SUPPLEMENT TO ACCOMPANY LESSON 13
OF
REACTOR PHYSICS FUNDAMENTALS

Reactivity Control Devices in the Control Loop

(Power Control)

Summary of Monitoring Instruments

Long Term Reactivity Control

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Control: Regulation & Protection

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Summary of Monitoring Instruments

Before devices can adjust core reactivity there must be instruments to monitor the requirements. Neutronic ("flux" measuring) Instruments used in a typical CANDU reactor are described in the handout for lesson 10. Here is a summary of the requirements for CANDU power monitoring instruments.

The RRS instruments:

In the normal operating range, must allow precise control of:

(i) reactor thermal power output;
(ii) rate of change of power, and;
(iii) spatial power distribution.

At low power they monitor

(i) neutron power, and
(ii) rate of change of neutron power.

The SDS instruments:

Monitor neutron power level and rate. They must limit:

peak local power (channel powers &/or bundle powers);
the rate of increase of neutron power (fission rate) at all power levels.

Thermal and Neutronic Instruments Combine to Satisfy the Following:

respond quickly to power changes (at all power levels)
monitor power from very low to high power
monitor rate of increase of neutron power (at all power levels)
monitor spatial distribution of power (in the high power operating range)
measure thermal power accurately (in the high power operating range)
represent average power in the region being regulated (core total for bulk power & zone average for each of 14 zones)

Thermal Measurements come from:

Channel Powers using Channel Flow and Channel ΔT
Boiler Power (secondary side power)

Neutronic Measurements come from:

In Core Detectors
Ion Chambers (including Startup Ion Chambers at low power)

Core Reactivity Effects & Requirements

The following reactivity feedback effects require compensating device actions in order to hold power at setpoint, to regulate spatial power, to ramp power at a controlled rate (up or down) and to provide fast shutdown.

REACTIVITY FEEDBACK EFFECTS

Requiring Power Regulation ***(RRS)***	***Requiring Rapid Shutdown***
fuel burnup reactivity loss	*rapid coolant voiding*
on-power refuelling effects	*failure of RRS*
xenon override	
xenon effects on power maneuvers	
xenon simulation with poisons	
xenon oscillations	
power coefficient	
other temperature effects	

Reactivity Control Devices in the Control Loop

A typical CANDU is configured as follows:

- 14 liquid zones (distributed water compartments) automatically regulate bulk power and spatial power distribution from moment to moment;
- a set of 4 control absorber rods is normally out of core to provide setback (gradual power reduction) or stepback (fast power reduction) as required and to back up the zones on high level;
- a set of adjuster rods is normally in core for flattening flux, and can be removed for xenon override or reactivity shim, and to back up low zone level;
- poison addition and purification systems allow adjustment of neutron absorbing chemicals in the moderator for xenon simulation, fresh fuel simulation, as a shim to allow limited excess fuelling and for GSS;
- SDS#1 and SDS#2, are independent, separated, diverse, fast acting emergency shutdown systems; shutoff rods and liquid injection respectively. They shut down the reactor if the regulating system fails or is unable to adequately control key parameters.

Small reactivity changes can be made by adjusting moderator temperature, but this is not a normal part of reactor regulation.

CONTROL = REGULATION + PROTECTION

This handout discusses how the combination of devices (under RRS control or fast circuitry) cover off the reactivity effects introduced on the previous page.

RRS (FOR REGULATION)

The LZC is the first line of regulation: to hold power at setpoint, for power ramps and to limit xenon oscillations. The LZC system is backed up on high and low zone levels (when spatial control is inadequate), or on large power error (an indication of loss of bulk power regulation) by control absorbers and adjusters. The regulating system can operate an automatic poison addition system if there is a large, positive power error with power increasing.

Fuelling (or poison shim removal) raises low zone levels into their normal operating range. Manual poison addition lowers high zone levels into range.

Adjusters, included in the design for flux flattening, are used for xenon override and for shim.

Control absorbers are used for power setback (ramp back to a predetermined power level) and stepback (prompt reduction to a predetermined level).

SDS#1 & SDS#2 (independent fast circuitry) (FOR PROTECTION)

SDS#1 & SDS#2 are independent rapid emergency shutdown systems. i.e. they are independent of each other and of the regulating system. Each uses triplicated logic with sensors, circuitry and reactivity devices not used by any other equipment.

Long Term Reactivity Control

On line fuelling with the help of moderator poisons, if required, adjusts the core reactivity so that the liquid zone compartments remain, ideally, near 40% full. The zones then have available ± 2 to 3 mk range of reactivity:
(i) to ramp power, overcoming prompt temperature reactivity feedback;
(ii) to hold power at setpoint, compensating for on-power reactivity effects;
(iii) to limit xenon oscillations by adjusting zone to zone relative flux.

Fuel management maintains both bulk core reactivity and overall spatial flux distribution. Spatial flux distribution (flux flattening) is assisted by design features discussed in Chapter 6:

- reflector
- adjusters
- bi-directional fuelling
- differential fuelling

Figure 6.4 to 6.7 in the text illustrate how these affect the overall flux shape. This allows the core to achieve its design thermal power output without any fuel channel or bundle exceeding a maximum rated power output.

The Neutron Overpower Protection System (NOP) is designed to protects against high channel power during slow loss of regulation accidents. The fuelling engineer tries to select channels for fuelling to avoid local flux peaks (hot spots) that reduce NOP trip margins.

Flux flattening with adjusters reduces fuel burnup. For example, with the adjusters withdrawn, the extra neutrons permit the fuel to remain in the core to higher burnup, at the expense of a peaked flux shape. Operation in shim mode (with banks of adjusters withdrawn) requires the operator to reduce bulk power to make sure fuel is not overrated or trip margins exceeded.

Flux flattening by differential fuelling also costs fuel. The fuelling engineer leaves fuel to achieve high average burnup in the high power central region. High parasitic absorption and reduced fission rate flatten the central flux peak. Fuelling rates in the outer core are increased to compensate, and to maintain high outer core flux.

Notice the contradictory requirements of flux flattening and high fuel burnup. If priority is always given to replacing the highest burnup fuel, the fuelling engineer will soon be trying to fuel a core with one or more hot spots. If channels for fuelling are selected with the single criterion of keeping local flux peaks as low as possible the fuelling engineer will sometimes have to discharge fuel before it has achieved high burnup.

The highest reactivity fuel is not fresh fuel, but fuel at the plutonium peak. Peak reactivity typically occurs a month to six weeks after fuelling. The delayed response makes it complicated to foresee the appropriate fuelling locations. Fuelling near detectors, which cannot always be avoided, can also produce unwanted responses, both during fuelling and later, when reactivity reaches its maximum. Computer code SORO (Simulation Of Reactor Operation) helps the fuelling engineer select channels for fuelling.

Devices

Reactivity devices used to control power in most CANDU reactors vary neutron absorption in the reactor core, i.e. they adjust thermal utilization (f).

The ***liquid zone control*** (LZC) system provides moment to moment power regulation. Fourteen light water compartments are distributed in the core near the midpoint of each reactor zone.

Helium fills the space above the light water absorber in each LZC compartment. The helium circuit gas pressure forces water out of each compartment at a constant rate. Water flows into the 14 compartments through inlet control valves. The Reactor Regulating System (RRS) adjusts the amount of neutron absorption in the compartment by varying the individual valve settings, $(\text{Valve Lift})_j$ where j = 1 to 14, according to:

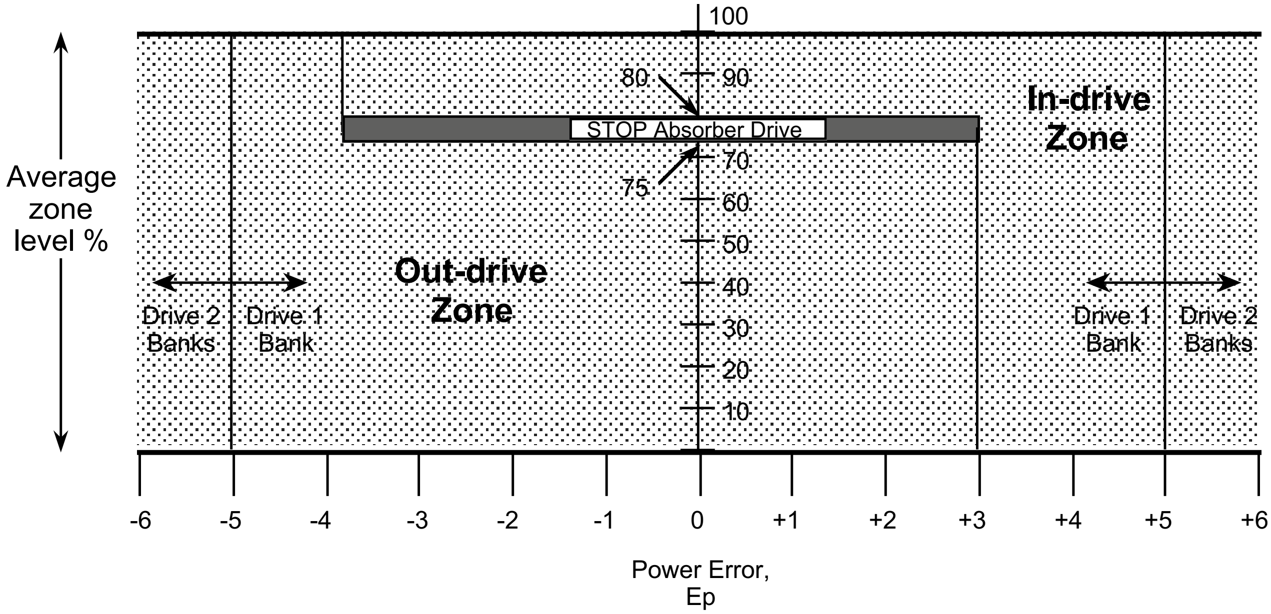
$$\mathbf{(Valve\ Lift)_j = (Bias)_j + (Bulk\ Lift) + (Differential\ Lift)_j}$$

Each valve bias setting, $\mathbf{(Bias)_j}$ matches the inlet flow to the constant outlet flow, keeping the zone level fixed. Each valve is biased near 50% open, but individual variations are needed to accommodate each different flow resistance.

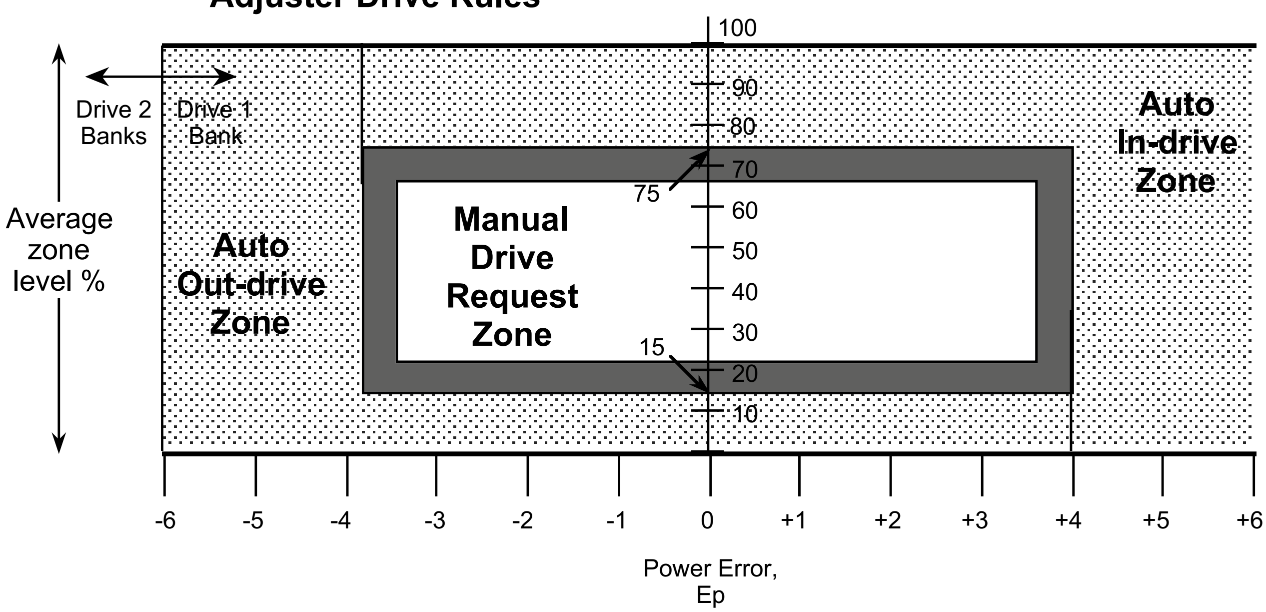
The **(Bulk Lift)** term is the same for all 14 valves. This term is proportional to the bulk power error. A power error exists when the measured power differs from the requested power. (An exact expression is given later.) The following example illustrates how the bulk power error affects zone levels.

Suppose the reactor is running at 90% F.P. and the power setpoint (request) is reduced to 80% F.P. The measured power is above the requested power, giving a positive power error and a positive (Bulk Lift) term. This causes the inlet valves to open from their bias settings. Inflow increases while outflow remains constant so the water levels rises. More neutrons are absorbed, power decreases, the size of the power error is reduced and the valves close in towards the bias settings. The zones stabilize with inflow matched to outflow and the level 5% or so higher than they were (because the fuel temperature decrease causes a reactivity increase).

Control Absorber Drive Rules



Adjuster Drive Rules



The 10% decrease in bulk power initiates a transient increase in xenon so the zone levels gradually drop to hold power at setpoint. The flux is not completely flat so the xenon buildup varies across the core and bulk power regulation, by itself, is not good enough. Individual zone adjustment are required, using the differential lift term, to limit the development of a tilt or oscillation.

The **(Differential Lift)**$_j$ term for each zone is proportional to the difference between the zone power and the average zone power. e.g. If the power in any zone is above the average, the increased valve lift for that zone increases water inflow and returns the zone power to the average.

Zone levels that are too high or too low cause operating problems. For example, to raise power the zone levels must decrease, which they are not able to do if they are too low to begin with. Paradoxically, a power decrease is also difficult if the starting level is too low. Zone level increases reduce power easily enough, but the resulting xenon transient requires the zones to drop below their starting position to hold power at setpoint.

The regulating system phases out the differential lift term gradually between 80% and 90% zone level and between 10% and 0% zone level, keeping some ability to regulate bulk power. Below 5% or above 95% level RRS acts more aggressively to prevent zones from draining or flooding regardless of the power error. If a zone drains completely, helium gas blows through the water lines. If a zone completely fills, water backs up into the helium circuits. In either case the LZC system loses its ability to regulate.

The operating staff keep the zones near the ideal 40% value by fuelling and with moderator poison adjustments if required. If average zone level goes high or low (causing loss of spatial control) RRS requests ***control absorber*** or ***adjuster rod*** drives. When the rods move, zone levels move toward their mid range positions to eliminate the power error.

A typical ***logic diagram for the rod drives*** is shown in the figures opposite. The rods also drive if the power error is large, which occurs only if the LZC system loses its ability to adequately regulate bulk power. In other words, the "drive" regions in the figures indicate rod movements attempting to restore bulk and/or spatial control.

The reactivity depth of the LZC system is extended as needed by the *manual* addition of ***poisons*** (neutron absorbing chemicals). The ***poison addition system*** can add D_2O solutions of the white powders boric anhydride [B_2O_3] → boric acid [D_3BO_3], or gadolinium nitrate [$Gd(NO_3)_3$ $6H_2O$] to the moderator. Boron or Gadolinium addition have a number of uses:

- xenon simulation
- negative shim for fuelling ahead and fresh fuel shim
- establishment of GSS

Xenon simulation is the addition of negative reactivity when normal Xe-135 is not present, e.g. after a long shutdown, when xenon has decayed, or on a restart immediately after a poison out, when I-135 is missing and xenon quickly burns out. After a day or two of steady operation the xenon returns to normal.

A poison shim is used to offset the positive reactivity of fresh fuel. Higher than normal fuelling rates may be used in anticipation of a fuelling machine maintenance outage. For a new reactor loaded with fresh fuel a much larger shim is required and must remain in place for weeks or months until the core approaches equilibrium burnup.

A guaranteed shutdown state (GSS) must be established whenever an important layer of defense in depth is removed, e.g. if SDS#1 or SDS#2 is taken out for maintenance or if RRS is unable to regulate bulk power.

Finally, RRS can *automatically* add gadolinium using the poison addition system (if it is selected to AUTO). This facility is activated on a high positive power error. The rate of negative reactivity addition is sufficient to overcome a reactivity increase from xenon decay or poison removal by inadvertent purification system operation.

There are a number of reasons for choosing boron or gadolinium for a particular use, but two properties of the poisons are particularly important:

- Boric acid is only weakly ionized, while gadolinium nitrate in solution is strongly dissociated.
- The microscopic absorption cross section of gadolinium in much larger than that of boron (by a factor of 64).

Because of its weak ionization, boron removal by ion exchange (IX) resins is slow and expensive. The IX resins and the boron solution reach equilibrium with about 6/7 of the boron attached to the resin and 1/7 in solution. Two or more columns are needed to achieve low boron concentration (1/7 x 1/7 ≈ 2%). An additional complication is that the IX resin holds the boron ions weakly, so they are easily displaced back into solution by other impurities.

For Gd removal a single IX column is used many times before it becomes saturated. The resins remove essentially 100% of the Gd passing through them. For a fixed flow rate they remove a constant fraction of the gadolinium each second. If the initial concentration is C_0, corresponding to initial mass m, and the flow rate is F, then the concentration after time t is $C(t) = C_0 e^{-Ft/m}$. This implies a half time for removal T_ ∝ 1/F. Based on purification cost and operating flexibility, gadolinium would always be the reactivity poison of choice. There are, however, a few circumstances that favour boron.

The high ionization of Gd promotes radiolytic dissociation of moderator water into D_2 and O_2 gases. Gadolinium should not be used if radiolysis is a problem.

At high power, poison burnout is much faster for gadolinium than for boron [$C = C_0 e^{-\sigma\phi t}$]. The Gd burnout rate and xenon buildup rate T_ are comparable, making Gd useful for xenon simulation. For xenon simulation by boron, IX columns must be in service. If there is a problem with purification (e.g. a second column is not available) there is risk that the reactor will poison out.

Conversely, when a long term shim is required, it is convenient to use boron (burnout T_ ≈ 15 to 20 days). If gadolinium is used, it needs continuous makeup. It may nevertheless be economic to use Gd with continuous addition and purification if the shim is relatively short term.

A few other factors affect the choice of poison.

The high solubility of gadolinium, together with its high cross section, make it relatively easy to add a large mk worth of poison. Boron, especially at high concentrations, is more likely to cake out on equipment, plug nozzles and lines etc.

Gadolinium will precipitate if the pH is high.

Regulation

The logic that adjusts the LZC valves (based on error signals), and rod drive mechanisms (based on zone level and power error) has been described. A few additional features should be mentioned. At low power, where spatial xenon effects are not significant, spatial control is not used. RRS gradually phases in spatial control as power rises from 15% F.P. to 25% F.P. A low power *level control* term that keeps each zone level close to the average level is phased out as spatial control is phased in.

The expression for power error (E_p) depends on the difference between the measured and demanded power level *and also* on the difference between measured and demanded rate of power change:

$$\mathbf{E_p = K_{level}\,[P(measured) - P(demanded)] + K_{rate}\,[Rate(measured) - Rate(demanded)]}$$

K_{level} and K_{rate} are gain factors. The program adjusts these to increase sensitivity to rate difference at low power to give better stability. Typically K_{rate} is fixed at 0.5 while K_{level} is 1 at high power and drops to 0.2 below 5% F.P.

The Module 10 Supplement explains how reactor power and rate of power change in the expression for E_p are measured. The ***Demand Power Routine*** within RRS calculates the demanded power and rate terms in E_p from the power and rate setpoints. The power setpoint is determined by the Boiler Pressure Control program in the turbine leading mode of unit operation, and is a direct operator input in the reactor leading mode.

Notice the distinction between the RRS *demanded power* and *setpoint*. In the example given earlier, the setpoint was reduced from 90% to 80%. If this 10% difference is inserted directly into the expression for E_p it causes a large initial change in the settings of the LZC inlet valves and a rapid initial rate of power change. Instead, the demand power routine calculates a smaller demand power and updates it with each program cycle, in effect doling out the power error a piece at a time. The demand power routine adjusts the size of the error to achieve the power ramp rate requested until the new setpoint is reached.

Control: Regulation & Protection

Setback and stepback, part of the normal regulating system, provide some protection against process system failures. In principle the regulating system, although not credited in safety analysis, can terminate any process upset except failure of the regulating system itself. In practice, the rate of stepback may not adequately limit the power pulse in certain large loss of coolant accidents. To protect against upsets[1] not terminated by regulation, CANDU reactors are equipped with two independent, fast acting safety shutdown systems.

The reactor must not be operated in a way that challenges the regulating system and risks a trip. An SDS trip in anger is a serious event. The attitude "Lets try . . . . The worst thing that can happen is a trip." removes a layer of Defense in Depth. The reactor should be operated as though normal systems are the last line of defense, keeping the special safety systems as backup.

Why Two Emergency Shutdown Systems?

Classical (Deterministic) Safety Analysis contemplates single and dual failure accidents, i.e. respectively, a process system failure, or a process system failure together with the failure of a *single* safety system. At least one of ECIS and Containment are expected to function and limit releases to the public in a worst case scenario *with the reactor shut down*.

The effectiveness of ECI and containment without reactor shutdown has not been analyzed. The risk criterion (risk = probability x consequences) meets AECB guidelines by the provision of two completely independent SDSs, each with a such a low failure probability that it is highly improbable that the reactor will fail to shut down in an emergency.

[1] A serious LOR accident in 1953 at Chalk River in the experimental reactor NRX motivated development of independent, fast acting safety shutdown systems in CANDU reactors.