

Module 15

Neutron Detectors And Reactor Instrumentation

7.1	MODULE OVERVIEW	3
7.2	MODULE OBJECTIVES	3
7.3	NEUTRON DETECTION	3
	Neutron Detection Methods	4
	Nuclear Reactions Used In Neutron Detection	5
7.4	THERMAL NEUTRON DETECTORS	6
	Boron Proportional Counters	7
	Fission Reaction Detectors.....	7
7.5	SELF-POWERED NEUTRON DETECTORS	8
	Self-Powered Neutron Detectors Based on Beta Decay	9
	Self-Powered Neutron Detectors Based on Secondary Electrons	12

7.6 NEUTRON DETECTOR APPLICATIONS	14
Startups and Low Power Neutron Detectors	17
Reactor Control at the High Power Range	19
Transfer of Reactor Control	19
Neutron Flux Mapping	20
Platinum Detectors Calibration Requirement	20
7.7 COMMON PROBLEMS OF NEUTRON DETECTORS.....	22
Ion Chamber Detector Failures.....	22
In-core Detector Failures.....	24
ASSIGNMENT	26

7.1 MODULE OVERVIEW

This module will cover the different types of thermal neutron detectors and their applications including various failure modes of these detectors when used in reactor instrumentation and control.

7.2 MODULE OBJECTIVES

After studying this module, you should be able to:

- LIC 7.1 State why different detectors are used in reactor instrumentation.
- LIC 7.2 State the principle of operation of a neutron flux detector.
- LIC 7.3 Identify the different failure modes of reactor instrumentation.
- LIC 7.4 State why in-core neutron flux detectors require continuous thermal calibration.

7.3 NEUTRON DETECTION

Neutrons, like gamma-rays, have no charge and therefore cannot interact in matter by means of the coulomb force which dominates energy loss mechanisms for charged particles and electrons. Neutrons can also travel through many centimeters of matter without any type of interaction and thus can be totally invisible to a detector of common size. When a neutron does interact it is with a nucleus of the absorbing material. This interaction may either cause the neutron to disappear totally and be replaced by one or more secondary radiations, or change the energy or direction of the neutron significantly.

Secondary radiations resulting from neutron interactions are almost always heavy charged particles. These particles may be produced either as a result of neutron-induced nuclear reactions, or they may be the nuclei of the absorbing material itself which have gained energy from the neutron collisions. Most neutron detectors utilize some means of converting the incident neutron into secondary charged particles that can then be detected directly.

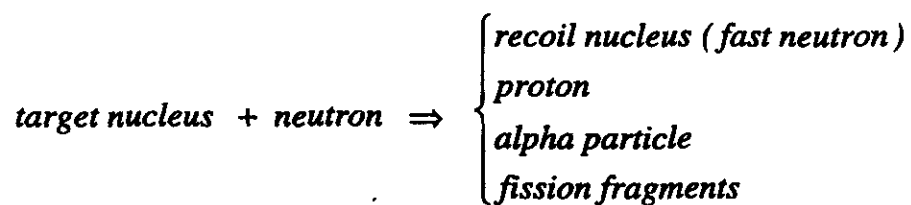
7.3.1 Neutron Detection Methods

Neutrons are detected through nuclear reactions which create energetically-charged particles such as protons, alpha particles, and so on. For slow (thermal) neutrons, significant interactions include elastic scattering with absorber nuclei and a large set of neutron-induced nuclear reactions. Because slow neutrons have a small amount of kinetic energy, very little energy can be transferred to the nucleus in elastic scattering. Consequently, this interaction cannot be used to detect slow neutrons. Several different neutron reactions have been used to detect slow neutrons. These include: (1) prompt capture of neutrons resulting in charged particle emission, (2) delayed activation reactions where an activated nucleus emits some form of radiation within a convenient half-life and energy, and (3) fission reaction resulting from neutron capture.

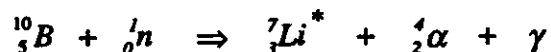
Because the capture cross section for thermal neutrons is high, many neutron detectors use thermal neutron capture reactions as the basis for their measurements. Any type of neutron (thermal, intermediate, or fast) can be measured with this kind of instrument as long as the neutron is in the thermal energy range (below 0.5 eV) when it enters the sensitive volume of the detector. This range is conventionally called the slow neutron region and is distinguished from intermediate and fast neutrons with energies above this value.

7.3.2 Nuclear Reactions Used in Neutron Detection

It is important to point out that all common reactions used to detect neutrons create heavily-charged particles, although very rare specialized detectors use gamma rays produced in the reaction. Possible reaction products are listed below:



The boron-10 reaction is the most popular way to convert slow neutrons into directly detectable particles. The reaction may be written



The Li* indicates that the reaction product ${}^7\text{Li}$ may be left in its ground state or in its excited state. When thermal neutrons induce the reaction, about 94% of all reactions lead to the excited state and only 6% directly to the ground state. The energy value in either case is very large (2.310 or 2.792 MeV). When the excited lithium returns to its ground state, it emits gamma rays, which always escape and do not contribute to the response of the detector. The two reaction products are emitted in opposite directions, and always share the energy of the reaction in the same manner.

This is a widely-used reaction due to: (1) its large cross section for thermal neutrons (3,838 barns), (2) the abundance of naturally-occurring boron-10 (19.9%), (3) its large release of energy per reaction making discrimination against gamma easy, and (4) the ease with which boron-10 gas can be incorporated into gas-filled detectors or used in solid form to coat the detector electrode.

Thermal neutrons can be detected by using ^{235}U , ^{239}Pu or other fissionable materials coated on the detector wall. When neutrons are captured by the fissionable material on the detector walls and a fission reaction takes place the fission fragments move in opposite directions. One enters the sensitive volume of the detector and the other strikes the wall. The advantage of a detector using the nuclear fission reaction is the large energy release that allows simple discrimination against gamma rays (which cause ionization that transfers much less energy).

The remaining two slow neutron detectors measure beta or gamma decay current produced after the neutron is captured as well as the secondary electrons produced by gamma decay. These detectors are discussed in more detail in the self-powered detectors section of this module.

7.4 THERMAL NEUTRON DETECTORS

A detector that is often used for slow neutrons is the proportional counter which uses boron as a fill gas, in solid lining, in an ion chamber, or in proportional counters coated with fissile materials (fission chambers).

7.4.1 Boron Proportional Counters

BF_3 (boron trifluoride) gases used in proportional counters are enriched to about 96% in ^{10}B which results in a level of efficiency five times greater than the natural boron gas. BF_3 tubes can discriminate against gamma rays that are often found with the neutron flux being measured. Gamma rays interact primarily in the wall of the counter and create secondary electrons that may produce ionization in the gas.

Because the stopping power for electrons in gases is quite low, a typical electron will only deposit a small fraction of its initial energy in the gas before reaching the opposite wall of the counter. Thus, most gamma ray interaction should result in low-amplitude pulses that can simply be eliminated by an electronic amplitude discrimination circuit without sacrificing detection efficiency.

Alternatively, boron can also be introduced into a conventional proportional tube by applying boron as a solid coating on the interior wall of the proportional tube. The advantage of this configuration is that a more suitable gas than BF_3 can now be used. When introduced as a wall coating, the boron is applied as boron oxide (B_2O_3) or boron carbide (BC_3). A detector using a boron wall coating is inferior to one that introduces the boron as a fill gas (BF_3) because a significant amount of the alpha particles are absorbed by the boron coating or the wall resulting in a smaller number of electrons being collected by the central anode. On the contrary, when BF_3 gas is used, a much larger amount of secondary electrons are collected by the anode. Thus, the most sensitive neutron detectors use BF_3 gas. This type of detector is used to measure neutron flux during the initial startup of the reactor.

7.4.2 Fission Reaction Detectors

The detectors that use the fission reaction to detect neutrons are called fission chambers. These small ion chambers are typically made of stainless steel walls and electrodes, with an operating voltage from 50V to 300V. The chamber walls are usually lined with highly enriched uranium to enhance the ionization current. Argon is the common choice for the chamber fill gas and it is used at a pressure of several atmospheres. The elevated pressure ensures that the range of fission fragments within the gas does not exceed the detector's small dimension. The pulses produced by fission fragments entering the sensitive volume of the detector are large, and because the ion chamber does not produce large current flows, the output from the fission chamber is a series of pulses that can be counted.

When the detector is operating, the fissionable material on the detector walls is being consumed (by fissioning). To help slow the rate of depletion, a fast neutron absorber such as ^{238}U is sometimes added to the fissionable material on the wall. When ^{238}U absorbs a fast neutron, ^{239}Pu is created after beta emission. The ^{239}Pu is itself a fissionable material.

Miniaturized fission chambers can be tailored for in-core use over any power range likely to be encountered in reactor operation. These detectors can be used as travelling detectors and as a reference point to calibrate self-powered detectors.

7.5 SELF-POWERED NEUTRON DETECTORS

A unique type of neutron detector that is widely used in reactor cores is the self-powered detector. Self-powered detectors are also known by a variety of other names. In recognition of the early pioneering work done by G.W. Hilborn, they are sometimes called Hilborn detectors. They are also referred to as beta emission detectors, collectrons, electron emission detectors, PENA (primary emission neutron activation), and self-powered neutron (SPN) detectors. However most CANDU stations use the term in-core detector (ICD) for this family of devices.

The advantages of self-powered detectors when compared to other neutron sensors, include size, low cost, and the relatively simple electronics required to use them. Disadvantages stem from the low level of output current produced by the devices, a relatively severe sensitivity of the output current to changes in the neutron energy spectrum, and for many types, for instance vanadium detectors, a rather slow response time.

7.5.1 Self-Powered Neutron Detectors Based On Beta Decay

In its simplest form, the detector operates by directly measuring the beta decay current after the neutrons have been captured. This current is proportional to the rate at which neutrons are captured in the detector.

Figure 7.1 illustrates the possible sequences which contribute to the measured current. The operation is very simple: The current that corresponds to the beta rays given off by the emitter is measured between the emitter and an outer shell, called the collector. The intervening space is filled with an insulator which is selected to withstand the extreme temperature and radiation environment typically found in a reactor core. Insulators are often made of metallic oxides, the most common being magnesium oxide. Collectors are generally made of high-purity stainless steel or Inconel. When these detectors are being fabricated, great care must be taken to keep the material as clean as possible to avoid contamination by substances that might also become radioactive and add an interfering current to the measured signal. Vanadium is the most popular emitter material.

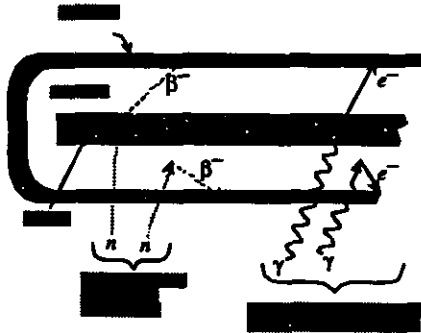


Figure 7.1: Events that occur in neutron detector based on beta decay

The name self-powered detector derives from the fact that the beta decay current is measured directly, and no external voltage is required. Figure 7.2 shows a sketch of a typical SPN detector based on beta decay. The heart of the device is the emitter, made from a material chosen for its relatively high cross section for neutron capture leading to a beta-active radioisotope. The rest of the detector should not interact strongly with the neutrons, and construction materials are typically those with relatively low neutron cross sections.

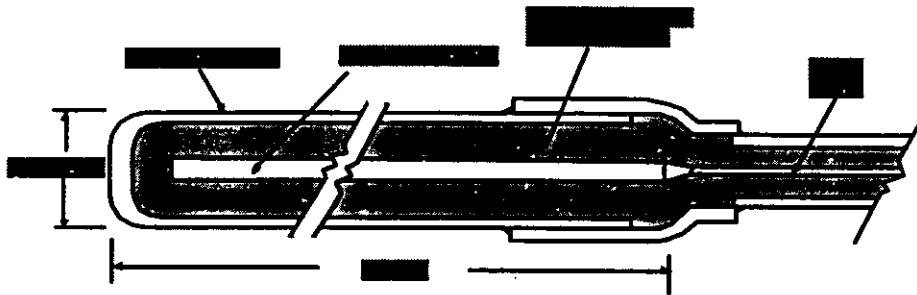


Figure 7.2: Cross section view of a typical detector based on beta decay

The choice of emitter material is the key to how well the detector performs. When selecting an emitter, it is important to consider its neutron capture cross section together with the energy and half-life of the resulting beta activity. The capture cross section should not be too high or too low because a very low cross section will lead to detectors with low sensitivity, whereas an excessively high cross section will result in rapid burnup of the emitter material in the high neutron fluxes associated with reactor cores. Sufficiently high-energy beta rays should be produced to avoid excessive self absorption in the emitter or insulator. As well, the half-life of the induced activity should be as short as possible to permit the detector to respond quickly to rapid changes in neutron flux.

Vanadium detectors have a prompt gamma ray response that is generally a few percentage points of the neutron response component of the signal. The ratio of prompt to delayed signal in commercial vanadium detectors is reported to be about 6.5%.

7.5.2 Self-Powered Neutron Detectors Based On Secondary Electrons

The primary disadvantage of self-powered detectors based on beta decay is their relatively slow response time. Some efforts have been made to remedy this situation by electronic or digital signal processing, but it is preferable to speed up the inherent response of the detector itself. One way to accomplish this objective is to rely on the secondary electrons produced by prompt capture gamma rays resulting from neutron capture in the emitter. Figure 7.3 illustrates the sequences which contribute to the measured current.

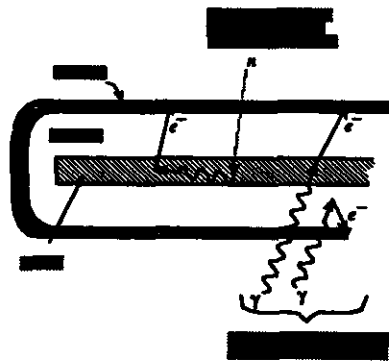


Figure 7.3: Events that occur in detector based on secondary electrons

Some fraction of these gamma rays will interact to form secondary electrons through the Compton, photo electric, and pair production mechanisms. The current of the secondary electrons can then be used as the basic detector signal. These capture gamma rays are emitted within a small fraction of a second, as opposed to the much slower decay of typical vanadium detectors.

The most commonly-used detector to optimize the signal from gamma rays coming from neutron capture is the platinum emitter detector (only 80-88% prompt when responding to flux change). With some exceptions, the neutron sensitivity of prompt detectors is substantially less than detectors based on beta decay. It should be noted that their faster response can make them the detector of choice for reactor power regulation and control.

The detector will also respond to external gamma rays. External gamma rays on the detector produce secondary electrons which yield a detectable signal as illustrated in Figure 7.3. The external gamma-ray induced signal can be either positive or negative, in that the net flow of the current may be in the same or the opposite direction to the neutron-induced current. Which polarity prevails depends on whether more gamma-ray-induced electrons flow from the emitter to the collector or vice versa. Either situation can exist, and this depends on the specific construction of the detector. Because they are sensitivity to gamma rays, these detectors are unusable at low neutron flux.

The most common variant of the platinum in-core detector used in CANDU reactors is the platinum-clad detectors. This type of detector is shown in Figure 7.4.

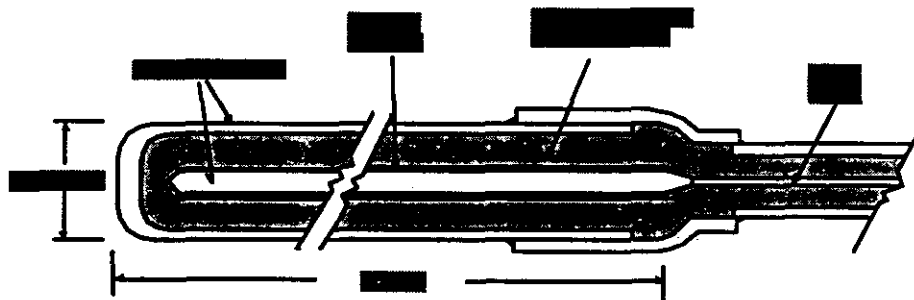


Figure 7.4: Cross section view of platinum-clad detector

7.6 NEUTRON DETECTOR APPLICATIONS

Power produced by thermal nuclear reactors is generated through fission induced by slow neutrons. Nuclear sensors that are part of reactor control or safety systems are generally based on detectors that respond primarily to slow neutrons. The detector types discussed earlier can be modified for reactor neutron measurement.

There are two general categories of reactor instruments: in-core and out-of-core. In-core sensors are those that are located within the reactor core and are used to provide detailed knowledge of the flux shape within the core. These sensors can be either fixed in one location or provided with a movable drive. Obviously they must be small to fit in between the pressure tubes or fuel channels in the reactor core.

Out-of-core detectors are located outside the core and thus respond to properties of the neutron flux integrated over the entire core. They measure leakage flux at their location, which, by calibration can be made representative of the whole core. The detectors may be placed outside the pressure vessel and normally will be located in a much less severe environment than that of in-core detectors. Size restrictions are also less of a factor in their design.

The neutron detectors used in a typical thermal nuclear reactor must satisfy the following requirements:

- fast response,
- monitoring over a wide range from low to high power,
- monitor the rate of increase of neutron power at all power levels,
- accurate power measurements at high power,
- control of spatial power distribution on medium & high power levels,
- SDS instruments must be able to limit peak local power (channel or bundle powers and high rate with power increase),
- RRS signals must represent average power in the regulated region.

In choosing specific detector types, consideration must be given to the expected neutron signal level compared with noise sources, the speed of response of the detector, and the ability to discriminate against gamma-induced signals. Each of these criteria assumes different importance over various ranges of reactor power, and as a result multiple detector systems are usually provided, each designed to cover a specific subset of the power range.

Protection and regulation for a nuclear reactor require the capability of fast response over the complete range of neutron flux. Figure 7.5 gives a typical value of the flux for power level 10^{-14} fraction full power and 150 % full power. Figure 7.5 illustrates the three sets of sensors with overlapping operating range to cover the entire range of the reactor as no single instrument gives adequate coverage for all flux conditions encountered.

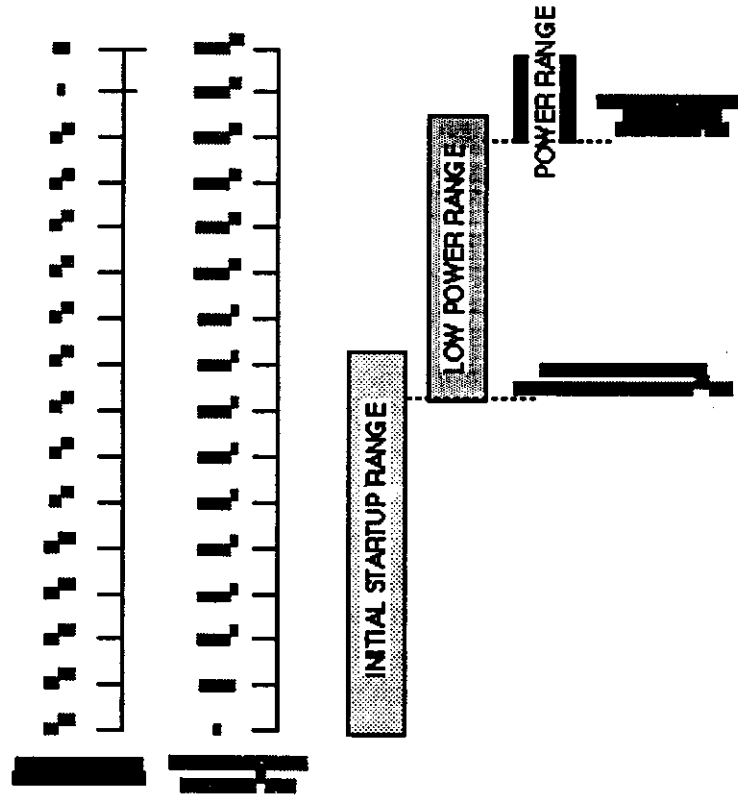


Figure 7.5: Range sensitivity of nuclear instrumentation for reactor power measurement and control

7.6.1 Startups And Low Power Neutron Detectors

Neutron sensors used for startups and low power operations are gas-filled. Their advantages in this application include:

- inherent gamma-ray discrimination properties (sensitive only to neutrons),
- give immediate response to flux change,
- sensitive over wide range (at high power log rate signal used for SDS),
- can be accessed on power (installed out of core),
- easy testing of device.

The lowest range, usually called the initial startup range, is encountered during the initial startup of the reactor power. At startup, there is not enough neutron flux and the neutron interaction rate is very low. Good discrimination against gamma rays is essential in this range, and it can be accomplished by using either fission chambers or BF₃ proportional counters.

As the power level increases to the low power range, the neutron flux is usually so large that gamma-ray-induced currents in ion chambers are no longer significant, and simple uncompensated ion chambers are commonly used as the principal neutron sensor. Because these instruments are often part of the reactor safety system, there is a premium placed on simplicity which also favours the use of uncompensated ion chambers. Figure 7.6 shows a simplified illustration of an ion chamber neutron detector system that is commonly used in reactor control.

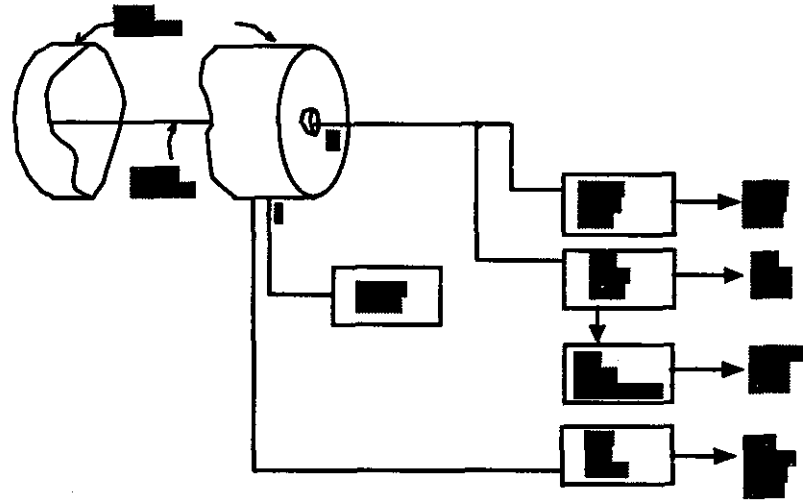


Figure 7.6: Ion chamber neutron detector system

The presence of high voltage on the HV electrode of the chamber is detected by the tell-tale alarm circuit. This tell-tale connection detects the loss of the applied high voltage.

The linear amplifier produces a voltage output that is proportional to the ion chamber current. This output is then used as input to the reactor regulation system.

The log amplifier is capable of producing output voltage proportional to the logarithm of the ion chamber current. The voltage signal produced by the log amplifier is used for reactor control at lower power levels. As the power level increases the thermal neutron flux signal is supplied by the linear amplifier.

The differentiator produces a log rate signal (which is a time derivative of the log signal), that it supplies for the safety system to monitor how fast the log signal is changing. The log rate signal remains accurate and continues to be used right up to, and beyond, full power.

After a shutdown, reactor restart monitoring is done by the ion chambers. Initial startup instruments are required only during initial startup or after a shutdown during which the ion chamber system has gone off-scale.

7.6.2 Reactor Control At The High Power Range

At the higher end of the power range the ion chambers are not sufficient for power control. Although the ion chamber and the linear amplifier are accurate to 150% full power, the leakage flux they monitor is not a good representation of the flux in the reactor core for the simple reason that these detectors are normally installed outside the reactor. The leakage flux will be strongly affected by moderator poison, fueling in adjacent channels, flux tilts, movements of nearby reactivity devices, etc., and it will be relatively insensitive to power changes in the central core or the far side of the reactor.

In these high power ranges specially designed self-powered platinum detectors are used because of their much faster response than vanadium detectors.

7.6.3 Transfer Of Reactor Control

During reactor restart, the RRS ion chamber monitors reactor power at low power and the rate of power increase at all power levels. At low power when ion chambers are used for reactor control, the requirement for accurate thermal power measurements can be dropped, but a good indication of the rate of change of fission power is needed. At high power, the in-core platinum detectors are used and these are calibrated to give thermal power level. However, thermal calibration of the ion chambers is required so that control passes smoothly from one set of regulating instruments to the other as power increases or decreases.

7.6.4 Neutron Flux Mapping

Flux mapping is the method of monitoring the three dimensional power distribution within the reactor so that the individual fuel bundles and fuel channels can be operated within their design limits.

Flux mapping uses a large number of in-core vanadium detectors located throughout the reactor. The response of these detectors, unlike those of the platinum ICDs, is all due to thermal neutron absorption in the emitter. This means the signal output is exactly proportional to the thermal neutron flux at the detector. Their accuracy, neutron sensitivity and very localized "point" flux readings make them ideal for providing information on in-core spatial variations of neutron flux (flux mapping). This information is necessary for fuel management and as a reference in calibrating the other detectors used for reactor control. Vanadium detector readings must be corrected by independent thermal power readings.

7.6.5 Platinum Detectors Calibration Requirement

The reactor regulating system's platinum ICDs monitor bulk power and zone average flux at high power. Accurate measurement must be provided to prevent overrating the fuel. However, platinum ICDs will respond to both neutron and gamma flux, and not directly to fuel thermal power. The actual ICD signal will not be an accurate indicator of fuel power for the following two reasons, and it therefore requires continuous thermal calibration.

- Platinum ICD signals, although very fast, do not reliably indicate average power in the zone because they only sample the flux in their region. They are therefore susceptible to localized flux changes such as refueling or reactivity mechanism movement.
- Platinum ICDs have delayed components, approximately 15% to 17% of the total signal lags power change by a time constant varying from a few seconds to hours. So the signal produced by the detector during a power change may not accurately represent the true fuel power.

Corrections to these measurements are made by using bulk thermal power measurements and/or using spatial information derived from the set of in-core vanadium detectors that are part of the flux mapping system.

Thermal measurements are capable of providing accurate indication of the actual power output from each channel. Thermal measurement is done by measuring the power output from some of the channels in the inner zone of the reactor where average power output can be obtained that is independent of the local flux variations. These thermal power measurements are used for calibrating the platinum ICDs and vanadium detectors. This calibration will ensure accurate measurement by the platinum detector for prompt power indications over the operating range.

Although thermal power measurement is accurate, it is not used for reactor power regulation for the following reasons:

- Slow response time because of the thermal lag of the fuel, coolant and temperature detectors. This lag is in the order of 20 seconds or more. Precise control of bulk power would be difficult with this lag in the control system.
- Thermal measurements can only measure the sum of the bundle power in the channel. Since the fuel channels pass through inner and outer zones of the reactor, thermal measurements cannot assess the individual contributions of the two zones to the total channel power. For zone control the power in each zone must be known and so thermal measurement alone are not suitable.

7.7 COMMON PROBLEMS OF NEUTRON DETECTORS

Faulty detector operation will be apparent from erratic, high or low signals. The operator may be able to determine this by comparing the signal with the other detectors installed in the same location. Comparison can also be made with fuel channel temperature profiles, channel power measurements, or signals from other in-core detectors of SDS1 and SDS2.

7.7.1 Ion Chamber Detector Failures

Proper operation of ion chamber systems is essential to avoid unnecessary shutdowns, especially at low power when the in-core flux detector system is not capable of providing accurate data and therefore is not used. To achieve high reliability of the ion chamber system, the following features are incorporated in their designs:

- the use of three independent channels,
- the use of two computers for one signal,
- computer intercomparison checks between channel signals, and irrationality checks by using the upper and lower signal margins,
- alarm system for loss of ion chamber polarizing voltage,
- use of guard shields to bypass leakage current,
- vibration resistant design and construction.

Even with these features, problems can occur:

- electrical breakdown of the ion chamber or cables,
- noisy output signals,
- failure of polarizing voltage,
- low or negative log signal.

Electrical breakdown will cause the high voltage supply to decrease or fluctuate. Ion chambers can also fail due to broken connections or the amplifiers could fail due to high humidity with condensation producing erratic signals.

A leak into the chamber volume will result in a reduction of the insulation resistance between the guard shield and reactor ground. This could result in high leakage current and contamination of the ion chamber's sensitive volume and upset its saturation.

Noisy output can also be caused by faulty (or incorrect) grounding, vibration of the ion chamber, pickup from a strong source of noise, or failure of the amplifiers.

An indication of loss of polarization voltage can be due to the following failures:

- power supply failure (broken fuses),
- faulty tell-tale circuit or incorrect setting,
- lost connection in the interconnecting cables,
- electrical breakdown of the ion chamber.

A lower or negative signal can be caused by either the reactor power being off scale (that is, less than 10% to 7%), or a failure in the system. The other two channels will determine whether the power is off scale. A failure can be caused by a faulty amplifier or a broken conductor in the ion chamber or interconnecting cable.

7.7.2 In-core Detector Failures

There are two failure modes of self-powered detectors: open or short-circuit faults, and deterioration of insulation resistance. The open or short-circuit fault appears as an absence of all or part of the signal, or the appearance of intermittent transients. The other fault is not easy to detect without making periodic measurements of the insulation resistance, unless erratic signals appear. The usual cause of insulation failure is either a failure of the sheath or the epoxy end seal, leading to the ingress of moisture into the hygroscopic MgO. Another possible cause of low insulation resistance is deterioration of MgO insulation due to radiation effects. This should not occur if MgO of the proper purity is used in fabrication of the detector.

Detectors used for flux mapping are designed to be tolerant of faults in individual detectors and associated amplifiers, cabling, etc. Failure of one or a few detectors is not normally expected to result in noticeable degradation of mapping accuracy. However in operating in off-normal states, (for example, adjusters withdrawn or mechanical control absorbers inserted), mapping errors due to failed detectors may become relatively large (several percent or more), depending on the location of the failed detectors. In particular, failure of detectors located close to a removed reactivity device will tend to result in larger than normal errors in detecting the associated reactivity device modes. This may cause comparatively large "local effects" errors in mapping bundle fluxes and channel powers located near the reactivity device in question.

If a significant number of signal are "failed" (about 5% or more depending on detector location), convergence of the correction loop, and mapping accuracy in general, will begin to show considerable degradation. Under this circumstances it become increasingly important to correct the fault condition or, if the fault is in the detector themselves, to replace the defective detectors.

Assignment

1. Identify two applications wherein boron is used in ion chambers for neutron flux detection.
 - i) _____
 - ii) _____
2. In low neutron flux where gamma rays are present, BF_3 can effectively measure neutron flux by eliminating (*gamma pulse/electrons*) through the use of an electronic discrimination circuit.
3. Neutron induced pulses have (*lesser/greater*) amplitude than gamma induced pulses.
4. At higher power levels, neutron flux is usually so large that gamma pulses have no effect in the signal produced. (*true/false*)
5. Identify two common failures of in-core detectors.
 - i) _____
 - ii) _____
6. Vanadium detector sensitivity is not affected by the reactor flux changes. (*true/false*)
7. A vanadium detector is 100% sensitive to neutron flux. (*true/false*)
8. Give examples of two applications of vanadium detectors.
 - i) _____
 - ii) _____

- 9. A platinum detector (*is, is not*) suitable for low power neutron flux measurements because incident gamma can cause (*accurate/false*) neutron flux signal.
- 10. At higher power levels, ion chambers (*are/are not*) sufficient for reactor control.
- 11. Ion chambers can give an accurate representation of the neutron flux in the reactor core at high power levels. (*true/false*)
- 12. Three factors that can affect the ion chamber neutron flux measurement at high power are:
 - i) _____
 - ii) _____
 - iii) _____
- 13. Platinum detectors have a (*faster/slower*) response than vanadium detectors.
- 14. Self-powered detectors based on beta decay have a much (*faster/slower*) response than detectors based on secondary electrons.
- 15. Give two reasons why thermal power calibration of platinum detectors is required when they are used as neutron detectors during high power operation.

16. Identify the method used to detect ion chamber detector failures while in operation.

17. Give the special feature used by ion chambers to detect failure of high voltage supply.

18. List four ion chamber problems that can be encountered during operation:

- i) _____
- ii) _____
- iii) _____
- iv) _____