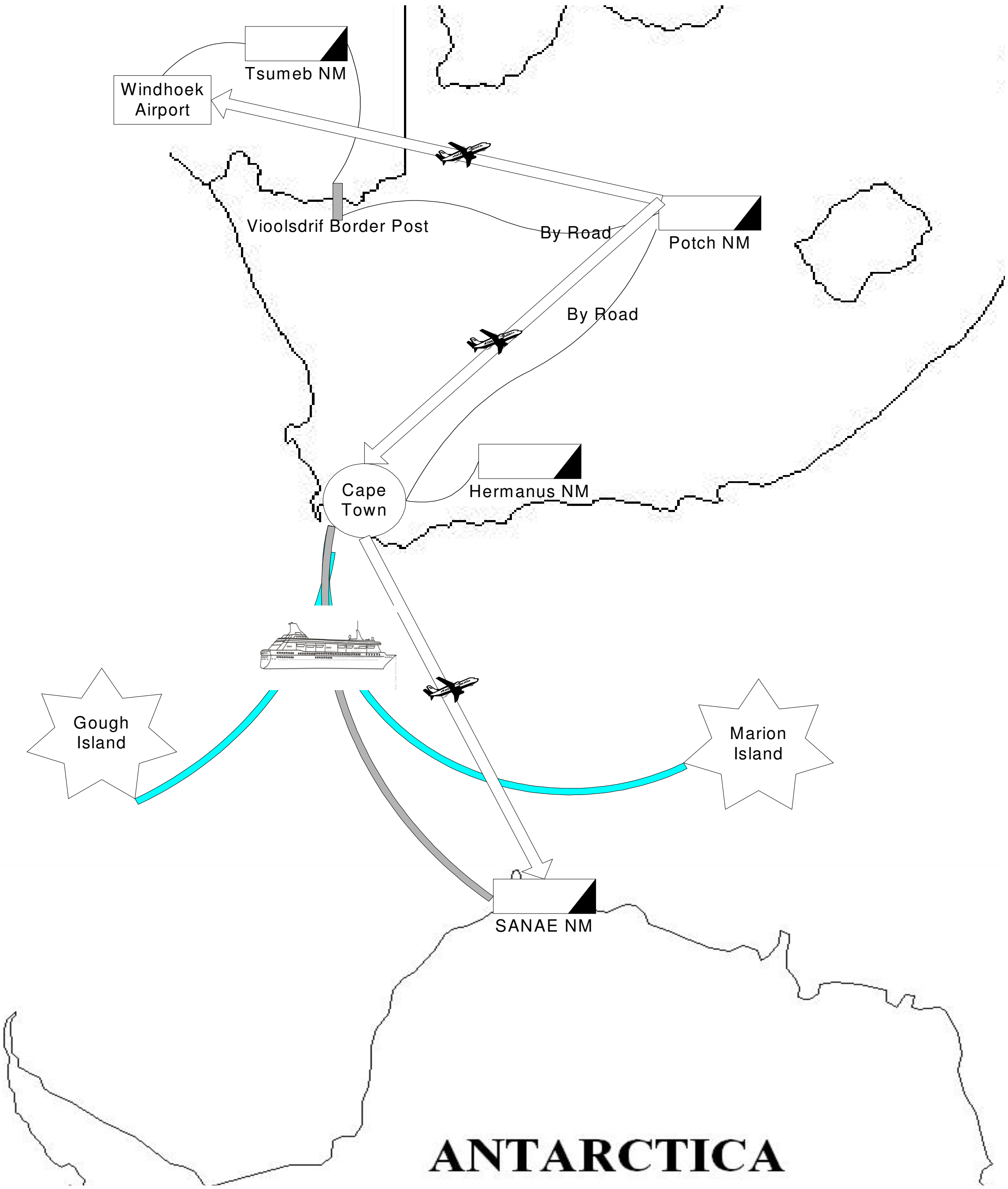

Figure 6 Logistics map of CSR neutron monitors

2.4 Power generation and supply requirements

All stations rely on a supply of power to operate their electrical and electronic devices, control temperature etc. Each station also has certain devices to cope with power failures since these failures, as well as the resulting power surges when the main power supply is restored, can seriously damage electronic equipment. In general, PC's do not respond well to power failures and the design of electronic components to handle power surges can only be built to absorb surges within reasonable limits (Williams 2007, 13, 259).

UPS's must be used to filter out unwanted power dips and surges and a well-designed, reliable UPS is critical.

2.4.1 Potchefstroom NM

The Potchefstroom neutron monitor obtains its power from the national Eskom grid after it has been filtered by an online UPS with 10kVA rating. In line with the UPS is a smaller 1kVA Line-Interactive UPS to drive only the PC's recording the NM's data. This setup can support the entire Potchefstroom NM system, consisting of two PC's and low-voltage and high-voltage supplies, as well as pressure and temperature measuring devices for a period of 6 hours. This 6-hour backup time includes the UPS power being shared between the NM and feeds in the CSR offices that are used for connecting PC's. The CSR's building is being upgraded at the time of this document and a UPS should be allocated for exclusive use by the NM.

The CSR would rather not want the UPS to use up all its backup power, so a generator and Lister motor were installed close to the NM years ago. With a long-lasting power failure (such as an Eskom load shedding power failure) one of the CSR personnel usually starts the Lister and monitors the power to turn the Lister off once normal power from the grid has been restored. This procedure will be preserved with the upgraded building, that is, to supply the UPS with backup power should the grid power fail.

The North-West University itself invested in backup generators for the whole Potchefstroom campus to provide power should Eskom load shedding take place. The NM of the CSR also benefits from these generators, as the Lister can then still be used as backup, and the UPS will filter out unwanted spikes and dips without draining its batteries for backup.

2.4.2 Hermanus NM

Just as the Potchefstroom NM, the Hermanus neutron monitor receives its power from the Eskom grid after it has been filtered by two independent UPS's. The current configuration is still that the two UPS's effectively split the recording system by running one PC and measuring instruments from the one UPS, and the remaining PC with other measuring instruments and the counter box and master-slave box on the other UPS.

The Hermanus NM runs from the same supply grid as the rest of the HMO so it has a mutual interest in uninterrupted power to the HMO. The HMO has its own diesel-electric generator for backup.

A manual restart by HMO personnel has been negotiated in case of power down at the NM in Hermanus – this alleviates the burden on Potchefstroom personnel.

2.4.3 Tsumeb NM

As Tsumeb is situated in Namibia, it is reliant on Namibia's national electricity provider – Ministry of Mines and Energy, Namibia - and grid to supply power. UPS's are installed. A 10kVA inline invertec UPS receives the supplied electricity from grid or generator and connects it through to the neutron monitor. Another smaller UPS is connected between the large UPS and the NM computers for redundancy on the computer systems. There is a power generator for backup power for the whole station and the Ministry of Mines and Energy has an agreement with the operator at the neutron monitor to inspect and repair the generator as well.

2.4.4 SANAE NM

All electrical or electronic equipment at SANAE relies on the three diesel generators at the base. These generators form the heart of SANAE, as it is the main source of both power and heat.

The theory behind three generators is that any two can be used at any one time, and that there is always one generator for backup. This backup generator then takes over automatically when one of the other two generators experience a problem or needs to be taken out of the electricity supply system for scheduled maintenance. When the base was opened for use in 1997, the three generators could deliver al least 160kVA each, but as time went by, capacoty declined to between 100 and 140kVA. The generator control system is also showing the effect of ageing and the system as a whole requires an upgrade or total reconditioning.

The effect of ageing is that generators start to hunt (as a result of voltage differences) as the base's electricity demand starts rising (especially in winter time and with take-over). The water cooling system op the diesel engines are no longer working optimally and also requires maintenance. Operators have started improvising and the hangar door is left open in order for the engines to cool down, which causes air pressure problems throughout the base.

This hunting can cause problems in the base, ranging from from minor irritations like dimming lights to serious damage like UPS's that are damaged due to power fluctuations and surges. A damaged UPS causes major secondary damage when computers and other sensitive equipment break.

Being engines that run on diesel fuel, they are dependent on a constant diesel supply. The amount of diesel consumed per year amounts to about 400,000L that has to be supplied by the SA Agulhas at every change-over. A diesel leak in the fuel line (any failure of the fuel line) is thus a major risk that must be mitigated – a requirement is thus to monitor and manage the fuel line (either procedurally or automatically).

During change-over the exhaust system of the diesel engines are cleaned, which results in at least a day where the base is without electricity. During this time all experiments are shut down in order not to drain the UPS batteries unnecessarily.

The base itself has 3 x 20kVA UPS's, of which one is solely used to power the generator PLC's (programmable logic controllers – used to monitor and control power generation), and emergency lighting in the hangar, engine room and B-Block. One generator is used to power emergency lighting in A-Block, as well as the base VHF radio's and emergency medical equipment. The third generator is used to power all the scientific equipment inside the base and has lines to various scientific instruments outside that also require UPS power. See **Appendix A: Physical layout** for a layout of the SANAE base.

Figure 7 Diesel generators at SANAE IV

Separate from the base is the satellite hut, containing the satellite communications dish as well as its own UPS. Slightly further on are the diesel bunkers, connected to the base with a long pipeline, that feed into a day-tank that keeps enough fuel for at least 3 days.

Figure 8 Diesel bunkers and diesel pipeline to base

2.4.5 Cape Town

Cape Town does not have a neutron monitor, but the data communication satellite access point is in Cape Town, adjacent to the Department of Environmental Affairs' (DEA) offices.

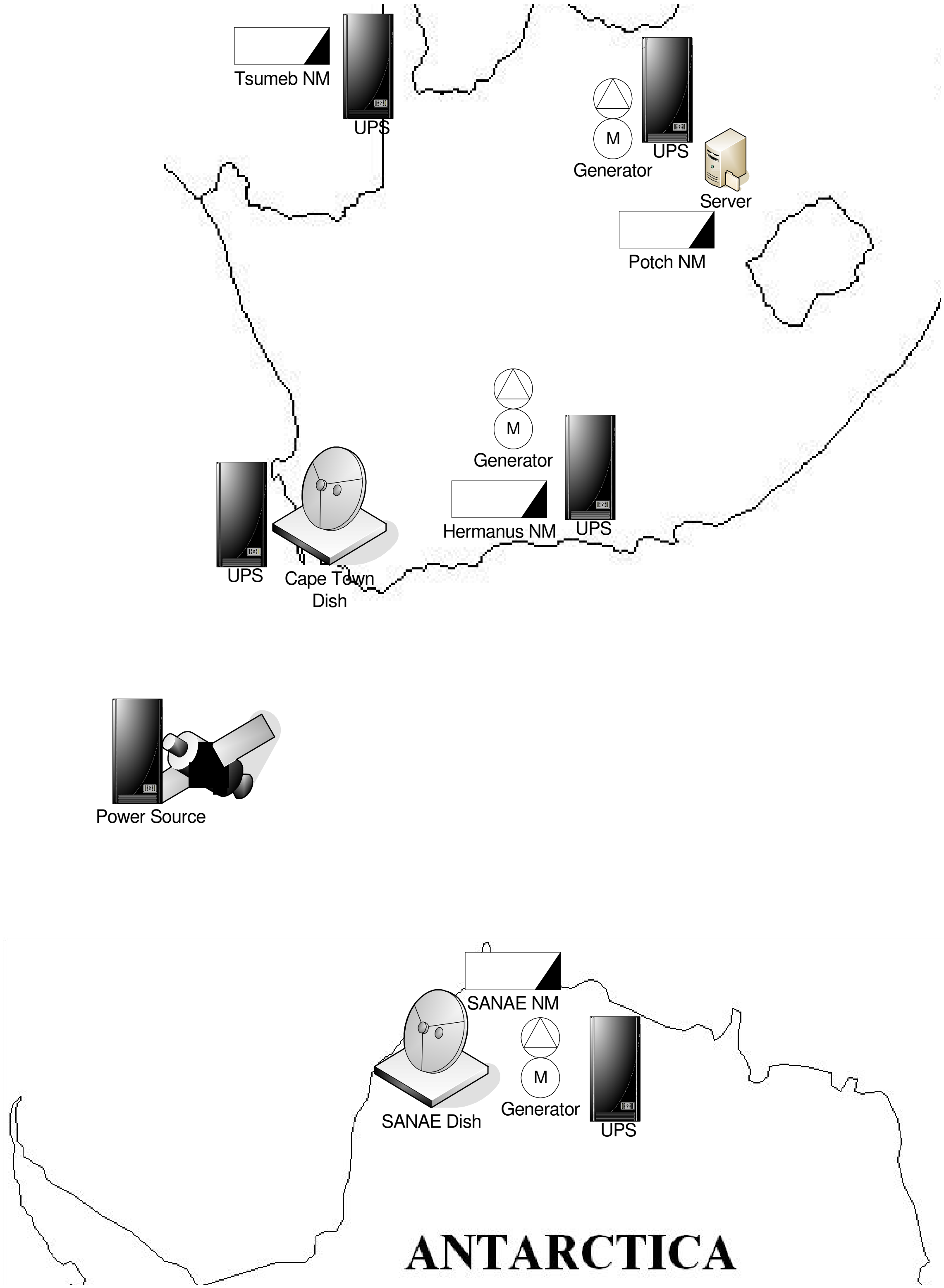

Figure 9 Energy setup for the CSR NM's

The satellite-ADSL communication system in Cape Town is the central distribution point for both data and telecommunication to and from SANAE and the two islands, Marion and Gough. It also forms part of the DEA's telecommunication and internet network, so the SANAE monitor benefits from the fact that there is maintenance and support from a third party with similar commitment.

The central distribution point is also reliant on Eskom grid power and has a UPS backup. No generator backup is provided for either the satellite link or the offices.

2.4.6 The satellite (InfoSat)

The satellite itself runs from batteries and solar panels onboard and has been operating without failure. Previously the Department of Foreign Affairs managed the satellite connection as South Africa rented a certain amount of bandwidth from the satellite operators. But should the satellite's power supply fail, the data generated by the SANAEM NM should at least be stored on site and brought back to Potchefstroom.

2.5 Data transmission and access requirements

The software specialist in Potchefstroom (who is also the person responsible for collecting and storing all four stations' data) is responsible for (or in the case of the SANAE NM should at least be able to) retrieving the data collected by all four NM's. In order to achieve this a very good duplex data channel between Potchefstroom and the neutron monitors needs to exist.

2.5.1 Potchefstroom NM data retrieval

The Potchefstroom neutron monitor is connected to the university's local network (wired LAN, not wireless), so data retrieval from this NM is done by logging in to the NM PC's and copying the data. The Potchefstroom NM is also close by the CSR head office, so should the network be down for maintenance or because of failure, the data can be retrieved by connecting a flash drive or external hard drive to the PC's and copying the data.

2.5.2 Hermanus NM data retrieval

The Hermanus NM data can be retrieved over the internet. The kind of data that the CSR collects with its NM's is not of a sensitive nature and security is not a major concern. The same person responsible for the Cape Town to SANAE data connections also manages the internet and data connections to Hermanus. This person authorises data access to specific IP addresses, one being the IP address from the software specialist in Potchefstroom responsible for retrieving the data.

2.5.3 Tsumeb NM data retrieval

The Tsumeb NM is reached by first using a dial-up connection to a GSM modem installed at the Tsumeb station. This is because there is no landline installed and the cost of installing a line has made it more attractive to use a GSM modem. Then, as with the others, the internet is used to copy the data to Potchefstroom. When the software specialist from Potchefstroom cannot get internet access to the Tsumeb NM, a system reset is done by personnel at Tsumeb.

2.5.4 SANAE NM data retrieval

The same person who is responsible for data systems and IP address authorisation at the HMO is also responsible for the same authorisation for SANAE NM data acquisition. SANAE and the Islands have a dedicated satellite communications connection to Cape Town, from where it connects to the internet using an ADSL line. This line is also used for the entire Cape Town DEA internet and the satellite bandwidth is shared among SANAE and the Islands. This can make the connection and therefore data retrieval very slow.

The software specialist at Potchefstroom does not need (but should always be able) to retrieve data. Instead, the CSR year team member sends the data to Potchefstroom and leaves it on a secure cluster computer in Potchefstroom. The software specialist then collects the data from the cluster and makes it available to the academics for editing.

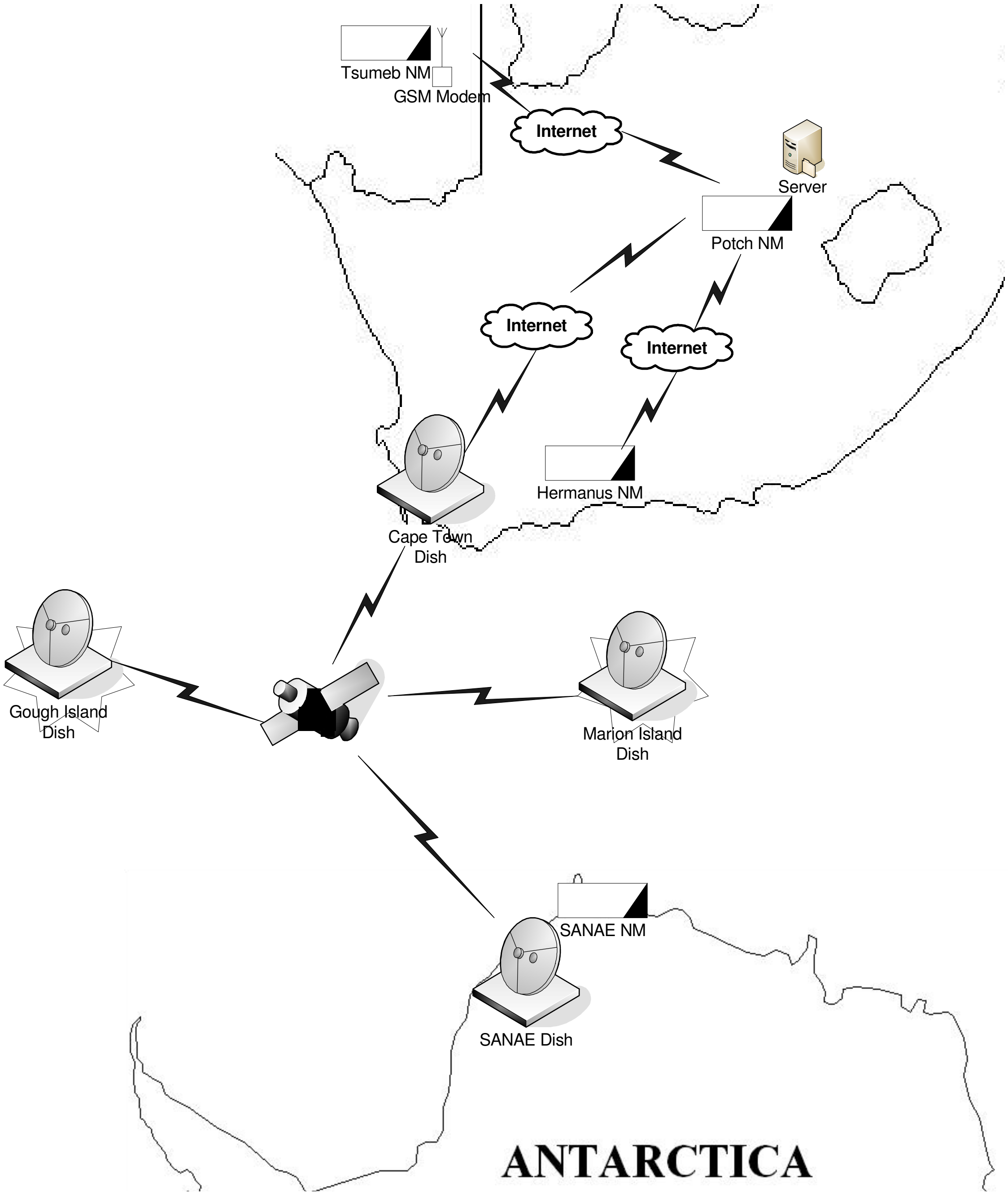

Figure 10 Data Channels for the CSR neutron monitors

2.6 Physical configuration

In order to gain an improved understanding of the operations, it is necessary to analyze each station's "as is" physical configuration. This provides insight into the layout and resources required to perform "as is" functions.

The diagrams in **Appendix A: Physical layout** show the physical layout of each neutron monitor station. From these diagrams, system functions and issues (such as EMC) become evident for consideration when the complete system analysis and systems engineering solution is done. This is to ensure that future development (towards an improved neutron monitor) keeps all aspects in mind that could potentially hamper the neutron monitor's reliability and the implementation of a detailed operational, maintenance, upgrade and commissioning plan. In addition, this analysis will result in a thorough design specification and requirements document for upgrading or modifying the existing monitor in the long term.

To perform this analysis, a significant amount of time was spent to study the existing facilities, personnel job descriptions, equipment layout and reticulation amongst others. It also included a year-long visit to the SANAE station where the challenges where experienced first-hand. Each station was analyzed and is shown in **Appendix A: Physical layout** *for the sake of being comprehensive, after which a logical abstraction was done. The abstraction was done to ensure technology independence and to simplify the risk analysis (and to make the risk analysis applicable to future technology upgrades as well). In the sections that follow this abstraction is presented as the logical configuration of each station.*

2.7 Logical configuration

Physical systems layout can be confusing at times, so the logical layout of a neutron monitor system was done to simplify and improve the description of the system (representation of the system at facilities and equipment level – i.e. level 2). Also, the interconnectivity and interfaces between resources become clear and risks are highlighted with much more ease. Here, each resource and interface will also receive a reference (tracking) number to ensure traceability throughout the system analysis and ensuing lifecycle phases.

An abstract view is also useful when mapping all resources and system components for functionality and critical component failure analysis later on when the risk analysis on the current neutron monitor system setup is done.

Most of the resources and interfaces are the same for each neutron monitor station, the only difference being their physical location or, as in the case of the human resources, the different people needed for the successful operation of the neutron monitor. The biggest difference in logical setup is with SANAE, where the logical power distribution and connectivity are different from the mainland. The resources and interfaces are described in detail, with special attention to those resources and interfaces that differ from their mainland equivalents.

As the Potchefstroom neutron monitor is situated at the CSR head office and it being the most well known monitor of the four used by the CSR, its resources and interfaces are taken as the norm, and all the other neutron monitor stations' configuration will be described with reference to those of the Potchefstroom monitor. The Potchefstroom NM configuration was done to create a baseline and all the resources and interfaces were given global descriptive names and acronyms. These resources and interfaces are therefore divided into three distinct groups that form the basic building blocks for operating and maintaining any neutron monitor: Counter, Energy and Data.

Counter sub-system: The Counter sub-system includes all the resources and interfaces necessary for the neutron monitor to count neutrons. This is the main function of the neutron monitor system.

Energy sub-system: The Energy sub-system includes all the resources and interfaces to deliver electricity to the neutron monitor and to enable the Counter-subsystem to operate. This sub-system depends on external factors that must be taken into consideration when doing a risk analysis.

Data: The Data sub-system includes all the resources and interfaces to collect, store, review, edit and publish the neutron monitor data. It also relies on the Energy-subsystem for electricity, and on the Counter-subsystem for its initial data. Therefore it has both Counter- and Energy-subsystems as interdependent resources.

2.7.1 Counter sub-system

The resources and interfaces for the neutron monitor counter-subsystem are depicted in Figure 11 on the following page. The resources are either equipment that give a certain input to the monitor (tangible devices that connect to the neutron monitor computer, like the pressure and temperature sensors), or people operating, maintaining or checking the neutron monitor operations.

The interfaces are all the input/output connections and devices (like wires and computer mouse and keyboard) used by the neutron monitor to connect to its resources. These interfaces can be either hardware (like the physical wires, connectors and computer mice) or software (connections between programming procedures and sections of code).

The neutron monitor system software (software resources) is the hub where all the peripheral devices and interfaces converge to give the neutron monitor its meaning and purpose. These resources include, for example the gathering of the neutron counts by the counter tubes and the value of the atmospheric pressure, as well as daily operations to make sure the neutron monitor functions correctly.

It is necessary to distinguish and describe the three human resources required for neutron monitor operation. It is instructive to firstly define the hierarchy of human interface in order of importance, namely: Scientist, Maintenance, and Operator.

The **Scientist** is at the the top of the hierarchy, because this person is going to use the data for scientific work and make it publicly available to other scientists that will benefit from the collected data. It is therefore the Scientist who has the last say whether data is correct and ultimately whether the neutron monitor functions correctly. When the scientist notices an error or problem with the neutron monitor, the maintenance person (called the “Maintainer” for the sake of simplicity) should be notified immediately so the necessary actions can be taken. <u>The Scientist is in certain instances also the Maintainer and Operator in terms of functional definition</u>.

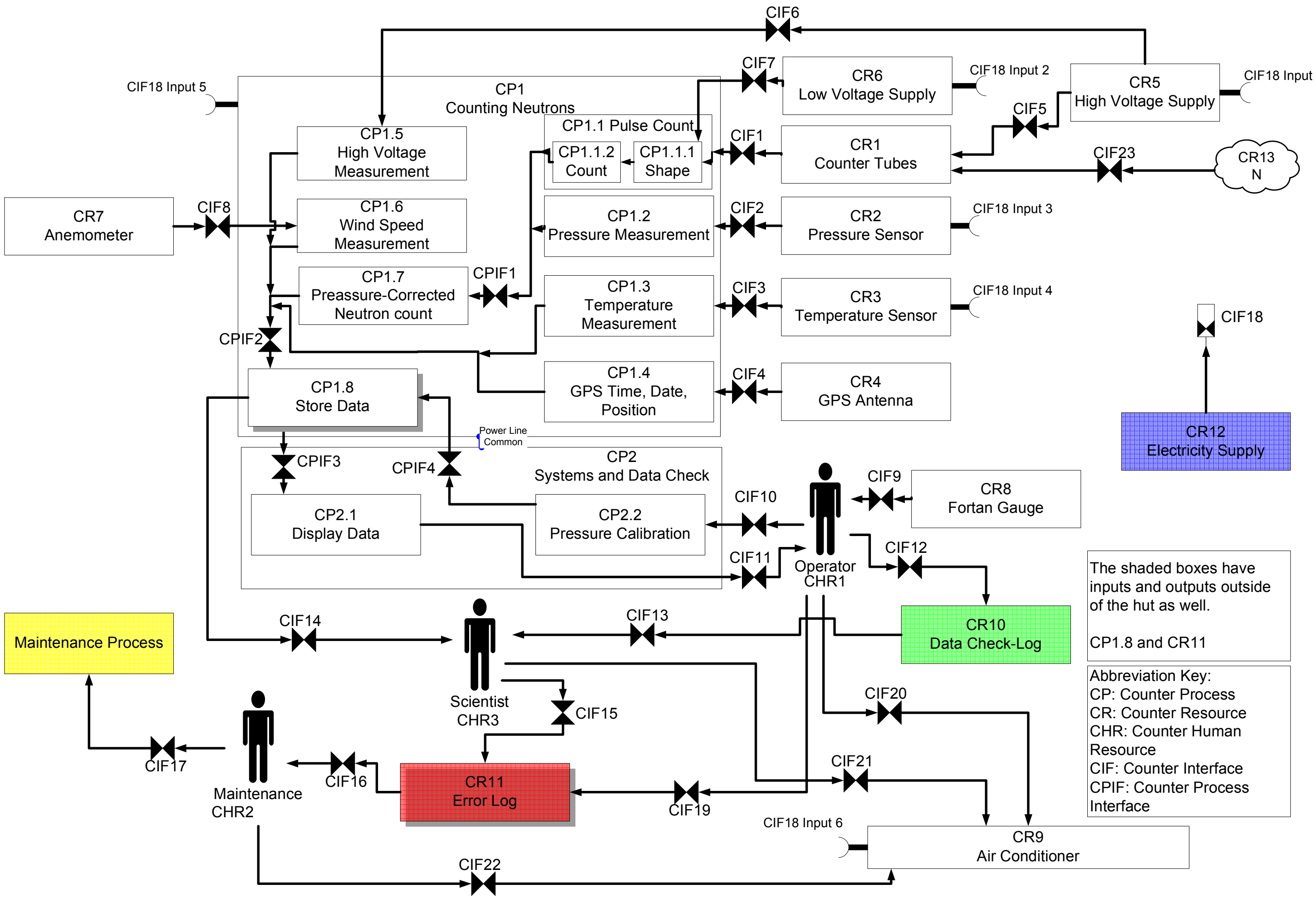

Figure 11 Neutron monitor logical layout of the Counter-subsystem

The **Maintainer** must ensure that the neutron monitor functions correctly based on what the Scientist instructs. The Operator can also report on technical faults to which the Maintainer must respond. The Maintainer traces, tracks and repairs all faults and problems that are noticed in the neutron monitor system, either from scheduled or unscheduled maintenance activities. When the Maintainer notices an error or problem, the Scientist should be notified immediately so the severity of the problem can be determined and necessary actions be taken. The Maintainer is in certain instances also the Operator, but never the Scientist.

The **Operator** executes the daily monitoring procedures of the neutron monitor and makes sure by means of inspection (having been trained by the scientist what the neutron monitor system response should look like) that the neutron monitor operates correctly. If the Operator notices an error or problem with the neutron monitor, the Scientist and Maintainer should be notified immediately to take the necessary actions. The Operator acts on his own and cannot be the Scientist or Maintainer.

2.7.1.1 Counter sub-system hardware resources

CR1: The proportional **counter tubes** of the neutron monitor are the first and foremost resources of the neutron monitor system. The precise operation of these tubes has been discussed previously, and the reader will gain insight in the setup of these tubes. Each station has a different number of tubes, resulting in a differing neutron count due to the rigidity of the earth's magnetic field lines and the number of counter tubes used. The different tubes also use different high voltage inputs that result in different pulse outputs.

CR2: Also of importance is the **pressure sensor** for measuring atmospheric pressure. The amount of particles directly above the neutron monitor (and therefore also directly in the way of incoming neutrons) is directly related to the static air pressure at the site where the neutron monitor is operated, and because this variable directly influences the energy of the incoming neutron, it must be measured in order to do pressure corrections on the neutron count. At least two Paroscientific Pressure Standard devices are used at each neutron monitor site for redundancy, and at SANAE one is used for inside pressure while the other one measures outside pressure.

CR3: **Temperature sensors** measure the neutron monitor temperature at the counter tubes, the ambient temperature in the room where the neutron monitor is operated, and measure the outside temperature as well.

At SANAE there are temperature sensors for both neutron monitor setups (6NM64 and 4NMD) as well as laboratory and outside temperatures.

For the other three stations only the room and counter tube temperatures are measured.

CR4: The **GPS Antenna** is mounted outside the neutron monitor room or building to get an unobstructed line of site for GPS satellites, preferrably on top of the roof of the structure that houses the NM.

CR5: To register and count neutrons, the counter tubes must be connected to a **high voltage DC supply** to operate in the proportional region. The high voltage value for each neutron monitor type is different depending on the type of counter tube. It is currently a fixed value for the type of tubes that are used, but if it could be adjusted for fine-tuning it would yield better results and additional flexibility for improved research.

CR6: To amplify the pulse coming from the proportional counter tubes, the electronic circuit needs a **low voltage DC supply**. The low voltage value from the power supply is the same for all four neutron monitors regardless of the counter tubes.

CR7: It was thought that wind could have an impact on the neutron count, especially at SANAE where the wind speeds regularly exceed 100km/h. Therefore (and only at SANAE) an ultrasonic **anemometer** was installed to measure the wind speed and direction and ever since the SANAE IV neutron monitor was operational the wind at SANAE was recorded. It is also **only** at SANAE where the wind is measured.

CR8: Before the Paroscientific Pressure Standard devices were used, the pressure at each station was measured by a **Fortan Barometer** which first had to be calibrated by hand, after which the pressure measurement would be inserted into the neutron monitor program. Currently the Fortan is used to verify the Paroscientific measurement and to make sure that pressure drift and pressure measurement errors are quickly noticed and resolved. The Paroscientific devices are certified to show a maximum drift of about 0.1% per year, and it is recommended that each device be calibrated at least once every three years. The Fortan is also only used at the Potchefstroom and SANAE neutron monitors.

CR9: It is recommended by the academics that the neutron monitor temperature (therefore, the room or building temperature in which the neutron monitor is operated) be kept constant, or then for all practical reasons kept within acceptable bounds as far as possible. Each neutron monitor station except SANAE has a dedicated **air conditioner** unit to keep the neutron monitor room temperature between 21^{o}C and 28^{o}C, with the ideal neutron monitor counter tube operating temperature between 23^{o}C and 25^{o}C. With the temperature response of the Potchefstroom neutron monitor, for example, the temperature effect on the tubes causes a lag in termperature change far behind the change of the room temperature as has been observed.

CR10: A concise **data check log** is kept and daily information about the neutron monitor behaviour is appended to it. This is where manual tracking of the neutron monitor Paroscientific pressures against Fortan Barometer pressures are kept for comparative purposes.

CR11: Should any errors in neutron monitor data be noticed, or a general problem or fault is picked up at the neutron monitor site, the particulars of this problem are recorded in the **error log**. From here maintenance begins.

CR12: The neutron monitor system and peripheral devices are all connected – either directly or through UPS – to the **electricity supply**.

CR13: The cosmic origin and supplier of neutrons, shown here to be comprehensive.

2.7.1.2 Counter sub-system human resources

CHR1: The **Operator** performs daily checks and verifies that the neutron monitor is operating correctly. This individual completes the data check log and inspects the neutron monitor site for possible problems, in event of which he completes the error log and informs the Scientist and Maintainer.

The Operator for:

- Potchefstroom – is an employee of the CSR in Potchefstroom;
- Hermanus – a function performed as a courtesy by one of the HMO employees;
- Tsumeb – a function performed as a courtesy by one of the local personnel who look after the AWI site;
- SANAE – The CSR-SANAE expedition member.

CHR2: The **Maintainer** reads the error log in the event of an error logged by the operator or scientist, tracks and repairs the problem. The Maintainer is also responsible for routine maintenance on the neutron monitor system in conjunction with the scientist.

The Maintainer for:

- Potchefstroom – is the engineer or technician at the CSR in Potchefstroom;
- Hermanus – is the engineer or technician at the CSR in Potchefstroom, who has to travel to Hermanus to maintain the Hermanus NM;
- Tsumeb – is the engineer or technician at the CSR in Potchefstroom, who has to travel to Tsumeb to maintain the Tsumeb NM.
- SANAE – is the engineer or technician at the CSR in Potchefstroom, who has to travel to Hermanus to maintain the Hermanus NM.

CHR3: The **Scientist** reviews both the data check log as well as the physical neutron monitor data and is able to overrule any inscriptions in the error log, should the Scientist decide that it is correct neutron monitor behaviour. On the other hand, the Scientist can add inscriptions and notify the Maintainer of problems with the neutron monitor system.

The Scientist for:

- Potchefstroom – is the academic (professor) at Potchefstroom;
- Hermanus – is the scientist (professor) at Potchefstroom;
- Tsumeb – is the scientist (professor) at Potchefstroom;
- SANAE – is the scientist (professor) at Potchefstroom as well as the CSR-SANAE team member.

2.7.1.3 Counter sub-system software resources

The process of counting neutrons is divided into two sections, one being the physical counting and the other one the systems and data display and checking.

CSR1: Counting neutrons is the main objective of the neutron monitor. In order to achieve this, software resources must be utilised to gather and extract data. Specific software resources are directly linked to counter resources through counter interfaces while others accept input from a number of counter software resources and process data to determine the average neutron count per hour, as described below.

CSR1.1: The process of counting pulses can be further split in two software resources, as follows:

CSR1.1.1: The pulse that was generated by a neutron entering the counter tubes gets amplified by a pre-amplifier, analysed by a discriminator with fixed input-amplitude level and then shaped to a block pulse by a logic level converter before it can be counted. This is to **shape** the pulse before it is counted as described earlier.

CSR1.1.2: The counter recognises the block pulse as a valid, instantaneous neutron interaction and adds it to the minute-count. This minute-count is then averaged to give the neutron counts per minute. This is where the actual **counting** takes place.

CSR1.1 therefore consists of the pre-amplifier, discriminator, logic level converter and counter. All the relevant pulses generated by the counter tubes must be counted, so the **pulse count** process determines how many pulses were generated for a given time period. This value is not used as the number of neutrons counted, but it is adjusted using external measurements (environmental) to determine the exact number of neutrons.

CSR1.2: The **pressure measurement** is read from the Paroscientific using the mmHg (millimetre mercury) unit for pressure measurement. This value also forms part of the final neutron count.

CSR1.3: The **temperature measurement** is less important when looking at final, average neutron count, but it has an effect on the functionality of the counter tubes. It must therefore be monitored and recorded in order to ensure correct neutron monitor operation.

CSR1.4: The **GPS information** is used to compare neutron monitor data from around the world with the neutron monitor data from the four stations that the CSR operates. This serves to standardise the time used and to draw comparisons between stations with different geographical locations without too much effort. It also aids in fault finding between different neutron monitors, which enables the researchers to ensure that a specific neutron monitor reacts the same to a space-atmospheric as another neutron monitor.

CSR1.5: The **high voltage** value must be monitored in order to ensure that the tubes operate in the correct radiation region. If the voltage level changes too much, a different voltage region can be entered, resulting in erroneous measurements.

CSR1.6: The **wind speed** is only measured at SANAE, but the software for all four neutron monitor stations was designed to be capable of accepting wind speed data. It is not used in the final count calculations as it does not affect the incoming neutrons.

CSR1.7: In order for the neutron monitor to give the correct neutron count, the number of neutrons counted must be adjusted to yield a **pressure-corrected neutron count**. This process takes the instantaneous neutron count and adjusts the number of neutrons based on the atmospheric pressure at a specific instance. The relative energy for neutrons reaching the earth's surface at the different neutron monitor sites is known (based on the magnetic rigidity and each cosmic ray's required energy to reach the earth's atmosphere right above each neutron monitor station) as is the effect of a certain column of air on the movement of the resulting neutron, so the actual number of neutrons that should be counted can be calculated.

CSR1.8: All the data collected or generated by the other counter software resources are stored in the **store data** process. Instead of simply storing data on multiple disks (for redundancy and data security), the whole data capture and recording system is duplicated and two PC's simultaneously record the same data, with built-in mutual data verification. The stored data is then available for data editing and publication (the data-subsystem), so it is also referenced in other software groups.

CSR2: System and data check allows the Operator to see if the neutron monitor is functioning correctly. This is where the Operator can input Fortan readings and inscriptions in the data check, and where errors are logged for investigation and repair.

CSR2.1: All the recorded data is displayed to the Operator. From here the Operator can verify whether the neutron monitor is operating correctly or whether there are any failures.

CSR2.1: The Operator does a **pressure calibration** every time the Fortan readings are entered. This data is also saved together with the rest of the neutron monitor data. The pressure difference between the Paroscientific and the Fortan is calculated and shown in mmHg - this value is then also recorded in the data check log.

2.7.1.4 Counter sub-system interfaces

CIF1: A block pulse (that represents a neutron) is sent from the counter tube to the counter box by means of long and rather unstructured coaxial cable. The counter box to PC is connected via serial cable with 3 wires (RX, TX, and Gnd).

CIF2: All the Paroscientific Pressure Standard devices have serial (RS-232) data connectors and the baud rate is adjustable from the connecting PC. It uses a standard RS-232 connection.

CIF3: The temperature probe is connected by a thin coaxial cable to its temperature measurement box, and from there to the PC it is serial.

CIF4: The GPS antenna is connected to the GPS receiver-module by means of coaxial cable.

CIF5: The counter tube high voltage is delivered to the tubes by means of thick coaxial cable over a long distance, which from an EMI perspective is not ideal.

CIF6: The high voltage is measured for correct value - the measurement connection is by means of a thin coaxial cable from the high voltage supply to the counter box.

CIF7: The low voltage to the counter tube electronics is an unscreened 4-core cable using GND, +5V, -12V, +12V.

CIF8: The anemometer connection (only for SANAE) is by means of thin coaxial cable from the anemometer outside to the counter box inside the facility.

CIF9: The operator has to calibrate and record the pressure reading and record the temperature reading of the Fortan Barometer daily. This is only done at the Potchefstroom and SANAE neutron monitors.

CIF10: The recorded Fortan data must be entered into the neutron monitor software program by using the PC. This is done at the Potchefstroom and SANAE neutron monitors. Since this is a human-machine interface, it is identified for effectiveness in terms of usability.

CIF11: The Operator works through the neutron monitor graphs and checks the recorded values and calculated neutron counts for errors. This is also a human-machine interface.

CIF12: The Operator then files out the Data Check Log at the Potchefstroom neutron monitors only. This is a human-machine interface.

CIF13: The Scientist views the Data Check Log to verify if the neutron monitor operations are acceptable - only at the Potchefstroom neutron monitor. This is a human-machine interface.

CIF14: The Scientist analyses the stored neutron monitor data once a week to thoroughly check whether the neutron monitor is functioning correctly and that the data output is accurate. This is a human-machine interface.

CIF15: If the Scientist finds a problem with the stored data, the error log is updated with the symptoms and procedures followed to identify the problem. The Scientist must then also inform the Maintainer of the problem. This is a human-machine interface.

CIF16: The Maintainer reads the error log when there is an error that has logged, and prepares for unscheduled maintenance. This is a human-machine interface.

CIF17: After the Maintainer has reviewed the error log, the maintenance process starts. The Maintainer is responsible for all the components of the neutron monitor, so interfaces for components of the neutron monitor are grouped under this one interface - the maintenance of each component is described later.

CIF18: This is the general power (mains) interface for every component that needs to be connected to mains power. Some equipment is connected directly to the buildings' mains supply, while more critical and sensitive equipment go through the **UPS**. The individual components that are connected to mains power through CIF18 are:

1. Mains supply to the high voltage source (**UPS**);
2. Mains supply to the low voltage source (**UPS**);
3. Mains supply to the Paroscientific Pressure Standard device (**UPS**);
4. Mains supply to the temperature sensor measurement box (**UPS**);
5. Mains supply to the neutron monitor computers (**UPS**);
6. Mains supply to the air conditioner.

CIF19: If the operator notices faults at the neutron monitor hardware, the monitor's data or configuration, or peripheral devices of the monitor, those faults are appended to the error log for the information of the Maintainer. The Operator must then also inform both the Scientist and the Maintainer accordingly.

CIF20: When the neutron monitor or room temperature needs adjustment, the Operator makes adjustments to the air conditioner temperature setting to keep the room temperature between the specified ranges.

CIF21: The Scientist can make alterations to the neutron monitor room temperature by adjusting the air conditioner temperature accordingly, and the adjustment and new ranges should be communicated to the Operator and Maintainer.

CIF22: Should a problem arise with the air conditioner, the Maintainer can access the air conditioner to make necessary alterations or to do / contract repairs.

CIF23: The interface between the proportional counter tube and the neutrons coming into the earth's atmosphere should be clear of obstacles that may interfere with the movement of the inbound neutrons.

CSIF: CSIFs are the counter process interfaces (interfaces between sections of software program).

CSIF1: The pulse count and pressure value are sent to CSR1.7 to calculate the pressure-corrected counts.

CSIF2: All the data generated and recorded by the counter software is sent to CSR1.8 to be stored.

CSIF3: The stored data is retrieved to be displayed to the operator for checking.

CSIF4: The Fortan pressure and temperature are taken as input from the operator and saved together with the counter process data.

2.7.2 Energy sub-system

In Figure 12 (on the next page) the resources and interfaces for the energy-subsystem of the neutron monitor are shown. Being concerned with the electricity delivery to the neutron monitor itself, the counter reference CR12 is also included here as a resource, but will not be described again, since it has been described in **section 2.7.1.1**.

In essence, the resources and interfaces for the energy group look the same for every neutron monitor station, with major differences regarding the neutron monitor operated at SANAE. This is because the SANAE IV station is operated as a stand-alone unit with its own power generation and people responsible for the maintenance of the power and communications network.

2.7.2.1 Energy sub-system hardware resources

Please refer to figure Figure 12 for identification of all resources and interfaces that are discussed below.

ER1: To ensure the correct and reliable operation of the neutron monitor, the first resource that must be in place is a **UPS**. The UPS of the neutron monitor is its first line of defence against power surges and spikes, critical component failure, system downtime due to power interruptions and, in the case of the SANAE NM, power down for routine maintenance:

- Potchefstroom – one 10kVA UPS and one 1kVA UPS in series;
- Hermanus – two 10kVA UPSs each supporting one PC and some of the peripheral devices;
- Tsumeb – One 10kVA UPS and one 1kVA UPS in series;
- SANAE – two 10kVA redundant UPS's, powering PC's additional to the neutron monitor and other electrical systems connected to the same grid as the NM's. One 1kVA UPS is found in-line for each PC and low voltage power supply for each NM tube assembly.

ER2: The amount of time that the UPS can support the neutron monitor system is determined by the amount of current the neutron monitor is using, and the amount of **battery power** the UPS has on hand. The following is found at the different stations:

- Potchefstroom – 10x12V 102Ah deep-cycle batteries connected in series;
- Hermanus – Sealed UPS battery packs;
- Tsumeb – 10x12V 102Ah deep-cycle batteries connected in series;
- SANAE – 12V 7.2Ah battery bank; single 12V 7.2Ah battery.

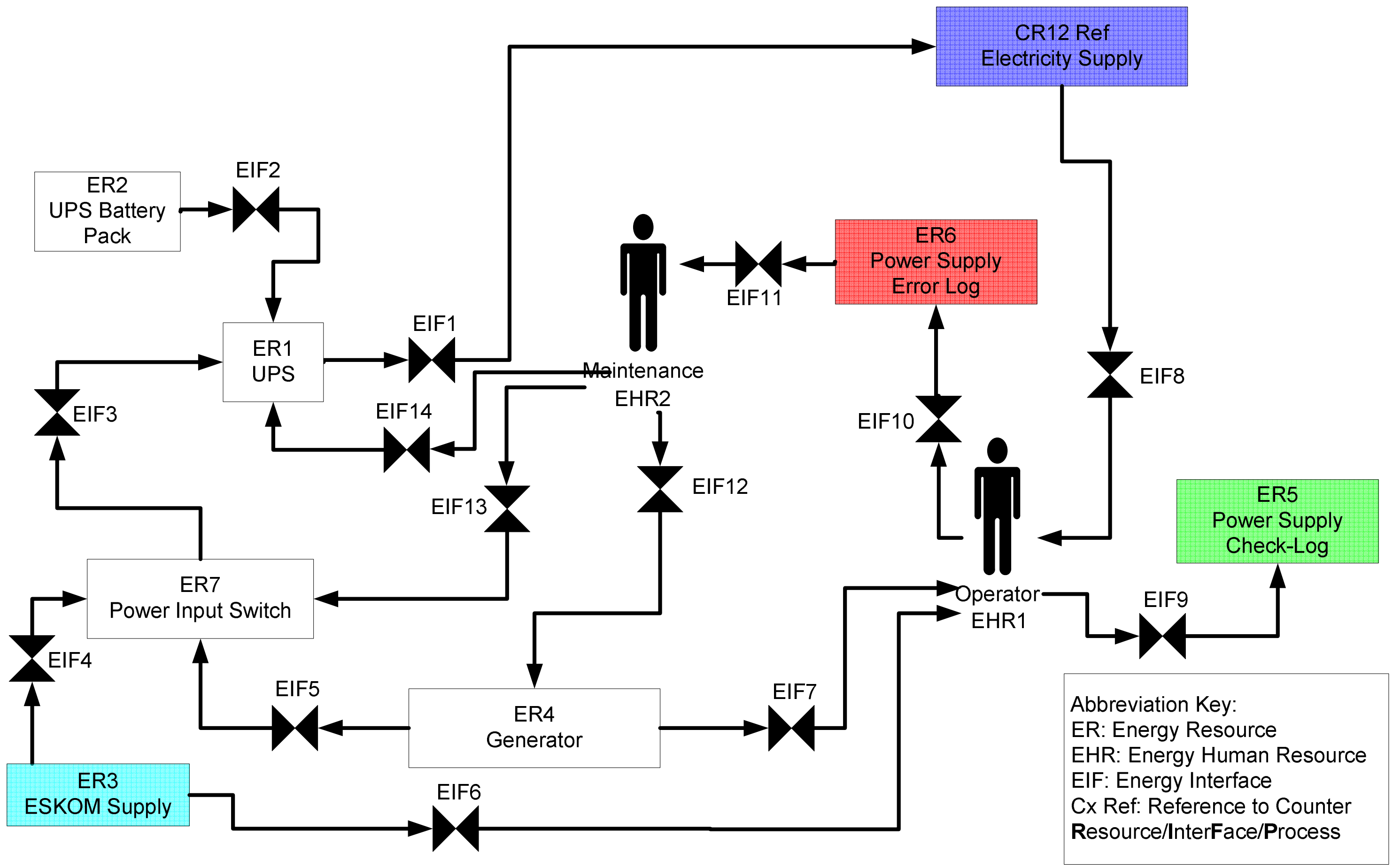

Figure 12 Neutron Monitor Logical Layout of Energy-subsystem

ER3: The main power supplies for Potchefstroom and Hermanus come from the local **Eskom** power grid, and due to the fact that this power supply belongs to an independent third party, the stability of the power supplied is paid for and managed according to SLA.

The main power supply for the Tsumeb neutron monitor comes from the Ministry of Mines and Energy.

The SANAE base is not supplied with grid power.

ER4: In the event of grid power failing, a backup **generator** is started in order to aid the UPS's in keeping the neutron monitors running. Should the generator then fail, the UPS will be the sole energy provider for the NM's. The entire SANAE base is dependent on the three diesel generators for its electricity, making it in part the CSR-SANAE member's responsibility to help maintain the generators.

- Potchefstroom – 3-cylinder Lister with generator, for NM and offices;
- Hermanus – HMO generator, for NM and HMO use;
- Tsumeb – MME generator, for the whole AWI building and NM;
- SANAE – Three ADE diesel engines with 160kVA generators.

ER5: When the energy section of the neutron monitors is in good working order, the **power supply check** log is updated by the operator so that the Operator, Scientist and Maintainer can track the time of failure. This ranges from verification UPS status (batteries, etc) to verification of diesel levels.

ER6: Should a problem occur with the energy section, the **error log** is updated and both the Scientist and Maintainer are informed.

ER7: Depending on which power input to be used (either grid like Eskom or MME), the **power input switch** is used to select the appropriate power input. For the Potchefstroom NM this switching takes place manually (between Eskom and generator) and for Hermanus and Tsumeb it takes place automatically. SANAE is permanently connected to generator power, so this type of switching does not apply to the SANAE NM.

2.7.2.2 Energy sub-system human resources

EHR1: The **Operator** is responsible for checking the electricity supply to the neutron monitor and reports all problems to the Maintainer and Scientist.

- Potchefstroom – an employee of the CSR in Potchefstroom;
- Hermanus – courtesy of one of the HMO employees;
- Tsumeb – courtesy of one of the local personnel looking after the AWI site;
- SANAE – The CSR-SANAE expedition member.

EHR2: The **Maintainer** reviews the error and check logs for fault finding and repairs upon notification by the Operator. He / she is responsible for switching over the selector switch between grid and generator power, for refuelling the generator, for checking the UPS, and for outsourcing and contracting of maintenance and repairs to the power supply.

- Potchefstroom – the engineer/technician at the CSR in Potchefstroo;
- Hermanus – the engineer/technician at the CSR in Potchefstroom, who has to travel to Hermanus to maintain the Hermanus NM;
- Tsumeb – the engineer/technician at the CSR in Potchefstroom, who has to travel to Tsumeb to maintain the Tsumeb NM;
- SANAE – the electrical, electronic and mechanical engineers and diesel mechanics on the overwintering team.

2.7.2.3 Energy sub-system interfaces

EIF1: From the UPS the power to the neutron monitor goes through a circuit breaker, and depending on how many devices are connected together with the neutron monitor, the size of the breaker will differ. Also, the output of the UPS (as is the case of the SANAE NM) is shared between the NM and other scientific equipment, each supposedly on its own UPS circuit breaker.

EIF2: The connection of the batteries to the UPS differs from long cabling (Potch, Tsumeb and SANAE) to built-in batteries with short leads (Hermanus). It is DC voltage, with moderate current being drawn by the load.

EIF3: In the case of the Potch, Hermanus and Tsumeb neutron monitors, the power supplied from either the generator or the grid is switched by an input power selector to go to the neutron monitor. SANAE has only generator power and no additional option of power input or generation, so this switching does not apply to the SANAE NM.

EIF4: The grid power is divided in different lines, ranging from lights and plugs to other UPSs and servers. One of these lines goes through a dedicated circuit breaker to the selector switch and from there to the UPS and NM. This applies to Potch, Hermanus and Tsumeb only.

EIF5: The generator power goes through a dedicated circuit breaker to the selector switch.

EIF6: The grid supply power is checked by the operator by means of inspection and confirmation of "Power On."

EIF7: The generator and generator power is checked by the Operator through visual inspection of the status of electricity (when the generator is in use) and by visually inspecting the generator for diesel and oil levels.

EIF8: The electricity to the neutron monitor is checked by the Operator and it adds to confirm that EIF1 is in working order. This is verified by means of visual inspection making sure that the neutron monitor PCs and peripheral devices are in working order.

EIF9: The Operator updates the power supply check log and confirms that the neutron monitor energy state is OK.

EIF10: Should there be a problem with the neutron monitor power supply, the Operator updates the error log and appends the problem details, where after the Maintainer is notified.

EIF11: The Maintainer works through the power supply error log after having been informed by the operator on a particular problem with the power supply. In SANAE the Maintainer usually notices there is a problem with the generators when the lights are dimming throughout the base.

EIF12: If the problem resides with the generator, the Maintainer verifies the status of the generators and diesel levels. He / she repairs the generator as necessary, or contracts out repairs. If the problem is with the grid power being down, the Maintainer starts the diesel generator and then uses EIF13 to switch the power supply over to generator (ER7). In the case of SANAE the Maintainer must check the generators and either do engine control adjustments or service and repair the generators.

EIF13: If either the grid power fails and the generator must be used for electricity generation, or the grid power is stable again and the generator power is no longer needed, the Maintainer switches over to the applicable power supply. In SANAE this interface does not exist as the switch ER7 does not exist.

EIF14: The Maintainer verifies the UPS for faults and correct battery levels, replaces batteries if necessary, and contracts out major repair work to be done. In SANAE the electronic and electrical engineers are responsible for checking and maintaining the UPS's throughout the base.

The data group logical layout of the neutron monitors of the CSR is shown in Figure 13. The ER1 Ref UPS resource is referenced here due to the fact that the PCs used for editing the neutron monitor data in Potchefstroom uses the same UPS as the Potchefstroom neutron monitor.

Also, the data stored by the different neutron monitor sites gets used, edited, analysed and published here. Therefore, the CSR1.8 Ref Store Data process is also referenced here. These referenced resources are described above.

A future integration of resources and interfaces will be to integrate the CSR neutron monitor database with the international NMDB database. The full NMDB data requirements and format can be found in Appendix D.

2.7.3 Data sub-system

2.7.3.1 Data sub-system hardware resources

DR1: The **error log** is the only logging resource the data group has, and both the Scientist and the Operator can append comments. Errors are logged in the data group because the data gets edited and published if no errors were logged in the counter-subsystem section. There may, however, be suggestions made about the operation of the neutron monitor and these suggestions or possible non-optimal functioning of the neutron monitor can be given through to the Maintainer to make corrections according to the Scientists' suggestions.

DR2: The **NMDB International Database** is, as the name implies, an international database of neutron monitor data from right around the world. It was founded and is operated by the European Union's 7th Framework Programme, and the CSR wishes to both incorporate the NMDB data as well as send its data to the NMDB for international use and accreditation (arsssen 2009). Keeping the NMDB data requirements in Appendix D in mind, the CSR's NM data already includes all the necessary data types to be able to contribute to this international NM data repository. The only aspect that has to be changed is the data structure of the current CSR neutron monitors to adhere to the NMDB standards. This data group is where the necessary data structure transitions will have to take place.

2.7.3.2 Data sub-system human resources

DHR1: The **Scientist** uses data editing software to finalise the neutron monitor data before publishing it. Any issues with the data editing software that are encountered, or any previously unnoticed irregularities to the neutron monitor data (that the scientist picks up during this final data editing process) are appended to the error log and the Maintainer is notified. He / she works in conjunction with the Maintainer to resolve the problems with the software or to make minor adjustments to the neutron monitor configuration.

DHR2: The **Operator** in this respect includes end users in the public sector as well as the general operators of the neutron monitors. Anyone with authorised access to the final, published neutron monitor data may use it for their own scientific work or other research purposes. Should one of these independent end users or operators find any problems or irregularities within the CSR neutron monitor's data, they can inform the CSR and indirectly append the problems to the error log.

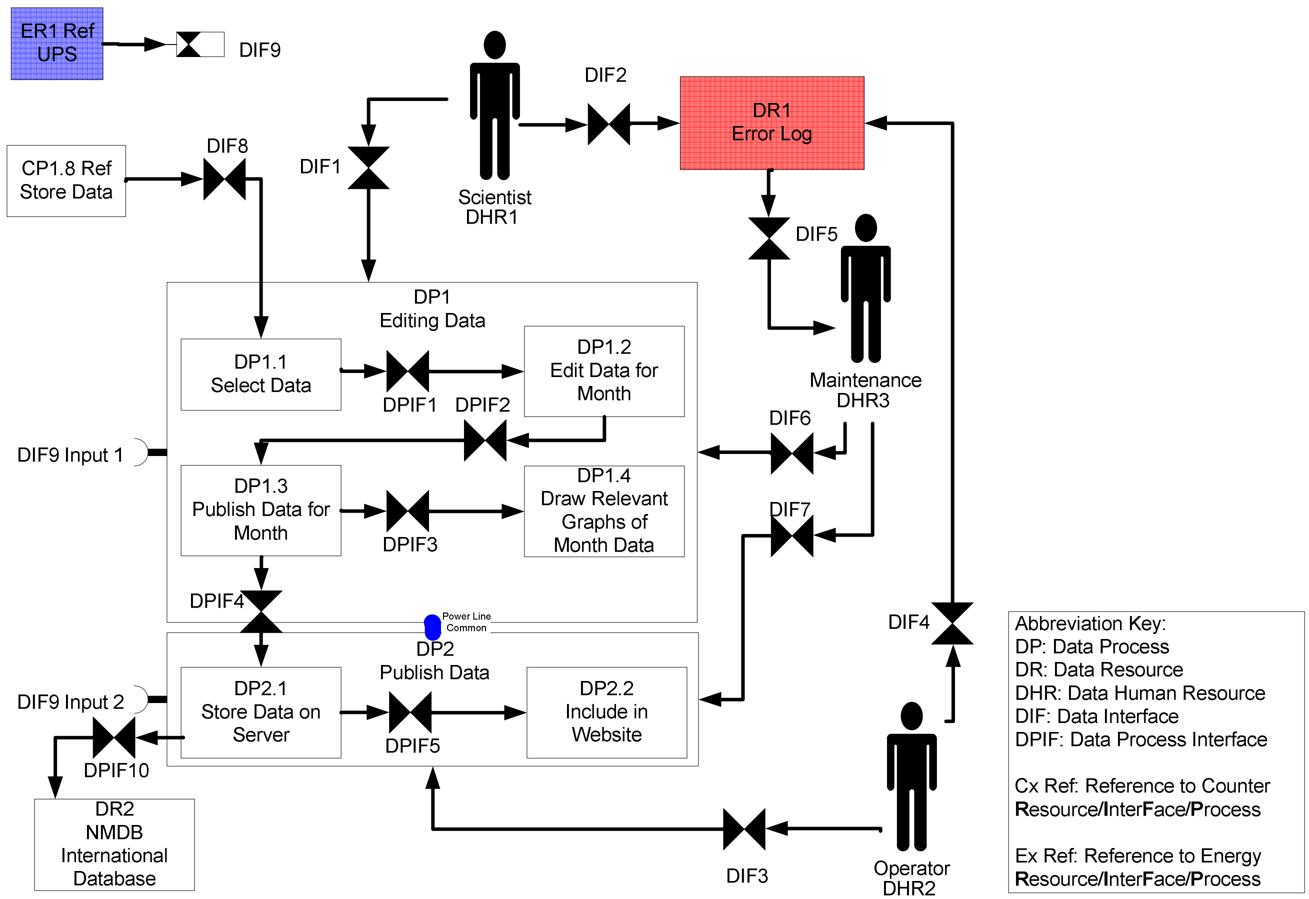

Figure 13 Neutron Monitor logical layout of data group

DHR3: Should the issue be unexpected or undesired deviations in the data, the **Maintainer** works in conjunction with the Scientist to adjust the neutron monitor's configuration / setup. The Maintainer would have already repaired any problems regarding the neutron monitor's hardware or support system because it would have been noted in the counter error log CR11.

2.7.3.3 Data sub-system software resources

DSR1: In the **editing data** process, the data that has been collected and stored by the neutron monitor registering and counting system (**section 2.7.1 Counter-subsystem**) is recalled and opened for final editing and data verification before it gets published to the general public.

DSR1.1: The data for a specific month gets **selected** out of the data repository created by the CSR1.8 Store Data process, and entered into the data editing program.

DSR1.2: The **data gets edited**, which comprises month-averaging and removal of outliers in the different data channels, ensuring that neutron monitor result trends fall within expectation – that is, correlating with previous neutron monitor data and physics theories.

DSR1.3: The edited data is ready for **publication** on the NWU-CSR webpage and data server for general usage and stored on the CSR data servers.

DSR1.4: Monthly graphs of the data are drawn and data is viewed in a historic format from the beginning of the neutron monitor. The responses of the different stations are compared to one another to showany distinguishable cosmic ray trends based on solar activity.

DSR2: The data that is ready for **publication** is copied to the NWU web server in order to give external researchers (the end users and independent operators) authorised access.

DSR2.1: The publish-ready data is copied to the NWU **web server**.

DSR2.2: The data sets are linked to the NWU CSR website from where it can be <u>viewed only</u> by other users or researchers.

2.7.3.4 Data sub-system interfaces

DIF1: The Scientist uses specific PC editing software to edit the neutron monitor data to get it ready for international publication (on the CSR and NWU's own servers, not to be misjudged with the NMDB international database).

DIF2: Should any irregularities with the neutron monitor or problems with the editing software appear duering data edits, the Scientist appends these irregularities to the error log.

DIF3: The Operator accesses published data through the CSR web interface and views (uses) the neutron monitor's data for citation or other scientific work not done by the Scientist, but used in his / her own capacity.

DIF4: Any one of these operators may append the error log should any of the published data be questionable.

DIF5: Should any problems with the data arise and be noted by either the operators or the Scientist, the Maintainer is notified and works through the error log to trace the software error.

DIF6: If a problem has been noted with the editing software, the Maintainer opens up the program code and rectifies the problem. IDL is currently the programming language of choice of the CSR, so an IDL editor and compiler must be used.

DIF7: If a problem has been noted with the published data, the Maintainer opens up the program code and rectifies the problem.

DIF8: The data that has been generated by the neutron monitors is retrieved from storage CSR1.8 Ref Store Data and used in the data editing processes.

DIF9: Both the editing and publication computers are supplied by UPS power from ER1 Ref UPS resource.

DIF10: When incorporating the CSR neutron monitor data with the NMDB International Database data sets, the CSR data format has to be changed to suit the format used by the NMDB, and all additional information included in a typical NMDB data set must be appended or excluded (with comments) from the CSR NM data.

DSIF1: The selected data is transferred internally to the editing section of the program. The data selection and editing software form part of the same PC software module.

DSIF2: The edited data is temporarily stored by the editing software and then retrieved by the publications software on the same PC.

DSIF3: The published data values are then again temporarily stored and retrieved by the graphing software on the same PC.

DSIF4: Inter-process interface - The edited data then change hands from one PC to another to be stored on the data server. This is done on a separate PC.

DSIF5: The stored, edited data is then included on the website for public access.

2.8 System functional flow at operational level 2

With an existing system, it is easier to analyze archtitecture (form) and interdepencies (fit, in the form of interfaces), to be followed by functional flow that describes processes. With new developments, the order is sometimes changed. In this work, the architectures were first recorded and then abstracted in order to provide a framework for an analysis of risks and to simplify future upgrades.

The system operational flow is presented and analyzed in order to depict the dynamic behaviour of the individual elements and the overal system – this is done in the sections that follow.

2.8.1 Operational flow

The system operational flow is depicted in Figure 14 where the operation of the existing NM runs in parallel with the analysis and upgrade of the same system (as seen in Figure 5 where the overall system life cycle is shown. As seen in Figure 14, the existing system consists of operations (operational functions) such as counting neutrons and measurement of system and environmental variables. Each of these operational functions will be described in detail later on and will be used in the NM system risk analysis.

Tasks 1-7 in the operational flow take place simultaneously and form part of the instantaneous and daily operational routines of the neutron monitor. Tasks 8-9 take place on a weekly and/or monthly basis and are more concerned with the neutron monitor data than the neutron monitor operation.

The dependencies of these functions on the physical structures, peripheral devices, resources and hardware of the neutron monitor will be shown in the section on risk assessment.

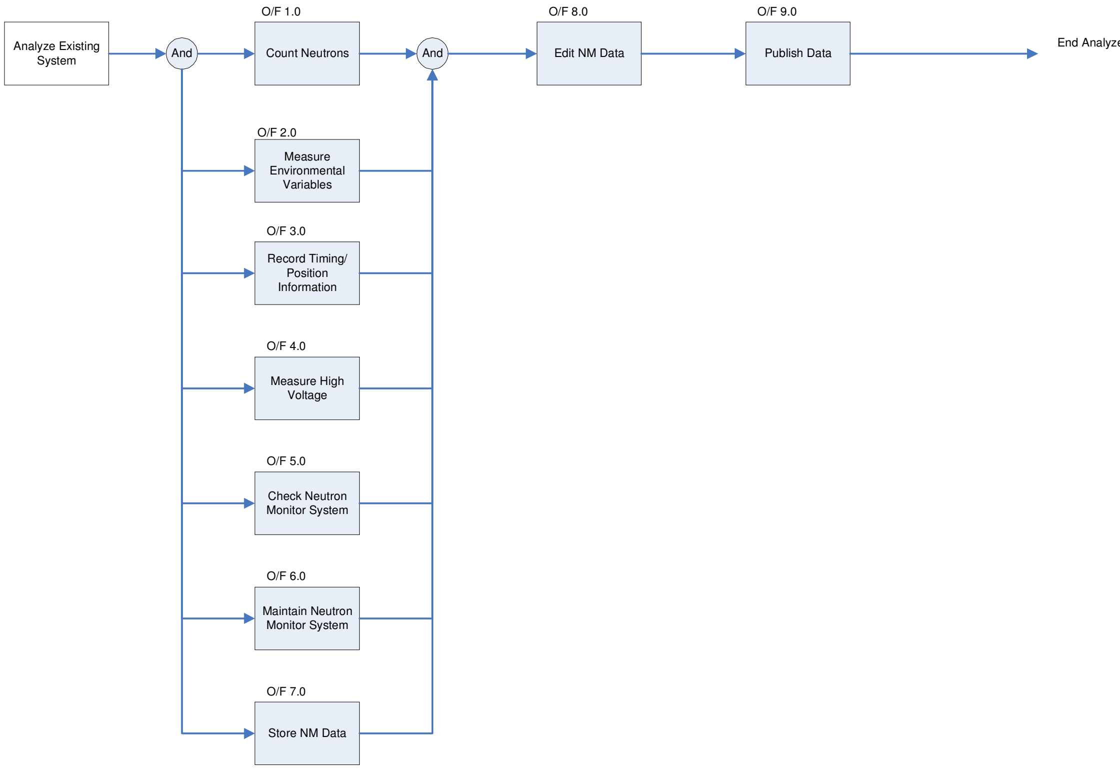

Figure 14 NM System operational flow

2.8.2 O/F 1 Count neutrons

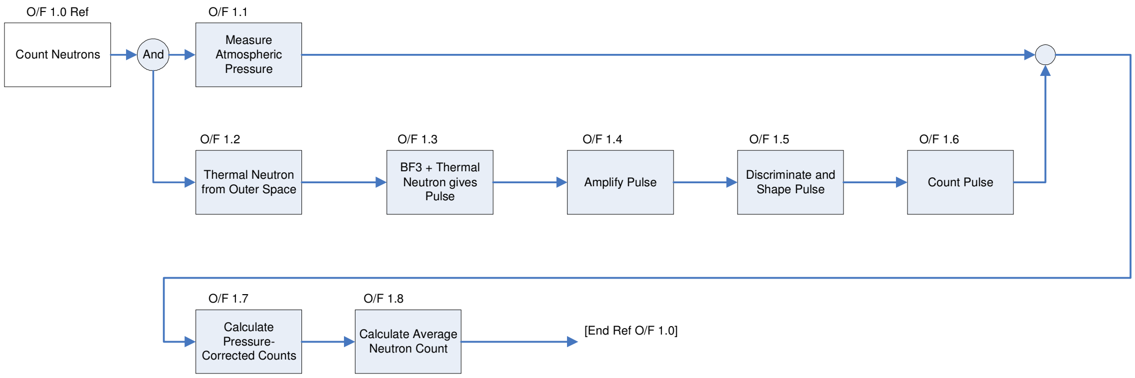

Figure 15 O/F 1 Count neutrons

The core function of the neutron monitor is described in Figure 15, where a neutron of cosmic origin gets counted. From the work flow diagram it is clear that the counting of neutrons takes place in parallel with the process of measuring the atmospheric pressure.

The parallelism is critical to the functionality of the neutron monitor because the inability to compensate for air pressure variations will render the neutron monitor data useless.

O/F 1.1: This task takes the atmospheric pressure value as input by means of a Paroscientific measuring device.

O/F 1.2: This is where the neutron formed by the collision between a cosmic particle and the earth's atmosphere.

O/F 1.3: The inbound neutron enters the NM proportional tubes and reacts with the BF_3 gas inside.

O/F 1.4: The reaction of the neutron with the gas in the presence of the constant electric field causes a small pulse, as discussed earlier.

O/F 1.5: To count the pulse, it is discriminated (if it is of the correct amplitude it is passed on to the logic level converter) and converted to the correct amplitude to be read and interpreted by the serial port on the counter box.

O/F 1.6: The pulses get converted by the logic level converter and counted by the NM counter box.

O/F 1.7: After the neutron count has been done together with the pressure measurement, this data is sent to the NM computers for a pressure-corrected count.

O/F 1.8: The acceptable standard for displaying pressure-corrected counts is for averages of 1 minute (instantaneous), 5 minute and one hour. These are calculated in real-time and the system gets updated at the end of each respective time period.

2.8.3 O/F 2 Measure environmental variables

The atmospheric pressure at the neutron monitor was grouped with the operational flow section of counting neutrons due to its criticality.

Measurement of the other variables in the neutron monitor environment that have a small but notable effect on the neutron count are depicted in Figure 16 and explained thereafter.

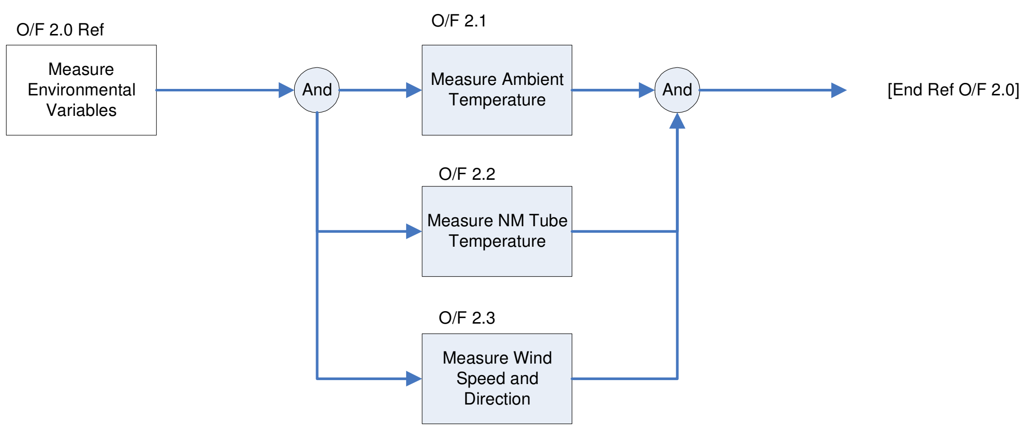

Figure 16 O/F 2 Measure environmental variables

O/F 2.1: The ambient temperature inside the neutron monitor enclosure (be it a hut, room or other kind of permanent enclosure) is measured by this function and it is recorded in degrees Celsius (^{o}C). In the case of SANAE both the ambient inside as well as outside temperatures are measured for sake of correlation and to see how badly the inside temperature gets affected by storms and extreme cold conditions. The global outside temperature extremes for neutron monitors operating under the CSR's control is 40^{o}C (Tsumeb) to -38^{o}C (SANAE).

O/F 2.2: The way this function measures the neutron monitor temperature is exactly the same as for the ambient temperature. Where the ambient temperature is more dynamic, the neutron monitor temperature is static (with a significant capacitive effect) and can have a negative influence on the operational capacity of the NM's proportional tubes. The measurement thereof is not critical, but pertinent thresholds are set, of which the top one must be adhered to the most. Typical values for the Potchefstroom NM is between 18°C and 23°C, and the temperature of all the other NM's are subsequently also controlled (where possible) to be between these values. At SANAE the temperature is difficult to control – because of the physical location of the SANAE NM in the base – and also a lot lower to begin with, so the threshold for the SANAE NM is between -5°C and 18°C.

O/F 2.3: This only applies to SANAE and was used to determine the effect that wind might have on neutron counts due to blowing snow. Nowadays it is informative to see what the wind speed and direction are like to be able to identify and prevent data corruption due to static electricity. High wind speeds cause blowing snow over the base which in turn cause huge amounts of static electricity. These electro-static charges cause spikes on the data, rendering it useless.

2.8.4 O/F 3 Record time and geographical information

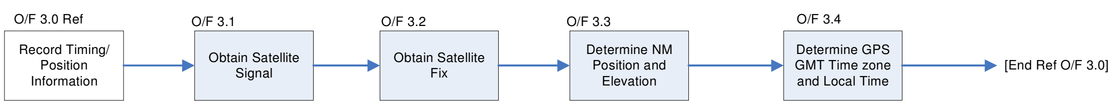

Figure 17 O/F 3 Determine time and position

The neutron monitor systems of the CSR generate data that can be used for correlation of and comparison to other neutron monitors around the world, but to make this possible the data that is generated must be synchronised to give the scientists working with the data a fixed reference for event tracking.

This reference is given by using GPS satellites to determine the GMT time and time zone for all neutron monitors. It provides the Scientists a means to compare different solar and cosmic ray events because they can now time-shift the two or more sets of data so the time at which the event occurred (based on GMT time) can be tracked.

O/F 3.1: This function is done by using an active GPS. At SANAE this can become a troublesome task due to extreme temperatures outside and poor line of sight of GPS satellites from inside the base.

O/F 3.2: This task obtains satellite signals to determine a position fix and receive the GMT time information from the satellites, from where the NM process and timing calibration is deduced.

O/F 3.3: The NM coordinates and height above sea level are determined by this task. This can be used for pressure measurement comparisons, but based on the exceptional track record, guarantee and experience with the Paroscientific pressure-sensing devices, this was not necessary.

O/F 3.4: The data string that is obtained from the satellites contain information regarding GMT time, date and day. These are all used – especially the timing information in the form of a per-second pulse – to synchronise NM processing and recording of counted neutrons and measured variables.

2.8.5 O/F 4 Measure high voltage supply

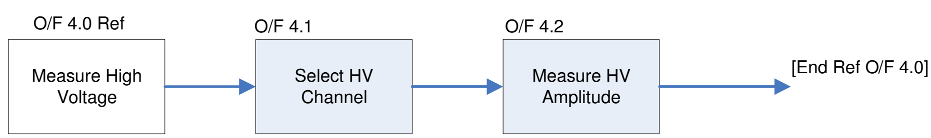

Figure 18 O/F 4 Measure high voltage supply

O/F 4.1: The NM setup generally has more than one HV channel for redundancy as well as current limiting. The different channels are polled to see if the correct HV output is being supplied to each tube. The current NM setup only shows the individual HV channels but does not monitor the HV for each tube.

O/F 4.2: The high voltage is obviously measured in kilovolts, where the range differs depending on the type of tubes that are used. The HV ranges from -2850V to +3600V DC, and fluctuations of less than 10 Volts are generally acceptable.

2.8.6 O/F 5 Check the neutron monitor operations

The Operator is tasked to check the neutron monitor operations on a daily basis, perform basic pressure-measurement related tasks, and report all issues and faults to the Maintainer and / or Scientist.

O/F 5.1: The UPS conditioned power source to each neutron monitor may differ slightly. It is the operator's responsibility to verify that the power supply to the neutron monitor is regulated within the required limits (210VAC to 240VAC at 50Hz) for reliable operation.

O/F 5.2: The neutron monitor atmospheric pressure is correlated and calibrated by the Operator using a Fortan barometer and then entering the pressure value as well as temperature value in the NM recording software.

O/F 5.3: The Operator must observe the response of each tube and log any abnormalities in the data.

O/F 5.4: The Operator observes the NM temperature levels and adjusts the temperature. The operator is allowed to make minor adjustments to the thresholds of the ambient temperature to rectify temperature errors.

O/F 5.5: The Operator observes the high voltage levels on each of the HV outputs and establishes a relation between HV spikes and disturbances on the neutron monitor tube outputs. The Operator then logs any discrepancies on the data due to HV problems and informs the Maintainer.

O/F 5.6: Where applicable (for SANAE only), the Operator observes the wind speed and direction and either switches off the NM system entirely based on the weather and static electricity, or logs the event of bad weather for later data editing purposes.

O/F 5.7: The Operator observes pressure-corrected counts for any obvious data processing problems and informs the Maintainer and Scientist of such observations.

O/F 5.8: The Operator verifies that the NM system still has GPS lock and that the PPS (pulse-per-second) is registered. Good practice is to check that the date of the data and PC date of the last-minute recorded data are the same.

O/F 5.9: All observations that were made by the Operator are logged. Thus, all errors and adjustments are logged and given through to the Maintainer and Scientist.

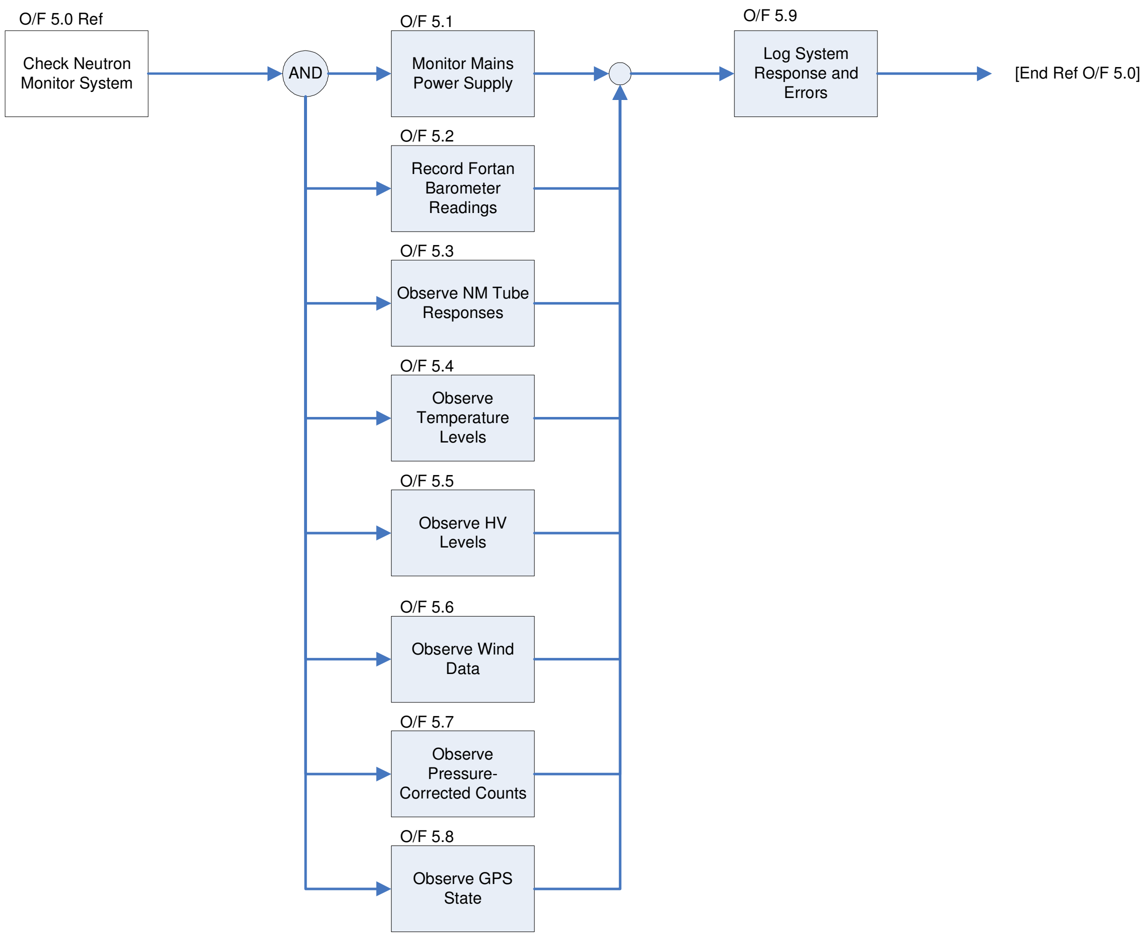

Figure 19 O/F 5 Check the neutron monitor

2.8.7 O/F 6 Maintain the NM system

The Operator and / or user contribute to a minimal extent to the maintenance of the system, but they can give valuable insight in the response of the system through to the Maintainer. This, when efficiently logged, aids the Maintainer significantly when doing fault finding and repairs.

In some instances the Maintainer of the system is not necessarily one of the CSR personnel. As before, for the SANAE NM, personnel responsible for maintenance of for example the neutron monitor's power supply, form part of the over-wintering SANAE team's technical people. In Tsumeb it is the responsible person appointed by the MME (Ministry of Mines and Energy) that ensures the power supply to the NM is checked and maintained.

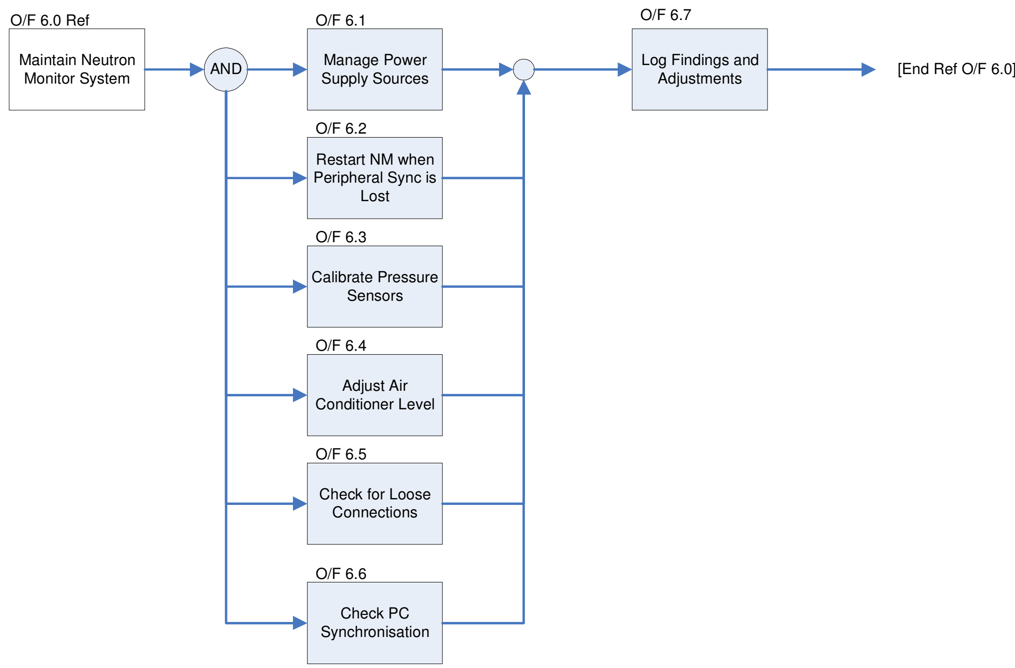

Figure 20 O/F 6 Maintain the neutron monitor

O/F 6.1: Maintenance of the power supply sources include – for Potchefstroom specifically – to verify if power comes from the grid (Eskom) or the generator. The Maintainer also starts the generator and switches its supply to the UPS and NM when grid power is down, and returns the switch to grid power and switch off the generator when grid power is restored (manually). The Maintainer also inspects the UPS for problems and maintains both UPS and generator up to and including outsourcing of replacement and repair.

O/F 6.2: When the neutron monitor counting process does not execute, or when GPS sync is lost, the Maintainer restarts the NM system and ensures synchronization of the GPS and system times. The NM system must also be restarted when one of the pressure measurement devices or any other peripheral device gets disconnected from the system, of when its data signal gets corrupted.

O/F 6.3: The pressure sensors are calibrated at least once a year by adding another pressure sensor to the system. This calibrating sensor is exactly the same as the sensor regularly used for pressure measurements (it is the same type of Paroscientific device) and the recording software has a dedicated open “slot” for a third pressure device specifically for this purpose. This additional pressure value is then recorded and displayed alongside the regular pressure values and serves to confirm the pressure value of the other devices. This particular pressure sensor is then also used for calibrating the other NM's of the CSR.

O/F 6.4: The Maintainer observes the temperature levels' behaviour, specifically when an adjustment and subsequent log has been made by the operator. He then makes additional adjustments to the temperature thresholds of the enclosed NM space (if it is controllable) in conjunction with the scientist and informs the operator of the new threshold levels.

O/F 6.5: Any reparations to the NM must be performed by the Maintainer, and an inspection for loose wires and connectors is done regularly. HV and general power supply connectors are prone to lose connection, which may result in spikes and data loss.

O/F 6.6: Each of the neutron monitors operated by the CSR has two PC's collecting neutron counts and other NM data in synchronized form. This is for data redundancy and a first line of backup and protection against data loss. The PC's are synchronized in a master-slave configuration, and the Maintainer must check and ensure that the recorded time of the two PC's are exactly the same for the last-minute recorded data. If not, the NM system is restarted as in O/F 6.2.

O/F 6.7: All adjustments that the Maintainer made to the system and all repairs must be logged and reported to the Scientist. The Scientist takes note of these adjustments and checks the NM data accordingly. Should any ambiguity or data-based problem arise from the adjustments made, the Scientist will inform the Maintainer who will then work in together to resolve the problem. Task O/F 6.7 is actually an iterative process – at lower level – to accommodate additional recommendations from the Scientist to resolve certain problems.

2.8.8 O/F 7 Store NM Data

All the data that is generated and measurements that are taken by the neutron monitor is stored on a per-minute base, so the files that are generated by the NM system has data lines for every minute that the NM counted neutrons. These lines then contain values for pressure and temperature measurements, as well as the most important pressure-corrected neutron counts.

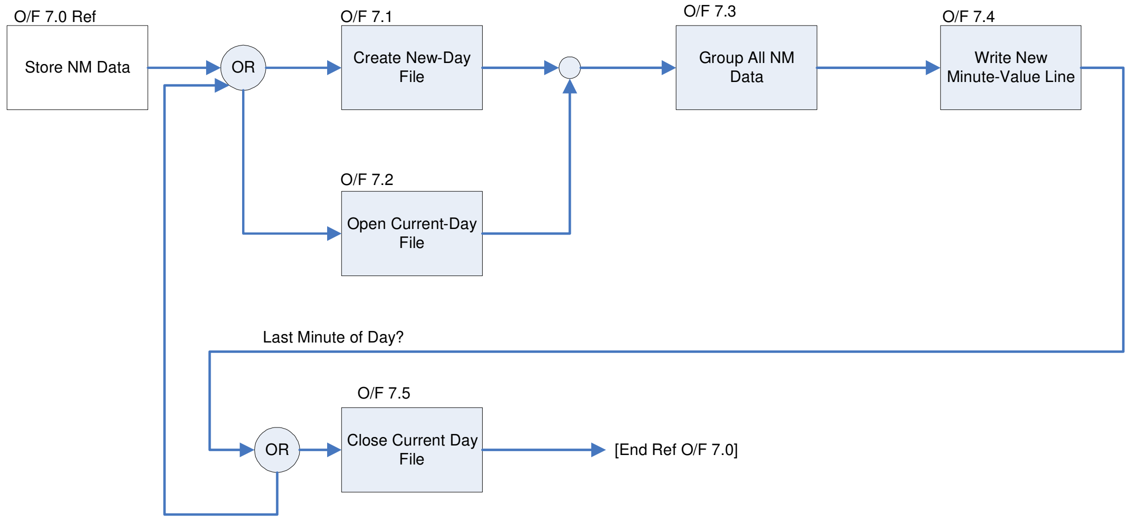

Figure 21 O/F 7 Store data

F 7.1: At the beginning of each new day – based on the GMT time and day number – a new yyddd.dat file is created. It includes a header with column descriptors of the values that each column will contain, and the first line of data begins with the time of 00:01:00 that the NM recorded (starting at 00:00:01).

O/F 7.2: If a file for the specific day already exists, the data is appended to the existing data file at one minute increments.

O/F 7.3: All the values that the NM generates through measurements and counting either get averaged over 60 seconds or an instantaneous value at the 60-second mark is taken, and grouped in the specific format as required by the yyddd.dat file. Measurements for the other environment variables except pressure can be taken instantaneously as their drift in a 60-second period is not as significant as the pressure drift.

O/F 7.4: The grouped data values are written in the per-minute format to the relevant day's file.

O/F 7.5: At the last minute of a day (23:59:59), that day's data file is closed and O/F 7 repeats by starting a new file.

2.8.9 O/F 8 Edit NM data

After the data has been recorded, it is edited to remove unwanted outliers (from spikes) and to remove other problems like static that has caused data corruption and inaccuracies. This usually happens on a monthly basis for month-end data, and a weekly basis for weekly checks and editing. The monthly data editing ends in the data set being published (O/F 9) whereas the weekly data editing just ensures that problems are spotted and resolved quicker and to ease monthly editing by "pre-editing" the data.

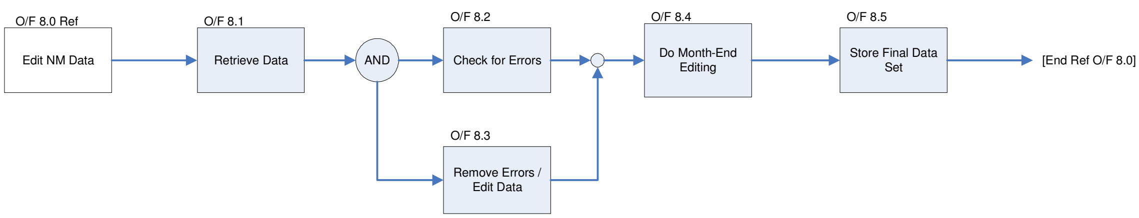

Figure 22 O/F 8 Edit data

O/F 8.1: Data is retreived from the master NM PC (it does not matter which PC the data is retrieved from, because through PC synchronisation the data sets are exactly the same) onto a data editing PC that runs editing software.

O/F 8.2: Data is checked for errors and time and date of error occurrences are verified in the operator's data and maintenance logs. Any significant finding in these comparisons should be carefully investigated and given to the Maintainer if the problem is hardware-related.

O/F 8.3: Remove errors and interpolate data sets where necessary. The editing done by this operational function takes place on a weekly basis to ensure the early detection and rectification of serious NM problems.

O/F 8.4: Edit the data for the end of the month, remove additional spikes and follow the data trend by creating the necessary and relevant images. The final data set and historical trendline from the beginning of the neutron monitor data is created here (interestingly, one can clearly see the sun cycles from this image in Figure 23) (NOAA 2010) (Gupta, Mishra and Mishra 2005).

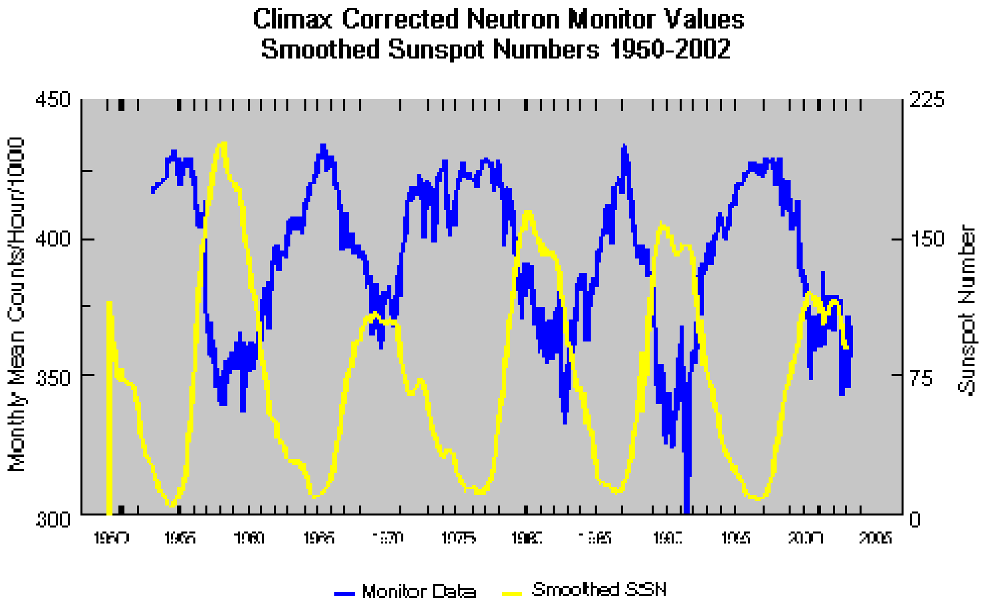

Figure 23 Cosmic ray counts (blue) vs. sunspot cycle (yellow)

O/F 8.5: Store the final data set on a separate part of the NM master PC HDD, as well as on the data editing PC and a blank CR-ROM disc.

2.8.10 O/F 9 Publish the edited data

After the data has been edited at each month-end and the Scientist is satisfied with the data set generated, the data is published. This is the point where the data is analysed for scientific meaning.

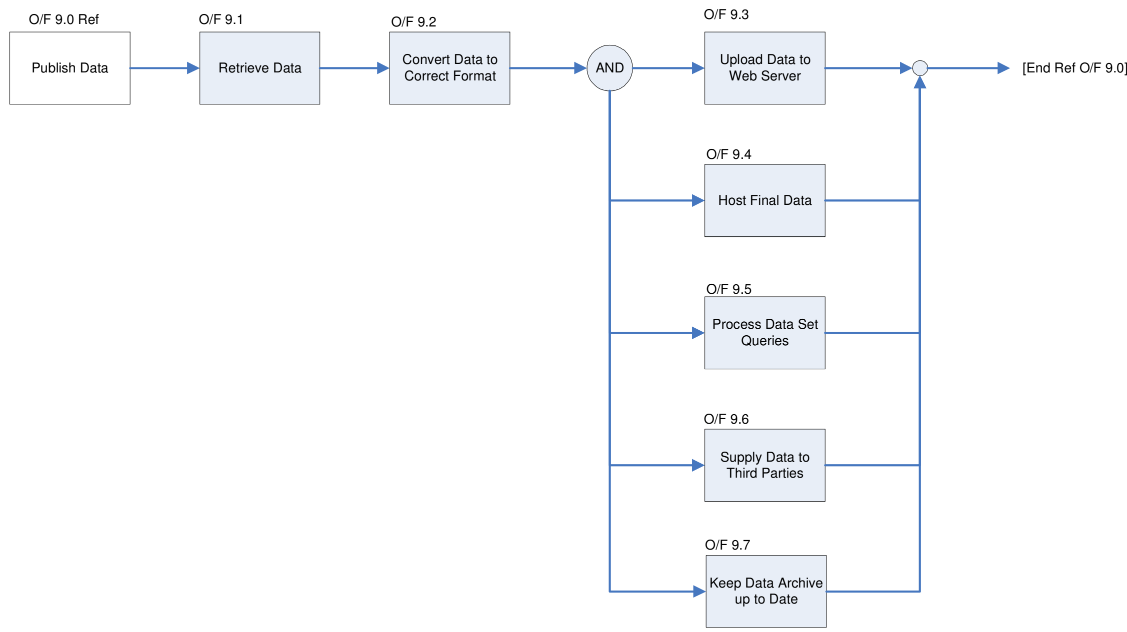

Figure 24 O/F 9 Publish NM data

O/F 9.1: The data that has been stored after editing is retrieved for publication. The published data and original edited data are – for safety and security reasons – not stored on the same place.

O/F 9.2: The data has to be converted to the correct format to be displayed on the CSR's website (that forms part of the NWU website) and also has to be converted later on for the inclusion into, and compatibility with the International neutron monitor Data Base system.

O/F 9.3: The data is uploaded to a web server.

O/F 9.4: The data is hosted on the NWU-CSR website. Data is categorised per year, month and day number.

O/F 9.5: Users and viewers of the website may query sets of NM data based on a specific date.

O/F 9.6: Third parties can receive data as .csv files – this might change based on the NMDB setup.

O/F 9.7: Maintain the data archive and keep the website up and running.

2.9 Resource allocation

The neutron monitor system makes use of resources that must be linked to the operational functions that were discussed in **section 2.8.** Each of the operational functions will require one or more system resources, and also one or more interfaces. A resource allocation is done for the following reasons:

1. When a resource fails, a function may / will fail. The dependency of functions on resources must be known in order to understand the criticality of resources;
2. Resource loading becomes evident from this allocation. That is, when a specific resource is present in many functions, the resource becomes critical and could be overloaded. In such cases it may be necessary to introduce resource redundancy;
3. Function overloading also becomes evident. That is, when a task or high-level function requires many resources, the reliability of that function becomes an issue, particularly if resources are acting in series (if one resource fails, the function fails);
4. In future upgrades, the dependancy of functions on resources will be clearly visible. This means that, when a resource (technology) is updated or changed in future, the effects of such a change can be easily traced through to other resources (by also using interface links). This simplifies decision making and reduces risk significantly.

The resources and interfaces are separated for the sake of clarity. Inspection of the tables readily shows resources and interfaces that are heavily loaded by looking at the horizontal and vertical links. The tables also serve as input to the risk analysis process since dependencies are clearly evident from inspection.

Table 1 NM System resources allocated to operational functions

		Resources																																													
		CR1	CR2	CR3	CR4	CR5	CR6	CR7	CR8	CR9	CR10	CR11	CR12	CR13	CHR1	CHR2	CHR3	CSR1.1	CSR1.2	CSR1.3	CSR1.4	CSR1.5	CSR1.6	CSR1.7	CSR1.8	CSR2.1	CSR2.2	ER1	ER2	ER3	ER4	ER5	ER6	ER7	EHR1	EHR2	DR1	DR2	DHR1	DHR2	DHR3	DSR1.1	DSR1.2	DSR1.3	DSR1.4	DSR2.1	DSR2.2
O/F 1	1.1		X										X						X																												
	1.2													X																																	
	1.3	X				X							X	X																																	
	1.4	X					X											X																													
	1.5																	X																													
	1.6																	X																													
	1.7																	X	X					X																							
	1.8																	X	X					X																							
O/F 2	2.1			X									X							X																											
	2.2			X									X							X																											
	2.3							X															X																								
O/F 3	3.1				X																X																										
	3.2				X																X																										
	3.3				X																X																										
	3.4				X																X																										
O/F 4	4.1					X							X									X																									
	4.2					X							X									X																									
O/F 5	5.1												X																	X	X				X												
	5.2								X						X												X																				
	5.3														X											X																					
	5.4									X					X											X																					
	5.5														X											X																					
	5.6														X											X																					
	5.7														X											X																					
	5.8														X											X																					
	5.9										X	X			X											X						X	X		X												
O/F 6	6.1																														X		X	X		X											
	6.2											X	X			X		X	X	X	X	X	X	X	X	X	X																				
	6.3		X										X			X			X																												
	6.4									X		X	X			X																															
	6.5	X	X	X	X	X	X	X		X			X			X												X	X	X	X		X	X		X											
	6.6											X	X			X									X	X																					
	6.7															X																															
	6.8												X			X		X	X	X	X	X	X	X	X	X	X																				
	6.9																											X									X				X	X	X	X	X	X	X
O/F 7	7.1												X												X																						
	7.2												X												X																						
	7.3												X							X	X	X	X	X	X		X																				
	7.4												X												X																						
O/F 8	8.1																								X			X											X	X		X					
	8.2																											X											X	X							
	8.3																											X													X						
	8.4																											X											X				X				
	8.5																											X											X					X	X		
O/F 9	9.1																																													X	
	9.2																																					X									
	9.3																																													X	
	9.4																																														X
	9.5																																													X	
	9.6																																													X	
	9.7																																													X	X

From the above table one can deduce that – for the risk analysis that follows – the highly loaded resources are those that will most likely cause a catastrophic system failure. For example, it can be seen that CR12 (the power supply) is critical – this is fairly obvious from experience. However, CHR1 (the Operator) is also critical and requires a support system in terms of training, decision making, occupational health and safety, management and so forth. A more detailed analysis is done in the risk analysis where critical resources are identified and associated risks are mitigated.

Conversely, functions that rely on too many resources are more likely to fail since failure of a single resource may lead to functional failure when resources are connected in series.

2.10 Interface allocation

Interfaces are known for being risky due to their inherent nature. That is, an interface effectively cuts through all system layers, from business through operational and down through all technical layers. Furthermore, interfaces are responsible for transfer of data, materials, energy etc. Interfaces are also risk hand-off points and are usually managed by using interface control documents that define responsibility, data format, electrical definitions, and other shared requirements. As a result, it is important to view functional dependencies on interfaces.

A similar argument as for resources holds for interfaces with respect to loading. The more an interface is loaded, the more flow will take place across a specific interface in order to execute functions that use different resources (functions cut across interfaces). Interfaces that are heavily loaded are thus, per definition, also critical since a faulty interface (at whatever level) will affect more than one resource, and thus a number of functions as well.

From the analysis, it is evident that CIF18 (the energy supply) is critical. However, instead of just being the resources (generator, UPS), the interface itself contains inherently fallible components such as cables and connectors. A more detailed discussion is given later in this document where risks are analyzed.

Table 2 NM Interfaces allocated to operational functions

		Interfaces																						
		CIF1	CIF2	CIF3	CIF4	CIF5	CIF6	CIF7	CIF8	CIF9	CIF10	CIF11	CIF12	CIF13	CIF14	CIF15	CIF16	CIF17	CIF18	CIF19	CIF20	CIF21	CIF22	CIF23
O/F 1	1.1		X																X					
	1.2																							X
	1.3					X													X					X
	1.4	X						X																
	1.5																							
	1.6																							
	1.7																							
	1.8																							
O/F 2	2.1			X															X					
	2.2			X															X					
	2.3								X															
O/F 3	3.1				X																			
	3.2				X																			
	3.3				X																			
	3.4				X																			
O/F 4	4.1						X												X					
	4.2						X												X					
O/F 5	5.1																							
	5.2									X	X													
	5.3											X												
	5.4											X									X			
	5.5											X												
	5.6											X												
	5.7											X												
	5.8											X												
	5.9											X	X							X				
O/F 6	6.1																							
	6.2																X	X	X					
	6.3		X															X	X					
	6.4																X		X				X	
	6.5	X	X	X	X	X	X	X	X								X	X	X				X	X
	6.6																	X	X					
	6.7																	X						
	6.8																	X	X					
	6.9																							
O/F 7	7.1																		X					
	7.2																		X					
	7.3																		X					
	7.4																		X					
O/F 8	8.1																							
	8.2																							
	8.3																							
	8.4																							
	8.5																							
O/F 9	9.1																							
	9.2																							
	9.3																							
	9.4																							
	9.5																							
	9.6																							
	9.7																							

		CSIF1	CSIF2	CSIF3	CSIF4	EIF1	EIF2	EIF3	EIF4	EIF5	EIF6	EIF7	EIF8	EIF9	EIF10	EIF11	EIF12	EIF13	EIF14
O/F 1	1.1																		
	1.2																		
	1.3																		
	1.4																		
	1.5																		
	1.6																		
	1.7	X																	
	1.8	X																	
O/F 2	2.1																		
	2.2																		
	2.3																		
O/F 3	3.1																		
	3.2																		
	3.3																		
	3.4																		
O/F 4	4.1																		
	4.2																		
O/F 5	5.1										X	X	X						
	5.2																		
	5.3			X															
	5.4			X															
	5.5			X															
	5.6			X															
	5.7			X															
	5.8			X															
	5.9													X	X				
O/F 6	6.1															X	X	X	X
	6.2																		
	6.3																		
	6.4																		
	6.5					X	X	X	X	X						X	X	X	X
	6.6			X															
	6.7																		
	6.8	X	X	X	X														
	6.9																		
O/F 7	7.1																		
	7.2																		
	7.3		X		X														
	7.4																		
O/F 8	8.1																		
	8.2																		
	8.3																		
	8.4																		
	8.5																		
O/F 9	9.1																		
	9.2																		
	9.3																		
	9.4																		
	9.5																		
	9.6																		
	9.7																		

		DIF1	DIF2	DIF3	DIF4	DIF5	DIF6	DIF7	DIF8	DIF9	DIF10	DSIF1	DSIF2	DSIF3	DSIF4	DSIF5
O/F 1	1.1															
	1.2															
	1.3															
	1.4															
	1.5															
	1.6															
	1.7															
	1.8															
O/F 2	2.1															
	2.2															
	2.3															
O/F 3	3.1															
	3.2															
	3.3															
	3.4															
O/F 4	4.1															
	4.2															
O/F 5	5.1															
	5.2															
	5.3															
	5.4															
	5.5															
	5.6															
	5.7															
	5.8															
	5.9															
O/F 6	6.1															
	6.2															
	6.3															
	6.4															
	6.5															
	6.6															
	6.7															
	6.8															
	6.9					X	X	X	X	X						
O/F 7	7.1															
	7.2															
	7.3															
	7.4															
O/F 8	8.1	X		X					X	X						
	8.2		X		X					X						
	8.3					X	X	X		X						
	8.4	X								X		X				
	8.5	X								X			X	X		
O/F 9	9.1														X	
	9.2										X					
	9.3															X
	9.4															
	9.5															X
	9.6															
	9.7															X

2.11 Conclusion

The operations of the neutron monitor system of the CSR clearly entail more than just gas tubes, electronics and measurement devices. It also makes use of much more than just people to operate it. Through the operational analysis of this chapter, it becomes very clear that there are multiple resources and interfaces that need to be managed and checked on a regular basis. The neutron monitor system is of such a magnitude that it requires a thorough technical and system management plan.

Now that the system has been analyzed and described in its logical and physical form, function, and fit, the potential risk of failure of each of these components at operational level can be determined. This will result in risk mitigation actions in order to reduce the impact of a failure. By using the resource and interface allocation tables, it is now possible to identify each operating function's dependencies and associated risk profile to identify the resources that will most likely fail.

Chapter 3 Risk analysis

3.1 Introduction

So far, the system has been defined in terms of resources, functions, and interfaces by means of an "as is" analysis and an abstraction. This functional analysis forms part of the overall technology roadmap as the system to be upgraded has now been thoroughly defined. Also, critical elements can be found by means of inspection from the resource and interface allocation tables. A risk analysis can now be performed by first performing a failure modes, effects and criticality analysis (FMECA). This analysis identifies all critical components in a systematic way so that the whole system can be analysed for existing and future risks.

The analysis of the impact of failure is subjective since the probability of occurrence and severity rely on historical data from the Scientist, personal experience with the system, and commonly known

3.2 Failure modes, effects and criticality analysis (FMECA)

The modes of failure are certain possible erroneous points in the NM operation where the NM system's integrity is compromised to a point where reliable neutron count data can no longer be assured. This can be represented by the FMECA technique for failure analysis and is based on failures of systems in industry (Hoyland 2004).

According to the IEEE Standard 352 the objectives of FMECA are to:

- Aid in the selection of highly reliable and safe design alternatives;
- Ensure that every possible system failure along with its consequent effect on the system has been considered;
- Calculate the impact of each failure's effect on the system;
- Develop testing methods and their minimum requirements;
- Give first light to reliability and availability analysis;
- Documentation generated by this study will aid in analysis and design change decisions;
- Provide data needed to decide upon functionality trade-offs;
- Maintenance prioroties can be based upon the outcome of this study;

- The requirements for system redundancy, failure detection and fail-safe operation can be created based on this study.

Table 3 Ratings table based on severity and failure

Severity rating					
Rating	1	2	3	4	5
Explanation	Data not affected	Long-term operation affected	Measurement corruption	Data corruption	Complete data loss
Severity	Minimal	Minor	Crucial	Severe	Catastrophic

Failure rate					
Rating	1	2	3	4	5
Explanation	Pratically impossible	Very unlikely	Could occur	Has occurred	Common occurrence

The detailed FMECA - **as presented in Appendix B – Failure mode, effects and criticality analysis** - is the result of a time-consuming process, with the main purpose to identify risk of failure and to propose mitigating actions. The failure rate estimates have been obtained from historical data (specifically on the counter tubes and electronics), as an employee at SANAE, input from Scientists, and literature on human failure ([16 – 25]).

A relative improvement in risk may be obtained from the identification of existing shortfalls in terms of failures and by reducing these risks by application of the mitigating actions – this improvement is subjective but serves to illustrate the point that, in some cases, risks have not been fully addressed.

It is imperative to note that existing risks already have controls that reduce the unmitigated risk, while the proposed mitigating actions mentioned in the table serve to reduce the existing, controlled risk even more.

From the FMECA, all mitigating actions that have been derived are combined in the following section - from experience of the Scientist, Operators, the Maintainer, and the author - that will provide guidelines for the technology upgrade.

3.2.1 Risk-reducing factors from FMECA

Before mitigation, the risk figure is around 400, while after mitigation the estimate is around 260. This is a subjective measure of risk reduction and does not constitute an actual gain, but rather a relative measure to show that a significant reduction in risk is possible.

The risk-reducing factors in the FMECA table (**Appendix B – Failure mode, effects and criticality analysis**) have been enumerated as listed in the last column. The list of factors is given here:

1. Ensure that Paro pressure input is unobstructed and clearly indicated;
2. Implement early warning and informative systems to inform users / maintainers NM encountered a problem;
3. Regularly check Paro batteries and ensure that battery is charging when connected to mains;
4. Ensure that a sound electrical connection is maintained between devices;
5. Monitor power supply to prevent / minimize effects of power loss, and add additional UPS;
6. Make sure there are no neutron obstructing materials above or around the neutron monitor;
7. Check tubes for material degradation, rust or dents on a regular basis;
8. Check tube connections for broken connectors or anode wires;
9. Place the HV cables in protective ducting;
10. Regularly inspect Hv cables and connectors for damage or loose connections;
11. Eliminate cables by incorporating HV supply units in NM modular design for each tube;
12. Implement LV monitoring input in the NM;
13. Eliminate cables by incorporating LV supply units in NM modular design for each tube;
14. Regularly check cables and connectors for damage;

15. Regularly calibrate the system and check for required response to a specific radiation input;
16. Review data on regular basis;
17. Regularly calibrate NM system;
18. Design for better ESD protection;
19. Include ESD and wind speed compensation;
20. Check GPS antenna connections regularly to eliminate high wind speed damage;
21. Add additional power supply and backup capabilities;
22. Visually inspect Fortan pressure sensor for damage;
23. Keep check logs up to date;
24. Do regular power tests;
25. Review software operation and behaviour;
26. Train and manage Operator and Maintainer;
27. Ensure critical components are protected using interface protection;
28. Keep NM documentation up to date;
29. Design for ability to include pressure measuring device into tube design;
30. Personnel check-in system and computer software to keep track of checking and error logs;
31. Re-design of pulse amplification, shaping and counting circuitry and associated software;
32. Adapt data editing and storage structure to conform to NMDB format.

The above list is not prioritized and not all mitigating actions are critical. A list of critical factors is discussed after all critical components have been identified by means of a criticality analysis.

Critical components are defined as those components that are either (i) heavily loaded and / or will (ii) severely impact (multiple) functions of the system as obtained from the FMECA.

Critical components will indicate which mitigating actions are normative - less critical mitigating actions are included in the list above (for the sake of being complete) and are considered to be informative.

3.2.2 Critical components

3.2.2.1 Counter sub-system

The critical components of the Counter sub-system from the above analysis are listed below - each critical component is considered for improvement:

Component	Overload status	Impact after mitigation	Improvement
CR1: Counter tubes	3	8	Not necessary
CR2: Pressure sensor	3	6	Better personnel training [26],; fixed schedule and procedures for calibration [15] [28]; early warning on device failure [2]; include device in tube design (modular)[29].
CR5: High-voltage supply	4	8	Early warning system on HV failure [2]; include HV unit in tube design (modular)[11]; check cable connections regularly [9] [10].
CR6: Low-voltage supply	2	4	Early warning system on LV failure [2] [12]; include LV power circuit in tube design (modular) [13]; check cable connections regularly [14].
CR7: Anemometer	2	5	Shield against and design for EMC withstanding [18] [19] [27];
CR11: Error log	4	6	Better training for personnel [26] [28]; fixed schedule and procedures and order for filling error logs [23] [26] [28]; design check-inn system for log completion and make log electronic [30].

CR12: Electricity supply	17	34	Early warning system / fast notification on electricity supply failure (both generator and grid) [2] [5];
CR13: Cosmic Ray Source	2	4	In the event of a NM being relocated or a new NM site being built, generate check log that ensures the NM enclosure free of carbon-rich materials [6].
CHR1: Operator	8	12	Improve training and procedures as from FMECA [26] [28].
CHR2: Maintainer	7	2	Supply with documentation on system [26] [28]
CSR1.1: Pulse Counter Hardware / Software	7	12	Fixed schedule and procedures for calibrating amplification and shaping circuits [15] [23] [26] [28]; redesign of amplification and shaping circuits for NM upgrade [27] [31].
CSR1.2: Pressure Software	6	8	Early warning system [2]
CSR1.3: Temperature Software	5	6	Fixed schedule and procedures for calibrating sensors [15] [23] [26] [28].
CSR1.4: GPS Software	7	10	Early warning system [2]
CSR1.5: HV Software	5	6	Early warning system [2]
CSR1.7: Pressure-Correction Software	5	6	Fixed schedule and procedures for checking calculated results [15] [26] [28].
CSR1.8: Data Storage Software	8	14	Early warning system [2]; check saved data on regular basis for correctness [16] [23] [26].
CSR2.1: Data Display Software	10	2	Check data on NM PC's to ensure display is working [16] [25] [26].

3.2.2.2 Energy sub-system

The critical components of the Energy sub-system from the above analysis are listed below - each critical component is considered for improvement:

Component	Overload status	Impact after mitigation	Improvement
ER1: UPS	7	14	Add additional UPS backup time in the form of additional smaller UPS's to keep PC's going [5] [21] [24]; early warning system on UPS state [2].
ER2: UPS Battery Bank	1	4	Add additional UPS backup time in the form of additional batteries [21] [24]; early warning system monitoring UPS batteries [2].
ER3: Grid Power Supply	2	3	Early warning system for power interruption notification [2]
ER4: Generator	3	5	Fixed schedule and procedures for maintaining and servicing the generator [21] [23] [26] [28].; early warning system on generator failure or problems [2].
ER6: Power Supply Error Log	3	5	Better training for personnel [26] [28].; fixed schedule and procedures and order for filling error logs [23] [26] [28]; design check-inn system for log completion and make log electronic [30].
ER7: Selector Switch	2	4	Better training for personnel [26] [28]; fixed schedule and procedures for testing and operating selector switch [26] [28];

3.2.2.3 Data sub-system

The critical components of the Data sub-system from the above analysis are listed below - each critical component is considered for improvement:

Component	**Overload status**	**Impact after mitigation**	**Improvement**
DSR2.1: Web Server Data Storage Software	3	10	Conform to NMDB standards for uploading data to the international repository; better training for personnel [26] [28] [32].

3.3 Conclusion

In this chapter, the overall system was analysed according to the risk profile of each operational function and the different failure modes for each function were identified. Each failure mode has its own set of physical devices (resources) and the result of each of these failing was noted for the system's performance as well as sub-system influences.

Mitigating actions were identified for each resource in order to reduce the chance of it failing and compromising the NM system. It is important to note that the consequence of a specific resource failure stays the same regardless of mitigation or not, because each resource's influence when failing will result in exactly the same effect on the system as long as the system architecture and functional flows remain unchanged. Impact may be lowered or designed out of a system by either adding or removing functions or resources – that is, by means of design.

Following the above, critical components were identified based on the FMECA and load function tables and the mitigating actions to reduce the associated rates of failure were described in detail. In the next chapter, prescribed actions to be implemented by the developer (who will do the upgrade) are given.

The developer must implement these improvements by incorporating them into the new neutron monitor design and must ensure that future designs and upgrades will adhere to the same critical component requirements, or should at least use this document as a reference for new analyses. As the neutron monitor design progresses, however, this document will be revised, including new critical components and their risk profiles.

Thus, by using existing engineering tools, such as functional analysis (systems engineering), reliability analysis (that can be considered to belong to systems engineering, but this is a personal view), and risk management (combined systems engineering and project management, if done in this way) it is possible to derive guidelines for further development or change – clearly this is a comprehensive way of proposing a technology road map for future change.

Chapter 4 Conclusion and recommendation

4.1 Introduction

The work done so far has focused mainly on the documentation, abstraction, functional analysis, and risk analysis of the neutron monitor system. In itself, the documentation and analyses are invaluable for any new developer (engineer or scientist) to understand the system and its complexities.

In addition to the internal system and its shortfalls, it is necessary to understand where and how external factors will influence the system in the future.

4.2 External factors

External factors that affect the continuity of the operation of the neutron monitor include the following critical factors:

1. Scarce human resources: It is known that engineers and scientists are becoming scarce and expensive. Therefore, the system must be designed to use less skilled resources – this implies usability in operation, modularity for maintenance, and testability for repair;
2. Unreliable utility services: The power supply from national suppliers is becoming more unreliable for various reasons. This suggests a more robust backup system and less power-consuming and sensitive equipment (EMC design);
3. Financial support and investment: Limited resources for research imply that equipment must be designed for cost-effectiveness with a balance to be struck between modularity and cost. Logistical costs imply reliability in design and ease of maintenance (modularity and usability);
4. Technology: Technology has progressed to the point where sophisticated electronics can be used in seemingly unsophisticated equipment. As a result, diagnostics, communication and other forms of intelligence can simplify operation and maintenance. Cost of low-level electronics has also decreased and modularity can be achieved at limited expense;
5. Expectations: The international scientific community relies on data from the CSR programme. This implies business continuity, which in turn places a demand on configuration management and reliability.

4.3 Actions based on critical components

A complete list of mitigating actions were given in section 3.2.1 based on the risks identified and listed in the FMECA table in Appendix B. The resources that pose the largest risk of failure of the system – based on their failure rate and loading – were then listed in section 3.2.2.

It is of paramount importance to put the necessary procedures in place to eliminate risk or, at least, reduce risk. The following descriptions provide more detail on the mitigating actions regarding critical components.

Mitigation 2 - Implement early warning and informative systems to inform users / maintainers NM encountered a problem

Design and implement a simplistic early notification system that informs the operator and maintainer that something is wrong with the neutron monitor. This includes, but is not limited to, warnings and error messages for HV, LV, GPS, Power Supply, Generator Status, UPS status, temperature and pressure readings.

Mitigation 5 - Monitor power supply to prevent / minimize effects of power loss, and add additional UPS

Monitoring systems and measurement inputs for the main (grid) power supply as well as UPS state (input and output voltage, battery level, charge voltage, capacity and current load) should be included in the system upgrade design, and linked to the early warning system. At least one additional UPS should be added that can be redundant and act as backup for the primary UPS, and at least one additional UPS should be added to the NM PC's for added data backup and protection.

Mitigation 6 - Ensure there are no neutron obstructing materials above or around the neutron monitor

Inspect the NM site and surrounding areas for neutron-obstructing materials on a scheduled basis. NM sites are usually not very busy, but occasional human passing occurs. It is very important to ensure that no neutron-obstructing materials like lead and carbon-rich materials are stored, placed or discarded on top of or at least 5 meters from the NM tubes.

Mitigation 9 - Place the HV cables in protective ducting

While the final upgrade of the neutron monitor system is not yet accomplished, at least safeguard the HV cables by enclosing them in sturdy, protective ducting where they cannot be stepped on or accidentally kicked by the operator, maintainer or scientist.

Mitigation 10 - Regularly inspect HV cables and connectors for damage or loose connections

For each tube in the current NM setup there is one HV cable travelling from the HV source to the tube itself. Due to temperature fluctuations, movement around the tubes and accidental bumps to the tubes, these connectors loosen bit by bit, causing dips and sparks on the HV lines and hence on the anode wires as well. Ensure that all HV connectors are regularly checked and fastened, or replaced if serious damage was sustained.

Mitigation 11 - Eliminate cables by incorporating HV supply units in NM modular design for each tube

With the design of the new neutron monitor system the HV lines must be eliminated by including the HV circuitry or device into the tube design. This dramatically shortens the length of copper between the HV and tube anode wire and will assist in ESD protection and EM noise.

Mitigation 12 - Implement LV monitoring input in the NM

Design and implement measurement and recording of the LV supply values for the amplifier, shaping and counting circuit. Add this value to the early warning system.

Mitigation 13 - Eliminate cables by incorporating LV supply units in NM modular design for each tube

As with the current HV, there is a LV line running from the LV source to the tube to drive the amplification, shaping and counting circuits. Eliminate these cables and the effect of EM noise on the LV line by incorporating the LV source into the tube design.

Mitigation 14 - Regularly check cables and connectors for damage

Make the checking of cables and connectors part of the operator responsibility for scheduled checks, and provide space for the checking thereof in the logs.

Mitigation 15 - Regularly calibrate the system and check for required response to a specific radiation input

Design a scheduled system calibration test procedure in order to determine the accuracy of neutron counts and to verify that the system's response is still correct for a given, predetermined level of test radiation. Through this procedure and the thorough documenting of the tests and results, problems such as drift in pressure readings, temperature control and tube response due to erroneous HV supply levels (to name a few) can be determined early and rectified before the NM data becomes unreliable.

Mitigation 16 - Review data on regular basis

The scientist should review the recorded and pre-edited data on a regular basis in order to eliminate count-correction errors in terms of pressure and temperature. By doing this regularly, the chance of drifting NM data due to other parameters drifting (pressure, temperature, position, GPS data regarding position and altitude) can be greatly reduced as uncommon or unexpected system behaviour can be easily spotted. The scientist must also train the operator to identify certain erroneous trends in the data to resolve the NM problems even quicker.

Mitigation 18 - Design for better ESD protection

Research and implement good ESD and EMC circuit design in order to minimize noise on small signals, and also to prevent circuits and devices from getting damaged by strong electrostatic discharge. Even when no ESD occurs, long conductors like power and data communication lines will get charged and result in floating values.

Mitigation 19 - Include ESD and wind speed compensation

The first line of defence against ESD in high wind speeds (especially SANAE) is good ESD design. Secondly the data recording and device interface hardware should be designed to be able to deal with ESD in the event of it occurring, and shut down or disconnect susceptible devices. The wind speed at SANAE can be used as a good indication on which to set the device disconnect or shutdown level for ESD protection.

Mitigation 21 - Add additional power supply and backup capabilities

The single UPS filtering the supply power and acting as backup for the Potch NM does not have any assistance in either the event of a really long, total blackout (disregarding the generator) or the possibility that the UPS itself will fail. In that case it is very important to add another UPS of equal or larger capacity and enable the UPS's to relieve each other in the event of a UPS problem or sustained blackout. For all the other stations there are at least two UPS's and the backup capacity in terms of extra batteries could be increased.

Mitigation 23 - Keep check logs up to date

The operator should be meticulous about the system check logs for this is used as a major indication and informant of the cause of failure in the NM in the event of something going wrong. Both the maintainer and scientist will use this log to trace the cause of a problem, and to identify possible problems early on in the NM operation cycle.

Mitigation 24 - Do regular power tests

Test the UPS and generator capability on a regular level and use it as a training exercise for new employees in terms of how to switch power supply sources in the event of grid power failure. These tests will also indicate whether or not it is necessary to change UPS batteries or to service the generator

Mitigation 25 - Review software operation and behaviour

Check to see if the software handles the required operations correctly. This forms part of the regular data review [16] to ensure that software operations are executed correctly

Mitigation 26 - Train and manage Operator and Maintainer

Detailed, thorough and systematic training procedures must be put in place to train the NM Operators and Maintainers, including the necessary documentation to support the different devices and operations of the NM so the Operators and Maintainers can easily cross-reference specific procedures, actions and reactions of the system.

Mitigation 27 - Ensure critical components are protected using interface protection

This forms part of the EMC compatibility design requirement. The design of critical hardware should be in such a way that maximum protection against ESD will be ensured, and that compliance to EMC standards are followed.

Mitigation 28 - Keep NM documentation up to date

The documentation of the NM should be kept up to date and a document repository should be included in the NM system in order to keep document revisions sorted. Every addition, deletion, modification and calibration result should be added to the repository, and the check logs should be entered into the repository as well. This will provide a solid base for historic trends and solutions and aid in future maintenance, upgrade and system improvements.

Mitigation 29 - Design for ability to include pressure measuring device into tube design

In the event of a stationary NM like the Potch, Tsumeb, Hermanus and SANAE neutron monitors, one pressure sensor can be used for all the tubes. But in the event of a travelling NM like the calibration neutron monitor, the upgraded NM system must be able to use the same electronics and have the added functionality of connecting the pressure measuring device to the tube. The system becomes more flexible and redundant this way, and the calibration of pressure devices can be accommodated throught this functionality.

Mitigation 30 - Check-in system and computer software to keep track of checking and error logs

Rather than using paper and a clipboard to log the system response, the checking operation should be integrated in the NM system and the document repository in order to keep an easily traceable record of system behaviour at a specific time of day. This will also aid in the management of system checks performed to ensure that scheduled system checks are complied with.

Mitigation 31 - Re-design of pulse amplification, shaping and counting circuitry and associated software

Analyse the existing amplification and shaping circuits alongside the pulse output requirements of both the scientist and the specific tube that is used. Develop new electronic circuits (update the existing circuits in terms of available components) for regular system and component upgrades in order to sustain the life of the NM system. Thorough research must be done on proposed components in order to ensure the future procurement or ease of adaptation in the event of components being discontinued. The design must also include adaptation between the different counter tubes that are used. Redesign the pulse recording software to include added pulse analysis functionality and tube type to correctly identify the resulting pulse.

Mitigation 32 - Adapt data editing and storage structure to conform to NMDB format

Restructure the NM data file layout to fall in with the data format requirements of the NMDB (Appendix D). All the necessary data fields already exist in the current NM data file format, but it is up to the scientist and operator concerned with data upload to the server to ensure that the NMDB data format is adhered to.

4.4 General design guidelines

In addition to the important <u>specific guidelines</u> above, <u>general design guidelines</u> were extracted from both internal and external factors and are listed below:

1. <u>Reliability</u>: Define resources to operate reliably. This implies that (i) humans need to be informed, trained, and managed (ii) technology must be tested and qualified before and during use at remote stations such as SANAE, both by means of accelerated stress testing and life testing, (iii) data in the form of documentation must be kept current to reduce maintenance down time, (iv) logistic and other support systems must be verified regularly;
2. <u>Maintainability</u>: In order to design a system that is maintainable by using less-skilled resources in this case, the design should be modular for ease of replacement – this will reduce maintenance down time when repairs or scheduled maintenance is done. This is particularly true for remote stations, and the repair policy should allow for keeping stock of critical items (as identified) on site;

3. Interoperability: All functions must be defined and documented (as in this document) for lower levels, interfaces must be defined, documented, and made available so that future upgrades are seamless. Good electro-magnetic compatibility and, in fact, proper overall physical-layer design are critical requirements for interoperability;
4. Testability: Maintainable systems must be testable. In this case, diagnostic testing is critical when limited human resources are available. System errors must be visible, preferably before failure by means of system health monitoring;
5. Usability: Simplification of interfaces, easily accessible processes and procedures, decision-support information and other ergonomical factors determine usability. In this case, the Operator and Maintainer are not as highly skilled as the Scientist, and periodic personnel turnover results in a lack of business continuity. Good interface design and training documentation will address this issue;
6. Environment: The environment in SANAE is challenging, to say the least. This implies a need for good electro-magnetic compatibility, temperature compensation, shock and vibration resistance during transport, and the ability to operate under conditions of high humidity;
7. Optimality: It is critical that the system should be both modular and integrated, which may seem contradictory. However, the existing counter sub-system is fairly distributed and bulky due to out-dated components. This implies that components can be combined and replaced by digital processing as opposed to analogue processing. Modules can now be made intelligent, both in terms of operations and maintenance. This trade-off must be done in light of the criticality of both functions and resources by, for example, not integrating expensive non-critical components with inexpensive critical components. A failure of a critical component them implies replacement of a non-critical expensive component – critical components should therefore form part of separate modules;

4.5 Cost, time and development resources

Cost has not played a major part in the analysis up to this point. This was done specifically so as not to interfere with the technical analyses – by separating cost and performance, the focus is maintained on functional and performance analysis. Cost, time, and development resources all form part of the project management that will play a major role in the development of items as part of the upgrade phase of the project.

Cost-performance trade-offs will be done when high-level architectural design takes place. Selection and grouping of functions into physical modules, sub-assemblies, assemblies etc, will be constrained by a budget and will thus form part of further research and development.

4.6 Conclusion

The four NM's of the CSR have been in operation since the late 1950's. Looking at Figure 25, an undisputed and nearly uninterrupted track record of continued operation for almost 60 years is evident. The continuation of this track record into the future provides the reason for the technology roadmap that is the objective of this document. The system has been defined to allow future upgrades and maintenance projects that can be based on the solid foundation that has been created till present.

The analysis in this thesis began with the description of a typical neutron monitor in terms of its basic building blocks. It presented the typical setup of a neutron monitor and how how the elements operate to count a single neutron of many. The analysis of the neutron monitors as a complex system began by describing the deployment characteristics of the system in terms of locations, data paths and logistics needed to keep a neutron monitor station functional.

The operational analysis continued by viewing the neutron monitor firstly in its physical form for each station and then in its logical state, separating the counting, energy, and data sub-systems from one another. The logical configuration shows the functional units in the neutron monitor system that represents the overall system. This has not been documented in this comprehensive fashion before.

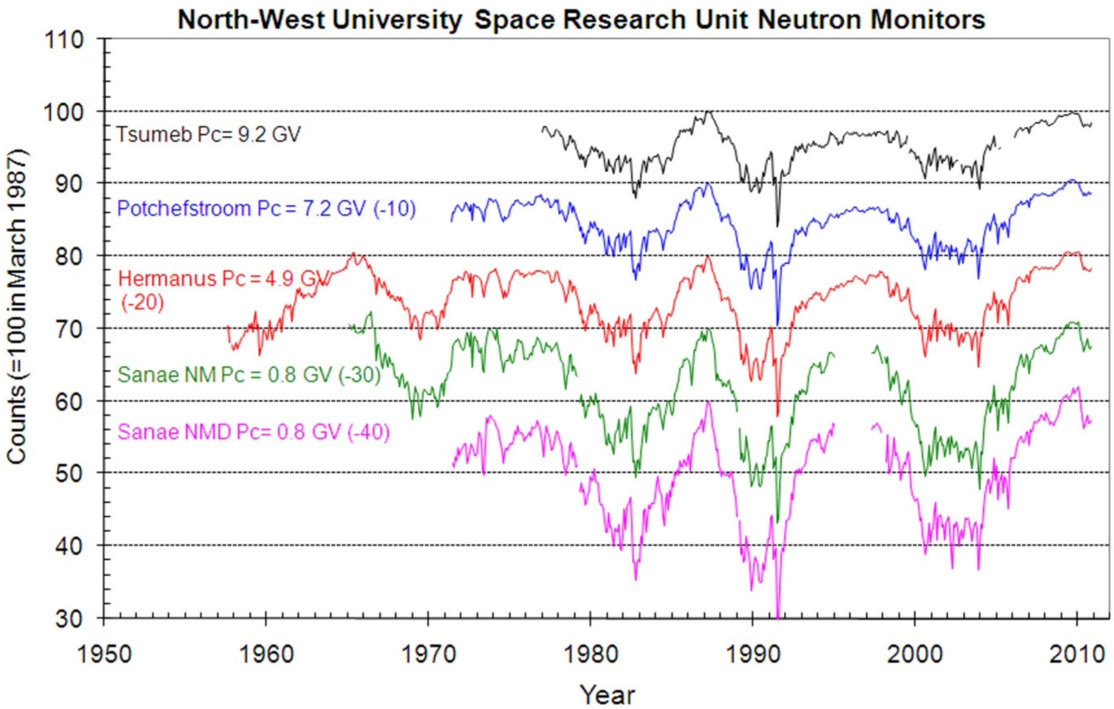

Figure 25 Neutron count history from the CSR Neutron Monitor stations

Following the “as is” definition and logical abstraction, the system was described in terms of its operational functions by means of a functional flow analysis. It is realtively straight forward to allocate the physical resources that each operational function will use to perform its function. Resource and interface allocation tables were used to visually identify loading of resources and interfaces.

After these tables had been created, the risk analysis could commence. A failure mode, effects and criticality analysis was done to identify resources that are risky. In this FMECA study the rate of failure, failure effect on the system, and rate of failure after mitigating actions could be summarized for each failure mode and failure mechanism (the resources failing). Mitigating actions were defined and listed for each failure mode.

From the resource allocation table the overloaded (more than 5 operational functions depending on a resource) were listed. The critical resources were derived by (i) taking into consideration the loading of resources and (ii) using the FMECA’s failure rates and effects to find components that must be improved.

From the above, all critical components and their associated mitigating actions were identified and combined to give specific and general guidelines for an upgrade to the neutron monitor system.

These mitigating actions will be used as guidelines and suggestions to improve the current neutron monitor system as well as ensure that future upgrade and maintenance support systems are put in place. Operational and maintenance documentation shall be generated and updated as part of configuration management.

The NM system of the CSR with its processes, hardware, software, human resources and data control can be used as benchmark for the other neutron monitor systems across the globe.

List of references

[1] arsssen. *Neutron Monitor Databse.* 2009. www.nmdb.eu/?q=node/200 (accessed 2010).

[2] Bieber, Evenson, Pyle. *NEUTRON MONITORS IN THE 21ST CENTURY ?* Bartol Research Institute and Department of Physics and Astronomy,, 2008.

[3] Dighe, Priyamvada M. “New cathode design boron lined proportional counters for neutron area.” *Nuclear Instruments and Methods in Physics Research A 575*, 2007: 461–465.

[4] Gupta, Mishra and Mishra. “Correlative study of solar activity and cosmic ray intensity for solar cycles 20 to 23.” *29th International Cosmic Ray Conference Pune 2*, 2005: 147-150.

[5] Hawkes, N.P. “Pulse shape discrimination in hydrogen-filled proportional counters.” *Nuclear Instruments and Methods in Physics Research A 574*, 2007: 133–136.

[6] Hoyland, Rausand and. *System Reliability Theory: Models, Statistical Methods and Applications.* John Wiley and Sons Inc., 2004.

[7] Integrated Publishing. *Nuclear Power Training.* 2003a. http://www.tpub.com/content/doe/h1013v2/css/h1013v2_35.htm (accessed 2009).

[8] —. *Nuclear Power Training.* 2003b. http://www.tpub.com/content/doe/h1013v2/css/h1013v2_39.htm (accessed 2009).

[9] NOAA. *National Geophysical Data Centre.* 27 October 2010. www.ngdc.noaa.gov/stp/solar/cosmicrays.html (accessed 2010).

[10] Steigies, Rother. *NMDB: Real-Time database for high resolution Neutron Monitor Measurements.* Combination of Collaborative Project and Coordination and Support Action, Kiel, Germany: e-infrastructure, 2008.

[11] Stoker, Dorman, Clem. “Neutron Monitor Design Improvements.” *Space Science Reviews no. 93* (Kluwer Academic Publishers), 8 June 2000.

[12] Williams, Tim. *EMC for Product Designers.* 4th Edition. Newnes, Elsevier, 2007.

[13] W.J. Fabrycky and B.S. Blanchard, "Systems Engineering and Analysis", *Prentice Hall*, 1998

Appendix A: Physical layout

Potchefstroom neutron monitor physical layout

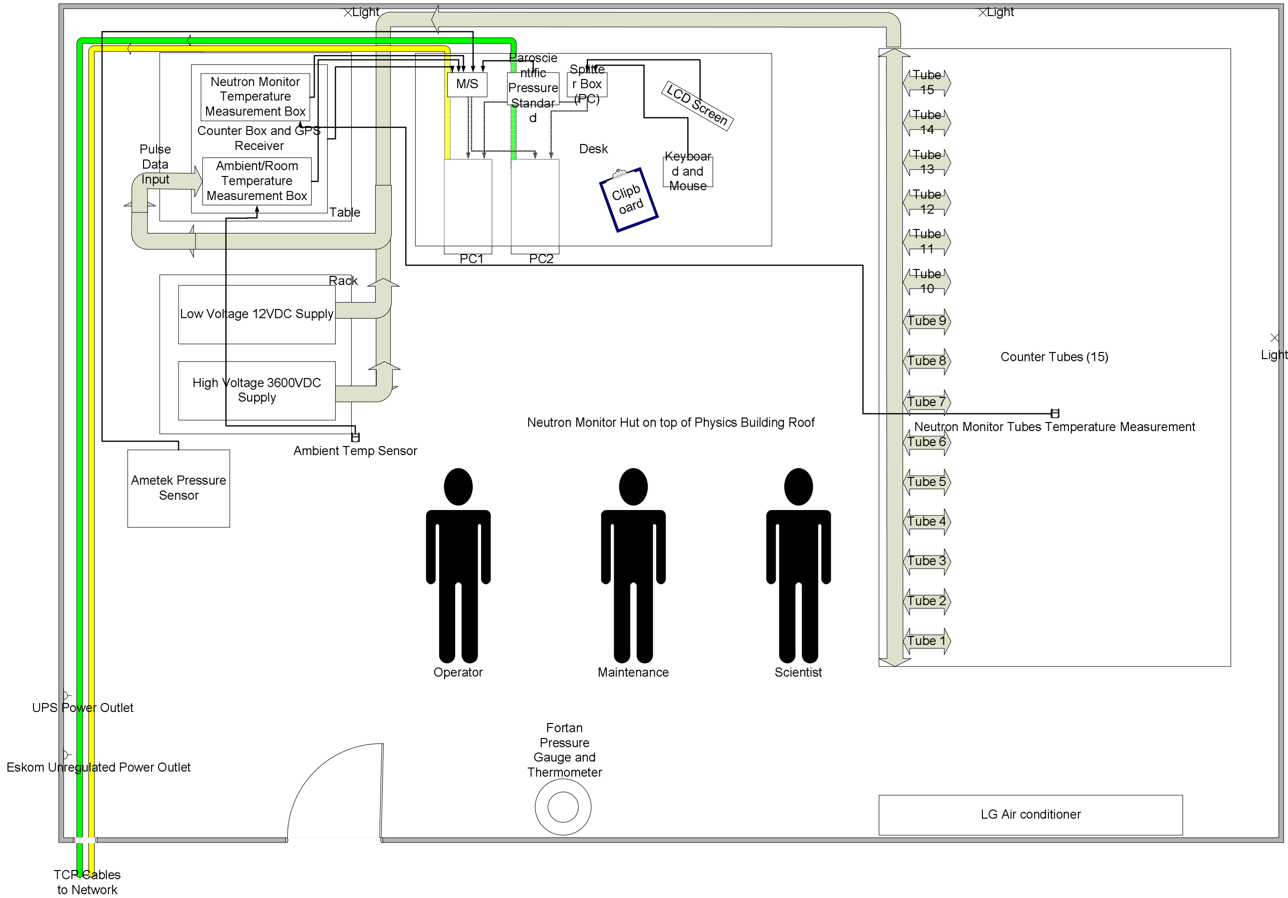

Figure 26 Potchefstroom rooftop NM layout

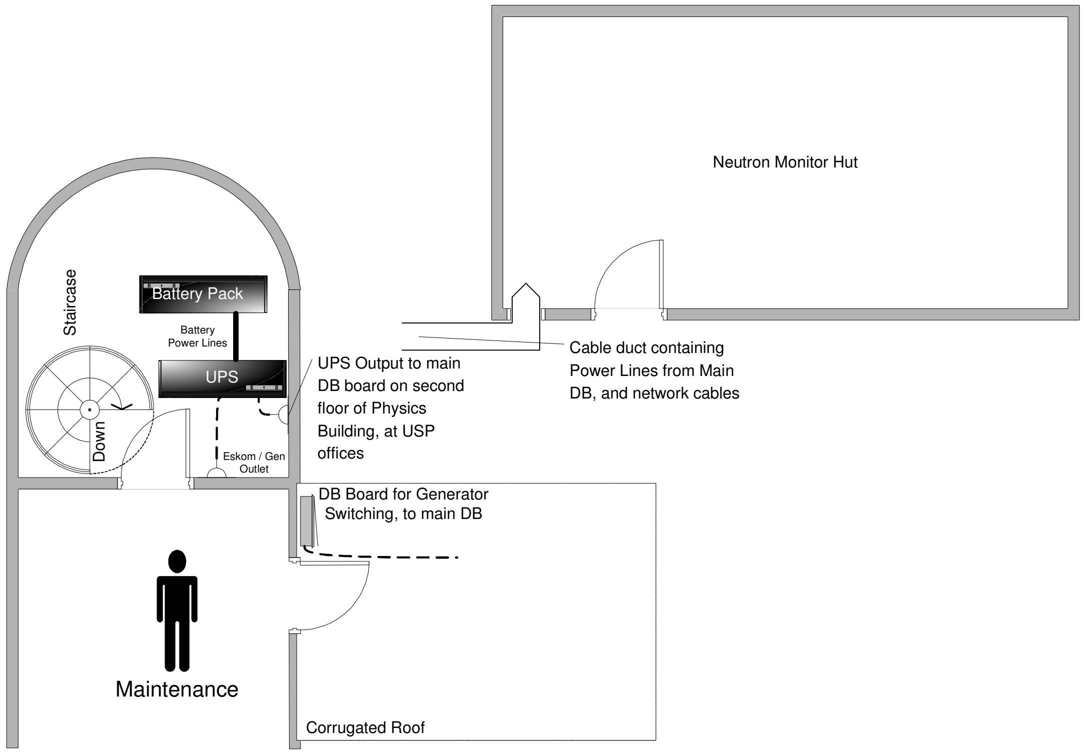

Figure 27 Potchefstroom rooftop power and building layout

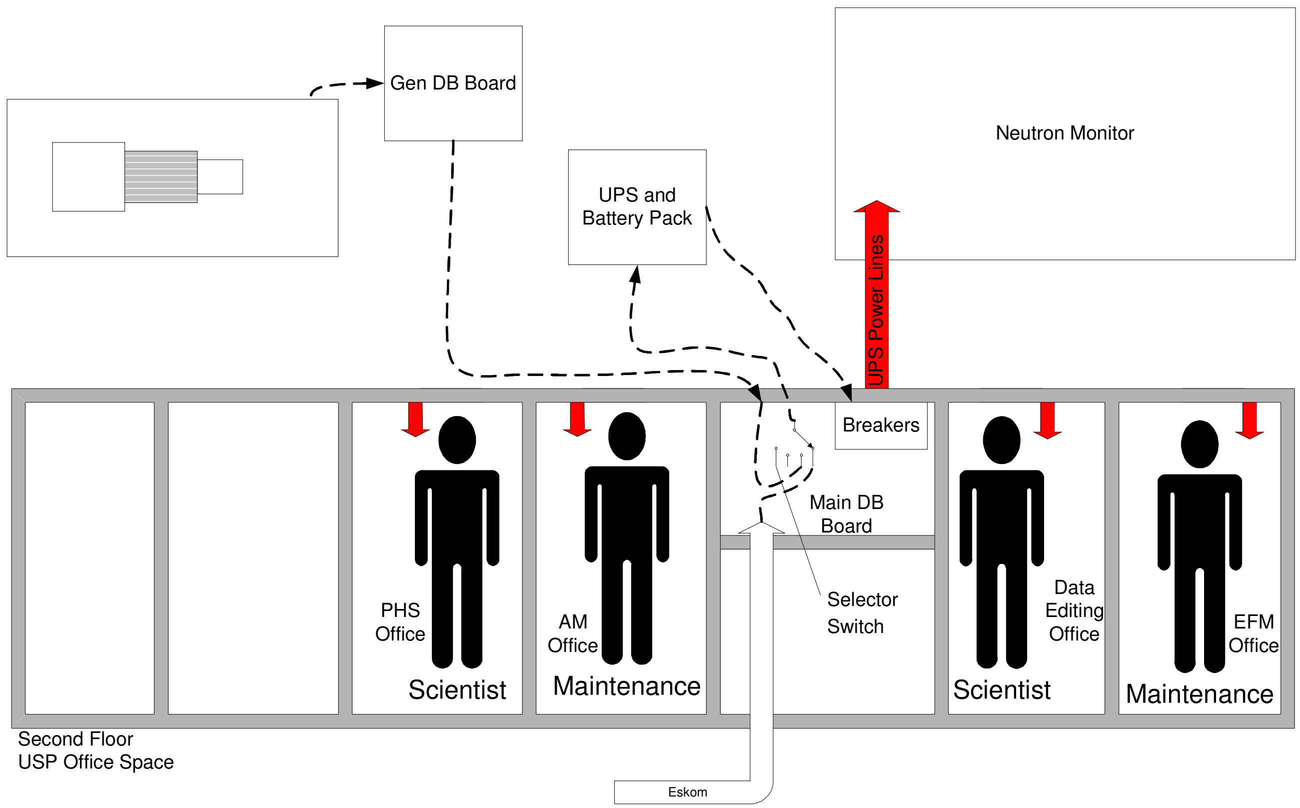

Figure 28 Potchefstroom floor power supply layout

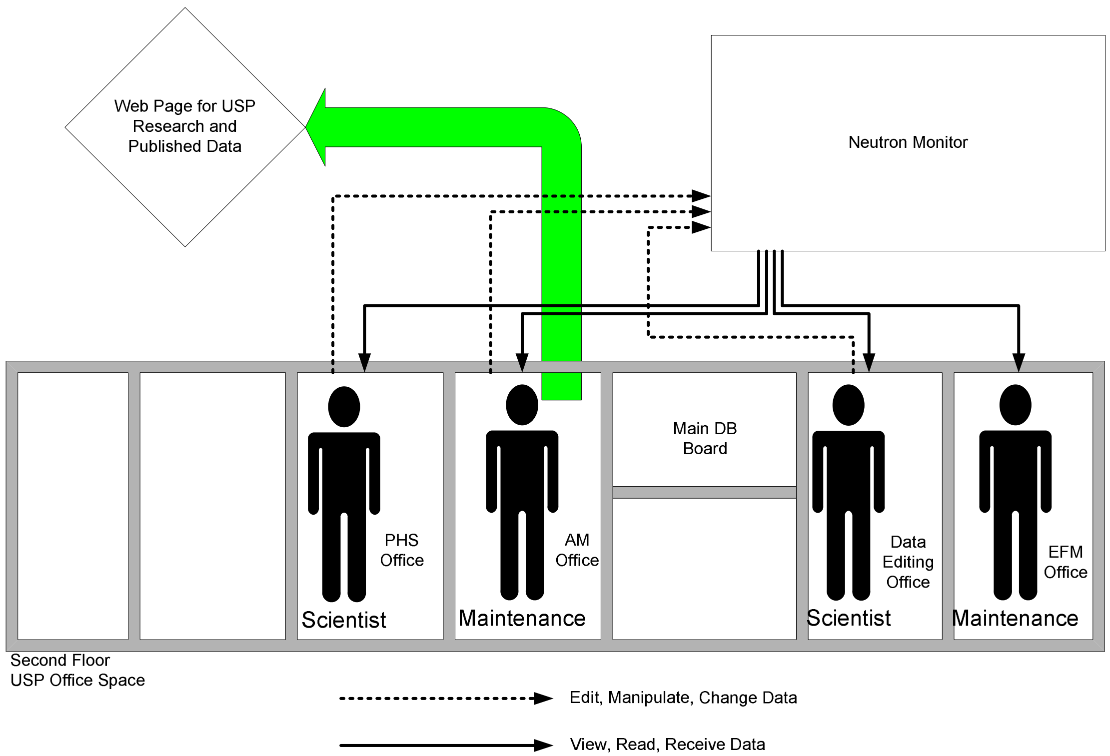

Figure 29 Potchefstroom NM data path layout

Hermanus neutron monitor physical layout

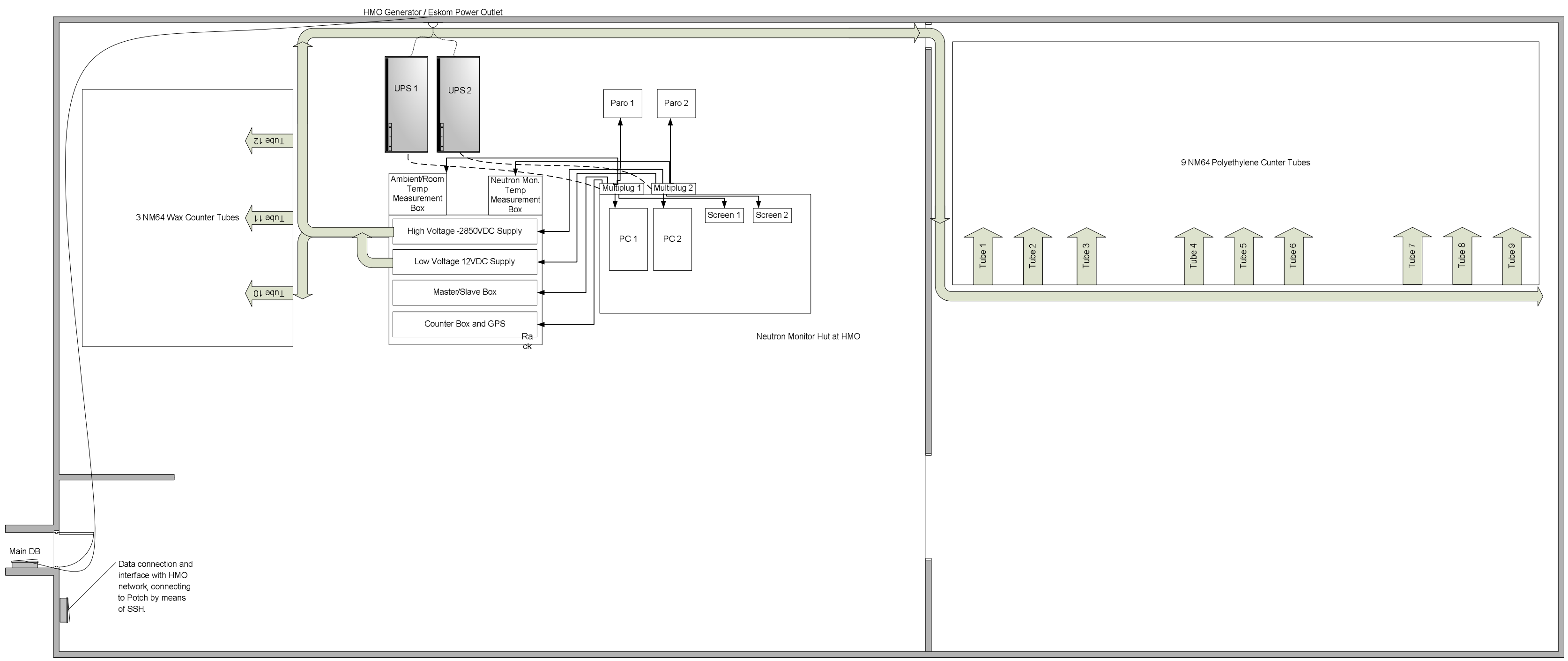

Figure 30 Hermanus NM layout – 1

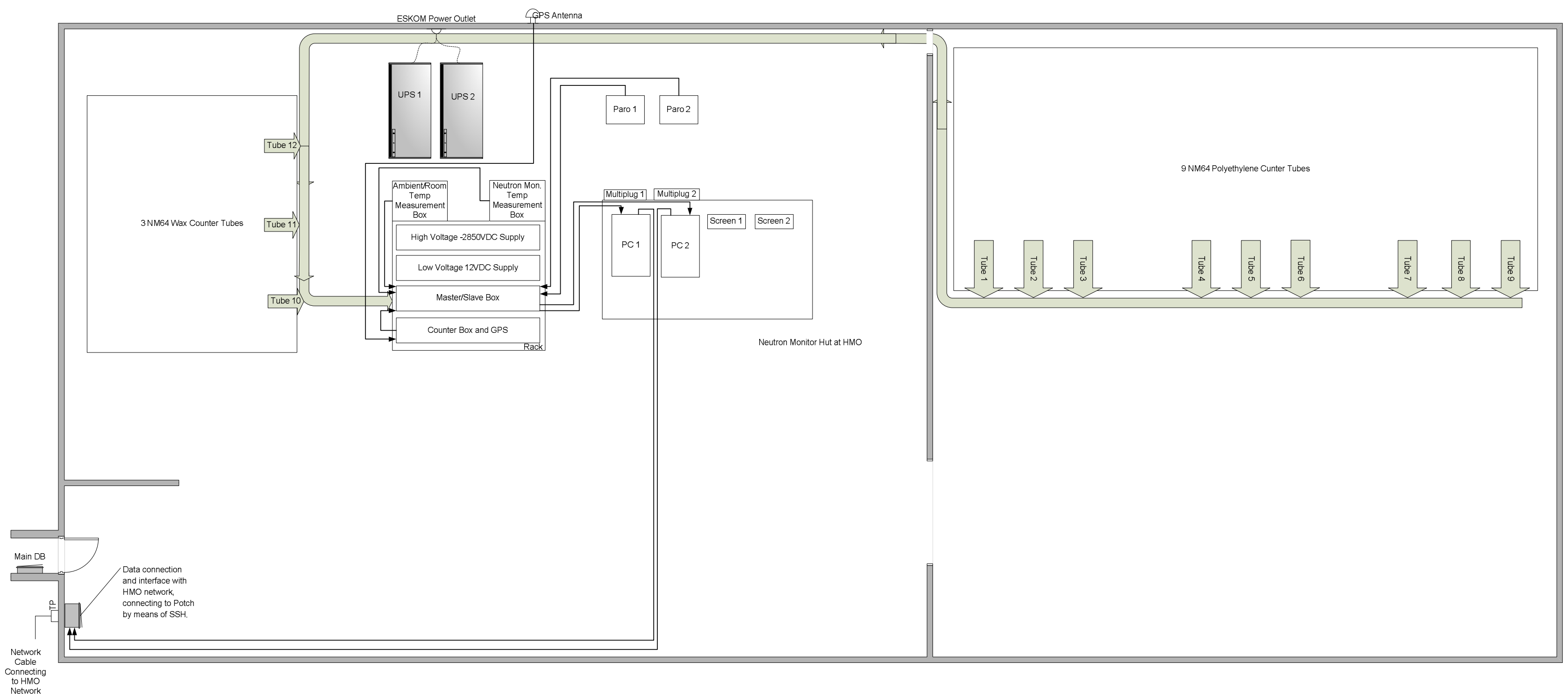

Figure 31 Hermanus NM layout – 2

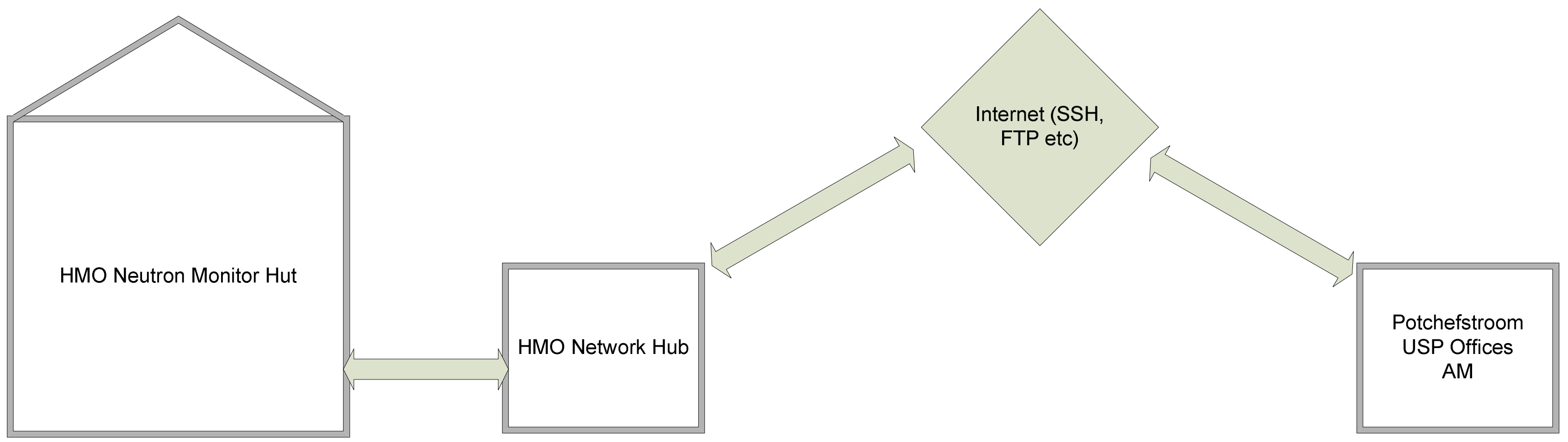

Figure 32 Hermanus data path layouts

Tsumeb neutron monitor physical layout

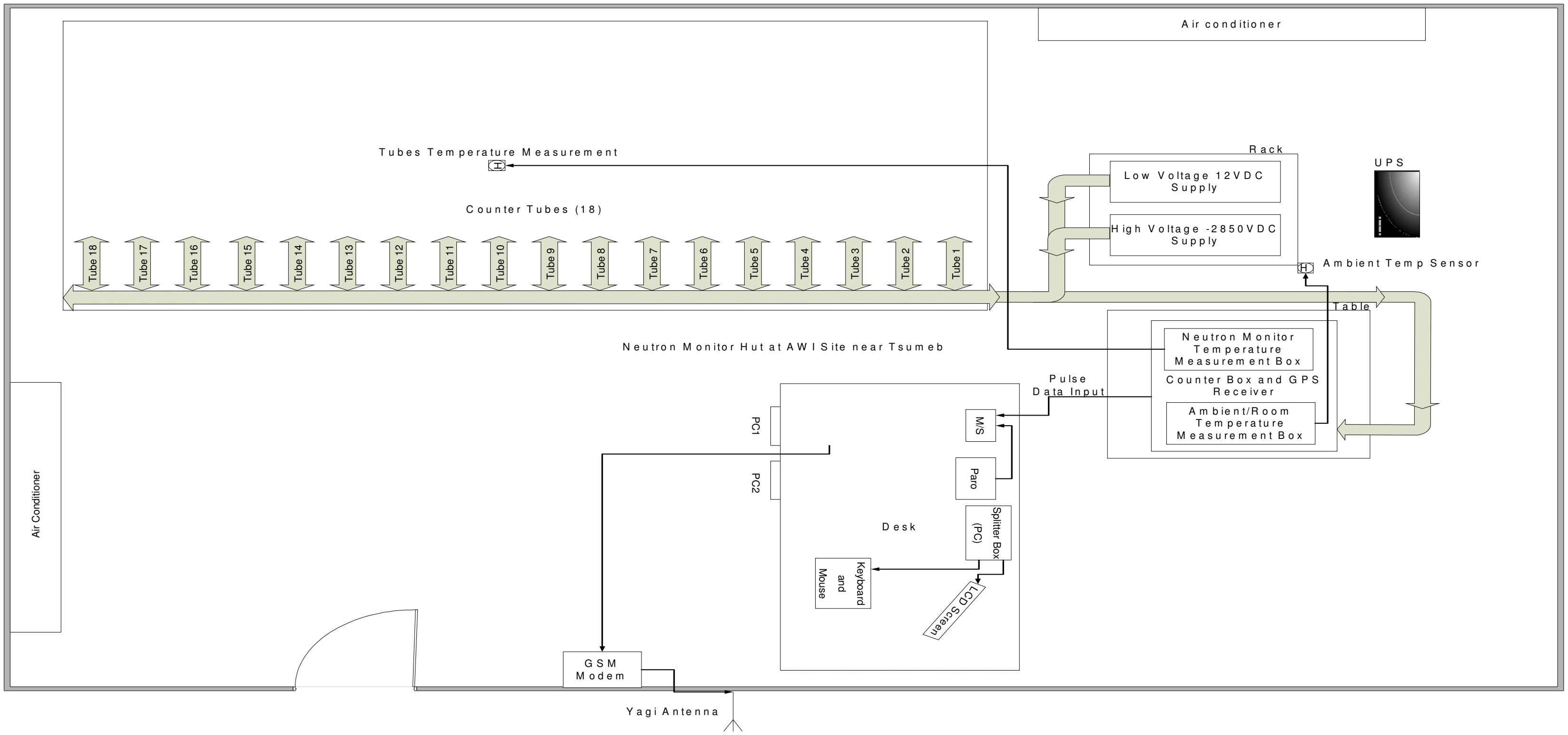

Figure 33 Tsumeb NM layout

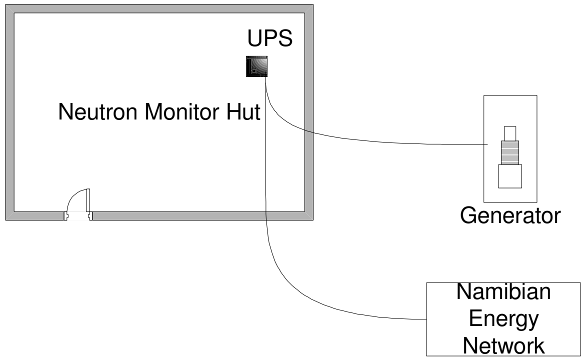

Figure 34 Tsumeb NM power layout

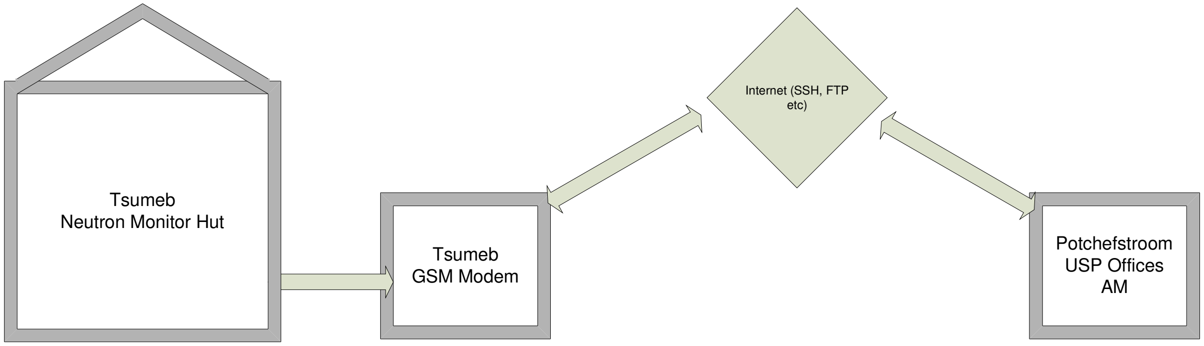

Figure 35 Tsumeb NM data layout

SANAE neutron monitor physical layout

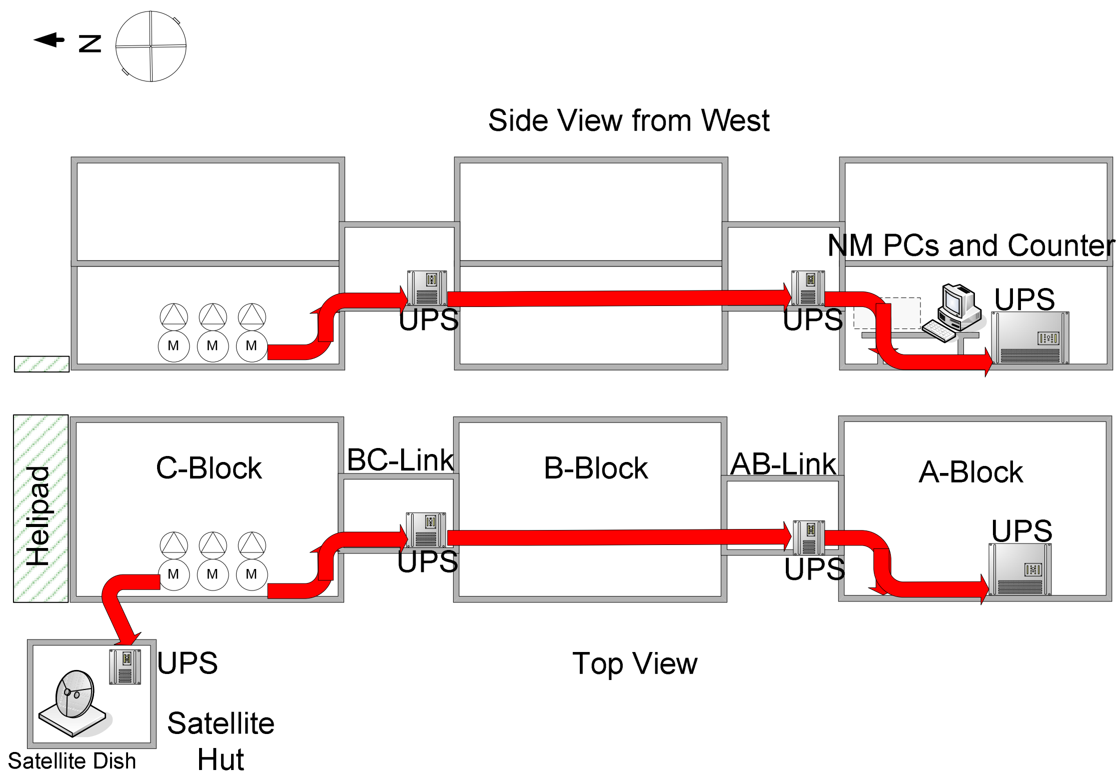

Figure 36 SANAE Base power generation and distribution setup

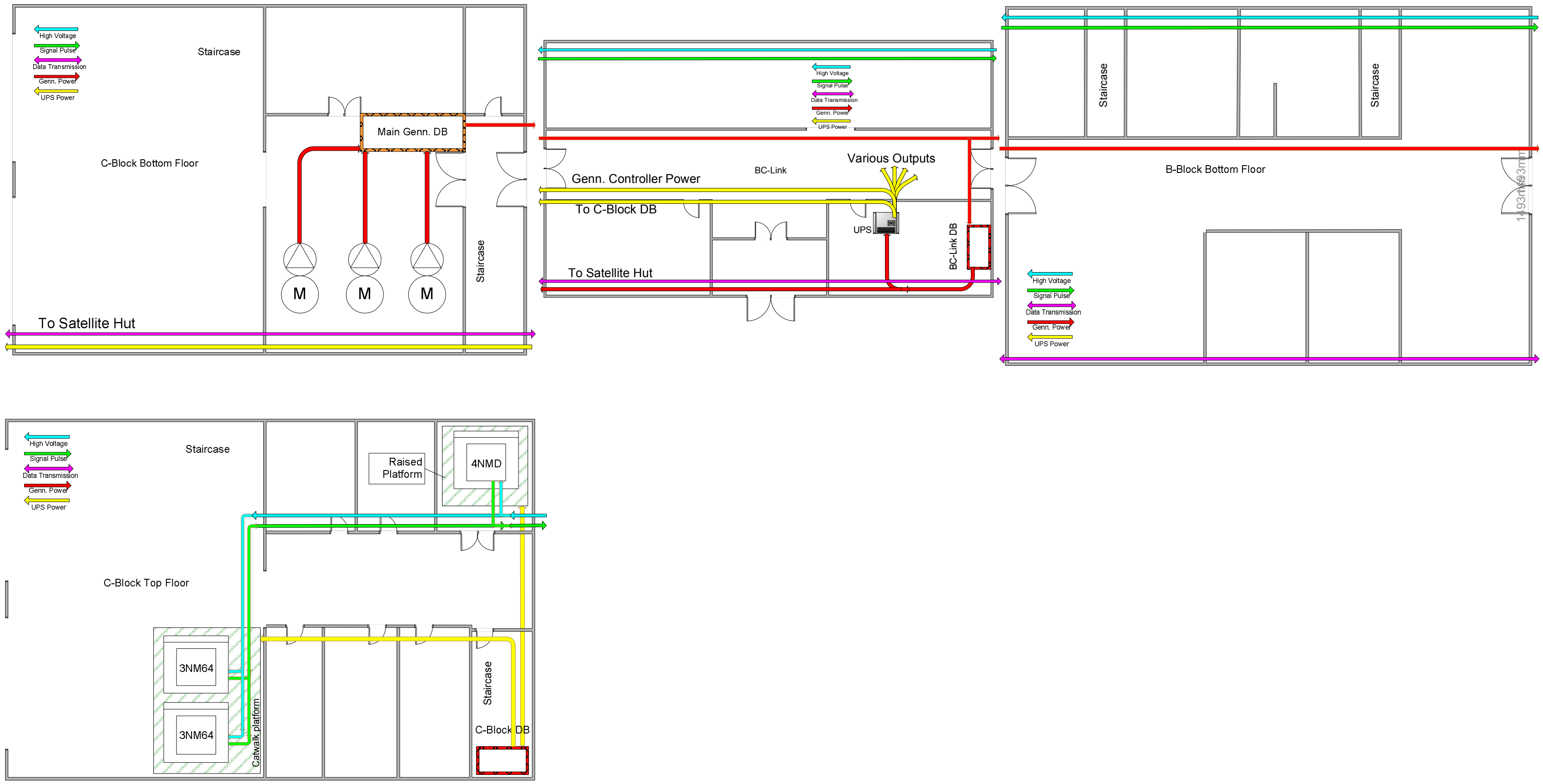

Figure 37 SANAE Power distribution and data paths: C-Block to B-Block

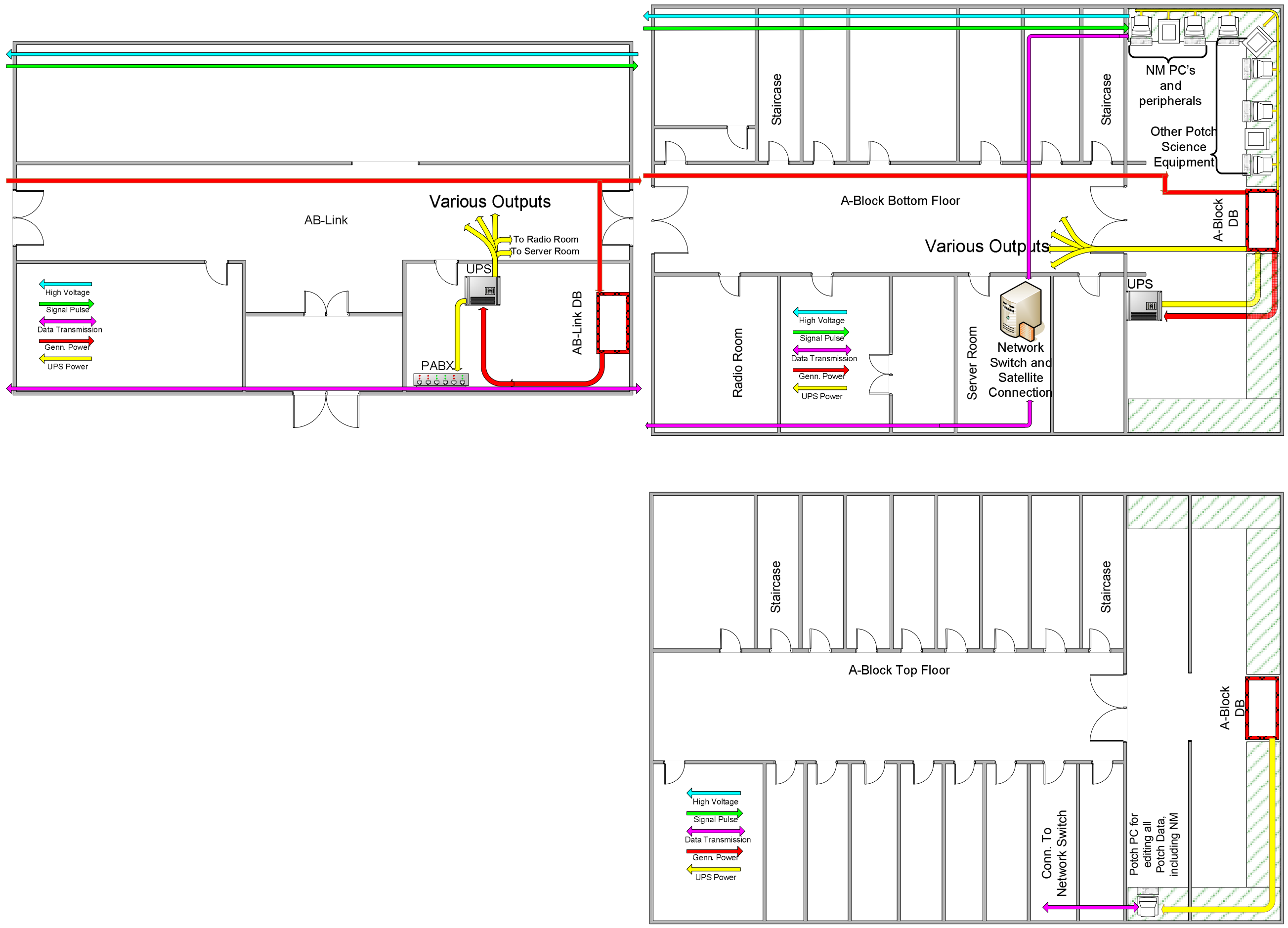

Figure 38 SANAE Power distribution and data paths: From B-Block (previous figure) to A-Block

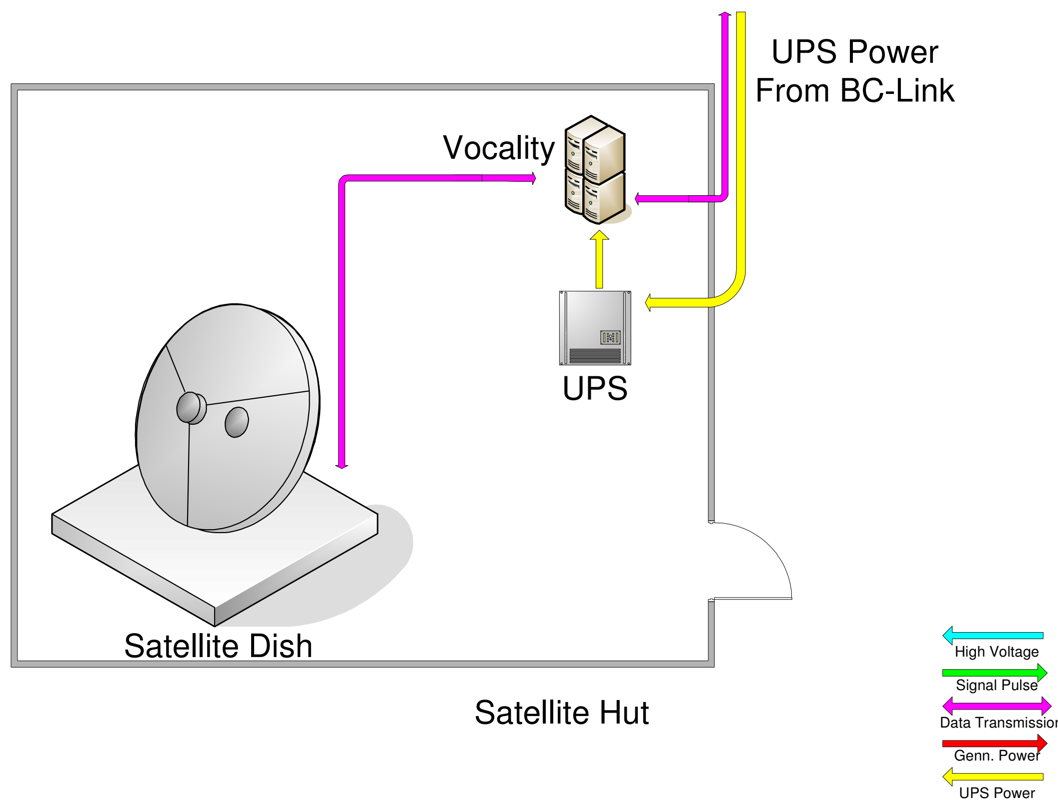

Figure 39 SANAE Satellite hut with power and communications/data Lines

Appendix B – Failure mode, effects and criticality analysis

Description of unit			Description of failure			Effect of failure		Current failure rate	Severity	Mitigated failure rate	Mitigating actions
Ref number	Function	Operational mode	Failure mode	Failure mechanism	Detection of failure	On the sub-system	On system function				
O/F 1.1	Measure atmospheric pressure	Continuous	Performance failure	Pressure measurement device damaged or compromised (CR2)	Incorrect pressure value recorded (*Hidden failure*)	Devices may stop operating when Paro is not responsive	Incorrect pressure corrections on counted neutrons	3	4	2	[1] [2] [3] [29]
			System failure	Power supply interrupted (CR12)	Device battery does not charge, causing data loss after battery is dead (*Evident*			3	4	2	[2] [5] [4]

					failure)						
			Performance failure	Pressure measurement software fails (CSR1.2)	No pressure data recorded (*Evident failure*)			3	4	2	[2]
O/F 1.2	Receive neutron	Random	Performance failure	Enclosed in material that inhibits neutron propagation (CR13)	Decrease in count rate / low count rate to begin with (*Hidden Failure)*	None	Unreliable neutron count	3	3	2	[6]
O/F 1.3	Generate pulse	Based on neutrons received	System failure	Gas leak on tube (CR1)	Decrease in count rate / low count rate to begin with (*Hidden Failure)*	None	No pulses to count	2	4	2	[7]
				No output pulse from tube (CR1)	No data recorded for specific tube (*Evident failure*)			2	4	2	[8]
				No high voltage present on tube (CR5)	- No HV level detected and recorded for specific tube			4	4	2	[2] [4] [9]

					(*Evident failure*) - No proportional output from specific tube; tube count lower than other tubes (*Hidden failure*)						[10] [11]
				NM enclosed in material with high carbon content (CR13)	Lower count rate due to neutrons being deflected / inhibited (*Hidden failure*)	None		3	3	2	[6]
			System failure	Power supply interrupted (CR12)	HV and LV supplies are down and no data is recorded (*Evident failure*)	None		3	4	2	[2] [4] [5]
O/F 1.4	Amplify pulse	Based on proportional output and pulse amplitude relevance	System failure	No output pulse from tube (CR1)	No data recorded for specific tube (*Evident failure*)	Short-circuit can damage the system power supply and cause additional damage	No pulse data being recorded so NM system does not serve any purpose	3	4	2	[8]

				Low Voltage not present or short-circuited (CR6)	Visual inspection of recorded data, noting that tube data is not recorded (*Evident failure*)			3	3	2	[2] [12] [13] [14]
				Pulse counting PC / software fails (CSR1.1)	No counts recorded (*Evident failure*)			3	4	2	[2] [31]
O/F 1.5	Discriminate and shape pulse	Depending on amplifier output	Performance failure	Pulse shaping fails (CSR1.1)	Incorrect count rate / low count rate (*Hidden Failure)*	Adjustments to correct wrong measurements will affect sub-systems	Incorrect counts resulting in unreliable data	3	4	2	[15] [31]
O/F 1.6	Count pulse	Continuous	System failure	Pulse counting PC / software fails (CSR1.1)	No counts recorded (*Evident failure*)	None	Incorrect counts resulting in unreliable data	3	4	2	[2] [31]
O/F 1.7	Calculate pressure-corrected counts	Continuous	System failure	Pulse counting PC / software fails (CSR1.1)	No counts recorded (*Evident failure*)	Adjustments to correct wrong measurements will affect sub-systems	Incorrect counts resulting in unreliable data	3	4	2	[16] [17] [31]

				Pressure correcting PC / software fails (CSR1.7)	Data ambiguous as compared to pressure effects (*Hidden failure*)			3	3	2	[16] [17]
			Performance failure	Pressure measurement PC / software fails (CSR1.2)	No or notably incorrect pressure data being displayed (*Evident failure*)			3	3	2	[16] [17]
O/F 1.8	Calculate average neutron count	Periodical	System failure	Pulse counting PC / software fails (CSR1.1)	No counts recorded (*Evident failure*)	Adjustments to correct wrong measurements will affect sub-systems	Data output not reliable based on pressure effects not accounted for	3	4	2	[16] [17] [31]
				Pressure Correcting PC / software fails (CSR1.7)	Data ambiguous as compared to pressure effects (*Hidden failure*)			3	3	2	[16] [17]
			Performance failure	Pressure measurement PC / software fails (CSR1.2)	No or notably incorrect pressure data being displayed			3	3	2	[16] [17]

					(*Evident failure*)						
O/F 2.1	Measure ambient temperature	Continuous	Performance failure	Temperature sensor fails (CR3)	No or irrelevant ambient temperature data recorded (*Hidden failure*)	Damage to other system components due to unmonitored, out-of-bounds temperature value	Incorrect temperature correction on counts	3	2	2	[2] [4] [14] [15]
				Power supply interrupted (CR12)	Temperature power is down and no temperature data is recorded (*Evident failure*)			3	3	2	[2] [4] [5]
				Temperature recording software fails (CSR1.3)	No or irrelevant temperature data recorded (*Hidden failure*)			3	2	2	[2] [16]
O/F 2.2	Measure NM tube temperature	Continuous	Performance failure	Temperature sensor in NM tube enclosure fails (CR3)	No or irrelevant NM tube temperature data recorded (*Hidden failure*)	Damage to other system components due to unmonitored, out-of-bounds temperature	Incorrect temperature correction on counts	3	2	2	[2] [4] [14] [15]

						value					
				Power supply interrupted (CR12)	Temperature power is down and no temperature data is recorded (*Evident failure*)			3	3	2	[2] [4] [5]
				Temperature recording software fails (CSR1.3)	No or irrelevant temperature data recorded (*Hidden failure*)			3	2	2	[2] [16]
O/F 2.3	Measure wind speed and direction	When wind blows	Performance failure	Anemometer gets damaged (CR7)	No or incorrect wind speed data recorded (*Hidden failure*)	Other devices might get damaged due to ESD	None	5	2	3	[2] [18] [19]
				Wind speed recording software fails (CR1.6)	No or incorrect wind speed data recorded (*Hidden failure*)			3	2	2	[2] [16]
O/F 3.1	Obtain satellite	Continuous	System failure	GPS Antenna fails (CR4)	No satellite fix and no time sync; system time drifts	Sub-systems will not start until	Unreliable data timing and no data sync between	3	2	2	[2]

	signal				(*Evident failure*)	GPS available	PCs				[20]
				GPS recording and extraction software fails (CSR1.4)	No satellite fix and no time sync; system time drifts (*Evident failure*)			3	2	2	[2] [20]
O/F 3.2	Obtain satellite fix	Continuous	System failure	GPS Antenna fails (CR4)	No satellite fix and no time sync; system time drifts (*Evident failure*)	Some subsystems will not start until GPS has found satellite fix	Unreliable data timing and no data sync between PCs	3	2	2	[2] [20
				GPS recording and extraction software fails (CSR1.4)	No satellite fix and no time sync; system time drifts (*Evident failure*)			3	2	2	[2] [20]
O/F 3.3	Determine NM station position and elevation	Continuous	Performance failure	GPS Antenna fails (CR4)	No satellite fix and no time sync; system time drifts (*Evident failure*)	None	No specific positional and elevation information that adds value to studies based on earth magnetism	3	1	2	[2] [20]
				GPS recording and extraction	No satellite fix and no time sync;			3	1	2	[2]

				software fails (CSR1.4)	system time drifts (*Evident failure*)						[20]
O/F 3.4	Extract GMT and local time	Continuous	System failure	GPS Antenna fails (CR4)	No satellite fix and no time sync; system time drifts (*Evident failure*)	None	Unreliable data timing and no data sync between PCs	3	2	2	[2] [20]
				GPS recording and extraction software fails (CSR1.4)	No satellite fix and no time sync; system time drifts (*Evident failure*)			3	2	2	[2] [20]
O/F 4.1	Select HV channel	Periodic	System failure	HV supply damaged (CR5)	No HV detected on specific tube (*Evident failure*)	None	No data recorded about specific HV source	3	3	2	[2] [4] [8] [10]
				Power supply interrupted (CR12)	No HV output on any of the HV channels (*Evident failure*)			3	4	2	[2] [4]
				HV recording software fails	No HV data recorded			3	4	2	[2] [15]

				(CSR1.5)	(*Evident failure*)						
O/F 4.2	Measure HV amplitude	Continuous	System failure	HV supply damaged (CR5)	No HV detected on specific tube (*Evident failure*)	No HV might indicate short-circuit and result in damage to other system components	No data recorded about specific HV source	3	3	2	[2] [4] [8] [10]
				Power supply interrupted (CR12)	No HV output on any of the HV channels (*Evident failure*)			3	4	2	[2] [4]
				HV recording software fails (CSR1.5)	No HV data recorded (*Evident failure*)			3	4	2	[2] [15]
O/F 5.1	Monitor power supply	Periodic	Performance failure	Power supply absent or insufficient (CR12)	Data corruption, spikes on data (*Hidden failure*)	Sub-system components can be damaged over long period of time	Data loss and corruption	3	4	2	[2] [4] [5] [21]
				Power grid failure (ER3)	System running on UPS power (*Evident failure*)			4	2	1	[2] [21]

				Generator power failure (ER4)	System running on UPS power (*Evident failure*)			4	2	1	[2] [21]
O/F 5.2	Record Fortan arometer readings	Periodic	Performance failure	Fortan gauge damaged (CR8)	Fortan reading not present (*Evident failure*)	None	Elementary pressure calibration not done, so pressure drift might be missed, resulting in inaccurate neutron counts	3	2	2	[22]
				Fortan value logging software fails (CSR2.2)	Operator not able to enter Fortan value, or Fortan value not included in calculations (*Hidden failure*)			3	2	2	[17]
O/F 5.3	Observe NM tube response	Periodical	Performance failure	Data display software fails (CP2.1)	Data not displayed (*Evident failure*)	Tube response not available for inspection	Data integrity is compromised	3	2	2	[2]
				Operator fails (CHR1)	Faulty tube remains unnoticed	Data processing is affected	Data integrity is compromised	4	2	2	[2] [16]

					(*Evident failure*)						[26] [27]
O/F 5.4	Observe temperature levels	Periodical	Performance failure	Air conditioner fails (CR9)	NM temperature varies uncontrollably	Sensitive equipment may be damaged	Incorrect temperature correction on final data sets	3	2	2	[2]
				Operator fails (CHR1)	Temperature drift is sensed later by Operator; Low data quality observed by later inspection (*Hidden failure*)	Data processing may be affected; Sensitive equipment may be damaged	Incorrect temperature correction on final data sets	4	2	2	[2] [16] [26]
				Data display software fails (CP2.1)	Data not displayed (*Evident failure*)	Temperature not available for inspection	Incorrect temperature correction on final data sets	3	2	2	[2]
O/F 5.5	Observe HV levels	Periodical	Performance failure	Data display software fails (CP2.1)	Data not displayed (*Evident failure*)	HV values not available for inspection – tubes operate in wrong region	Data integrity may be compromised if this failure occurs with other failures	3	2	2	[2] [28]

				Operator fails (CHR1)	Low data quality observed by later inspection (*Hidden failure*)	Tubes may operate in wrong region	Data integrity may be compromised if this failure occurs with other failures	4	2	2	[2] [16] [26] [27] [28]
O/F 5.6	Observe wind data	Periodical	Performance failure	Data display software fails (CP2.1)	Data not displayed (*Evident failure*)	Wind speed is not available for inspection and data corruption due to static cannot be distinguished	No effect on counter operation	3	2	2	[2]
				Operator fails (CHR1)	Wind speed failure remains unnoticed (*Evident failure*)	None	No effect on counter operation	4	2	2	[2] [16] [26]
O/F 5.7	Observe pressure-corrected counts	Periodical	Performance failure	Data display software fails (CP2.1)	Data not displayed (*Evident failure*)	Pressure-corrected count calculations not available for inspection	Data integrity may compromised if this error occurs with other failures	3	2	2	[2]
				Operator fails	Pressure-corrected	Data processing	Data integrity may	4	2	2	[2]

				(CHR1)	counts remain unnoticed (*Evident failure*)	may be affected	be compromised if this failure occurs with other failures				[16] [26]
O/F 5.8	Observe GPS state	Periodical	Performance failure	Data display software fails (CP2.1)	Data not displayed (*Evident failure*)	Cannot determine if GPS sync is still maintained	Data integrity may be compromised if this failure occurs with other failures	2	2	1	[2]
				Operator fails (CHR1)	Low data quality observed by later inspection (*Hidden failure*)	None	Data integrity may be compromised if this failure occurs with other failures	4	2	2	[2] [26] [27]
O/F 5.9	Log system response and errors	Periodical	Performance failure	Operator failure, Data check log not completed (CR10)	Gaps in recorded logs (*Evident failure*)	Sub-system errors might exist that cannot be rectified if log is not kept up to date	System response may diverge without any record, compromising maintenance	3	3	2	[23]
				Operator failure, data error log incomplete (CHR1, CR11)	Gaps in logs when errors are evident (*Evident failure*)	As above	As above	3	3	2	[23] [30]
				Data display	Data not displayed	As above	As above	3	2	2	[2]

				software fails (CP2.1)	(*Evident failure*)						
				Operator failure, power supply check log incomplete (CHR1, ER5)	Gaps in logs when errors are evident (*Evident failure*)	As above	As above	3	3	2	[23]
				Operator failure, power supply error log incomplete (ER6)	Gaps in logs when errors are evident (*Evident failure*)	As above	As above	3	3	2	[23] [30]
O/F 6.1	Manage power supply sources	Periodical	System failure	Maintainer failure / UPS maintenance not done or inadequate (ER1)	UPS does not deliver adequate backup and protection to system	Operational availability is affected – all sub-systems are affected	Significant data loss	3	5	2	[2] [5] [24] [26]
				Maintainer failure / UPS batteries not maintained (ER2)	UPS does not deliver adequate backup and protection to system	As above	Significant data loss	3	5	2	[2] [5] [24] [26]

				Maintainer failure / Generator maintenance not done or inadequate (ER4)	System power fails, power quality down (*Hidden failure*)	As above	Significant data loss	3	5	2	[2] [5] [24] [26]
				Maintainer failure / Power supply error log not used for error tracking, and incomplete (ER6)	Gaps in logs when errors are evident (*Evident failure*)	As above	Possible data loss	4	3	2	[23] [26] [30]
				Maintainer failure / Power selector switch not correctly operated (ER7)	UPS does not receive power from active source (*Evident failure*)	As above	Significant data loss	3	5	2	[2] [5] [24] [26]
O/F 6.2	Restart system upon peripheral sync lost	Unexpected	System failure	Maintainer failure / Data check log incomplete (CR11)	Gaps in logs when errors are evident (*Evident failure*)	None	Loss of data due to unforseen system downtime and the need to restart the system	3	4	2	[15] [23] [26] [30]

				Power supply down or insufficient (CR12)	Data corruption, spikes on data (*Hidden failure*)	None	As above	3	4	2	[2] [4] [5] [21]
				Data recording software fails (CSR1)	No data recorded what so ever, even though peripheral devices are working (*Evident failure*)	None	As above	3	5	2	[2] [16] [17]
O/F 6.3	Pressure sensor calibration	Periodical	Performance failure	Maintainer failure / Calibration of pressure sensing devices not done regularly (CR2)	Pressure drift that will not be noticed until calibration is done (*Hidden failure*)	None	Unreliable data due to incorrect pressure correction	3	3	2	[1] [3] [5] [15] [26] [29]
				Power supply down or insufficient (CR12)	Spikes on data or no data recorded (*Evident failure*)	None	Unreliable data due to incorrect pressure correction	3	4	2	[2] [3] [21]

				Pressure measurement software fails (CSR1.2)	No pressure data recorded (*Evident failure*)	None	Unreliable data due to incorrect pressure correction	3	4	2	[2] [15]
O/F 6.4	Adjust air conditioning levels	Periodical	Performance failure	Air conditioner fails (CR9)	Air conditioner not running, ambient temperature changing dramatically (*Evident failure*)	Peripheral components might get damaged by extreme temperature levels	Incorrect temperature compensation results in variation in count averages	3	3	2	[2] [4] [7] [14] [15] [16]
				Data check log not completed (CR11)	Gaps in logs when errors are evident (*Evident failure*)	None	Possible data loss	3	4	2	[15] [23] [26] [30]
				Power supply down or insufficient (CR12)	Air conditioner not working (*Evident failure*)	None	Possible variation in count averages	3	4	2	[2] [3] [21] [26]
				Maintainer failure		None	Possible variation	3	3	2	[26]

				(CHR2)			in count averages				
O/F 6.5	Check for loose connections	Periodical	System failure	Maintainer failure / Counter tubes (CR1)	Spikes or no data on tube output (*Evident failure*)	Damage to peripheral components due to loose connectors	Unreliable / no data records	3	5	2	[2] [4] [7] [8] [10] [11] [12] [13] [14] [26]
				Maintainer failure / Pressure sensor (CR2)	No pressure data recorded (*Evident failure*)			3	4	2	[2] [4] [14] [23] [26] [29]
				Maintainer failure / Temperature	No temperature data recorded			3	3	1	[2] [4]

				sensor (CR3)	(*Evident failure*)						[14] [23] [26]
				Maintainer failure / GPS Antenna (CR4)	No GPS data recorded and loss of system time sync (*Evident failure*)			3	3	2	[2] [14] [20] [23] [26]
				Maintainer failure / High Voltage Supply (CR5)	Spikes on HV lines detected and data values out of bounds because of EMI (*Evident failure*)			3	4	2	[2] [9] [10] [11] [17] [23] [26]
				Maintainer failure / Low Voltage Supply (CR6)	No pulses counted due to loss of amplifying and converting power, but no direct			3	4	2	[2] [12] [13] [14]

					means of knowing it is LV failure (*Hidden failure)*						[18] [21] [26]
				Maintainer failure / Anemometer (CR7)	No wind data recorded (*Evident failure*)			5	3	2	[2] [14] [18]
				Maintainer failure / Air Conditioner (CR9)	Temperature levels out of bounds (*Evident failure*)			3	3	3	[2] [4] [14]
				Maintainer failure / Power supply connections fail (CR12)	Complete system down and spikes on data (*Evident failure*)			3	4	2	[2] [5] [14] [21] [24]
				Maintainer failure / UPS loose connections (ER1)	Complete system down and spikes on data (*Evident failure*)			3	4	2	[2] [5] [14] [21]

											[23]
				Maintainer failure / UPS Batteries loose connections (ER2)	Complete system down and spikes on data (*Evident failure*)			3	4	2	[2] [5] [14] [21] [23] [26]
				Maintainer failure / Loose connection from grid power to system (ER3)	UPS irregular operation and battery charge dropping (*Evident failure*)			3	3	2	[2] [4] [21] [26]
				Maintainer failure / Poor generator connection (ER4)	UPS irregular operation and battery charge dropping (*Evident failure*)			3	3	2	[2] [4] [21] [26]
				Maintainer failure / Power Supply error log not used for error tracking,	Gaps in logs when errors are evident (*Evident failure*)			4	3	1	[23] [26] [30]

				and not completed upon error rectification (ER6)							
				Maintainer failure / Connection of selector switch not good (ER7)	Inability to switch between generator and grid power and subsequent UPS power loss (*Evident failure*)			2	4	2	[4] [7] [14] [26]
O/F 6.6	Check PC synchronisati on	Periodical		Maintainer failure / Data check log not completed (CR11)	Gaps in logs when errors are evident (*Evident failure*)	None	Incorrect neutron data regarding time and position	3	4	2	[23] [30]
				Maintainer failure / Power supply fails (CR12)	System cannot synchronise due to lack of power			3	4	2	[2] [5] [14] [21] [24]
				Maintainer failure / Data unreliably	Data sync lost and therefore			3	5	2	[2] [5]

				stored (CSR1.8)	unreliable (*Hidden failure*)						[16] [17]
				Data display corrupt (CSR2.1)	Cannot determine whether data is in sync or not			3	3	2	[2] [5] [16] [17]
O/F 7.1	Create new-day file	Once a day	System failure	Software for Data Storage fails (CSR1.8)	New data file not created (*Evident failure*)	None	Data loss for at least one day	2	5	2	[2] [5] [16] [23]
				Power supply fails (CR12)	System down and no new-day file can be created (*Evident failure*)			3	3	2	[2] [5] [14] [24]
O/F 7.2	Append data to current-day file	Every minute	System failure	Software for Data Storage fails (CSR1.8)	Data for specific minute does not get recorded (*Hidden failure*)	None	Data loss inside a day-recording	2	5	2	[2] [5] [16]

											[23]
				Power supply fails (CR12)	Data file corrupted and data skipped in "middle" of day (*Evident failure*)			3	3	2	[2] [5] [14] [24]
O/F 7.3	Group all NM data	Every minute	Performance failure	Power supply fails (CR12)	Data file corrupted and data skipped in "middle" of day (*Evident failure*)	None	Data file created but with gaps in data, resulting in unreliable and unsynchronised data	3	3	2	[2] [5] [14] [24]
				Temperature measurement software failed (CSR1.3)	No or irrelevant temperature value (*Evident failure*)			2	3	2	[2] [4] [5] [14] [16] [23]
				GPS Software fails (CSR1.4)	No GPS timing or positioning recorded			3	3	2	[2] [4] [5]

					(*Hidden failure*)						[14] [16] [20] [23]
				HV measurement software fails (CSR1.5)	No HV value recorded for a specific tube (*Evident failure*)			3	4	2	[2] [4] [10] [11] [14] [16] [23] [24]
				Wind data software fails (CSR1.6)	No wind data recorded (*Evident failure*)			3	2	2	[2] [4] [14] [18] [19] [23]
				Pressure-	Neutron counts not			3	4	2	[1]

				correction software fails (CSR1.7)	compensated for pressure effects (*Hidden failure*)						[2] [14] [15] [16] [23]
				Software for Data Storage fails (CSR1.8)	Data for specific minute does not get grouped (*Hidden failure*)			3	4	2	[2] [5] [16] [23]
				Software for daily pressure calibration fails (CSR2.2)	Daily pressure cannot be entered to the system (*Evident failure*			3	2	2	[15] [23]
O/F 7.4	Write new minute-value line	Every minute	Performance failure	Software for Data Storage fails (CSR1.8)	Data for specific minute does not get recorded (*Hidden failure*)	None	The new collected data line is not written and data is lost for at least one minute	2	3	2	[2] [5] [16] [23]
				Power supply fails (CR12)	Data file corrupted and data skipped			3	3	2	[2] [5]

					in "middle" of day (*Evident failure*)						[14] [24]
O/F 7.5	Close current-day file	Once a day	System failure	Software for Data Storage fails (CSR1.8)	Data file for day does not get closed correctly (*Hidden failure*)	None	Data file for that day is corrupt	3	5	2	[2] [5] [16] [23]
				Power supply fails (CR12)	Data file corrupted (*Evident failure*)			3	3	2	[2] [5] [14] [24]
O/F 8.1	Retrieve data	Periodical	System failure	Data storage and retrieval software fails (CSR1.8)	Data not retrievable (*Evident failure*)	None	Data lost if file is not retrievable and corrupt	3	5	2	[16] [23]
				UPS supplying power to data editing PC fails (ER1)	No power for editing and final storage systems (*Evident failure*)			3	4	2	[2] [5] [23] [24]

				Data selection software fails (DSR1.1)	Data to be edited cannot be selected			3	3	2	[23] [24] [25]
O/F 8.2	Check for errors	Periodical	Performance failure	UPS supplying power to data editing PC fails (ER1)	No power for editing and final storage systems (*Evident failure*)	None	Data cannot be checked for arrors	3	4	2	[2] [5] [23] [24]
O/F 8.3	Remove errors, edit data	Periodical	Performance failure	UPS supplying power to data editing PC fails (ER1)	No power for editing and final storage systems (*Evident failure*)	None	Spikes and other faults in data cannot be removed and result in inaccurate data	3	4	2	[2] [5] [23] [24]
O/F 8.4	Do month-end editing	Periodical	Performance failure	UPS supplying power to data editing PC fails (ER1)	No power for editing and final storage systems (*Evident failure*)	None	Spikes and other faults in data cannot be removed and result in inaccurate data	3	4	2	[2] [5] [23] [24]
				Data editing software fails	Software not edited			3	3	2	[16] [23]

				(DSR1.2)	(*Evident failure*)						[25] [32]
O/F 8.5	Store final data set	End of month	System failure	UPS supplying power to data editing PC fails (ER1)	No power for final storage systems (*Evident failure*)	None	Final data cannot be stored due to power failure, resulting in possible data loss	3	5	2	[2] [5] [23] [24]
				Software used for publishing fails (DSR1.3)	Software not in correct format for use (*Evident failure*)			3	2	2	[15] [23] [25]
				Software used for drawing graphs of data (DSR1.4)	Graphical representation of data incorrect (*Hidden failure*)			3	2	2	[15] [23] [25]
O/F 9.1	Retrieve data	End of month	Performance failure	Software that collects data from repository fails (DSR2.1)	Data not on web server (*Evident failure*)	None	Data not retrieved and displayed	3	2	2	[25]
O/F 9.2	Convert data to correct	End of month	Performance failure	Software that converts data to NMDB standards	Data not in correct international	None	Data not universal for international	3	2	2	[25]

	format			fails (DR2)	format (*Evident failure*)		use				
O/F 9.3	Upload data to web server	End of month	Performance failure	Software that stores data on server fails (DSR2.1)	Data not on web server (*Evident failure*)	None	Data not accessible to public from web server	3	2	2	[25]
O/F 9.4	Host data	Continuous	Performance failure	Website hosting software Fails (DSR2.2)	Data not on web server (*Evident failure*)	None	Data not accessible to public from web server	3	2	2	[25]
O/F 9.5	Process data queries	Periodical	Performance failure	Software that handles data requests (DSR2.1)	Data requests not handled correctly (*Hidden failure*)	None	Incorrect data supplied to user	3	2	2	[25]
O/F 9.6	Supply data to third parties	Periodical	Performance failure	Software that supplies data to users on request fails (DSR2.1)	Data not supplied to user, or incorrect data supplied (*Evident failure*)	None	Incorrect or no data supplied to user	3	2	2	[25]
O/F	Keep data archive up to	Periodical	System failure	Software that stores data on	Data incorrectly or insufficiently stored	None	System and data integrity	3	3	2	[25]

9.7	date			server (DSR2.1)	(*Hidden failure*)		compromised, as this is another data backup location				
				Software that hosts data on website fails (DSR2.2)	Data incorrectly displayed and data archives not complete (*Evident failure*)	None	Users waiting for up-to-date data	3	2	2	[25]
							Total risk	399		261	

Appendix C: Resource and interface loading

An additional indication of the risk factor of the system is the dependency of operational functions on resources and interfaces. If a specific resource or interface is too heavily loaded (this means there are a great number of operational functions dependent on it), the consequence of that specific resource or interface failing is just so much more catastrophic.

There are resources which may only affect one operational function, that are also critical due to their impact. The table below does not show these dependencies and only a proper FMECA will indicate which resources and interfaces are critical, as has been done above. Nonetheless, the table below is one of the tools that highlights impact in terms of affected functions.

Table 4 Resource and interface dependency values

Resources		Interfaces			Resources		Interfaces	
CR1	3	CIF1	2		ER1	7	CSIF4	2
CR2	3	CIF2	3		ER2	1	EIF1	1
CR3	3	CIF3	3		ER3	2	EIF2	1
CR4	5	CIF4	5		ER4	3	EIF3	1
CR5	4	CIF5	2		ER5	1	EIF4	1
CR6	2	CIF6	3		ER6	3	EIF5	1
CR7	2	CIF7	2		ER7	2	EIF6	1
CR8	1	CIF8	2		EHR1	2	EIF7	1
CR9	3	CIF9	1		EHR2	2	EIF8	1
CR10	1	CIF10	1		DR1	1	EIF9	1

CR11	4	CIF11	7		DR2	1	EIF10	1
CR12	17	CIF12	1		DHR1	4	EIF11	2
CR13	2	CIF13	0		DHR2	2	EIF12	2
CHR1	8	CIF14	0		DHR3	2	EIF13	2
CHR2	7	CIF15	0		DSR1.1	2	EIF14	2
CHR3	0	CIF16	3		DSR1.2	2	DIF1	3
CSR1.1	7	CIF17	6		DSR1.3	2	DIF2	1
CSR1.2	6	CIF18	16		DSR1.4	2	DIF3	1
CSR1.3	5	CIF19	1		DSR2.1	6	DIF4	1
CSR1.4	7	CIF20	1		DSR2.2	3	DIF5	2
CSR1.5	5	CIF21	0				DIF6	2
CSR1.6	4	CIF22	2				DIF7	2
CSR1.7	5	CIF23	3				DIF8	2
CSR1.8	8	CSIF1	3				DIF9	6
CSR2.1	10	CSIF2	2				DIF10	1
CSR2.2	4	CSIF3	8				DSIF1	1
							DSIF2	1
							DSIF3	1
							DSIF4	1
							DSIF5	3

Appendix D: NMDB data structure requirements

(Steigies, Rother 2008)

All times and dates recorded in NMDB are in GMT. One DATETIME format which is accepted by MySQL is YYYY-MM-DD hh:mm:ss. All counts are given as counts per second for the whole monitor. Where not noted otherwise, SI units are used in NMDB.

All pressures are given in mbar. All temperatures are given in °C. All velocities are given in m/s. STATION stands for one of the stations from table 2.1. Hourly data is stored in the table STATION 1h. This table contains the best available hourly data, i.e. previous data is overwritten, in case errors in the data are corrected. The count rates stored in this table are hourly averages, the values represent counts per second for the whole detector.

Table 5 Appendix A: Hourly Data

column	format	comment
start_date_time	DATETIME	start date and time of the 3600 s count interval
uncorrected	FLOAT	uncorrected count rates, counts per second
corr_for_efficiency	FLOAT	count rates corrected for pressure and efficiency
corr_for_pressure	FLOAT	count rates corrected for pressure
pressure_mbar	FLOAT	atmospheric pressure in millibar
last_change	TIMESTAMP	automatically generated timestamp

High resolution data that is recorded in real-time is stored in the table STATION ori. This table contains data in the highest available time resolution and data is stored as measured, no data is ever overwritten. The countrates in this table represent counts per second for the whole detector.

Table 6 Appendix A: Original Data

column	format	comment
start_date_time	DATETIME	start date and time of the data collection interval
length_time_interval_s	FLOAT	duration of the data collection interval in seconds
measured_uncorrected	FLOAT	uncorrected count rates, counts per second
measured_corr_for_efficiency	FLOAT	count rates corrected for pressure and efficiency
measured_corr_for_pressure	FLOAT	count rates corrected for pressure
measured_pressure_mbar	FLOAT	atmospheric pressure in millibar

Revised high resolution data is stored in the table STATION rev. The format of this table is equal to STATION ori, but is only used if a data set in STATION ori needs to be revised. Only pieces of revised data shall be submitted here. The table contains an automatically updated timestamp _eld \last change", as well as a two digit integer:

\version" _eld.

Table 7 Appendix A: Revised Data

column	format	comment
start_date_time	DATETIME	start date and time of the data collection interval
length_time_interval_s	FLOAT	duration of the data collection interval in seconds
revised_uncorrected	FLOAT	uncorrected count rates, counts per second
revised_corr_for_efficiency	FLOAT	count rates corrected for pressure and efficiency
revised_corr_for_pressure	FLOAT	count rates corrected for pressure
revised_pressure_mbar	FLOAT	atmospheric pressure in millibar
version	INTEGER	version number of the data
last_change	TIMESTAMP	date and time of the last change of the data

Optional environmental data such as temperature, wind speed and humidity is stored in the table STATION env. The table also contains an automatically updated timestamp _eld \last change".

Table 8 Appendix A: Environmental Data

column	format	comment
date_time	DATETIME	start date and time of the 3600 s count interval (This must be identical to the date and time in the _ori and _rev tables.)
measured_temperature_c	FLOAT	air temperature in degrees Celsius
measured_relative_humidity	FLOAT	relative humidity (%)
measured_wind_speed_m_s	FLOAT	wind speed in m/s
last_change	TIMESTAMP	timestamp of the entry

Optional "human-generated" electronic log _les of the station are stored in the table STATION meta. This table also contains an automatically updated timestamp _eld \last change".

Table 9 Appendix A: Meta Data

column	format	comment
start_date_time	DATETIME	start of time period
end_date_time	DATETIME	end of time period
quality_flag	INTEGER	quality flag as per GLE standard
comment_environment_condition	TEXT	log entry
comment_revision	TEXT	revision of log entry
last_change	TIMESTAMP	timestamp of the entry

In addition to the station specific tables, NMDB contains one table with information from all stations (NM station information), describing the stations and their equipment. This table is called in by NKUA based on the query they generated in deliverable 3.1 and which has been called in by all participants. The query contains questions about the following topics: general information, station information, station electronics information, acquisition system, and local server information. For every change at a station, for example change of the station manager, change in the registration electronics, or change in the number of counter tubes, a new entry with the new information is created in this table. Since every entry also contains a start and an end date, the complete station history is recorded in this table. Details about the contents of this table are given in the report to deliverable 3.1 and will not be repeated here.