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Analysis of Operational Challenges of Existing Start-up Instrumentation (SUI) of CANDU Reactors at Bruce Power Stations

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Abstract

In thermal nuclear reactors such as CANDU, reactor regulation and power measurements rely on neutronic detectors for power adjustments, neutron overpower protection and safety system initiation. In this paper an attempt will be made to analyze and compare the two most common types of neutron detectors currently used in CANDU Start-Up Instrumentation (SUI), namely Boron Trifluoride (BF3) and Helium (He3) detectors. Their characteristics will be analyzed and compared along with the existing limitations and performance problems. Next, fission chambers technology will be proposed as an alternative approach to refurbishment of conventional start-up instrumentation (SUI) based on Bruce Power NGS history of operating challenges and concerns related to SUI equipment.

1. INTRODUCTION

In a normal CANDU nuclear operations lifecycle, it is often necessary to shut down the reactor for maintenance, refurbishment, or due to a surplice of electrical power on the market. Following the shutdown, a reactor is normally placed in one of the shutdown states, such as Overpoisoned Guaranteed Shutdown State (OPGSS), or brought back to criticality. In either case, following a shutdown, activity of neutron sources in the reactor core decreases exponentially with time. During the normal start-up and operation at power neutron flux is generated in the fuel pellets undergoing fission. This results in photo neutron production that remains steady until the reactor is shutdown. Following a continuous operation for a sufficient amount of time fission product activity builds up to a level where it can be monitored by either in-core vertical flux detectors or out-of-core ion chambers. After a shutdown, the fission product activity decays away and might diminish below the levels where Shutdown System 1 and 2 (SDS1&2) and Reactor Regulating System (RRS) ion chambers (IC) can no longer accurately detect the reactor neutron power and rate of change. Thus, a means to monitor neutron activity at low and very low power levels is required once the SDS1&2 and RRS ion chambers go off-scale to ensure that the operators in the Main Control Room (MCR) can monitor neutron flux and obtain timely and accurate information on the status of the reactor in question.

In this paper an attempt will be made to analyze and compare the two most common types of neutron detectors used in CANDU Start-Up Instrumentation (SUI), namely Boron Trifluoride (BF3) and Helium (He3) detectors. Their characteristics will be analyzed and compared along with the existing limitations and performance problems. Next, fission chambers technology will be proposed as an alternative approach to the start-up instrumentation implementation. Main features and characteristics of the existing fission chambers will be described in more detail along with the proposed design and installation for existing CANDU reactors at Bruce Power Nuclear Generating Station (NGS) based on the existing history of operating challenges and concerns related to SUI equipment.

2. START-UP INSTRUMENTATION SYSTEM PURPOSE AND DESCRIPTION

2.1. Start-Up Instrumentation (SUI) Purpose.

Start-up instrumentation (SUI) is used following a prolonged shutdown and during a re-start phase at low and very low power levels with the main goal to provide neutron overpower (NOP) protection via SDS1 trip circuits on high neutron count rate and to allow continuous monitoring of neutron flux level and rate. SUI equipment is normally engaged once the reactor power level falls below -5 decades (10^{-5} F.P.) and becomes the primary means of flux monitoring at -7.0 decades [1]. SUI detectors can be used reliably below about 10^{-6} F.P. which provides nearly one decade overlap with the RRS Ion Chambers (ICs), allowing for a bump-less transfer.

At Bruce A Nuclear Generating Station (NGS) SUI instrumentation is required to provide a reliable indication of the reactor power for a period of up to several weeks, with the required range of sensitivity from 10^{-14} to 10^{-6} of reactor full power (F.P.) [2] . Figure 1 below shows neutron count decrease as a function of number of shutdown days at Bruce A.

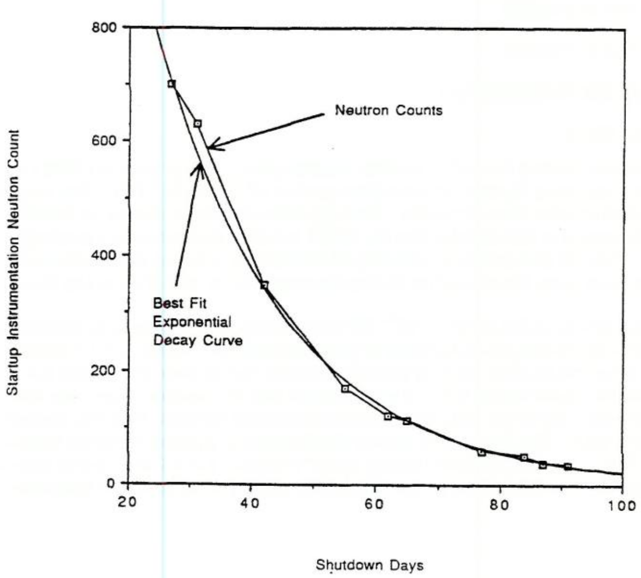


Figure 1. Neutron Decay Curve as a Function of a Number of Shutdown Days [2].

Once the reactor shutdown state is surrendered and poison is being pulled from the moderator to enable approach to criticality, SUI continues to provide flux and rate monitoring and SDS1 trip capabilities until the RRS Ion Chambers provide an accurate and reliable reading and RRS can resume normal control of the reactor. Table 1 below shows the nuclear instrumentation employed in CANDU reactors at various power levels.

Power Range	SUI	RRS/SDS Ion Chambers	RRS/SDS In-Core Flux Detectors
Lower Limit	10^{-14} F.P.	10^{-7} F.P.	10^{-1} F.P. and above
High Limit	10^{-6} F.P.	1.5 F.P.	

Table 1. Sensitivity ranges of CANDU Nuclear Instrumentation [2].

SUI equipment is required to be designed to fail-safe, i.e. should it experience a functional failure affecting system ability to perform its intended function it should be able to trip the reactor via SDS2 trip logic. There is no requirement for SUI to operate during a loss of coolant accident (LOCA) or design basis earthquake.

2.2. Conventional SUI Equipment Arrangement.

The start-up instrumentation most commonly used today in CANDU-based power plants typically consists of thermal neutron detectors, electronic modules, cables and connectors. There is typically a dedicated computer terminal located in the main control room that is used for SUI data collection and processing. There are two major categories of start-up instrumentation equipment used in CANDU power plants – in-core and out-of-core SUI modules.

In-core SUI instrumentation can be positioned at various locations throughout the reactor core, both in stationary and mobile manner. Stationary SUI detectors are permanently fixed at particular locations in the core to provide detailed information about the neutron flux distribution and magnitude. Mobile detectors could be of a “traveling type” where a detector assembly is outfitted with a mechanical drive unit and could be moved within the reactor core as needed. There are various types of in-core instrumentation available on the market, however they all share similar characteristics of size and shape restrictions imposed by the core geometry and available space between fuel channels [3]. One of the main advantages of using in-core SUI instrumentation is that it requires lower neutron sensitivity. This, however, is somewhat offset by the stresses imposed on the system by extreme environment inside the reactor core, which leads to faster component degradation and maintenance challenges due to physical inaccessibility.

Out-of-core SUI instrumentation is located outside the reactor core and is, therefore, better suited to provide bulk neutronic activity measurements. It is less affected by the reactor size and geometry factors as well as high-temperature and pressure environment in the pressure vessels. Out-of-core SUI instrumentation is more easily accessible for maintenance and inspection; however it requires higher sensitivity and gamma discrimination capabilities than the in-core models.

Either type of SUI instrumentation is connected to the main control room indicators via a number of cables and connectors. A number of amplifiers, pre-amplifiers, signal analyzers, power supplies and other components may be used to comprise a complete SUI circuit.

A typical set-up for conventional in-core SUI installation currently used at Bruce Power NGS is shown in Figure 2 below.

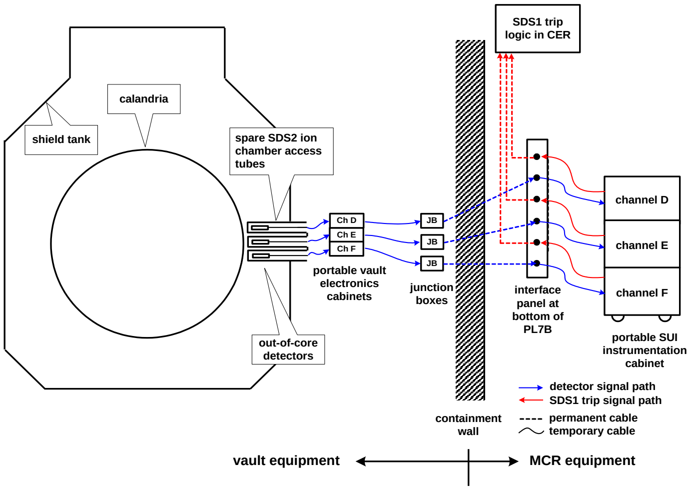


Figure 2. SUI Equipment Set-Up [4]

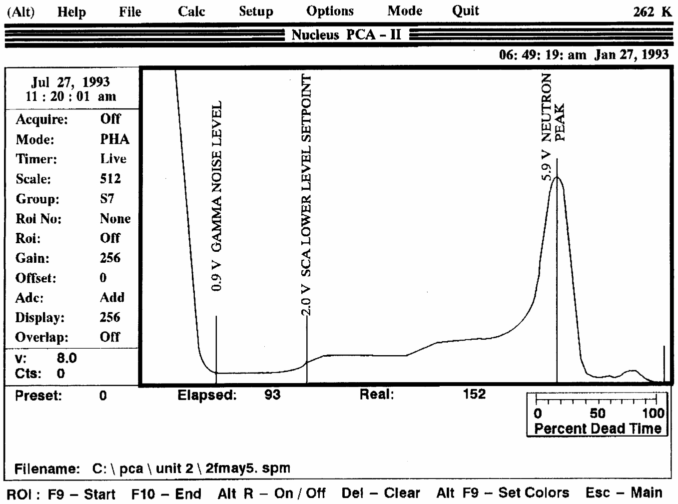
As shown in Figure 2 for reliability and redundancy reasons the SUI equipment is typically triplicated. Each of the three channels consists of a neutron detector, pre-amplifier, an amplifier, and a high-voltage power supply.

2.3. SUI Detector Signal Conversion and Alarm Response.

Thermal neutron detector types vary depending on the plant location and application but all of them, irrespective of the technology used, serve the purpose of detection of neutron activity, or so-called, neutron counts and discriminating it from the associated gamma noise. The majority of neutron detectors used for reactor start-up instrumentation are of the gas-filled type [5]. In CANDU power plants in Canada the two most common detector types used are uncompensated ionization chambers with Boron Trifluoride (BF3) and Helium (He3) detectors. Both are of the thermal neutron-sensitive type. The type of detector chosen as well as the size and the gas filled pressure depend on the reactor power level and installation methods. A detailed description and comparison between the BF3 and He3 detectors will be provided in the following sections.

A signal received from a neutron interaction in the detector is sent through the pre-amplifier to the spectroscopy amplifier. The amplifier shapes the pulse proportionally to the charge deposited on the detector during the neutron interaction event and is consequently transmitted to the main control room through a series of cables penetrating the containment. It is important to note that the amplifier boosts both the detector signal and the noise picked up at the detector lead, connectors or along the cable. Therefore, cables and connectors used for the SUI instrumentation should be a low-noise environmentally qualified and a very high quality of splicing and insulation materials should be used.

Once the signal is received in the main control room, it is connected by the single channel analyzer for information processing and interconnected to the SDS1 trip circuits for implementation of NOP protection. Single channel analyzer (SCA) is used to process the incoming signal to distinguish the true neutron activity response and the instrumentation and gamma noise. This signal is, in its turn, used by the counter and rate-meter components to determine the number of neutron counts per unit time, e.g. per second. This allows translating the amplifier signal into the number of neutron counts representing the neutron source activity in the core as well as rate of change to determine whether it is increasing or decreasing over time. Multi-channel Analyser (MCA) is normally connected to the SUI electronics, particularly during prolonged shutdown phases, to record the initial neutron count activities and count increase information. MCA creates a plot composed of the frequency with which specific pulse height voltages are recorded as function of the peak voltage via discretizing the voltage range into small portions or so-called channels. Each time the pulse height falls into the corresponding channel, its counter is incremented by “1”, and thus a neutron count is obtained even though the SUI detector does not directly interact with incident neutrons. Figure 3 below provides a sample output of SUI multi-channel analyzer where a neutron peak can clearly be seen at 5.9 V versus low-energy (0.9-2.0 V) gamma noise.



06: 49: 19: am Jan 27, 1993

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Acquire: Off
Mode: PHA
Timer: Live
Scale: 512
Group: S7
Roi No: None
Roi: Off
Gain: 256
Offset: 0
Adc: Add
Display: 256
Overlap: Off

V: 8.0
Cts: 0

Preset: 0
Elapsed: 93
Real: 152

Filename: C: \ pca \ unit 2 \ 2fmay5. spm

Figure 3. SUI Multi-Channel Spectrum Analysis Sample [6].

There is typically an alarm unit with high and low level alarm capabilities on the SUI main control room equipment. The high level alarm provides an indication that a potential loss of regulation may occur or the unit might be experiencing count rates higher than the design basis, which may lead to sensor damage or degradation. Low level alarm indicates to the control room personnel that the SUI detectors might be getting off-scale low or a loss of power for the SUI equipment has occurred.

To provide a good visual indication of the neutronic activity in the core there is typically a dedicated computer and printer installed in the main control room to be used with SUI equipment. This computer integrates the data obtained from the SUI channels and builds a graph that can be analyzed by the control room operators or station engineers and nuclear scientists to determine the accuracy of the SUI detector readings and to confirm the level of neutronic activity in the core.

3. CONVENTIONAL CANDU SUI DETECTORS

3.1. Conventional SUI Gas-Filled Detectors Overview.

There is a wide variety of neutron detectors available on today's market. However, when it comes to nuclear power plant application, not all detectors perform well due to specifics of harsh environment inside the reactor containment, general inaccessibility for maintenance and the need to accurately discriminate between neutron and gamma activities.

In CANDU power plants in Canada the two of the most commonly used types of neutron detectors, Boron Trifluoride (BF3) and Helium (He3), belong to a family of gas-filled detectors. All gas-filled detectors share the ability to discriminate between neutron and gamma ray energies and are typically well suited to work over a wide dynamic range. Scintillation-based detectors are less suitable because of higher sensitivity to gammas and semiconductor detectors are significantly more susceptible to radiation damage.

Boron Trifluoride (BF3) or Helium (He3) detectors have also been selected as the technology of choice for SUI instrumentation in CANDU power plants, such as Bruce Power Nuclear Generating Station (NGS). It is often the case that high levels of gamma radiation is present in the reactor core during low power or start-up phases which makes BF3 and He3 detectors' ability to discriminate between a gamma-ray process and a neutronic reaction an important factor.

3.2. Proportional Counter Detector Principle.

Both BF3 and He3 detectors are implemented based on the proportional counter principle. The detector gas tubes are constructed using a cylindrical outer cathode and a thin inner wire anode. Following exposure to neutron flux a number charged particles is created as a result of gas interaction with the incident neutrons. The charged particles recoil at high speed creating primary ion pairs and, thus, ionizing the gas inside the chamber resulting in a current flow between the cathode and anode. This current is subsequently detected and converted into voltage pulses, which are subsequently translated into neutron flux measurements. Table 2 below shows Bruce A Neutron Power Measurement and voltage conversion guidelines.

Flux	Amps	Volts	% Power	Decimal	10^	Decade
2.85×10^{14} n/s/cm^2	10^{-4}	4.0	100	1	10^0	0
			10	0.1	10^{-1}	-1
			1	0.01	10^{-2}	-2

			0.1	0.001	10^{-3}	-3
			0.001	0.0001	10^{-4}	-4
			0.0001	0.00001	10^{-5}	-5
			0.00001	0.000001	10^{-6}	-6
	10^{-11}	0.5	0.000001	0.0000001	10^{-7}	-7

Table 2. Bruce A Neutron Power Measurement and Voltage Conversion [7].

One of important features of all gas-filled detectors, including BF3 and He3 detectors, is a so-called wall-effect. The wall effect occurs when charged particles, both the alphas and the other ions, e.g. lithium ion, to reach the detector wall before they had an opportunity to loose their excess kinetic energy in the gas. This will result in a pulse smaller than the one produced if the charged particle deposited their entire energy in the gas. The ions' energy ends up being deposited in the detector wall material and become neutralized there. The wall effect is typically present on all SUI spectrum readings and is an important factor in selection of SUI multi-channel resolution and discriminator bounds.

3.3. BF3 Detectors for SUI Applications.

All BF3 detectors are based on a well-known principle of indirect neutron detection. In BF3 detectors, Boron Trifluoride serves both as target for thermal neutrons and a proportional gas. The detector gas is highly enriched in ^{10}B, up to 96% [5] to provide the necessary efficiency. The thermal cross section for the ^{10}B (n, α) reaction is 3840 barns [3], which makes it extremely suitable for applications in thermal reactors. Another main advantage of BF3 detectors is that Boron is a readily available element. Neutronic activity is derived from the ^{10}B interaction with an incident neutron, as shown in Equation 1 below.

$$^{10}\text{B} + \text{n} \rightarrow {}^{7}\text{Li}^{*} + \alpha + 0.48\ \text{MeV}\ \gamma\text{-ray} + 2.31\ \text{MeV}\ (94\%)$$
$$^{10}\text{B} + \text{n} \rightarrow {}^{7}\text{Li} + \alpha + 2.79\ \text{MeV}\ (6\%)$$

Equation 1. Boron -10 reaction with incident neutron [5] [8].

A typical result of the reaction statistically falls into two main categories – reaction product ^{7}Li in a ground or in an exited state as shown in Equation 1 above. It is well described in literature [5] [8] that about 94% of all reactions result in an exited state with the remaining 6% being in ground state. The produced lithium and lithium ions possess kinetic energies summing to b 2.4 MeV. If the entire kinetic energies are dissipated in the counter gas by ionization, approximately 80,000 primary ion-pairs are created. When a polarizing voltage of 1,800-2,000 Volts is applied, the avalanche results in 2x10 secondary ion-pairs. The conversion gain of the preamplifier is about -235 mV/(M ion-pair) so a positive pulse of 500 mV is obtained and passed on to preamplifier. The pre-amplifier functions well up to 5V DC corresponding to the count rates up to 5×10^{5} counts per second, which is well within the system requirements for SUI equipment [2].

BF3 detectors are commonly used in all Bruce A SUI instrumentation. Bruce A SUI detectors are tube-shaped Reuter-Stokes (Model No: RS-P1-0403-102) counters [2] made of 1100 aluminium alloy with alumina ceramic detector insulation material. Their physical dimensions are 1.27 cm OD by 15.6 cm long with the fill gas being 96% enriched Boron-10 with BF3-gas fill pressure of 55-60 cm/Hg. Table 3 below shows a summary of Bruce A BF3 detector specifications.

Parameter	**Value**
Diameter	5/8" (16 mm)
Overall Length	5 ½ " (140 mm)
with MHV Connector	addl. 7/8"
Active Length	1" (24 mm)
Cathode	Brass (0.035")
Anode	1 mil tungsten
Connector	MHV-teflon
Insulators	Ceramic and glass
Gas filling	Enriched BF3 (96% B^{10})
Gas Pressure	60 cm Hg
Temperature	-80 to +80°C
Neutron sensitivity	appx. 0.35 cps/nv
Neutron flux range	0.25 to 2.5×10^{4} nv

Table 3. Technical Specifications Summary for SUI BF3 detectors at Bruce A [2].

Bruce A detectors provide a sensitivity of 0.35 neutrons per second per square centimetre (cps/nv). This is quite sufficient for all normal and long shutdowns and subsequent approach to criticality. The BF3 detectors deemed to perform well with the count rates as low as 5 counts per second. The RSN137 model currently used is designed by withstand a range of flux of 0.25 to 10^4 n/cm^2/s [9] and a gamma dose rate of up to 100 Rad/h for 24 hours without significant deterioration [6].

Detection efficiency of a BF3 detector for thermal energy neutrons (0.025) eV is approximately 91.5%, which makes it very suitable for start-up instrumentation applications. However, there are a few disadvantages and limitation associated with using BF3 detectors as means of neutron detection in CANDU reactors, particularly in SUI instrumentation at Bruce Power A and B stations as described in the following section.

3.4. BF3 Detector Disadvantages and Limitations.

There are several known disadvantages and limitation associated with BF3 detectors. First, BF3 proportional gas detectors show degraded performance when operated at high pressure [7]. Therefore, the absolute pressure of gas inside the detector tube should be limited to 0.5-1.0 atm [5] and should be carefully monitored.

Also, because of high excitation voltage current leakage through the detector insulators are common. This becomes particularly troublesome in high humidity environment, such as CANDU reactors.

Performance degradation due to ageing and radiation damage [10] is another main issue affecting BF3 detectors. In 2003 degradation of Bruce Power SUI BF3 detectors resulted in failure of five of these while in-service [11].

Contamination of the anode and cathode components by the disassociation products of avalanche reactions is another factor contributing to the detector ageing and performance degradation. According to Dr. G. Knoll studies [5] this typically happen after 10^{10}-10^{11} counts.

Another limitation of BF3 counters are susceptibility to vibration and shock [12]. Mechanical shocks against the HV detector cables or detector themselves result in large noise pulse that is being interpreted by the SUI electronics as large spurious increase in neutron counts. This becomes particularly important limiting factor as the BF3 SUI detectors at Bruce Power A and B are used per mobile, out-of-core scheme and require frequent handling and positioning during unit outage periods. This will be discussed in more detail in the following sections where main operational challenges and concerns associated with current SUI instrumentation at Bruce Power are analyzed.

3.5. He3 Detectors for SUI Applications

A He3 proportional counter is another type of detector widely used for SUI applications. Bruce B SUI instrumentation is typically implemented via He3 detectors. He3 gas possess a cross-section for thermal neutrons of 5330 barns [1], which is noticeably higher that that of B10.

$$3\text{He} + n \rightarrow T + p$$
$$E_p=0.573\text{ MeV},\ E_T=0.191\text{ MeV}$$

Equation 2. He3 reaction with incident neutron [1].

Comparing with BF3 detectors, in the He3 gas-filled tubes of the same size and pressure the traveling distances of the reaction products is much longer, which results in a more significantly wall effect [13] . This is largely due to the fact that He3 has a very low atomic mass. Therefore, a small amount of a heavier gas, such as CO_2 or Ar is used in the fill-gas mixture. Overall, He3 filled tubes can be operated at much higher pressures and temperatures and can provide an acceptable performance output at temperatures as high as 200-250° degrees C.

He3-based SUI detectors used at Bruce Power are GE Reuter-Stokes models. A summary of their technical specifications is provided in Table 4 below.

Parameter	Value
Diameter	2.28” (57.9 mm)
Overall Length	15.69 “ (398.5 mm)
Connector Type	HN
Body Material	304 S.S.
Connector Material	Brass, silver plated
Insulators	Alumina Ceramic
Gas filling	He3
Gas Pressure	60 cm psig (0.41 MPa)
Temperature	-25 to +100° C
Plateau	200 V
Neutron sensitivity	110 cps/nv +/-10 %
Neutron flux range	1.004E-04 to 5.00E+02 nv

Table 4. Technical Specifications Summary for SUI He3 Detectors at Bruce A [2].

Another main difference between BF3 and He3 detectors is that the latter show a much higher sensitivity and are capable of working with very low neutron counts. Typically, He3 detectors can still produce accurate indication of neutronic activities in the reactor core with neutron counts below 5 counts per second and are known to have been successfully used for power levels approaching the source level with the counts as low as 0.3 counts per second [2].

3.6. He3 Detectors Disadvantages and Limitations.

Some of the main limitations of He3 detectors include the fact that He3 is a noble gas and must be used in its gaseous form to fill the detectors. Although, He3 gas is quite available for commercial applications [5], it could present higher costs in obtaining and maintaining the detectors. Both out-leakage of gas from the detector and in-leakage of air into the detector lead to performance degradation.

Although high neutron sensitivity of He3 detectors may become an important advantage in other applications, such as radiation detection in biomedical industry or research, it becomes a hindering factor for SUI instrumentation in commercial CANDU reactors, such as Bruce Power NGS. Neutron sensitivity as high as 110 cps/nv [8] migh result in slow response of the detector electronics and the maximum count rate it is capable to handle before burn-out damage will occur to the detector internals.

He3 detectors are also prone to build-up of electronegative poisons in the gas with time. Bruce Power operational history shows that He3 detectors are more susceptible to problems with electronic equipment saturating at high powers than the BF3 tubes. It is a regular operational concern that a rapid increase in reactor power at start-up might result in neutron fields being too high for the detectors' electronic to handle.

Another main limitation is a low neutron-gamma discrimination capability of the He3 detectors. They are significantly more sensitive to both gamma and neutrons which much lower ability to discriminate between the two and tend to count both. As a result of this, He3 detectors have to be shielded in lead even when positioned in-core.

4. OPERATIONAL CHALLENGES WITH CURRENT SUI EQUIPMENT AT BRUCE POWER NGS.

4.1. Overview of Current SUI Installation Practices at Bruce Power NGS.

At Bruce Power it has become an operational practice to install temporary SUI detectors in spare horizontal chambers of SDS2 Ion Chambers following unit outage. Detectors are installed 7-10 days following reactor shutdown and stay in service during approach to criticality and until the reactor power is raised up to 10-5 decades when RRS Ion Chambers can reliably indicate current neutron flux in the core. Typically, installation of SUI instrumentation is performed in the following several steps.

First, SUI detectors, scaffold materials and tools have to be transported to the accessible area. Once the scaffold is installed, the shield plugs are removed to allow the insertion of detectors in to the spare SDS2 Ion Chamber (IC) housing.

Next, the SUI neutron detectors are installed in each of the three SDS2 Ion Chamber housings, in the tube that normally hosts the spare ion chamber. To accommodate SUI detector the spare IC is removed and replaced by a SUI detector as shown schematically in Figure 4 below.

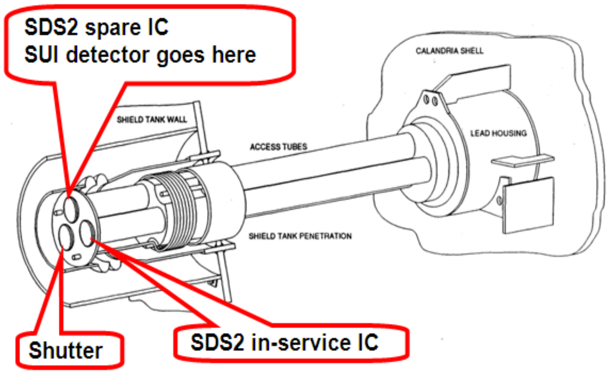


Figure 4. Schematical Arrangement for SUI Detectors in SDS2 Ion Chamber Housing [4].

Next, the detector is wired to the portable instrumentation rack positioned on the north side of the vault. The rack contains a pre-amplifier and a high voltage power supply unit.

Once the equipment is installed in the vault, it is connected to the main control room (MCR) panels via a number of cables so that output signal from the amplifier is sent to the MCR via a fixed penetration junction box and both the vault and the MCR equipment is powered up from the same 120 V Class II bus.

Lastly, the alarm unit output from the MRC panel is connected to SDS1 Channel D, E, and F trip logic.

4.2. Challenges Due To Detector Repositioning Routine.

Following a prolonged shutdown, it is expected to encounter core conditions, where the gamma flux from the fission product buildup may be significantly higher than the neutron flux. It may become necessary to vary detector's sensitivity to the magnitude of neutron flux. This is achieved by adjusting the depth of detector insertion in the tube. Initially, following a reactor shutdown, the detectors are inserted at various depths depending on the recommendations SUI engineers and Fuel & Physics specialists. Detectors are moved inside the access tube through the shield tank following the neutron decay pattern in the reactor core. During extended outages with very low power levels BF3 detectors can are further inserted down the IC housing lead shielding to maintain sensitivity.

To reduce sensitivity of detectors for subsequent start-up and approach to criticality this process is repeated in reverse, the detectors are pulled back away from the calandria wall, out of the lead shielding and into the outer shield tank wall area. BF3 detectors are typically repositioned several times until the maximum distance of 24 inches is reached. As neutron count rates halves with every 4 to 5 inches of withdrawal, at 24-inch distance the detector's sensitivity can be reduced by a factor of 100, or 2 decades in count rates.

4.3. Challenges Due To Detector Change-Out Routine.

Following prolonged outages and shutdowns BF3 detectors might need to be swapped for He3 detectors that possess much higher sensitivity and able to detect very low count rates. Detector change-out routine results in additional delays, dose rates and error-likely situations as the SUI BF3 detectors have to be removed from service and He3 detectors have to be obtained from the storage facility, calibrated and placed in service following the steps described earlier. Once the unit is on a ramp up to power raise and moderator purification columns are valved in, He3 detectors can no longer be used due to their high susceptibility to saturation at high power. Thus, the detectors have to be swapped again for BF3 counters, which in their turn will have to be re-positioned several times during approach to criticality.

4.4 Susceptibility to Mechanical Disturbances.

At very low power, any work performed on the SDS2 platform in the vault has the potential to trip SDS2, particularly if IC cables are jarred or even touched. It is, therefore, extremely important to make sure that only one IC is being approach at a time, so that the chance for a rated trip on more than one channel is minimized. There have been a number of trips and plant upsets resulting from arc-welding jobs taking place in a vicinity of instrument room as well as trips resulting from personnel walking near SUI cables [14].

One of the famous events occurred at Bruce A in 2003 while work was being done by U4 outage crews in a congested area near SUI location. Channels E and F tripped multiple times with count rates increasing dangerously close to an alarm level. It is believed that this may have been result of inadvertent contact with SUI cabling during scaffolding modification work [15].

Another typical example occurred on 8th of March 2007 when some SUI instrumentation was discovered missing from the Bruce Power Unit 6 vault [16]. The following investigation revealed that SUI equipment was unintentionally removed to another area. It was also discovered that there was garbage and other items left in the area dedicated to sensitive SUI equipment that could potentially cause contamination and mechanical damage to SUI units.

4.5. Susceptability to RFI/EMI Noise.

EMI/RF noise induced SUI trips have been a long standing issue for Bruce A. SUI detectors have been known to pick up noise from portable radios in and around the instrument rooms as well as that produced by motors, pumps and other rotating equipment. SUI connectors and cables that are presently in service at Bruce A are showing significant visible signs of wear and tear, as well as ageing related degradation. Control maintenance personnel routinely find that constant positioning and repositioning of cables results in accelerated wear and tear, which in its turn results in additional tasks and work orders that have to be completed prior to SUI installation as well as throughout the unit shutdown. Even though best efforts are made to improve signal cable connections and shielding in order to eliminate or minimize noise affecting SUI channels, it is still a very significant contributor to the number of spurious trips every outage.

4.6. Delays to Critical Path and Outage Extensions.

Delays in SUI installation have been a long standing issue at Bruce Power due to the detector assemblies' degradation problems, installation challenges and SUI equipment reliability.

For example, on 5 April 2007, Unit 4 was in a shutdown state with all three channels of SDS1 ion chamber readings of -7 decades. These readings were obtained with SDS1 Shutters already jumpered open on April the 3rd in order to increase the ion chamber signals. The actual readings, therefore, would have to be 0.1-0.2 decades lower that the ones shown above if the shutters were in the closed position. There also were several moderator level changes that affected the indicated power. SUI instrumentation, however, was not installed until April 8 with several delays in the process resulting in impairment to the neutron monitoring system as well as elevated stress on the operators, engineering and control room personnel during those uncertain times.

Similarly, for the Unit 8 outage there was approximately 13 hours delay with the installation. For unit 6 the System Engineer spent 16 hours on site for SUI installation. There were also multiple issues and delays for the installation of SUI during the A731 outage.

Overall, in the year 2009 Bruce Power lost approximately 70 reactor-days of generation because of extensions to planned outages, partially due to SUI equipment installation and condition issues.

4.7. Human Performance Errors.

It can be appreciated that the described earlier process of detector selection and installation/repositioning in service is quite a complex one, where input from multiple disciplines, e.g. Fuel and Physics, Engineering, Maintenance, Instrumentation &Components (I&C) department, etc., is often required several times throughout the unit outage work. Inadequate understanding of differences and specifics of Start-up Instrumentation detectors and neutron-gamma activities in the shutdown reactor core has resulted in multiple incidents and events. A typical example of this could be the event that occurred in 2002, when SUI instrumentation was found impaired during U7 outage due to a wrong type of detector, namely He3, being selected and placed in service [16].

The failure of SUI instrumentation to properly respond to the removal of moderator poison on approach to criticality resulted in an emergency shutdown and return to over-poisoned state (OPGSS). This resulted in additional delays in the outage schedule, stress to the plant equipment and dose rates to the maintenance crews. Furthermore, impairment to SUI equipment and intent function could have had a direct impact on nuclear safety, as it is believed that the SUI detectors provided an invalid indication of neutron flux from November 30 until December 24, 2002 [16].

4.7. Radiological Hazards and Dose Rates Due to Challenges with Existing SUI Equipment.

Installation, re-positioning and removal of SUI equipment as per current mobile scheme involve significant radiological hazards. Control maintenance personnel working in the vault have to be aware of high gamma fields present at SDS2 platform. Another source significantly contributing to radioactive exposure is the SDS2 piping located near the Shield Tank. High gamma fields in the range of Rem/hr exist at the IC access tube openings and around the neutron flux monitors (NFM) as well, but none is as high as the gamma and neutron beams emitting from empty SDS2 ion chambers access tubes. In 2005 installation of SUI instrumentation alone contributed a dose of 1 Rem per person per outage [17] at Bruce A.

4.8. Conventional Hazards of Existing SUI Equipment.

Some of the main conventional hazards associated with detector installation and re-positioning involve electrical hazards and chemical toxic substances.

Installation of SUI equipment in service and frequent adjustment and re-positioning of cables require control maintenance personnel to work in tight confined space in the vault. This results in elevated risks of inadvertently coming in contact with terminals of high voltage power supplies in the portable equipment racks.

Boron Trifluoride (BF3) fill-gas in the current Bruce A SUI detectors is a known severe lung, eye and skin irritant. Detectors have to be checked and the area monitored to ensure no gas leaks are present during detector calibration phase in the shop.

5. PROPOSED SOLUTION – PERMANENTLY INSTALLED SUI EQUIPMENT WITH FISSION CHAMBER DETECTORS.

5.1. Advantages of Permanently Installed SUI Detectors.

Potential benefits of placing SUI detectors in service once and leaving them in reactor core include eliminating a complicated SUI installation procedure, minimizing wear and tear on SUI instrumentation and, perhaps, most importantly significantly minimizing downtime and outage extensions due to SUI installation challenges and spurious trips. This, in its turn, will greatly reduce the additional dose rates incurred by the control maintenance personnel involved in SUI installation and removal phases as well as Operation and Maintenance (O&M) costs. Outage planning, scheduling, and coordination would be greatly simplified once the necessity to install SUI instrumentation is eliminated. The control maintenance personnel involved in SUI installation and placement in service has to possess highly specialized skills and knowledge as well as field experience, and are often in great deficit, particularly during busy shutdown schedule. With permanently installed SUI equipment, outage crews will be able to proceed to pertinent tasks and jobs without delays due to SUI detector installation and removal.

5.2. Bruce A Original SUI Design Changes and Results

Several attempts and initiative have been made in the past to determine the feasibility of setting up SUI instrumentation permanently in reactor.

Originally all Bruce A stations were designed with the intent for SUI instrumentation based on N. Wood BF3 detectors to be permanently installed in the core. However, degradation of SUI detectors over time became a significant factor in the decision to remove SUI in-core instrumentation and use it temporarily on as-needed basis.

Laboratory degradation tests at Chalk River Laboratories (CRL) [18] showed that the standard BF3 detectors originally used at Bruce A, as well as at most domestic CANDU stations, displayed undesirable degradation issues which could not be resolved at the time. As a result of these, Centronic BF3 detectors were chosen as the model showing the least amount of degradation [19] and subsequent changes were made to operating procedures and work management practices to incorporate installation and removal of SUI instrumentation into planned outage scopes. By 1984 original SUI detector guide tubes and assemblies were removed from viewing ports and SDS2 spare ion chamber housing was adapted to accommodate temporary SUI detector installation in both Bruce A and Bruce B units. A comprehensive set of procedures, training materials and qualifications had to be developed to ensure that the Control Maintenance personnel had sufficient knowledge and skills to operate according to the new procedures.

5.3. Industry Best Practices and Recommendations.

Attempts to resolve the degradation and short life expectancy of neutron detectors has been an on-going effort since the outset of commercial power generation industry throughout the world. In 1966 Stokes proposed to use activated charcoal as fluorine absorbent [20], however this technique was not investigated further or used by Reuter Stokes. Mitsubishi Electric has also been working on resolving the limitations of BF3 detectors [21] [22] in an attempt to create a detector with much higher resistance to degradation at exposures 1000 times larger than in the previous models by using activated charcoal [22].

In 1995 CANDU Owners Group (COG) SUI team made a recommendation to investigate the possibility and potential advantages of using modified BF3 detector types that may be left in CANDU stations [23], following which various other types and models of detectors have been proposed and tested over the years as an alternative to the traditional BF3 detectors. Imaging and Sensing Technologies (IST) BF3, modified He3 detector from Reuter Stokes and N. Wood detectors were thoroughly examined at CRL laboratories to determine the extent and nature of degradation for each detector type and model [19].

Up to date, these attempts have been unsuccessful mainly due to the lack of practical solution to address degradation mechanism affecting both BF3 and He3 detectors resulting from detector irradiation and burn out. The detector short useful life time and undesirable degradation/recovery characteristics remain the main obstacle for implementation of permanent SUI equipment installation in CANDU power plants.

5.3. Proposed Detector Technology – Fission Chambers.

Fission based counters have been known as a method for neutron detection for quite some time. Large amount of the kinetic energy of the fission fragments, 168 MeV [24], released in a fission reaction inside the fission chamber can be easily detected and distinguished from gamma-noise effects and other activities. This makes it an extremely attractive option for Start-up Instrumentation, as this detection mechanism is very effective even with very low count rates.

Typically fission detectors are implemented similar to ionization chamber principle with the inner surface coated with a fissile material that produces fissions in response to incident neutrons. The products of fission reactions inside the chamber will ionize the fill gas in the manner similar to proportional counter principle. Ion current from the fission chamber is then used to detect and measure neutronic activities in the reactor.

Highly enriched uranium is a common choice of fissile material. Fissile material selection initially presented some challenges as neutron sensitive material, such as U-235, will gradually burn up, thus causing a decrease in detector's sensitivity. An exposure to neutron flux of about $1.7\text{x}10^{21}$ n/cm^2 will result in 50% detector sensitivity decrease [25]. This limitation was subsequently solved by combining fertile and fissile material in the lining. While the original fissile material is being used in the burn up process, it will be replaced by fertile to fissile isotope conversion. Several mixture compositions have been studied over the cause of years and results as good as no more than +/-5% change over $4.8\text{x}10^{21}$ n/cm^2 flux have been achieved [26] using a mixture of U-234 and U-235 as well as U-238 and Pu-239.

The two fission fragments produced in the fission reaction induced by thermal neutrons are born with kinetic energies and large positive charges, so that they move in the opposite directions. As the initial charge of fragments is in order of 15 to 20 electronic charges [5], the energy losses at the beginning of their trajectory are most significant. As the energy loss continues and the fragments slow down, more and more additional charges are being picked up on the way. This may result in only one fragment reaching the active volume of the chamber. To counteract this phenomenon, various designs for fission chambers lining and backing material have been developed, but typically a common choice for fill gas for all detector models is Argon or Nitrogen. The detector is filled up to several atmospheres to ensure that the range of travel of fission fragment is within the dimensions of the detector.

A typical design for a fission chamber detector used in Boiling Water reactors (BWR) is shown in Figure 5below. The body of a typical fission chamber, similar to the one shown below, stainless steel is used for walls and aluminium electrodes with operating voltage in the range of 50 to 300V [5]. Operating voltage is an important factor in selection of fission chamber model. Increased voltage is required at higher count rates to achieve ion saturation and prevent recombination [5].

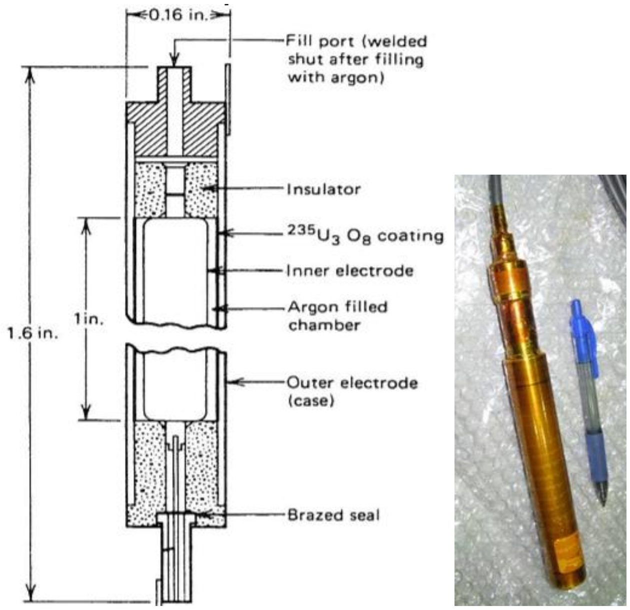


Figure 5. Typical In-core Fission Chamber Used in BWR NFMS [5].

One of the main challenges initially encountered with the fission chamber counters is the fact that the fissionable material used is typically an alpha emitter. This results in a consistent alpha particle production that cannot be eliminated or minimized. This feature, however, can be overcome quite easily since the alpha particle and the fission fragments have very distinctive energy signatures. Average alpha particle fragment typically possesses 5 MeV of energy while a typical fission fragment’s energy is 10 times larger [5]. No gas multiplication is required and fission chambers can be used in pulse-counting mode. Discrimination between alphas and fission fragments is based on the pulse amplitude with subsequent arrangement of signal processing components to suppress alpha pulse pile-ups [27].

5.4. Industry Experience with Fission Chambers.

Small size, ease of operation, resistance to harsh operating environments in high gamma radiation fields with minimum lead shielding, and high resistance to degradation make fission chamber detectors an ideal alternative to the existing conventional BF3 and He3 detectors used in most domestic CANDU power plants.

Fission chambers are widely used in Pressurised Water Reactors (PWR), Boiling Water Reactors (BWR) and Pebble Modular Reactors (PBMR) at various commercial nuclear power plants throughout the world. French Atomic Energy Commission (CEA) selected fission chambers technology for in-core reactor monitoring, start-up, intermediate and wide power range. Today, each Areva (formerly FRAMATOME) power plant uses 5 or 6 of CFUF43 fission chambers [28].

A special wide range of CFUE32 fission chamber operating in pulse mode has been developed for Studsvik Instrument, Sweden to be used during start-up mode for six ABB-ATOM BWR plants in Sweden and two in Finland. [32].

Beznau Nuclear Power Plant, Switzerland, employs LOCA and post-LOCA qualified CFUG08 wide-range fission chambers for the safety instrumented channels. Up to date, four detectors have been installed in Westinghouse PWR block to provide wide range neutron flux indications over a range of 11 decades [28].

WWER-based REKON Bohunice V1 plant in Slovakia have adapted CFUL08 fission chamber for the wide-range safety instrumentation and 12 fission chambers have been installed in the safety instrumentation channels of both blocks [28].

French COGEMA fuel reprocessing plants in Marcoul and La Hague are using fission chambers as well. Fission chambers are also used for non-destructive analysis (NDA) measurements for the DUPIC fuel cycle. Safeguard verification of mixed oxide (MOX) and spent-fuel assemblies are performed by a combination of a pair of 235U fission chambers and an ion chamber in a fork-shaped holder to verify the declared burn-up [29]. A complete list of nuclear facilities where Photonis fission chamber technology is used is provided in Appendix B.

Fission chambers are also routinely used in Test Research and Training Reactors (TRTR) and medical isotopes reactors, such as MDS Nordion reactor at AECL Chalk River Laboratories in Canada.

Although the need to upgrade aging, failure-prone neutron detection systems in domestic CANDU has been apparent for quite a while, very few attempts have been made to introduce fission chamber technology onto domestic nuclear instrumentation option list. A system consisting of fission chambers mounted in housings on the calandria shell is described as supplementing in-core flux detectors in the Advance CANDU Reactor ACR-700 [30], however no practical implementation of this technology on domestic CANDU market has been achieved yet.

CANDU 6 technical summary [31] released in June 2005 mentions two sets of triplicated fission chambers that are used to covers very low flux range of 10^{-14} to 10^{-10} F.P. and 10^{-11} to 10^{-6} F.P. of full power without explicitly naming the facility where this takes place. It is, however, believed to be based on Pickering A reactors example, where signals from fission chambers are used for reactor trip function and for monitoring the reactor power on a continuous basis [32].

6. CASE STUDY – USE OF FISSION CHAMBER BASED SUI INSTRUMENTATION FOR BRUCE POWER REFURBISHMENT

6.1. The Need for SUI Equipment Refurbishment.

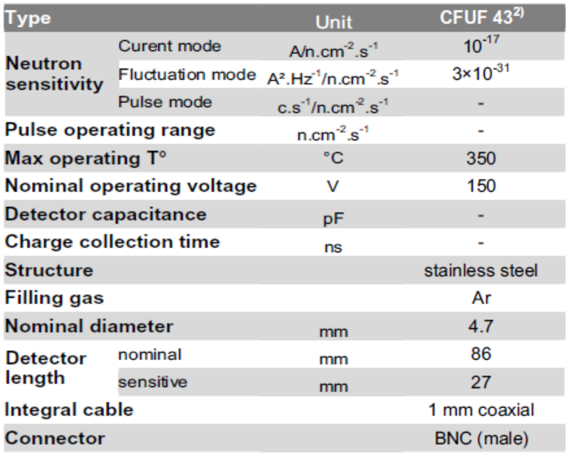
Currently SUI instrumentation at Bruce Power consists of older Centronic detectors and obsolete Tennelec and Canberra signal processing electronics, with no spares or replacement parts available for amplifiers, portable panels and MCA computers. IAEA-TECDOC-1402 released in 2004 [33] highlighted the trend formed over the last two decades where many major manufacturers of components for Nuclear Power Plants (NPPs) have ceased to supply or support products with which the plants were built [33].

With rapid evolution of modern digital technology, obsolescence factors are becoming increasingly concerning for Bruce Power Engineering and Control maintenance personnel. SUI, as a special safety system is, therefore, a prime candidate for technological overhaul during the upcoming Unit 3-8 refurbishment project to ensure that current Bruce Power units can continue safe and reliable energy production well beyond their initial design life period.

6.2. Proposed SUI Detector Technology.

As discussed earlier, fission chambers can be used for Star-up monitoring for power ranges as low as 10^{-14} F.P and up to 10^{-6} F.P. at which point the reactor monitoring function can be transferred to the RRS ion chambers. This should provide enough range to encompass both routine outage shutdowns as well as prolonged shutdowns required for unit refurbishments.

Several fission-chamber detector models were considered as an alternative to the ageing existing Bruce A gas-filled detectors. Three models, IST WX-33073 made by Mirion Technologies/IST, 300i Neutron Flux Monitoring System (NFMS) by Thermo Scientific, and Photonis Fission Chambers were initially selected as suitable candidates for replacement. It should also be noted that the detector length and geometry was a key factor influencing the selection, since the detector will have to be installed into the existing Bruce Power reactor units. Taking into consideration this factor, CFUF-43 detector by Photonis was selected as possessing high sensitivity while operating in temperature ranges up to 350° C as shown in Figure 6 below.



Type		Unit	CFUF 43[2)]
Neutron sensitivity	Curent mode	$A/n.cm^{-2}.s^{-1}$	10^{-17}
	Fluctuation mode	$A^2.Hz^{-1}/n.cm^{-2}.s^{-1}$	3×10^{-31}
	Pulse mode	$c.s^{-1}/n.cm^{-2}.s^{-1}$	-
Pulse operating range		$n.cm^{-2}.s^{-1}$	-
Max operating T°		°C	350
Nominal operating voltage		V	150
Detector capacitance		pF	-
Charge collection time		ns	-
Structure			stainless steel
Filling gas			Ar
Nominal diameter		mm	4.7
Detector length	nominal	mm	86
	sensitive	mm	27
Integral cable			1 mm coaxial
Connector			BNC (male)

Figure 6. CFUF-43 Fission Chamber Detector Model by Photonis [34]

6.3. SUI System Components and Interconnections

With the CFUF-43 detectors permanently installed in the reactor core, a complete new SUI system will consist of the following components:

- Source range detector assembly CFUF-43 (with integral cable)
- Junction box
- In-containment cable assembly (from junction box to inside penetration)
- Amplifier cable assembly (from outside penetration to amplifier)
- Amplifier assembly

- Optical isolator assembly
- Signal processor cables
- Source range signal processor
- Shut down margin monitor assembly
- Wall mount signal processor assembly

A conceptual block diagram for the proposed system outlining the installation in the wall, containment penetrations and connections to the portable NimBins and the MCR panels are shown in Figure 7 below.

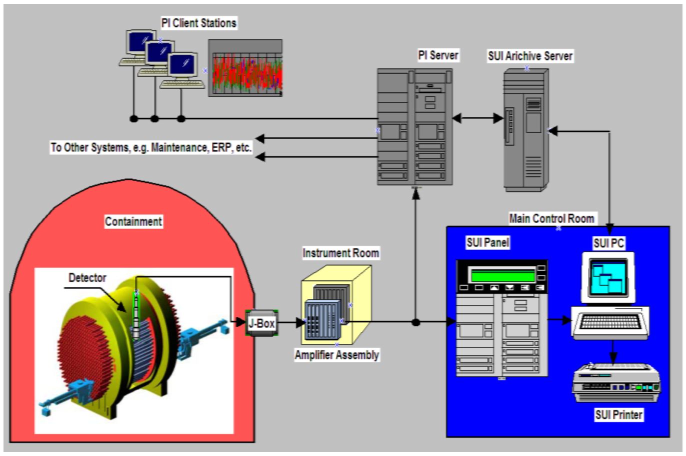


Figure 7. SUI Detector Arrangement in the Vault and Connection to the Portable SUI Bin.

As shown in Figures 7 above, the new SUI CFUF-43 detectors will be mounted vertically from the reactivity mechanism deck through the 6" diameter viewing port located in the centre top of the Calandria. This port is used only during commissioning, and is currently blanked-up and no longer actively in service.

Thus, the signal is obtained from the detector in core and is transmitted via a junction box to the amplifier assembly located in the existing Instrumentation Rooms outside the containment.

Next, the signals from the wide range amplifier are received by the rack mount signal processors located in the main control room (MCR). This panel will be dedicated to the SUI equipment and will be permanently installed in the MCR. The new Photonis neutron monitoring systems (NMS) are designed with a consideration that they will be used to replace existing Start-Up Instrumentation at older nuclear plants. Therefore, a request to Photonis will be made to ensure that the new signal processors look similar in appearance to existing equipment to minimize training of plant personnel and changes to plant operating procedures. Therefore, very little interruption to the normal operating policies and procedures are expected as a result of this addition.

Next, the MCR monitors convert the signals from the amplifiers into signals that represent the source range count rate and the rate-of-change of reactor power level. There are also alarm functions provided to alert the MCR operators when neutron activity in the core exceeds the set points. The Source Range signal processors used for Start-Up applications are designed in standard 19 inch rack mounted enclosures with LCD-digital screens and bar graph meters.

The output of the SUI MCR panel will be connected to the SDS1 trip logic on the MCR panel in the same way it is done today. The connection to the SDS trip circuits will be normally jumpered out during routine operations and will be activated only as required during outage periods.

6.4. Data Logging and Archiving Solution.

Currently Start-Up Instrumentation at Bruce A has no its own dedicated tags in the Plant Information, or so-called PI system [34] to enable real time data logging. Therefore, neither SUI engineers nor control room operators have the means to store SUI data for future trending and analysis electronically. SUI counts have to be printed off the MCA via a printer and are processed and logged manually in paper format.

Should it be desired to have the SUI connected to the PI interfaces, it is done at a custom request from the engineering personnel via spare unassociated tag circuits. This requires specialized knowledge of the station DCCs (Digital Control Computers) and PI application architecture, so an experienced professional from the Computer Design Group has to be closely involved in the set up of this arrangement. It can be appreciated that this arrangement is highly undesirable and is used very often due to complexity and time constrains.

To address this limitation, particularly in the view of upcoming prolonged reactor outage for the Unit 3 and 4 refurbishment project, it is proposed to establish connections between SUI channels and the PI servers as shown in Figure 7 above with an additional archiving server dedicated to viewing, documenting and copying of the SUI archive data.

7. CONCLUSIONS

In domestic CANDU reactors gas-filled SUI detectors, such as BF3 and He3 have conventionally been the primary means of monitoring neutron activity at low power to provide sufficient neutron overpower protection during unit shutdowns for routine maintenance.

However, several inherent disadvantages of gas-filled detectors have been well-known since the early day of CANDU program and several efforts have been made to provide a solution to address this issue. Originally SUI systems in domestic CANDU power plants, such as Bruce A were designed to be permanently installed in the vault to provide immediate core monitoring activities following a shutdown and subsequent start-ups. Since no progress was made to overcome rapid detectors degradation in high gamma fields, SUI implementation was re-visited and a portable, temporary solution was adopted. Original SUI guide tubes and view ports were removed and a complex, multi-step process of positioning, re-positioning and removal of detectors from service was developed and refined over the years.

In the view of upcoming Bruce A Unit 3 and Unit 4 refurbishment project, it is quite likely that the neutron flux in the reactors in question might decay to low and very low levels, potentially below 10^{-14} decades. It is expected that monitoring reactor powers after such an extensive shutdown with potential de-fuelling of some or all channels might present significant challenges for the ageing BF3 and He3 detectors and worn out SUI cables and connectors.

Features and characteristics of several neutron detectors based on fission chambers technology that are available on the market, such as Mirion Technologies/IST, Thermo Scientific and Photonis, were analyzed in addition to the conventional BF3 and He3 detectors presently used at Bruce Power. Their main key features have been analyzed and compared and a selection was made in favour of Photonis CFUF-43 fission chambers as the most suitable alternative to the ageing and obsolescent SUI gas-filled detectors at Bruce A.

Also, a proposal for permanently installed SUI instrumentation system based on the new fission-chamber technology was made, as opposed to the existing temporary SUI installation approach, in an attempt to eliminate the challenges and hurdles incurred by the Bruce A maintenance personnel during every outage due to time, effort and radiation dose involved in temporary SUI installations.

Finally, additional SUI data logging and archiving capabilities are proposed to provide SUI engineers and control room personnel with the options of computerized data analysis and trending as well as electronic SUI data storage facility.

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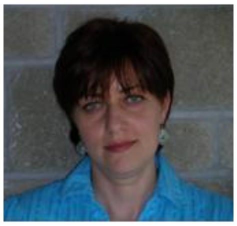

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