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# Neutron Flux Monitoring System in Prototype Fast Breeder Reactor

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***Abstract*— Prototype Fast Breeder Reactor (PFBR) is a 500 MWe pool type Sodium cooled reactor. In this, the neutron flux monitoring system (NFMS) measures the reactor power and the reactivity changes in the core. The neutron detectors sense the neutron flux at suitable locations representing the core flux and the signal conditioning electronics processes the signal to get logarithmic power, linear power, period and reactivity parameters. These parameters aid in control of reactor power and initiate safety action on crossing threshold.**

*Index Terms*—**Flux, neutron, detector, safety**

## I. INTRODUCTION

Energy is a vital component for development of economy and providing high quality of life to the citizens. In view of growing concerns on availability of resources, climate change and energy security, nuclear is a preferred option for providing sustainable energy. Among many nuclear energy systems, Fast Reactors (FRs) are the most efficient energy system for the effective utilization of uranium resources. FRs are the scientific choice for burning high level radioactive wastes containing long lived minor actinides and fission products. FRs with closed fuel cycle give us clear possibilities for the minimization of mining efforts in the fuel cycle and waste management burdens (about 200 times less storage space and less than 700 y time span for the activity to become close to the background value). These factors, on the long horizon, favour the acceptability and usefulness of nuclear energy in terms of providing sustainable energy security and clean environment, worldwide. Particularly, in India, the economically exploitable uranium reserves are limited and thus the sustainable development of nuclear fission energy depends on the fast breeder reactors with closed fuel cycle. The assessment by worldwide experts concludes that the sodium cooled fast reactors (SFR) have high potential for providing affordable energy in 10 to 20 years in the countries mastering this technology. The conclusion has been derived after rigorous discussions involving comprehensively all the issues such as economy, safety, environment, etc. In the domain of safety, the concerns expressed on safety particularly referring to the risk of an uncontrolled power excursion in case of large size fast reactor systems and positive sodium void effects in case of SFR are addressed by bringing out clearly underlying facts and experiences. This has been the basis for deploying the SFR in India towards meeting high energy demands, i.e. four folds in 10 years and ten folds in 40 years. In order to demonstrate the techno-economic viability of SFRs for the commercial exploitation, a 500 MWe Prototype Fast Breeder Reactor (PFBR) has been designed and developed. PFBR is under c onstruction at Kalpakkam. The design of future SFRs will be generally in line with the design of PFBR and changes will be made to simplify the design or to reduce cost. The primary sodium circuit consisting of two sodium pumps and four intermediate heat exchangers (IHX) housed inside the main vessel. The free surface of sodium in the main vessel is provided with argon as cover gas. A safety vessel is provided surrounding the main vessel. A replaceable control plug above the core supports the absorber rod mechanisms, neutron detectors, failed fuel location modules and thermocouples for core outlet temperature measurement. The reactor is provided with two shutdown systems having diverse design features.

## II. PFBR SAFETY AND CONTROL

Neutron Flux Monitoring System (NFMS) plays an important role in the safety of PFBR. The reactor safety and control is carried out using parameters that measure the neutron population or the no. of fissions, coolant temperatures and the flow rate. Signals such as absolute power, rate of change of power (period), change in multiplication factor (reactivity) are generated from the neutron population. These parameters aid in quicker & accurate safety and control actions in the reactor.

## III. NEUTRON FLUX MONITORING SYSTEM

The neutron flux monitoring system (NFMS) measures the neutron flux representing the core flux and processes the signal to get logarithmic power, linear power, period and reactivity covering the measurement range of 10 decades. The functions of the system are:

- To monitor the core status in all states of the reactor – shutdown, fuel handling, start-up, intermediate and power ranges and during design basis events, such as transient over power and short period to ensure that DSL's are not crossed.

## IV. TYPE AND LOCATION OF NEUTRON DETECTORS

The total neutron flux at core centre varies from 1x$10^7$ nv

($n/cm^2/s$) at shutdown to $8x10^{15}$ nv at nominal power. The neutron flux around the reactor is very low as neutron shields are provided to protect the components housed inside the main vessel and to reduce the secondary sodium activity. It is also a regulatory requirement to have Shut Down Count Rate (SDCR) of minimum of 3 cps to take up any operation in the reactor. A SDCR of > 3 cps is required to have a reasonably quick reactor start-up with good accuracy and less counting times. With a SDCR of 3 cps, the reactor start-up time is ~ 5.5 hours. Based on this criterion, various options are studied to finalize the detector location, such as inside the core, in the control plug, below the safety vessel and also considering the experience from other reactors. Fig.1 gives the location of neutron detectors in PFBR. Table 1 gives the flux, reactor state and temperatures in PFBR.**Details of NFMS in other reactors is given in Annexure.**

## V. EVOLUTION OF DESIGN

Originally it was proposed that it would be possible for monitoring the core in all states of the reactor, only with high temperature fission chamber of 1 cps/nv sensitivity in control plug. These detectors need to be developed in-house required > 90% enriched $U^{235}$. As there is uncertainty on availability of > 90% $U^{235}$, provisions are made in the design to meet the eventuality with LEU. With this, the sensitivity of the detectors came down to 0.2 cps/nv and these detectors are not useful for flux monitoring during power range due to the following reasons:

(i) High gamma current and leakage current.
(ii) Low neutron current due to reduced sensitivity of detector (due to 20% $U^{235}$ instead of > 90%).
(iii) Campbell method is not permitted to be used by the guides, as the only means of monitoring power in the last two decades of operation.

## VI. FLUX MONITORING DURING INITIAL FUEL LOADING & FIRST APPROACH TO CRITICALITY

Fig.1 gives the various locations that could be used for neutron detectors in PFBR. In this reactor, the first approach to criticality is planned to be done with steps of fuel loading. After criticality also, full core will be reached in steps of fuel loading only. To monitor the core during this stage, three High Temperature Fission Chambers (HTFC) with a sensitivity of 0.1 cps/nv are placed one over the other at the centre of a special central subassembly (Fig. 2) called Instrumented Central Sub-Assembly (ICSA). These detectors in ICSA are expected to give a count rate of ~ 25 cps with first batch of 52 Fuel Sub-Assembly loading. These detectors are used for neutron flux monitoring during initial core loading and first approach to criticality and also for start-up till Auxiliary Neutron Source is effective. During fuel loading, control plug is rotated, for which the detectors in ICSA need to be lifted up in the central canal plug, resulting in the signal level of ICSA detectors, coming down. In order to effectively monitor the core during the initial fuel loading operation, i.e., when ICSA detectors are lifted up, HTFC in control plug locations are replaced by high sensitive Boron-10 coated proportional counters (BCC). These 6 no. of BCC, each with a sensitivity of 12 cps/nv, are divided into two groups, each group consisting of 3 detectors connected in parallel to get a sensitivity of 36 cps/nv (Fig. 3). After full core loading, control plug BCC will be replaced by HTFC at the shutdown state of the reactor.

## VII. PROVISION OF SB-BE AUXILIARY NEUTRON SOURCE SUBASSEMBLIES TO LIMIT THE USE OF ICSA

In order to increase the shutdown count rate, Sb-Be Auxiliary Neutron Source (ANS) subassemblies - 3 no. are loaded in the core. The problems of getting the source pins irradiated somewhere else, handling and assembling them are avoided by loading the source subassembly initially without any irradiation. After full power operation for > 60 days, these source Sub-Assemblies are able to give a SDCR > 3 cps by the detectors in control plug. The source strength also decays with a half-life of 60 days. After first criticality, when the reactor power is raised above 1 kWt, the detectors in ICSA get saturated, HV is cut off to these detectors and then detector assembly is lifted up in the central canal to the elevation of control plug detectors, to enhance their life, using Start-up Neutron Detector Handling Mechanism (SNDHM). By this time, HTFC in control plug come on scale with sufficient count rates (Fig. 4). In the subsequent fuel handling, ICSA will be shifted to storage position.

## VIII. NEUTRON FLUX MONITORING DURING NORMAL START-UP AND INTERMEDIATE POWER

After loading the full core, BCC in the control plug are replaced with regular high temperature fission chambers (HTFC) of 0.2 cps/nv sensitivity. Then the reactor operation continues with these HTFC. After studying various options for detectors and instrumentation systems, it is proposed to provide 3 HTFC at 3 locations 120° apart in the control plug (in three housing tubes specially designed to lift / lower the detector along with MI cable), to monitor the measurement range from shutdown to full power with wide range channels operating in pulse mode (during start-up) and in Campbell mode (intermediate power) from 1 nv to $4x10^8$ nv. Two more HTFC are placed in control plug location (in two guide tubes placed 120° each apart around the core) for covering the entire measurement range from shutdown to full power to display reactor power in Control Console for manual power regulation.

## IX. POWER OPERATION

Below the safety vessel, it is found that neutron flux is $1.34x10^5$ nv at full power and gamma field is ~10 Sv/h (1000 R/h) and temperature is < 90 °C. It is observed that with fission chambers of sensitivity 0.75 cps/nv, the signal levels are sufficiently high during the last two decades of full power operation. Hence 5 fission chambers working in pulse mode (3 for safety and 2 for control) are placed below the safety vessel with concrete over the detectors removed for better flux availability. Fig. 5 shows the range coverage and various trips and interlocks during normal operation.

## X. WIDE RANGE FLUX COVERAGE

Initially it is planned to have the reactor start-up with ICSA channels in pulse mode. Above ~ 1 kWt these are inhibited by the control plug detectors in pulse mode. Once ANS is sufficiently built-up to give more than 3 cps with HTFC in control plug, reactor starts with control plug detectors only. The pulse mode of operation of control plug detectors is taken over by Campbell mode at around 500 kWt. Signals from control plug detectors are automatically inhibited when flux monitoring is taken over by detectors below Safety Vessel at 5% $P_n$. At any time, only one system is used for safety and control functions.

## XI. FLUX MONITORING DURING REFUELLING

To prevent multiple wrong loading of fuel subassemblies and control rods, leading to insertion of abnormal reactivity, it is required to provide an interlock on fuel loading, which is well below the count rate for criticality and well above the counts (max. 120 cps) due to the proximity of the fresh FSA that is being loaded. This interlock is variable as the criticality counts vary with SDCR, which is a function of reactor operation time and shutdown time. This interlock is set at 250 cps for a fresh core (with BCC 36 cps/nv) and at 250 cps for a BOEC core (with HTFC 0.2 cps/nv). The criticality count rates are 15000 cps on ICSA and 662 cps on control plug HTFC, in the above two cases respectively. In the former case, shutdown $k_{eff}$ is 0.90 and in the latter case it is 0.93**.** During refueling, the detectors in control plug get relocated with reference to the core centre, due to rotation of control plug, SRP and LRP. It is found that the readings of the detector at positions 1, 5 and 6 (Fig. 6) are the highest even with the plug rotation. Hence the detectors providing interlock during fuel handling are located in positions 1, 5, and 6 (for BOEC core). Location 2 is used for in-situ spare detector. The locations 3 and 4 are used for detectors of control channels.

## XII. REACTOR START-UP AFTER LONG SHUTDOWN

In case of an unforeseen long shutdown for more than 4 months after reaching full core (which may be a rare event for a power reactor), the shutdown count rate may become < 3 cps (HTFC with a sensitivity of 0.2 cps/nv), as ANS decays. For the subsequent flux monitoring during fuel loading and start-up, 3 Boron coated proportional counters (BCC) with a sensitivity of 4 cps/nv are placed side by side at the spare detector location in control plug. With BCC in control plug locations, the minimum count rate expected is > 10 cps, even when the detectors get relocated with reference to the core centre, due to rotation of control plug, for fuel handling. This will ensure smooth reactor start-up with overlap from HTFC (0.2 cps/nv). As soon as HTFC in control plug read > 10 cps, safety actions from these BCC are inhibited and HV is cut off. With these provisions, it is not required to put back ICSA again in the core centre and also it is not necessary to make parallel combination of 12 cps/nv BCC. Hence, ICSA can be dispensed with permanently from the core after attaining 2 months full power operation and normal Central fuel subassembly can be put back, as per initial design. Thus, ICSA is required only for first approach to criticality and initial operations till ANS gets saturated. The various trip, alarm and interlock parameters and their thresholds are given in Table 2. The schematic for wide range safety channel is shown in Fig. 7.

## XIII. CHALLENGES IN NEUTRON FLUX MONITORING INSTRUMENTATION IN SFRS

### *A. Location of Sensors*

Due to radial and axial shielding of the core, provided to protect the reactor components, neutron flux is highly attenuated at ex-core and ex-vessel locations and hence combination of detectors both in vessel and out vessel need to be designed.

### *B. Neutron detectors*

High temperatures and high gamma flux environment within the vessel and very low flux at ex vessel locations, necessitates the design of high temperature fission chambers (HTFC).

### *C. Challenges in HTFC technology*

- Disintegration of uranium coating due to thermal shocks.
- Unavailability of highly enriched uranium to attain higher sensitivities.
- Welding / brazing joints of the detector need to withstand high pressure and temperature fluctuations, causing cracks and leakage of the gases used for ionization.
- Cracks may develop in metal-ceramic seals due to thermal & pressure transients.
- Due to high temperature in the vessel, insulation resistance of ceramic materials decreases causing leakage currents.
- Gas diffusion and adsorption might occur by the structural material, electrodes, brazing material and MI cable.
- Uniformity of the electrode gap should be maintained even at high temperatures.
- Chemical cleaning of the gas and structural materials is required to the extent of ppb level.
- Breakdown pulses might appear due to MI cable.

### *D. Electronics*

Ultra low current pulses of very short rise time demanding high bandwidth and sensitive electronics, makes it prone to noise pick up. Poor signal to noise ratio due to temperature and gamma currents necessitates Campbell mode of operation.

## RECOMMENDATION

- For flux monitoring during initial fuel loading and first approach to criticality, an instrumented central subassembly (ICSA) containing three high temperature fission chambers (with a sensitivity of 0.1 cps/nv) is provided at the core centre and Boron-10 coated proportional counters (with a sensitivity of 12 cps/nv) are provided in control plug locations.
- For neutron flux monitoring during shutdown, fuel handling, start-up, intermediate and power ranges for a BOEC core, high temperature fission chambers (with a sensitivity of 0.2 cps/nv) in control plug locations and fission counters (with a sensitivity of 0.75 cps/nv) below safety vessel are provided.
- In case of an unforeseen long shutdown for more than 4 months, for the subsequent flux monitoring during fuel loading and start-up, three Boron-10 coated proportional counters (with a sensitivity of 4 cps/nv) are placed side by side at the spare detector location in control plug.

**Table 1 Neutron flux and Temperatures**

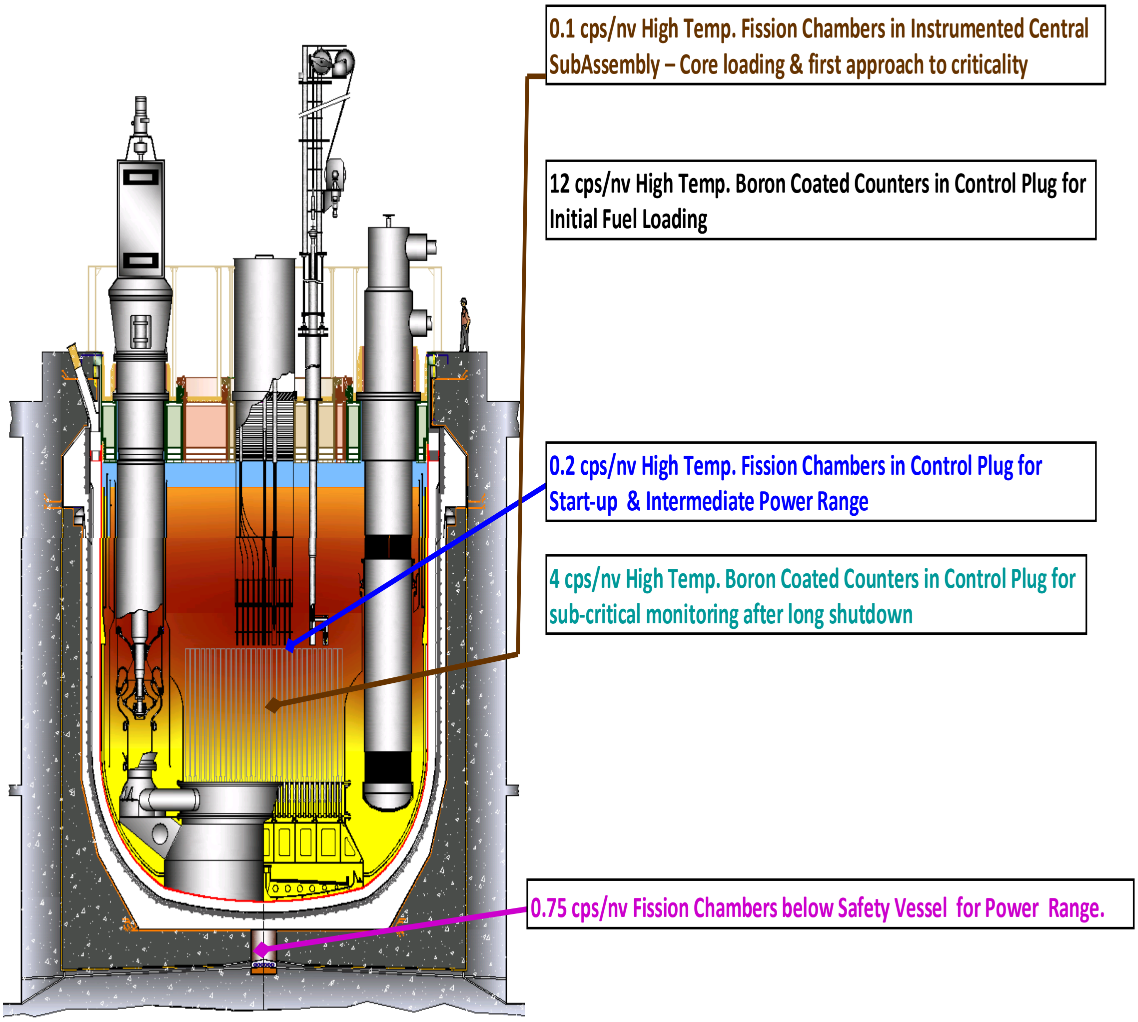
| **Location** | **Neutron Flux (U$^{235}$ fission equivalent flux) in nv and temperature in K** | | | |
|---|---|---|---|---|
| | **Shutdown** | | **P$_n$ (Full power)** | |
| **Core centre** | 1.3 x 10$^4$ **nv** | 473 K | 2.7 x 10$^{13}$ **nv** | 845 K |
| **Core cover plate** | 6 **nv** | 473 K | 2.7 x 10$^9$ **nv** | 840 K |
| **Below SV** | 1.1 x 10$^{-5}$ **nv** | 343 K | 2 x 10$^5$ **nv** | 343 K |

**TABLE 2 : SCRAM PARAMETERS & INTERLOCKS**

| **Sl. No.** | **Range of operation** | **Parameter** | **Threshold** | **Detector (sensitivity)** | **Purpose** |
|---|---|---|---|---|---|
| 1 | Source range (fresh core) | Log C$_0$ | ~ 3 cps | HTFC (0.1 cps/nv) in pulse mode in ICSA | Non-availability of adequate neutrons. |
| 2 | – ,, – | $\tau_C$ | 10 s | – ,, – | TOP events at low power. |
| 3 | – ,, – | Log C | 8x10$^5$ cps (~ 0.5 kWt) | – ,, – | Failure of take over of control plugs detectors. |
| 4 | Source range (BOEC core) | Log N$_0$ | ~ 3 cps | HTFC (0.2 cps/nv) in pulse mode in control plug | Non availability of adequate neutrons. |
| 5 | – ,, – | Log N1-IL | 250 cps | HTFC (0.2 cps/nv)–BOEC core / BCC (36 cps/nv) – fresh core / BCC (4 cps/nv) – long shutdown | Prevents multiple wrong operations during fuel loading. |
| 6 | – ,, – | Log N2-IL | 100 cps | HTFC (0.2 cps/nv) in pulse mode in control plug | Ensures take over of control plug detectors. |
| 7 | – ,, – | Log N | 10$^6$ cps (~ 2.5 MWt) | – ,, – | Failure of take over of intermediate range channels (detectors from control plug). |
| 8 | – ,, – | $\tau_N$ | 10 s | – ,, – | TOP events at low power. |
| 9 | Intermediate Range | Log P1-IL | 500 kWt | HTFC (0.2 cps/nv) in Campbell mode in control plug | Ensures take over of intermediate range channels. |
| 10 | – ,, – | $\tau_P$ | 10 s | – ,, – | TOP events at intermediate power. |
| 11 | – ,, – | Log P | 250 MWt (20% P$_n$) | – ,, – | Failure of take over of Lin P power range pulse channels. |

| | | | | | |
|---|---|---|---|---|---|
| 12 | Power range | Lin P1-IL | 62.5 MWt ($5\%$ $P_n$) | Fission chamber (0.75 cps/nv) in pulse mode with linear CRM, below the safety vessel | Ensures take over of Lin P channels and lifts the inhibition on reactivity. |
| 13 | – ” – | Lin $P_v$ | 125 MWt - 1375 MWt (10% to 110% $P_n$) | – ” – | Enables reactor operation at reduced power. |
| 14 | – ” – | Lin P | 1375 MWt (110% $P_n$) | – ” – | TOP events at high power. |
| 15 | – ” – | ρ | ± 10 pcm | – ” – | TOP events at high power, primary pump discharge, pipe rupture. |

$P_n$: nominal power of 1250 MWt TOP: Transient over Power ρ: reactivity IL: Inter Lock, τ: reactor period HTFC: High Temperature Fission Chamber BCC: Boron Coated Counter



0.1 cps/nv High Temp. Fission Chambers in Instrumented Central SubAssembly – Core loading & first approach to criticality

12 cps/nv High Temp. Boron Coated Counters in Control Plug for Initial Fuel Loading

0.2 cps/nv High Temp. Fission Chambers in Control Plug for Start-up & Intermediate Power Range

4 cps/nv High Temp. Boron Coated Counters in Control Plug for sub-critical monitoring after long shutdown

0.75 cps/nv Fission Chambers below Safety Vessel for Power Range.

Fig. 1 Neutron Detectors for PFBR

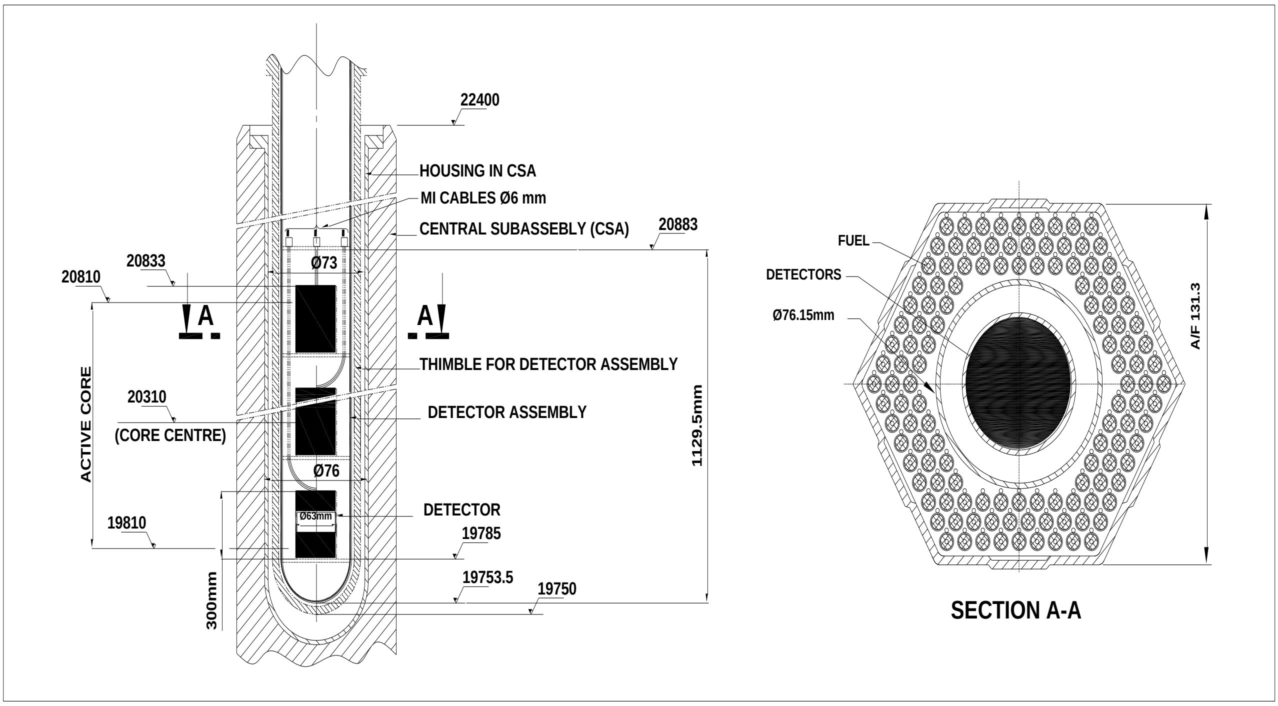


Fig. 2 Detectors in ICSA

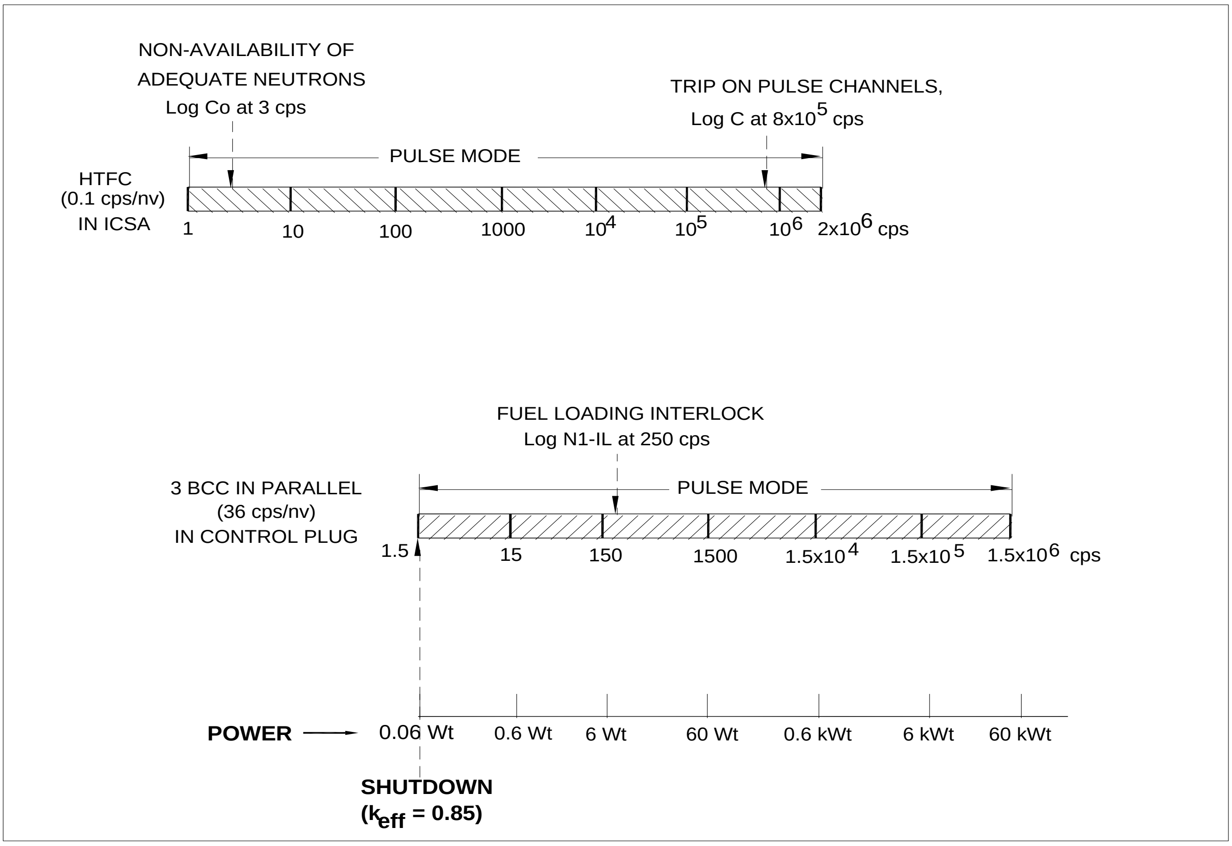


Fig. 3 Flux levels at Initial Core Loading

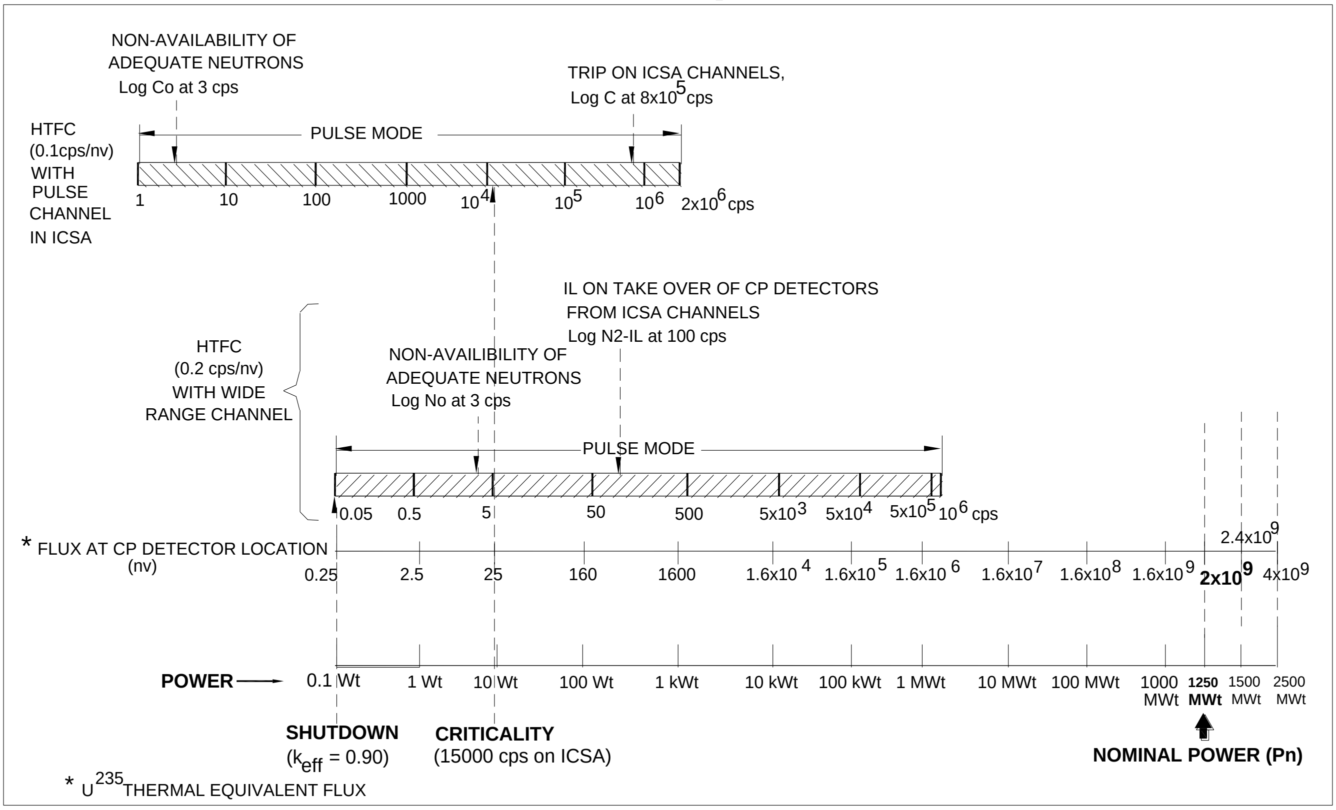


Fig. 4 Flux levels: ICSA and Source Range

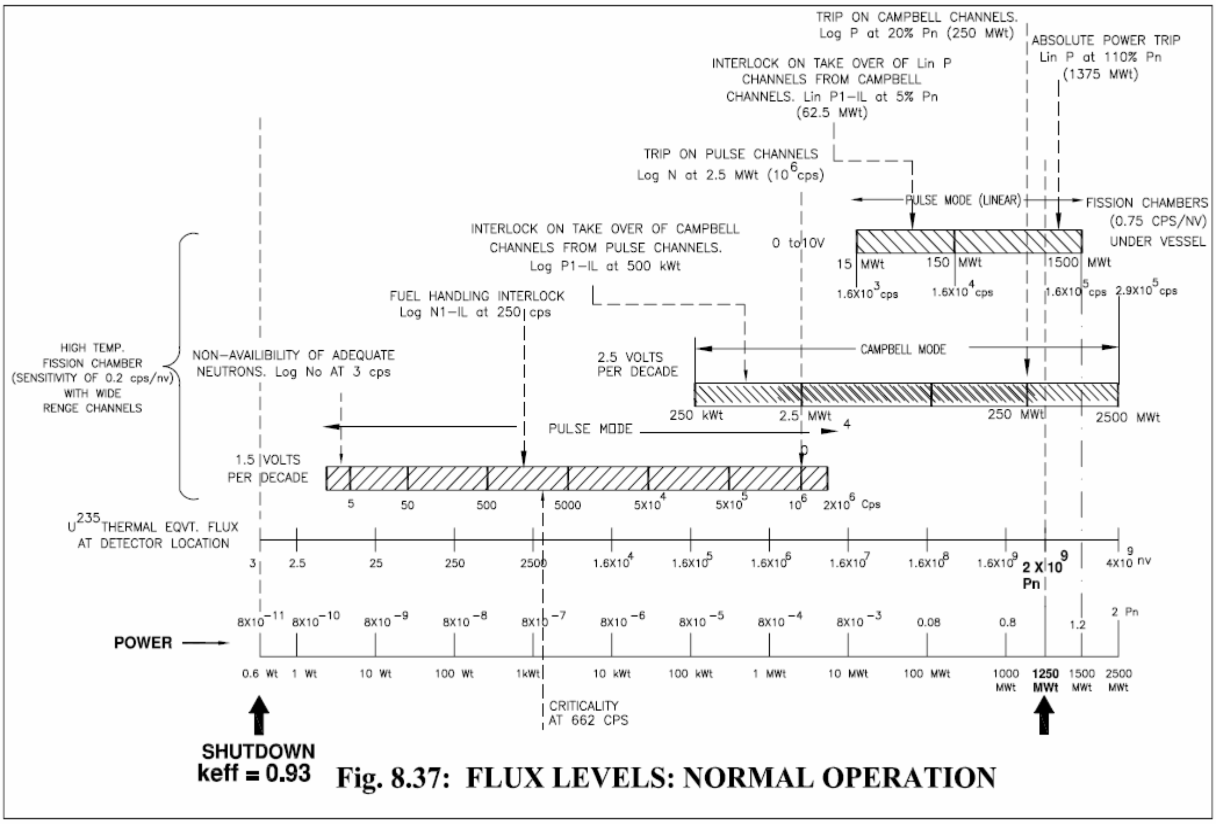
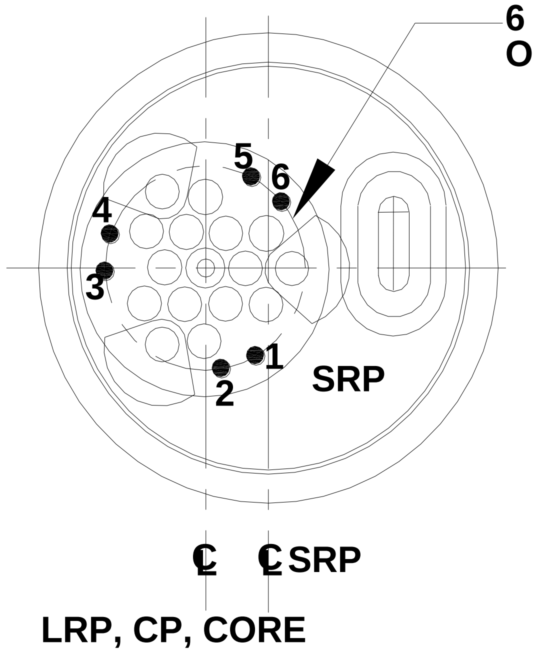


Fig. 5 Flux levels: Normal Operation



| DETECTOR NO. | ANGULAR LOCATION (°) WITH RESPECT TO CP CENTRE |
|---|---|
| 1 | 58 |
| 2 | 79 |
| 3 | 178 |
| 4 | 199 |
| 5 | 298 |
| 6 | 319 |

Fig. 6 Location of Neutron Detectors in Control Plug

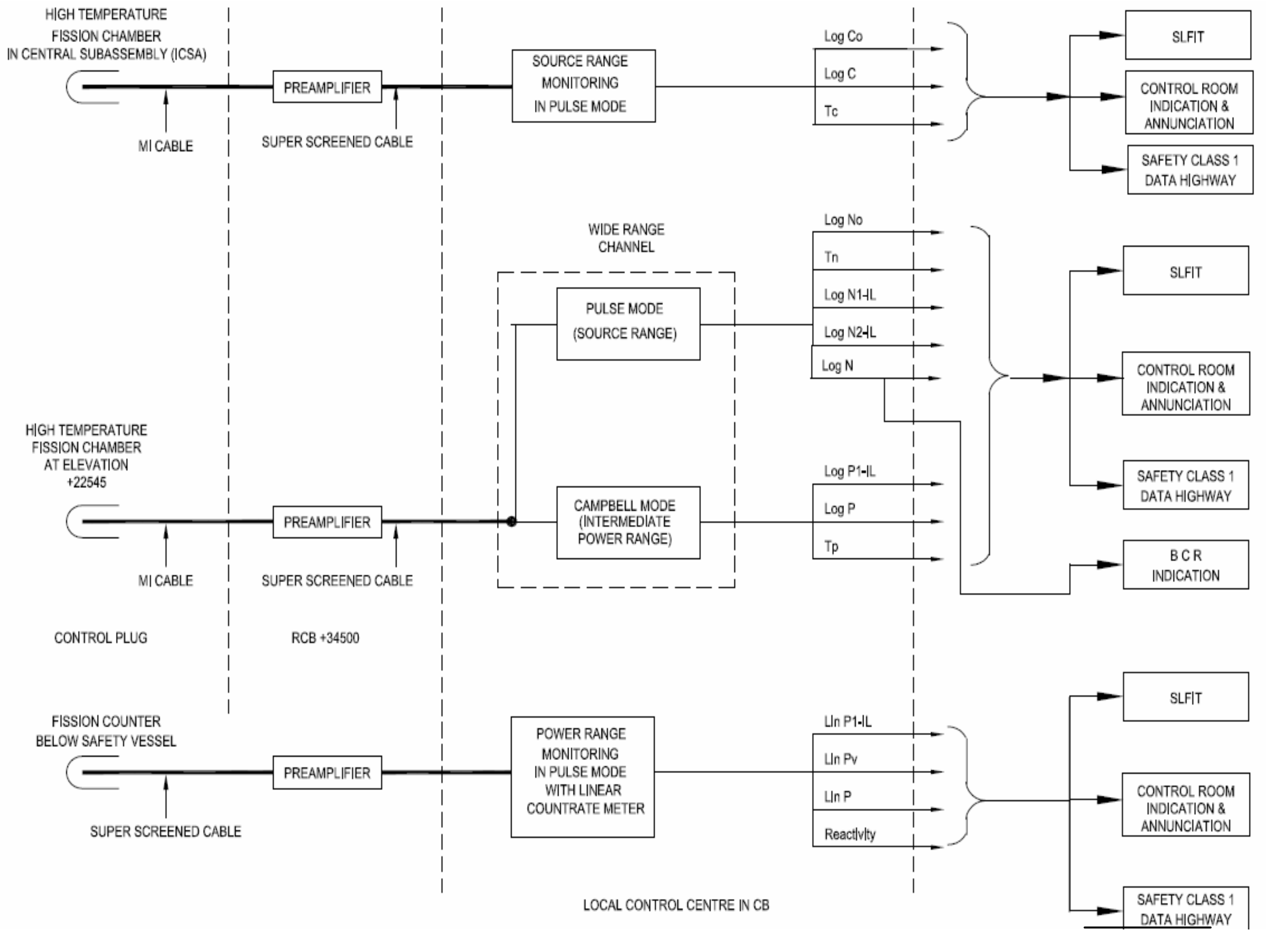


Fig. 7 Safety Channel Signal Flow

### Annexure: Neutron Detectors in other SFRs

| Reactor | Detector | Location | Range of coverage | Remarks |
|---|---|---|---|---|
| PHENIX | 3 high temp. fission chambers | In vessel, lateral neutron shield. | Shutdown, first period of start-up | Cooled to 483 K until 1986 and then qualified for 873 K. |
| | 3 Boron lined chambers | Under the vessel in a graphite block | Intermediate range | |
| | 3 Ionization chambers | Under the vessel, in a graphite block | Power range for safety and control | |
| SUPER PHENIX | Helium counters | Under the vessel below three neutron guide tubes placed at 120$^o$ on the core boundary. | Start-up | |
| | Fission chambers | | Intermediate and power range | |
| | High temp. Fission chambers | Special central sub-assembly, temp. 823 K | Core loading and start-up testing | |
| EFR | High temp. Fission chambers | Above-core-structure (ACS) | Shutdown to full power (10 decades) and apt to be used at 823 K with a high gamma field of $10^5$ R/h | The associated electronics is designed to cover automatically three operation modes: pulse, Campbell and current with overlapping. |
| FBTR | 3 Fission counters | Detector pits in biological shield concrete | Shutdown, Start-up upto 2 kWt | |
| | 3 Compensated Ionization chambers | | 200 Wt to 200 MWt for safety | |
| | 2 Compensated Ionization chambers | | 50 Wt to 50 MWt for control | |
| | 2 sets, each with two boron coated counters of 4 cps/nv connected in parallel | | Start-up after long shutdown | |