LESSON 6: NUCLEAR INSTRUMENTATION

MODULE 1: LOG AND LINEAR RANGES

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. **Explain why it is not practicable to control a reactor based on** *thermal power* **measurements**
2. **State the approximate range of** *neutron flux* **to full power operation from initial fuel load**
3. **Explain, with the aid of a sketch, why a** *linear range* **measurement is not adequate for low reactor power monitoring**
4. **Explain, with the aid of a sketch, why a** ***log range*** **measurement is not sufficiently sensitive for high reactor power monitoring**
5. **Sketch a reactor neutronic flux scale to show** *seven decades of flux* **from first fuel load to full power**
6. **Overlay a** *log amplifier* **output on the seven decade flux scale (use 2.0 volts per decade)**
7. **Overlay a** *linear scale* **output on the seven decade flux scale (use 2.0 volts per 10% flux)**
8. **Show the** *log to linear transition* **region on the seven decade flux scale.**

Introduction Nuclear Instrumentation Log & Linear Range

- **Any reactor generates** *thermal power* **from the heat produced by nuclear fission.**
- **Measurements of the actual** *thermal power* **output respond too slowly to** *neutronic power* **level changes for the purpose of controlling the reactor (there is a *time lag of about 25 sec* between a neutron flux change and its associated detection by the thermal measurement means).**
- **To control the reactor flux adequately, it is necessary to have *fast responding instrumentation* (one neutron lifetime is approxximately 0.1 seconds)**
- **The method of *measuring reactor power* by observing the *radiation directly associated with the fission* process is used.**
- **Each time a fission occurs, radiation (neutron, beta, gamma or alpha) is produced. The magnitude of this radiation is *directly proportional to the number of fissions*, which is in turn *directly determines the resultant reactor power level.***
- **The most appropriate radiation to select for monitoring is *neutron* flux. By measuring the neutron flux, we can *accurately estimate the corresponding thermal power* output of the reactor.**
- **In addition, monitoring neutron flux acts as a safeguard means against the possibility of losing control of the reactor.**
- **If the neutron flux exceeds a predetermined** *power limit* **or** *rate of power change*, **shutdown systems can be triggered by the independently sensed protection system neutron signals.**

Linear Measurement Range

- **The monitoring and control of a reactor is necessary over a *wide range of neutron flux* levels. Flux in the operating range can be considered as varying from 10^7 to 10^{14}N/(cm^2.s) - over *7 decades of flux.***
- **For all practical purposes we can assume that 10^7 N/(cm^2.s) is *zero thermal power*. In fact *significant* thermal power contribution does not occur until the flux rises to ~10^{12} (1% FP). A linear scale of power could be produced with an amplifier developing (arbitrarily) 2 volts/10% power change.**
- **Notice that if 100% FP corresponds to 10^{14} N/(cm^2.s) then 10% FP correspond to 10^{13} N/cm^2.s).**
- **A power change from 10% to 100% FP is a change by a factor of 10 or a** 1 decade **change.**
- **Similarly, a change in neutron flux from 10^{13} to 10^{14} is a 1 decade change.**

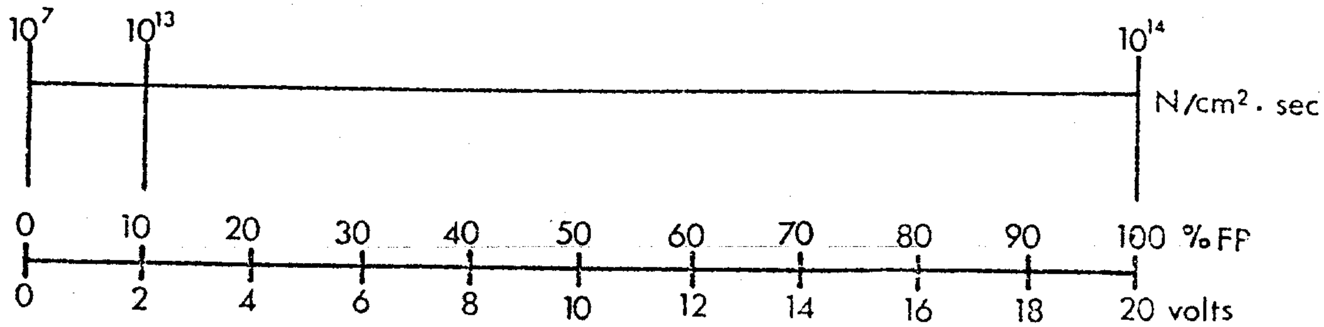

Figure 1: Flux vs. % Thermal Power - Linear Scale.

- **A power level change from 10% to 100% will result in an amplifier signal change from 2 to 20 volts. This change of 18 volts for a 1 decade power change will provide sufficient** sensitivity **for control sensing.**
- **For a power level change from effectively 0% to 10% FP the amplifier signal changes only 2 volts while the flux has changed 6 decades. (10^7 to 10^{13} N/cm^2.s); i.e. the sensitivity by a linear amplifier in this region is very low. Consequently, close control of the flux in this region would not be possible (<10% FP) as large N flux changes are required to develop a significant signal.**

Log Measurement Range

- **If a log amplifier was used, 2 volts/decade (illustrative value) could be developed so that as the flux level changes one decade, a recognizable signal change of 2 volts will occur:**

$$\textbf{Voltage signal} = 2 \log_{10} (\%FP)$$

% FP	Voltage Signal
100	4
10	2
1	0
0.1	-2
0.01	-4
0.001	-6

Table 1: Log Voltage Signals Relative to % Thermal Power.

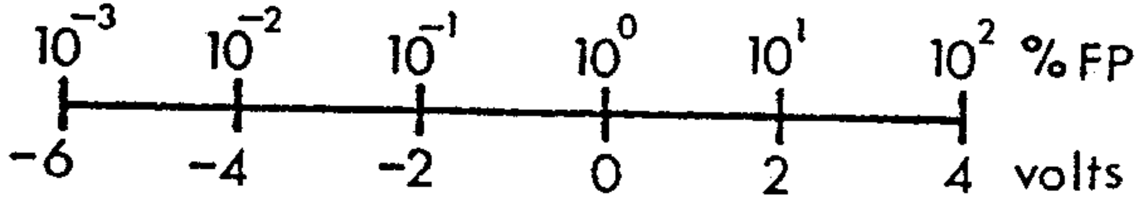

Figure 2: Log Voltage Scale Relative to % Thermal Power.

Now if the power level only changes from 10^{-3} to 10^{-2} %FP, the log amplifier voltage will change from -6 to -4 volts, a much more readable voltage signal amount.

Log Measurement Range

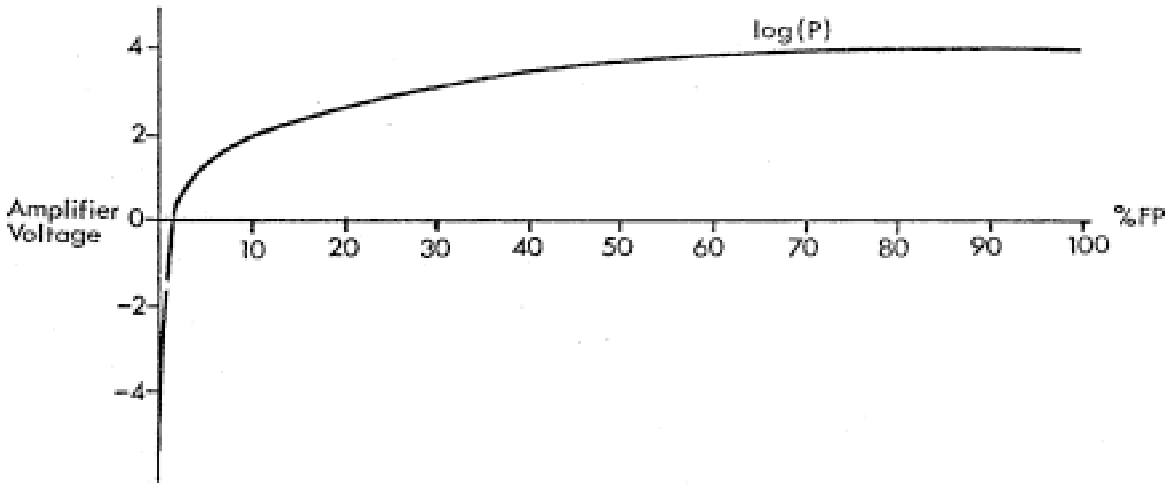

Figure 3: Graph of Log Amplifier Signal Relative to % Thermal Power.

- **Notice now that if the operation is below 10% FP that a useable signal change is developed.**
- **As the power rises above 10% FP, the amplifier response-curve will *flatten out*. The signal can be considered as bunching up towards the top end of the scale.**
- **Significant changes in %FP at the top of the scale will result in only small changes in signal from the log amplifier.**
- **A linear amplifier should be utilized over the last decade to allow closer control of power fluctuations. With a *linear amplifier*, as the power varies from *10 - 100%, the signal will change linearly* with respect to the neutron flux and power changes allowing closer control decisions to be made.**

Log/Linear Measurement Ranges

- **<u>Log control</u>: used over the <u>*lower 6 decades*</u> as the thermal power is raised to about 10% FP**
- **<u>Log Range</u>: 10^7 to 10^{13} N/cm^2/sec**
- **<u>Linear control:</u> used over the <u>*last decade*</u> where useful power production occurs.**
- **<u>Linear Range</u>: 10^{13} to 10^{14} N/cm^2/sec**
- **<u>Transition Region</u>: 0.5 x 10^{13} to 1.5 x 10^{13} N/cm^2/sec**
  [5% to 15 %FP - Log to Linear range transition region]

Module #1 - Log/Linear Measurements Module ASSIGNMENT

1. **Explain why it is not practicable to control a reactor based on** *thermal power* **measurements**
2. **State the approximate range of** *neutron flux* **to full power operation from initial fuel load**
3. **Explain, with the aid of a sketch, why a** *linear range* **measurement is not adequate for low reactor power monitoring**
4. **Explain, with the aid of a sketch, why a** *log range* **measurement is not sufficiently sensitive for high reactor power monitoring**
5. **Sketch a reactor neutronic flux scale to show seven decades of flux from first fuel load to full power**
6. **Overlay a** *log amplifier* **output on the seven decade flux scale (use 2.0 volts per decade)**
7. **Overlay a** *linear scale* **output on the seven decade flux scale (use 2.0 volts per 10% flux)**
8. **Show the** *log to linear transition region* **on the seven decade flux scale.**

LESSON 6: NUCLEAR INSTRUMENTATION

MODULE 2: LOG RANGE DETECTORS

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. **Sketch and label a typical** *ion chamber* **assembly**
2. **Briefly describe the principle of operation for an ion chamber**
3. **State the internal ion chamber** *ionizing reaction* **equation involving the Boron lining**
4. **Sketch and label a typical ion chamber housing installation to show the housing location with respect to the reactor core.**
5. **Sketch a typical ion chamber housing to show the two ion chambers (RRS & SDS) and the boron test shutter.**
6. **State the approximate ion chamber signal current range over seven decades of flux.**
7. **State why it is important to monitor the ion chamber polarizing voltage closely and to alarm on any significant deviation**
8. **Explain why it is important, from an operations perspective, to operate only one** *boron test shutter* **at a time.**

<u>Ion Chambers</u> [Log Range Sensors]

- **Basically, an ion chamber consists of an insulated electrode sealed within a gas tight housing.**
- **An Ionizing gas which is chemically stable under irradiation is used to fill the chamber.**
- **Hydrogen is one such filling gas.**

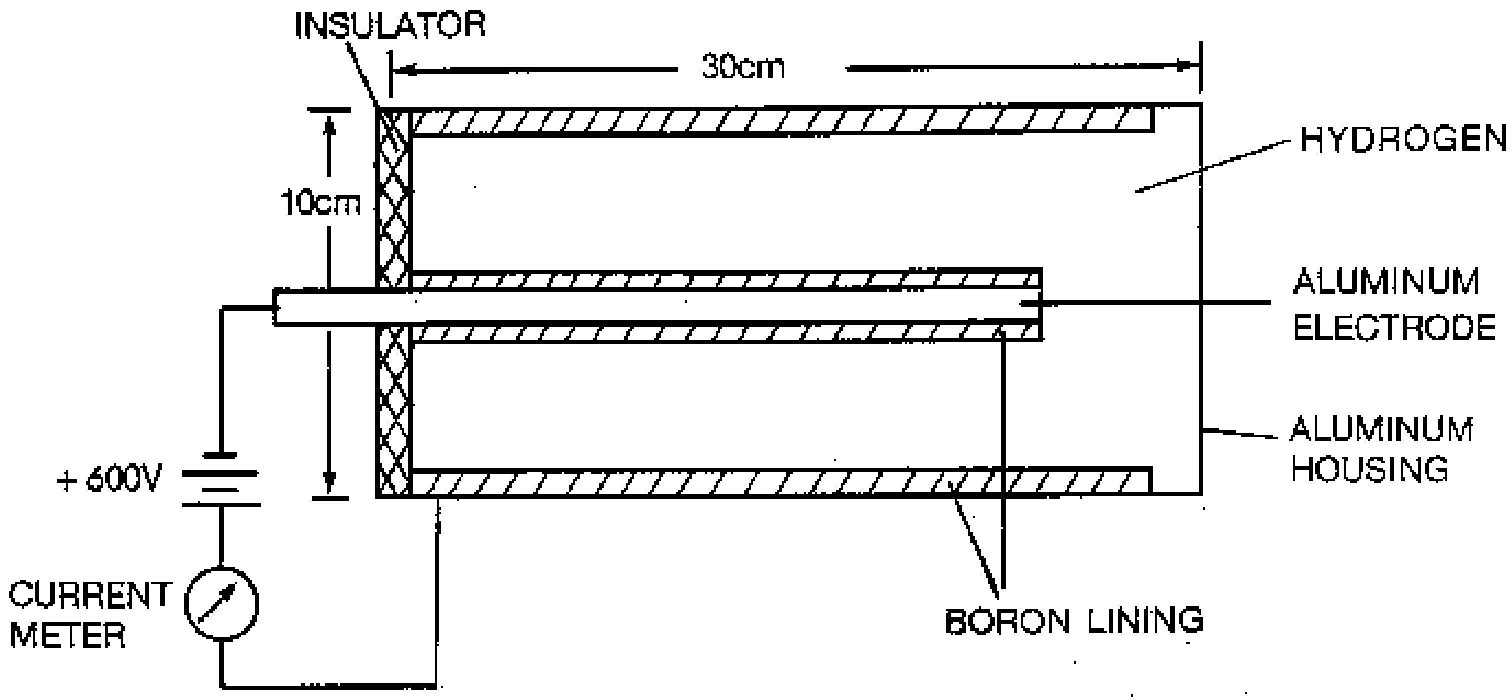

Figure 1: A Simplified Ion Chamber.

Ion Chambers

- **Since neutrons are uncharged, a coating of a sensitive material which will emit charged particles under neutron bombardment must be used to line the chamber.**
- **Boron-10 was chosen because its high cross-section for thermal neutrons gives high sensitivity.**
- **This is important since ion chambers are mounted** *outside the reactor core* **where the number of neutrons is reduced.**

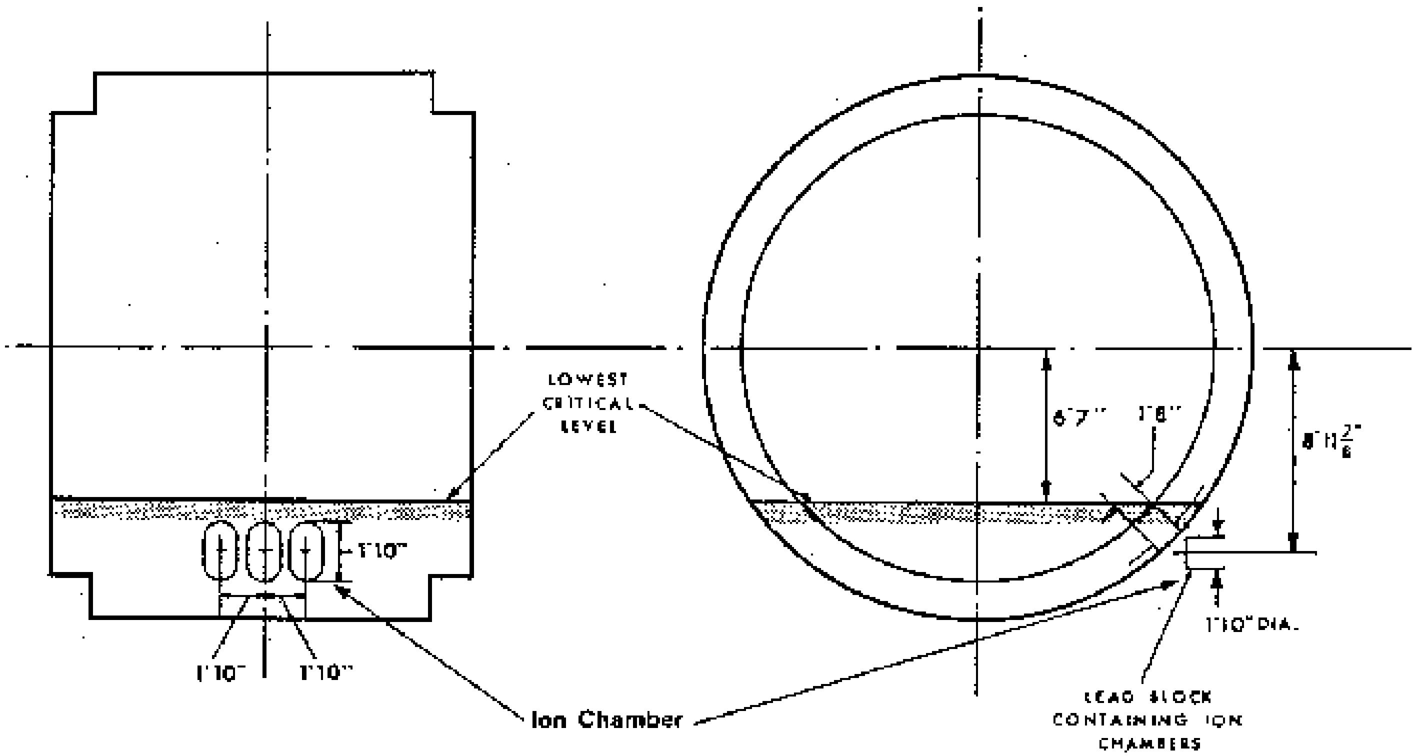

Figure 2: Ion Chambers Locations in a 500MWe CANDU reactor.

Ion Chamber Construction

- **Ion chambers are modified versions of a** *gas ionization detector*
- **The electrodes are closely spaced as parallel cylinders.**
- **The electrodes are coated with** *B-10* **to provide neutron sensitivity**
- **Boron absorbs a neutron and releases an ionizing** *alpha* **particle**
- **A polarizing voltage supply (600 Volts) is applied across the electrodes.**
- **The relatively *large surface area* for the electrodes, *small plate separation* distance, and *high measured flux levels* combine to produce a DC micro-amp signal as a function of the flux level.**

Principle of Operation

- **The metal used for the construction of the housing and electrode is usually *pure aluminum* because of its low residual activity as a result of neutron bombardment.**
- **A high polarizing voltage (typically +600 V) is applied to the aluminum housing, while the center electrode is normally kept at ground potential (see Figure 1).**
- **When the boron lining is bombarded by neutrons, alpha (α) particles are emitted:**

$$_5B^{10} + _0n^1 \rightarrow _3Li^7 + _2He^4 \ (\alpha).$$

- **Both Li^7 and alpha particles are positively charged. They *ionize the hydrogen gas fill* atoms and thereby produce free electrons and positive ions.**
- **As the free electrons are formed, they are *attracted to the housing due to the positive polarizing voltage*.**
- **This *creates a current flow pulse* which is detected by an external circuit.**
- **One of the problems with the ion chamber is that the detector does not discriminate against types of ionizing radiation and is affected by other incident ionizing radiation, especially gamma. (The external alpha and most beta radiation cannot penetrate the housing.)**
- **Since Gamma rays can also produce subsequent ionization, it is important to ensure both at power and after shutdown, when fission product gamma radiation is predominant, that gamma radiation does not give a false (high) indication of reactor power.**

Regulating and Shutdown System Ion Chambers

- **Ion chambers are used for the Reactor Regulating System (RRS) and Shut Down Systems (SDS) because of their measurement range and fast response time.**

- **In a typical CANDU ion chamber installation, a total of 6 ion chambers are provided - 3 for RRS (Channels A, B & C) and 3 for SDS (Channels D, E & F).**

- **At low reactor power level, say below 15% full power, control of *bulk reactor power* is important. Ion chambers, because of their fast response time, and high sensitivity are used for low power neutron flux detection.**

- **The ion chamber are located outside of the fuelled region of the reactor (hence their reading is often referred to as "*out of core*") and will generate a signal in the range from 10^{-5} to 100 μA over seven decades of flux.**

- **Loss of polarizing voltage at the ion chamber causes the instrumentation to read *zero reactor power* regardless of the actual power (*an unsafe failure condition*).**

- **The voltage monitor is set to alarm if the measured voltage at the ion chamber drops 5% below the operating voltage (i.e. below 570 Volts for a 600 volt supply).**

ION CHAMBER HOUSING and SHUTTER

- **The Ion Chamber Housing has three chambers - 2 for Ion Chambers and 1 for a** *test shutter*.
- **There are two ion chambers in each ion chamber housing; one for the RRS and one for the SDS1.**
- **The regulating channels must be *completely independent* of each other and of the shutdown system channels.**
- **There is also a pneumatically operated boron test shutter located in each housing to introduce a change in flux to the pair of ion chambers in that housing.**
- **The shutter is withdrawn at a set speed to simulate a rate of change of flux to test the trip system from the ion chamber right through to the final trip relay.**
- **The testing of the shutdown system by operating the shutter will also affect the regulating system since the flux variations will be sensed by both ion chambers in that housing.**
- **The test circuits are interlocked to allow the operation of *only one shutter* at a time.**
- **Similarly, maintenance would be carried out on one channel at time, and at full power when practical so that any changes and effects can be fully tested before returning the loop to service.**

Module #2 - Ion Chamber Module Assignment

1. Sketch and label a typical ion chamber assembly.

2 . Briefly describe the principle of operation for an ion chamber.

3 . State the internal ion chamber ionizing reaction equation involving the Boron lining.

4 . Sketch and label a typical ion chamber housing installation to show the housing location with respect to the reactor core.

5 . Sketch a typical ion chamber housing to show the two ion chambers (RRS & SDS) and the boron test shutter locations.

6 . State the approximate ion chamber signal current range over seven decades of flux.

7. State why it is important to monitor the ion chamber *polarizing voltage* **closely and to alarm on any significant deviation.**

8. Explain why it is important, from a continued operations perspective, to operate only one boron test shutter at a time.

LESSON 6: NUCLEAR INSTRUMENTATION

MODULE 3: LINEAR RANGE DETECTORS

MODULE OBJECTIVES:

At the end of this module, you will be able to:

1. **State three reasons why ion chambers are not used as in-core detectors.**
2. **Sketch and label a typical** *In-Core Flux Detector* **(ICFD) construction.**
3. **Describe the principle of operation for an ICFD.**
4. **State the approximate ICFD signal value at 100 %FP.**
5. **Provide a 3-D sketch of the core to show the approximate locations for the 28 RRS ICFDs.**
6. **Explain why it is necessary to correct the signals read from an ICFD.**
7. **Sketch and explain the general method of determining and applying** *thermal power corrections* **for ICFD signals.**

Introduction

- **Although ion chambers are very accurate neutron detectors, their relatively *large size*, requirement for *polarizing voltage* and *delicate construction* make them impractical to be used to detect flux distribution *inside* the reactor.**
- **For this purpose, simple and relatively inexpensive in-core flux detectors (ICFD) have been developed.**

Linear Range Detectors

- **In-core flux detectors (ICFD) are self-powered devices which produce a *micro-amp current* signal proportional to the fission rate within the reactor.**
- **This detector is selected for use over the *last decade* of flux to provide a linear measurement signal from approximately 5% to 100% FP.**

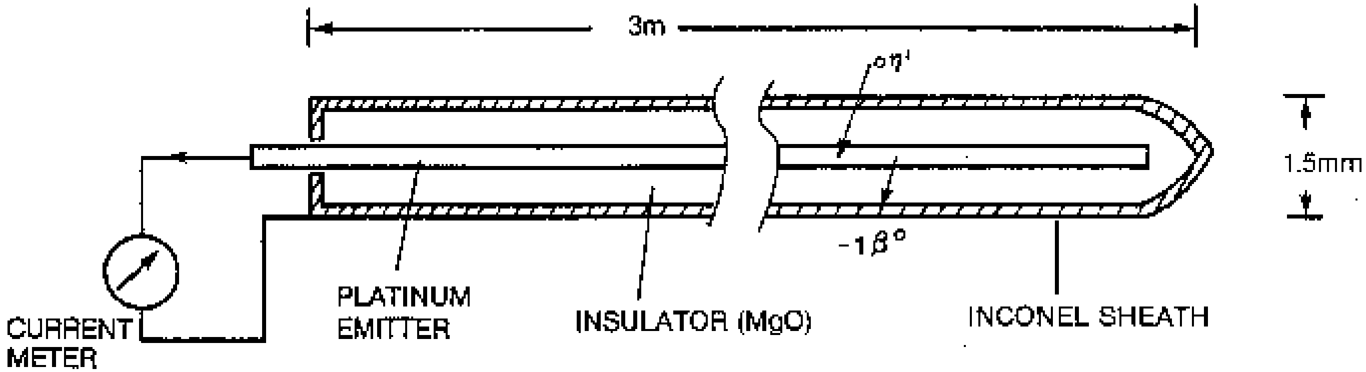

Figure 1: Simplified In-Core Flux Detector Construction.

The in-core or Hilborn detector (inventor), consists of :

- **an Inconel *outer sheath***
- **an inner *emitter* wire,**

(Various materials can be used for the emitter wire, the most common being *vanadium* and *platinum*)

- **separated by a layer of *insulation* (usually magnesium oxide, MgO).**

Operation of an In-core Flux Detector

- **When a thermal neutron is absorbed by the emitter, *an energetic electron is released* which has enough energy to exceed the dielectric strength of the insulator.**
- **The electron migrates to the collector producing a *net positive charge* on the emitter.**
- **The potential difference which exists between the emitter and collector will cause a *micro-amp current* flow through a connected external circuit.**
- **A current of approximately *one micro-amp* will flow at 100% FP**
- **It should be noted that some types of ICFD's are *gamma sensitive* which will affect readings considerably at low power levels where fission gammas are predominant.**
- **Problems with the ICFD are related to a gradual degradation of the insulating layer effectiveness which eventually will require the replacement of the faulty ICFD.**

Location in the Core

- **In a 500 MWe CANDU reactor the Hilborn detectors are wound on a zircalloy guide tube over a vertical distance of 55 cm and are located *two per zone* to provide a total of 28 ICFD's for the RRS.**

- **The incore detectors generate a low-level current signal that must be amplified and converted into a voltage. This voltage is then fed into the control computer multiplexers as flux measurement inputs for the RRS.**

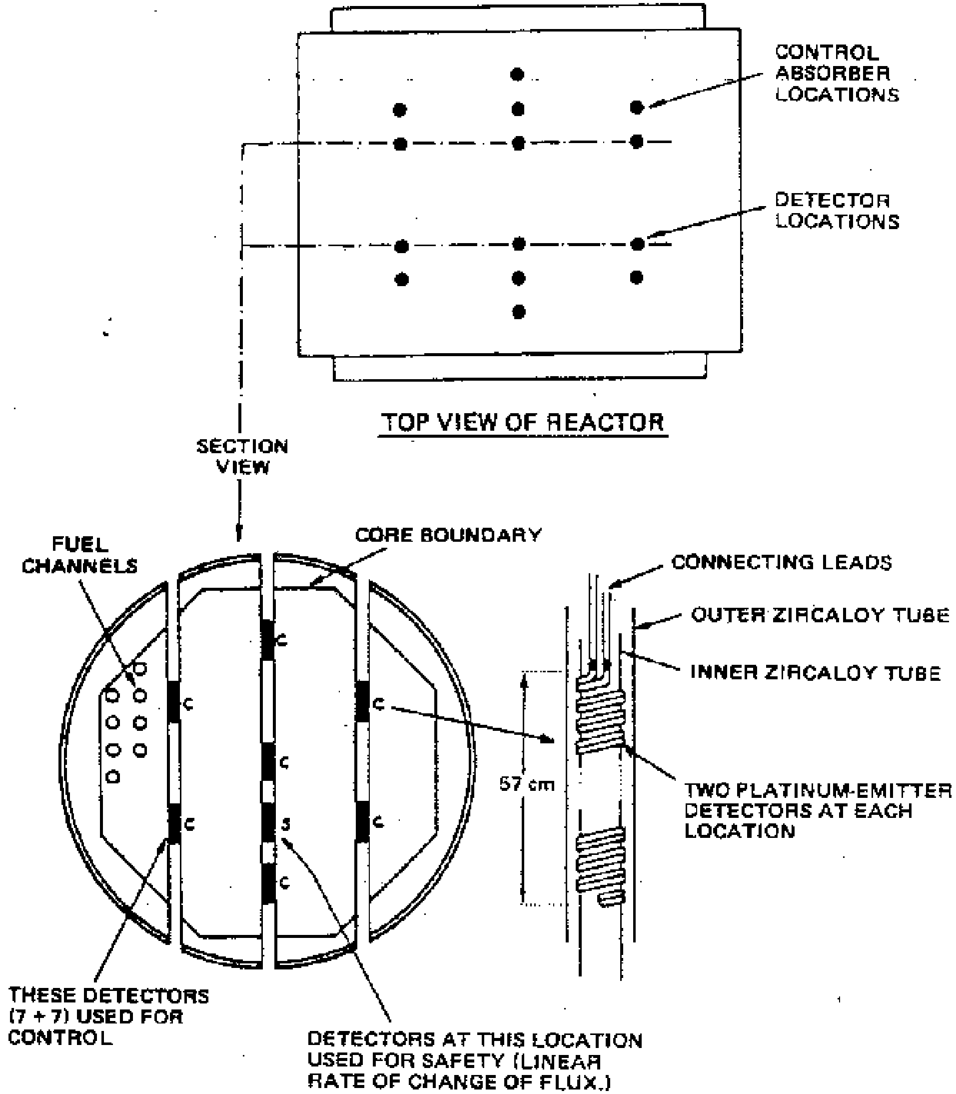

Figure 2:
In-Core Flux Detectors (500MW CANDU).

Detector Calibration

- **It is not possible to use a thermal power measurement as a means of reactor control due to the lags (≈25 seconds) existing between changes in neutron flux levels and the sensing of the associated temperature change at the reactor outlet headers.**

- **Temperature control is *inherently slow* and cannot be used as a practical method of reactor control.**

- **At low power, the decay heat from fission products effectively *masks small changes* in heat output due to changes in neutron flux - operation would be effectively blind for power changes up to about 2% FP (i.e about 6 decades of neutronic change).**

- **Measurements of neutron flux are prompt (approximately 90%) and wide ranging (7 decades) but it is important to establish the correct *steady-state relationship* between neutron flux levels and thermal output.**

- **For in-core flux detectors, this steady state correlation is achieved by taking measurements of reactor thermal power output and *correcting* the steady state neutronic signals.**

Reactor Thermal Power Measurement

- **In the 500 MWe CANDU, 22 fuel channels are fully instrumented with flow (venturis) and temperature (RTDs) sensing instrumentation.**

- **The power produced in these channels (*proportional to core flow and ΔT*) when calculated can be averaged and then can be multiplied by the total number of fuel channels to provide a *relatively accurate figure for total reactor thermal power*.**

- **ICFD's also require calibration because they suffer burn-up under irradiation, although, with the use of platinum emitter detectors, this is a relatively minor factor being limited to approximately 1% per year. In addition ICFD's are only 80 - 88% prompt when responding to a change in flux level.**

- **At stations where partial boiling is permitted in some channels the channel power is not directly proportional to mass flow and to ΔT. For these channels we need to know the proportion of steam (ie *steam quality*). This is determined by using venturis on both ends of the fuel channel to measure inlet and outlet volume flows.**

- **Reactor thermal power can also be determined by monitoring secondary side parameters such as the feedwater flow and feedwater entry temperature to the boilers along with the resultant steam flow and steam pressure. The energy needed to warm this feedwater and then convert it to steam at the saturated conditions is an accurate indicator of reactor thermal power.**

REACTOR THERMAL POWER CALCULATIONS

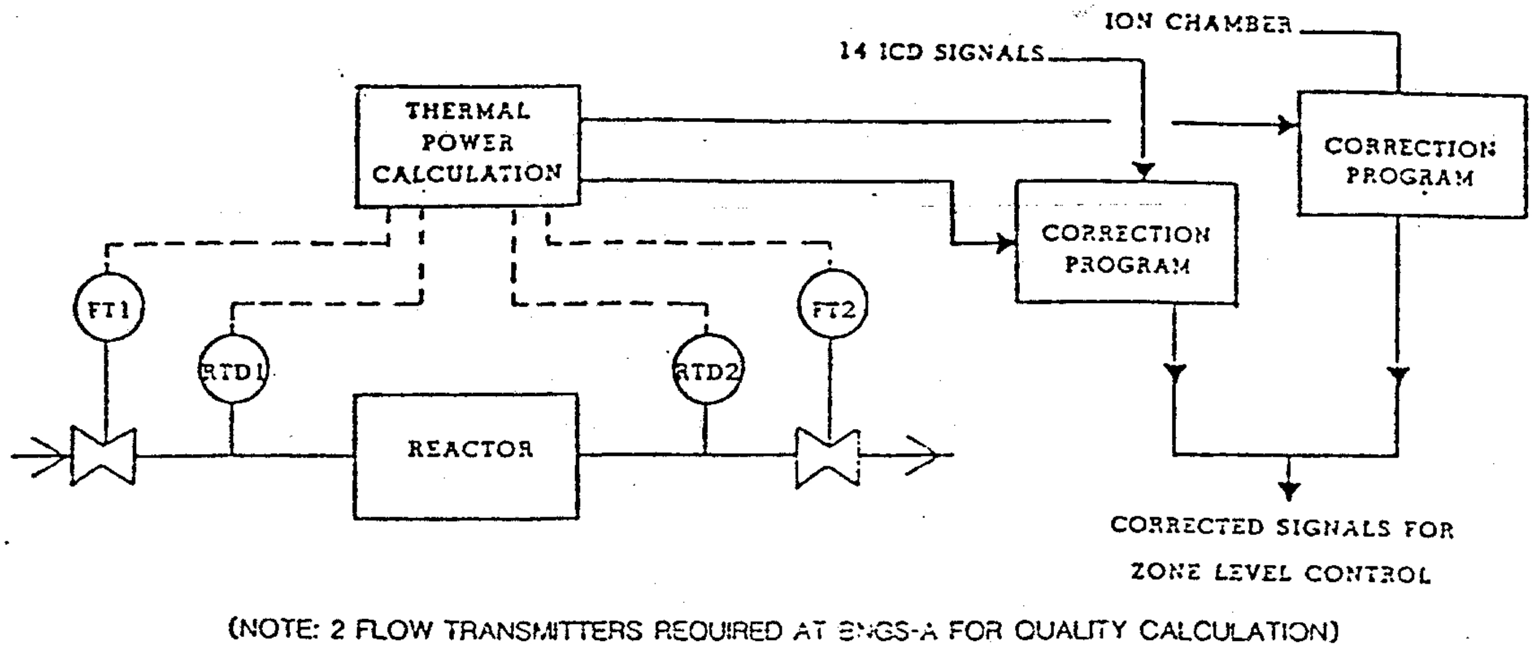

Figure 3. Reactor Thermal Power Correction Routine (ZOTPR)

Module#3 - In-Core Flux Detectors Module Assignment

1. **State three reasons why ion chambers are not used as in-core detectors.**
2. **Sketch and label a typical In-Core Flux Detector (ICFD) construction.**
3. **Describe the principle of operation for an ICFD.**
4. **State the approximate ICFD signal value at 100 %FP.**
5. **Provide a 3-D sketch of the core to show the approximate locations for the 28 RRS ICFDs.**
6. **Explain why it is necessary to correct the signals read from an ICFD.**
7. **Sketch and explain the general method of determining and applying thermal power corrections for ICFD signals.**