SUPPLEMENT TO CHAPTER 10
OF
REACTOR PHYSICS FUNDAMENTALS

This supplement reviews the text material and provides additional detail on power measuring instruments. You should be familiar with the text material before studying this supplement.

Power and Power Measurement

What is Power?

Instruments in the Control Loop

Control of Reactor Power

Corrections to Neutronic Instruments

Time Response of In-Core Detectors

Range of Nuclear Instruments

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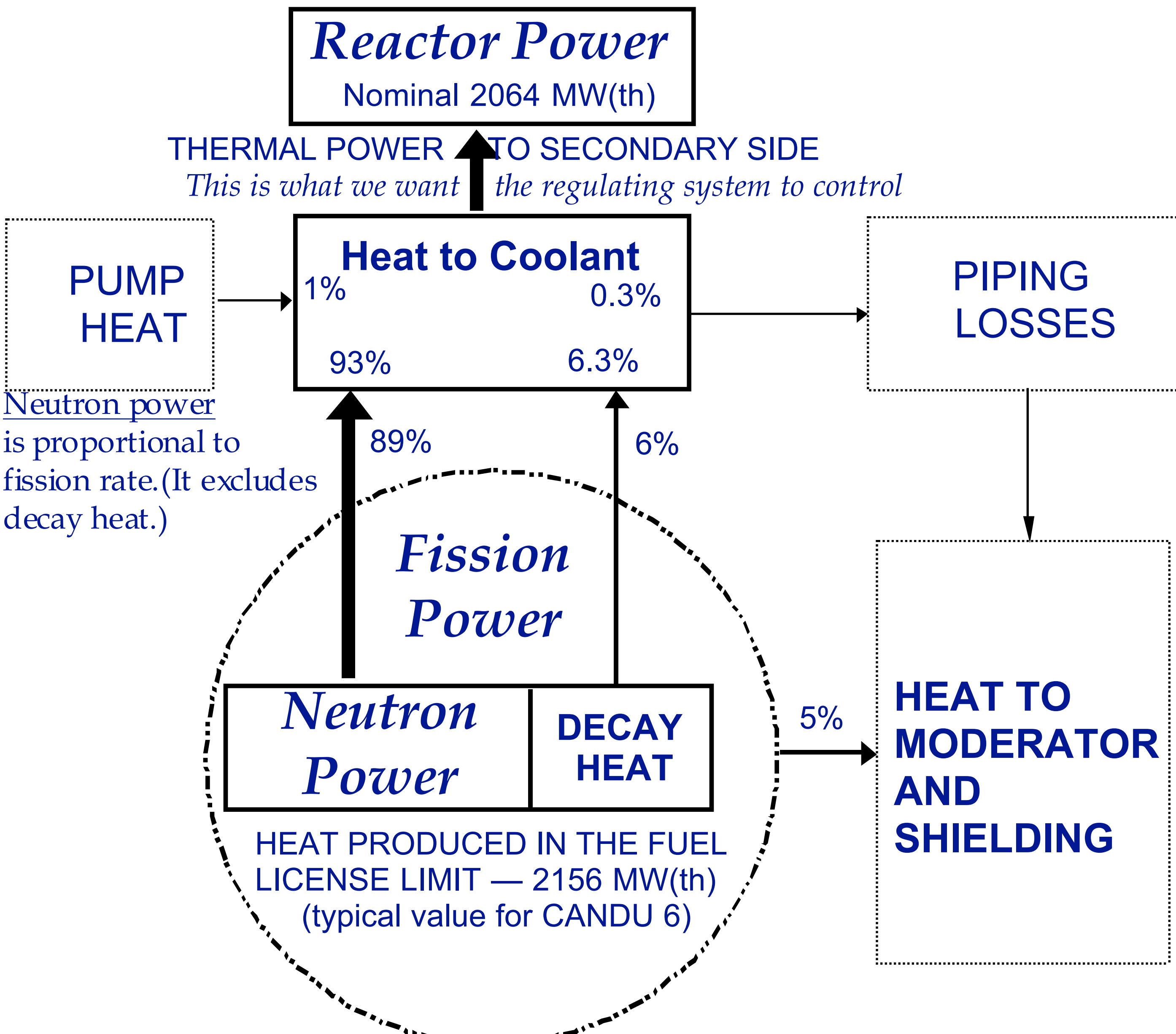
POWER MEASUREMENT

1. Thermal power (or reactor power) is the heat output to the secondary side.
[This includes pump heat but not heat losses to moderator & shielding.]



2. Neutron power is proportional to fission rate.(It excludes decay heat.)

3. Fission power (as used in the operating license) is the total heat output from the fuel = neutron power + decay heat.
[This excludes pump heat and includes heat to the moderator & shielding.]

1. Thermal Power

* How is it measured?

Below 80% power the coolant is sub-cooled. Measurements of temperature rise and coolant flow for each channel can be used to determine the primary side (reactor) thermal power.

At high power some of the reactor coolant channels reach boiling temperature. Measurements of secondary side steam flow, boiler steam pressure (and saturation temperature), and boiler feedwater flow and temperature determine the secondary side (boiler) thermal power.

* What are the limitations of thermal power measurements?

Slow rate of response is the main disadvantage. During the time it takes for the heat to get to where the measuring instruments are, and the time required for the thermal instruments to respond, the fission rate could increase beyond acceptable limits. (See text, section 10.5.1)

Core monitoring is required over the entire operating range of reactor power. At high power, temperature measurements stop rising when boiling occurs. At low power, decay heat keeps the instruments from dropping even when the fission rate drops to a low level.

At high power, the instruments must measure the spatial distribution of power so that local high power can be controlled. Thermal instruments give, at best, the radial power distribution.

* What are Thermal Power Measurements used for?:

Thermal power is used for calibration of the Reactor Regulating System (RRS) in-core neutronic detectors.

2. Neutron Power

* Advantages of Neutron Power Measurements:

Neutronic instruments (in-core detectors and out of core ion chambers) respond immediately to changes in the fission rate.

Neutronic Instruments can monitor power over a wide range, from about 10^{-7} F.P. for ion chambers (even lower for start-up ion chambers) to 100%+.

In-core detectors are distributed throughout the core so they can monitor spatial power distribution. There are 14 pairs of RRS (Reactor Regulating System) in-core detectors. The safety shutdown systems (SDS#1 & SDS#2) each have a larger number of detectors configured in the core to optimize sensitivity to local high power.

* Disadvantages:

Neutron Power and Thermal Power are not exactly proportional so the neutronic instruments must be calibrated to allow accurate control of thermal power.

Neutronic instruments make local measurements. Average measurements are required. Radiation varies from place to place across the core. Neutronic instruments must be calibrated so that the signal from a detector at a particular location accurately represents the power from a region.

Calibration

RRS regulates reactor *thermal* power in the high power range. This is not exactly what the in-core neutronic instruments measure. When there is a power change, the neutronic instruments respond quickly, but go slightly out of calibration because:

The response of the neutronic instruments is not exactly proportional to reactor thermal power change. (See text section 10.4)
Bulk calibration corrects for this.
Each detector is more sensitive to nearby changes than to changes far away. Spatial calibration corrects for this.

bulk Continuous on-line calibration by RRS forces the average over the 14 pairs of RRS in-core detectors to agree with an accurate bulk thermal power measurement.

spatial Continuous on-line calibration by RRS forces each of the 14 pairs of in-core detectors to agree with the average thermal power produced in its particular zone.

The result is fast, fairly accurate response that becomes increasingly more accurate as the temperature calibrations catch up.

Sources of Nonlinearity

Steady *thermal power* is about 93% from fission, 6% to 7% from fission product decay heat, almost 1% from pump heat, with a small amount (<1%) of the heat lost from the coolant channels into the moderator. When power changes, the neutron power changes immediately, the decay heat changes slowly. Pump heat and losses remain the same.

The in-core detectors measure neither thermal power nor neutron power. They are sensitive to both neutrons and gamma rays. Part of the signal (both neutrons and gammas) comes from fission and part from fission product decay (decay gammas), but the fraction from each of these is different than the 93% - 6% makeup of thermal power.

Neutronic Instruments - Ion Chambers

Ion chambers are normally sensitive to charged particles and gamma rays. To make them sensitive to neutrons, their electrodes are coated with boron so that neutrons entering the chamber create charged particles by reactions with boron.

There are locations for four sets of three ion chambers against the curved exterior of the calandria. In these locations the ion chambers measure leakage flux, indicative of flux in the core. Three ion chamber "housings" are arranged horizontally on opposite sides of the core, near the mid line. On one side of the core are three SDS#2 ion chambers and three empty locations for installing sensitive start-up ion chambers when these are required. On the opposite side of the core are three SDS#1 ion chambers and three RRS ion chambers (one each per housing).

Lead shielding is used to attenuate gamma radiation so that the ion chambers respond almost 100% to thermal neutron flux. However, at very low reactor power, near 10^{-7} of F.P., the ion chamber signal is mainly from gamma rays from activated impurities within the chamber and housing. Start-up ion chambers, more sensitive to low flux, are installed for low power monitoring. They are taken out when not needed to avoid buildup of activation impurities.

Neutronic Instruments - Self Powered In-Core Detectors

A self powered in-core detector looks much like a co-axial cable. It consists of a central emitter separated by insulation from a grounded sheath (the collector). Gamma rays interact with the emitter, knocking electrons from the material. Many electrons cross the insulator and escape to ground, leaving the emitter positively charged. A control signal is extracted by an amplifier that completes the circuit, providing a return path to the emitter for electrons.

The gamma rays detected are from: (n,γ) reactions in the detector; prompt fission gamma rays; and fission product decay gamma rays. The signals from the first two are proportional to the fission rate, but the decay gammas are "delayed" from the fissions that caused them. These devices cannot be used below a few per cent full power because of false signals generated by, for example, beta decay of activated impurities in the connecting cables.

* Uses of corrected Neutron Power Measurements:

The Reactor Regulating System (RRS) provides moment to moment control of reactor power by adjusting water (H_2O) flow into 14 compartments distributed in the reactor core. RRS adjusts all 14 valves together to control bulk power and controls individual valves as required to keep the distribution of power balanced across the core.

The flow control valves are driven from their normal steady state positions by three "errors"

POWER(measured) - POWER(required)
RATE OF INCREASE(measured) - RATE OF INCREASE(required)
ZONE POWER$_i$ - AVERAGE POWER OF ALL ZONES (i = 1 to 14)

RRS uses the power measurements from three out of core ion chambers [the log N signal] for wide range power control from low power to 5% F.P.

RRS uses power measurements from fourteen pairs of in-core detectors [the linear N signals] above 15% F.P.

RRS gradually transfers measurement of power between ion chambers and in-core detectors in the power range between 5% F.P. and 15% F.P.

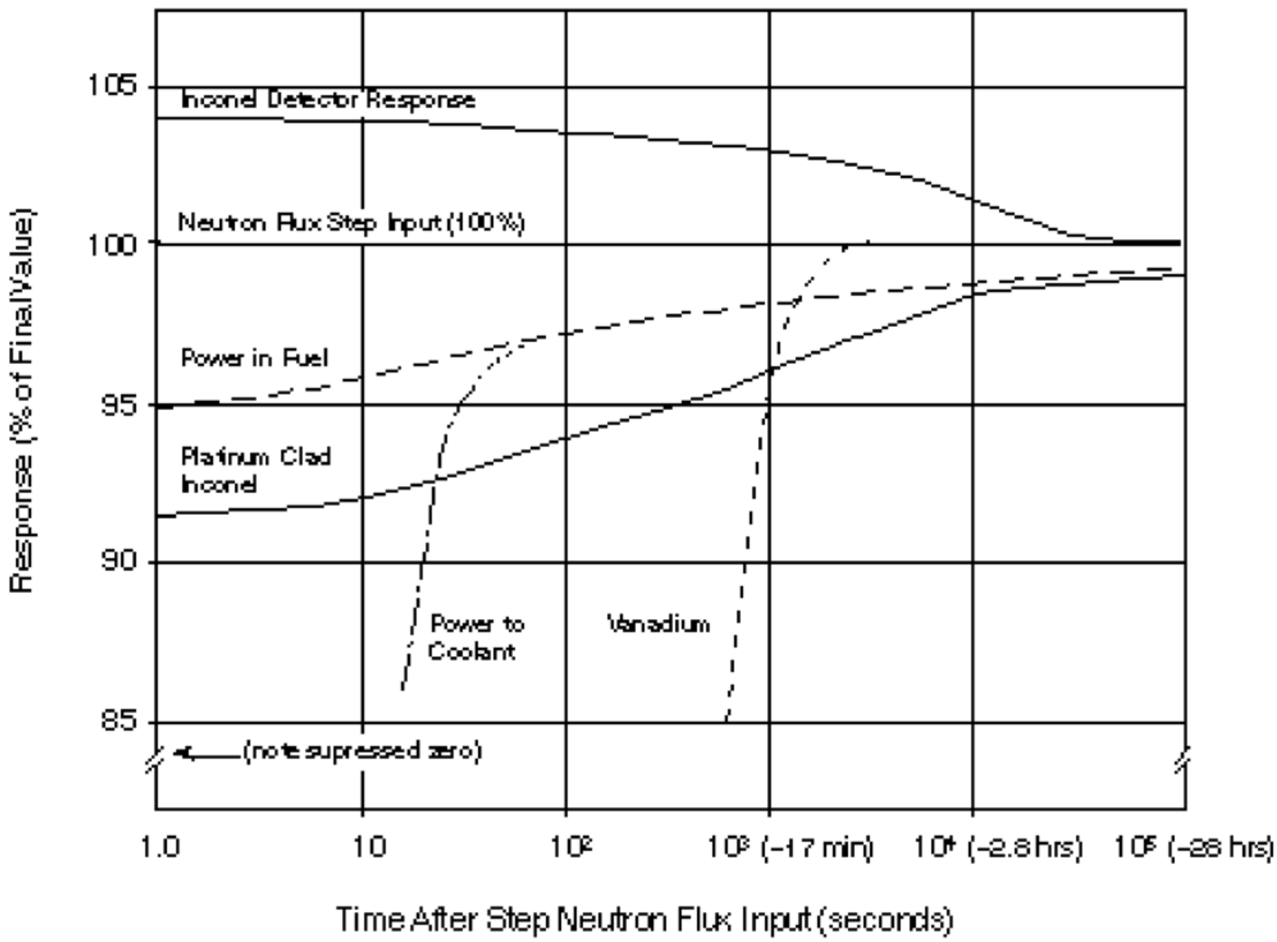
Above 25% F.P. RRS regulates spatial power (makes individual zone adjustments) as well as bulk power, phasing in spatial control gradually between 15% F.P. and 25%F.P.

RRS uses rate log N (from the RRS ion chambers) at all power levels to generate the rate dependent portion of the power error.

The Safety Shutdown Systems (SDS #1 and SDS #2) use independent sets of in-core detectors for protection against high power.

SDS #1 and SDS #2 use rate log signal (from SDS ion chambers, three independent ion chambers for each system) at all power levels to protect against fast power increases.

Figure 1 DETECTOR RESPONSE TO A STEP FLUX CHANGE



The figure above shows detector responses to a power change. A step increase in neutron flux (e.g. from 70% to 85%) at time t = 0 is assumed. The final flux is represented in the figure as 100% of the step change.

The vanadium signal in the figure is almost 100% flux proportional, after a delay. This is because the electrons come from β^--decay ($T_{\_}$ = 3.76 m) of the neutron activated vanadium emitter. The response is too slow for regulation, but a set of these detector measures the shape of the flux distribution to determine the spatial calibration mentioned earlier.

Two corrections to the raw signal make it represent reactor thermal power. Compensation corrects the incorrect prompt response of the detector to prompt neutrons and gamma rays; calibration adjusts its incorrect delayed response to decay heat production. The platinum clad detector signal in the figure is corrected with an initial boosts that brings it near to the power in the fuel. Subsequent correction keeps the signal in step with the fuel power, which matches the heat to the coolant about 1 minute after the change.

For normal regulation, [to achieve a power ramp or to damp a xenon oscillation], power changes are gradual. The prompt response of the neutronic detectors starts the regulating system responding in the right direction. The zone levels change slowly and by the time they stabilize, updated thermal calibration factors have been calculated.

The rate error does not require calibration. The measurement is a rate[log] from the ion chambers.

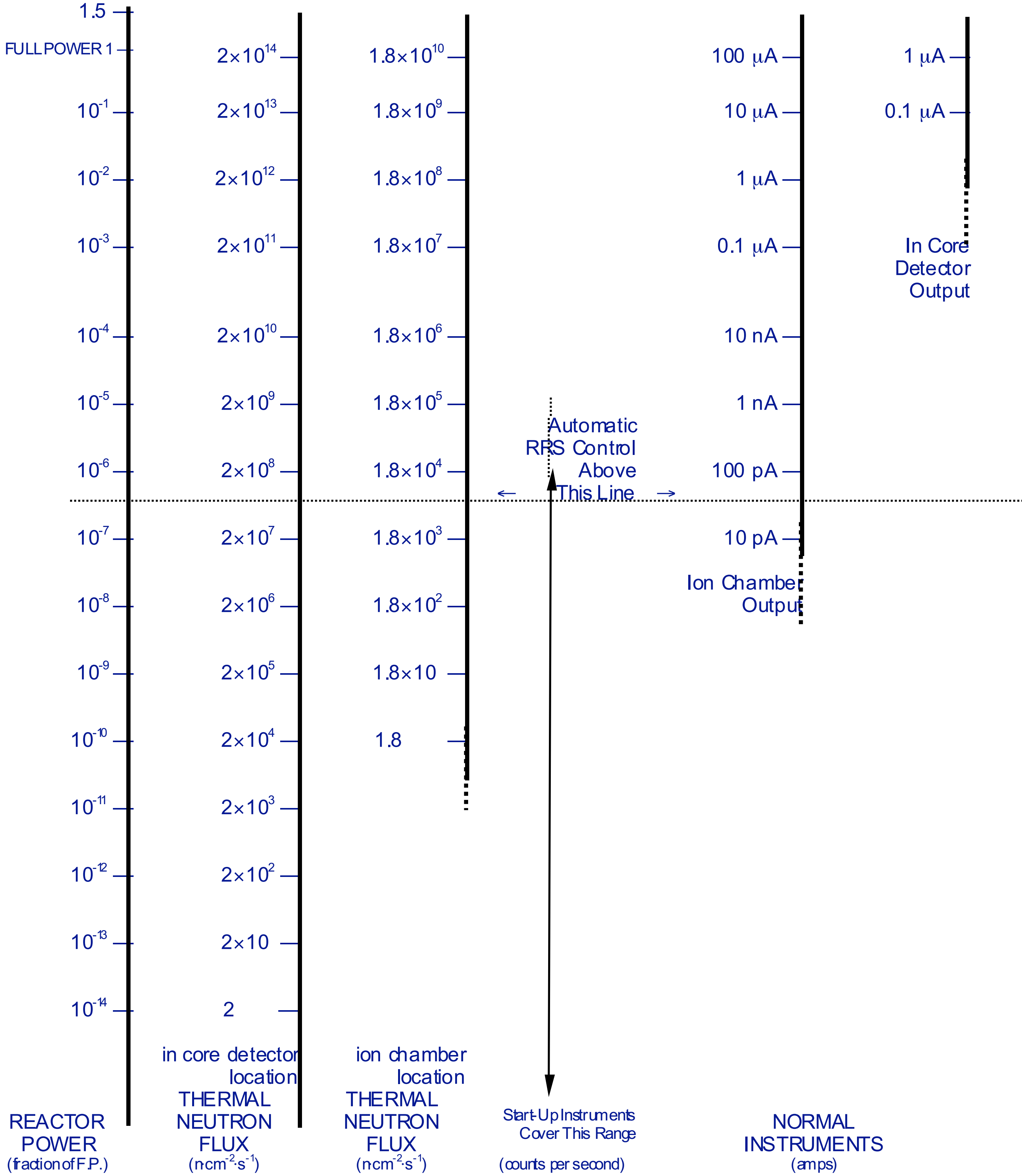
$$\frac{d(\ln P)}{dt} = \frac{1}{P}\frac{dP}{dt}$$

This measures a fractional power change per second. A calibration factor would cancel out in the numerator and denominator.

To allow for a smooth transfer of control between ion chambers and in-core detectors, the ion chambers are calibrated to represent bulk thermal power when they approach the transfer power range, or higher. At lower power the calibration is discontinued to allow the ion chambers to measure neutron power (and because thermal power measurements are inaccurate at low power).

In effect, at low power, with the ion chambers in charge, RRS regulates bulk **neutron** power. As power rises into the range where thermal power is significant, the neutronic signals are calibrated to thermal power, and then regulation is transferred to the in core detectors. This allows spatial control as well as bulk power regulation of **thermal** power as the power rises further.

Range of Nuclear Instruments



The figure opposite shows the range of sensitivities of nuclear instruments for the CANDU 600. Other CANDUs use nearly identical instruments. The column on the left shows over 14 orders of magnitude, from the lowest flux for a freshly fuelled reactor before first critical, to beyond the normal peak power.

The next column gives the estimated flux at a typical in core location. Flux in the fuel would be about half the value shown and peak moderator flux would likely be half again as big. Leakage flux at the location of the out of core ion chambers, in the next column, is lower by more than 4 orders of magnitude.

The final two columns show the range of coverage of the normal instruments. After several weeks of shutdown, the power of an equilibrium fuelled reactor drops below about 10^{-6} F.P. at which time startup ion chambers must be installed to extend this range to lower power.