Chapter 13

Reactivity Control Devices

How the Control Devices Work

Control = Regulation + Protection

- CANDU reactors use a dual computer system for automatic regulation of reactor power
  - the control room operator does not usually control reactor power directly, but monitors the automatic actions of the control computer.
- Two independent safety shutdown system, SDS #1 and SDS #2 are always poised to insert a large amount of negative reactivity
  - if their independent instruments indicate a parameter is outside its acceptable range

Regulation: requirements

- Hold reactor power at the demanded value (the power setpoint)
- Increase or decrease reactor power gradually at the controlled rate requested.
- In the high power range maintain spatial power control as well as bulk power control
- If bulk or spatial control or other parameters cannot be regulated, provide power setback or stepback to regain control and avoid challenging the SDSs

Protection

The 4 Special Safety Systems

Protective Systems

- There are four special safety systems
  - SDS #1 for independent rapid shutdown
  - SDS #2 for independent rapid shutdown
  - Emergency Coolant Injections
    - » to refill the Heat Transport System with water, rewet the fuel, and provide long term inventory and cooling after a loss of coolant accident
  - Containment System
    - » to prevent or limit radiation from escaping to the environment if there are fuel failures on a loss of coolant accident

The Capabilities of the SDSs

- Rate and Depth of Shutdown
  - these are fixed at the design stage by analysis of worst case design basis accidents
- Each SDS must be able, acting alone, to reduce reactor power to an acceptable level
- Each SDS must have an effective primary and backup trip for each upset.

SDS #1

- A set of 28 or 32 rods, cadmium tubes sheathed in stainless steel,
- Held out of core, against springs, by electric clutches that de-energize if any trip parameter is outside the acceptable range
- Fall by gravity (spring assisted start) into the core
- Worth at least 80 mk in newer stations
  - no credit given in the safety analysis to control absorbers dropping or zones filling,
    - the regulation system does this when it senses a trip.

SDS #2

- 6 to 8 tanks of Gadolinium Nitrate solution
- Injected through nozzles into the moderator by high pressure helium
- Quick acting valves apply the helium pressure when any trip parameter is outside its acceptable range
- Newer stations can inject more than 50 mk in a second and about 100 mk in just over 3 s

CANDU Reactivity Devices

Regulation

Physics of Reactivity Control

- The reactivity devices adjust the amount of absorbing material in the core
- This affects thermal utilization, f.
- Other reactivity control methods are possible:
  - » moderator temperature adjustments change reactivity, by density, path length, and spectrum effects
    - occasionally use in a limited way if fuelling machines are unexpectedly unavailable
  - » reducing moderator level increases leakage and reduces reactivity
    - was part of the control system in early CANDUs
  - » moderator dump: fast neutrons leak out and fission stops
    - simple, reliable but slow shutdown system in early, small CANDUs
  - » booster rods have been used in some CANDUs
    - no longer available or licensed for use

Rod Worth - Driven Slowly

- A rod is worth more in a high flux region than in a low flux region.
- As a rod is driven in, it starts in a low flux region (the top of the core) and then has more "bite" as it drives further.
- However, the rod itself depresses the flux in the region where it is being driven, making the rod less effective again at the end of travel.

Flux Distortion

- If the rod is driven in as a reactivity "shim", i.e. with the reactor still at power and the liquid zones dropping to compensate for the absorption in the rod
  - the flux depression at the location of the rod will be compensated by flux increase elsewhere
  - resulting in a distorted flux shape
- e.g. a rod driven into a high flux region near the middle "pushes" flux to the edge
  - it reduces reactivity mainly by absorption, but
  - partly by increased leakage.

Rod Worth - dynamic reactivity

- When SDS #1 rods drops quickly into core the prompt population immediately collapses
- The subcritical flux in the core comes from amplification of the delayed neutrons
- The delayed neutrons will be strongest where the pre-trip flux was highest & post trip flux is also highest at these locations
- SDS #1 rods are inserted, by design into the high flux regions, giving them maximum “bite”
  - Safety analysis, nevertheless, conservatively assumes “static” rod worths
  - the rods are assumed to cause flux depressions where they are inserted, reducing their bite.

the liquid zones

- 14 liquid zone compartments (variable H_2O level) distributed in the core
  - these are the first line of regulation for the automatic regulation system
  - they regulate bulk power and spatial power distribution
- The “worth” of the zones is about 0.07mk per % zone level
  - 7 mk from completely empty to completely full
  - best operating practice is to keep them near 40% , but definitely in the 20% to 80% range.
    - » this allows about +1.5, - 3 mk available

the control absorbers

- 4 Control Absorbers - same construction as SOR (cadmium tubes sheathed in stainless steel)
  - normally not in the core, poised for
    - » setback (gradual power reduction) and
    - » stepback (sudden power reduction)
  - setback and stepback are not completely independent of the regulating system
    - » they use the same instruments and are operated by the same control computers,
      - but are run by different computer software
    - » they are an integral part of the regulating system design to help make it more robust.
  - also used by regulating system if zones run out of room high

the adjuster rods

- A set of Adjuster Rods (mildly absorbing stainless steel rods) is normally in the core.
  - typically 21 or 24 rods in 6 or 7 “banks” of 2 to 4 rods
  - these can be removed from the core one bank of rods at a time to increase core reactivity, e.g.
    - » for override of a xenon transient
    - » reactivity shim when fuelling is not adequate
- Their function in core is to flatten the flux shape to allow a more even power distribution

Adjusters - reactivity shim

- Notice that each bank of adjusters, on removal, has the equivalent reactivity of approximately 50% zone level.
- If zones are low (15% level, say), withdrawal of 1 bank of adjusters while the zones hold the reactor power constant, results in zone level rising to about 60%
- Some flux flattening is lost with adjusters removed
  - it may be necessary to reduce bulk power to limit local flux peaks (hot spots)

Adjuster

- Adjuster banks must be removed and inserted in the correct, analyzed, design sequence
- Local flux peaks must be limited
  - operating rules determine the power reduction necessary before a bank can be withdrawn
  - analysis is invalidated if the sequence is changes
- The actual worth of a rod bank changes, dependant on the configuration of other rods in core

Adjusters

- The reactivity worth of a rod depends on the flux shape.
- A rod near the high flux center of the core has more reactivity worth than one at the edge.
- If the flux shape is increased or decreased in a region because other rods are deployed out of sequence, than the rod worth will not be what was analyzed
  - its effect will not be as predicted.
  - such rod interactions are called
    - » shadowing (when another rod reduces the rod worth)
    - » anti-shadowing (when another rod increases the rod worth)

Adjusters: Shim and Override

- When adjusters are removed to override xenon the core flux is less peaky than if the rods are removed to compensate for insufficient fuelling (i.e. to raise zone levels)
- Xenon transients are highest where the flux was highest, so the high peaks are normally depressed by the xenon.

the poison addition system (& purification)

- An addition system for soluble neutron absorbing chemical, (and purification system for removing such chemical), is used for:
  - xenon simulation
  - fuelling shim to allow limited excess fuelling
  - fresh fuel shim
  - establishing (and removing) the GSS
- Automatic (slow) addition is provided to offset reactivity addition e.g. by unmonitored xenon decay.

Which Poison Should We Use, Boron or Gadolinium?

- The text has quite a bit of information on this
- Some stations no longer use B as the removal cost is too high
- The most important features that distinguish these neutron absorbers are:
  - cross section: Gd has a much larger σ_a than B
  - ionization: Gd is strongly ionized in solution, B is weakly ionized

B and Gd, what does it matter?

- For Nuclear reasons (the cross sections) B should be used for long term shim (e.g. in the first few months of reactor operation with fresh fuel) because it burns out slowly.
- Gd should be used for xenon simulation, because it burns out at almost the same rate as xenon builds up to equilibrium

B & Gd Removal from Core

- When Ion Exchange (IX) columns are used to remove B from the core, the B ions are weakly attached to the resin.
- They equilibriate with about 5/6 of the B on the IX resin and 1/6 in the moderator water
- To clean up, a second IX column is needed, which removes 5/6 of what is left.
- This becomes very expensive if the original concentration is high.

Gd Removal from Core

- Gd is strongly ionized and the IX resins remove essentially all the Gd passing through them. Each IX column can be used many times before sending it to the waste disposal plant.
- For long term use, continuous addition and removal of Gd is less expensive than using B.
- One disadvantage is that high conductivity in the moderator water promotes radiolysis of D_2O to D_2 and O_2.
  - The recombination unit in the Moderator Cover Gas system can normally handle this with no problem.
- Other soluble compounds of Gd are being tested.

Reactivity Effects

Quick Review of Previous Chapters

burnup

- Fuel burnup at full power reduces reactivity by 0.3 to 0.4 mk per day
- This decrease can be offset by liquid zones
  - zones drop about 10% /day if there is no fuelling
- Refuelling typically increases reactivity by about 0.1 mk to 0.15 mk per channel fuelled
  - typically 4 or 8 bundles are replaced on a visit (in a channel of 12 bundles)

temperature & xenon on a maneuver

- On a power maneuver the immediate reactivity effect comes from temperature change (negative feedback)
- This is followed by a slower bulk xenon reactivity effect (slow, positive feedback)
- Since power is not uniform across the core, different xenon transient strength in different regions may trigger oscillations

device response to temperature and xenon on a maneuver

- If the zone levels are too high it is difficult to reduce power using the zones as they cannot go much higher
  - the temperature effect will add reactivity as power drops and prevent it dropping further
- It is also difficult to raise power with the zones too high
  - the initial power increase is easy, as the zones have lots of room to go down
  - the subsequent xenon transient, however, requires a large zone level increase

Equilibrium Xenon after Restart

- Restart on poison out after a trip
- The reactor is made critical as soon as possible after xenon decays following the poison out
- When the core is taken critical and power raised, the xenon will burn down, with no iodine decay to replace it
- The poison addition system is used to add neutron absorber. This is called xenon simulation
- More on start-up in Chapter 14

Cold Shutdown to Startup

- When shut down for maintenance the reactor is placed in the GSS, deeply subcritical
- Reactivity changes on warmup to zero power hot will not be a concern because the reactor will have sufficient poison to stay shut down
- Final warm up is done with pump heat and fission heat after taking the reactor critical in a controlled way.
  - the liquid zones are sized to handle the startup temperature changes

Miscellaneous Reactivity Effects

- Samarium, Plutonium, Rhodium etc. have small transient effects on a long shutdown or on restart after a long shutdown
- These effects are almost always overshadowed by xenon transient effects
- They contribute to the uncertainty of how subcritical the core is
  - demanding a careful start-up procedure (Ch 14)

  but they do not cause operational problems or problems of reactivity control.

Miscellaneous Reactivity Effects
(continued)

- The net effect of decay to Sm and Pu after a shutdown is about +6 mk, but this takes a week or two to build up.
  - on immediate restart after a poison out there is almost no net reactivity from this source
  - on restart following a long shutdown the extra reactivity is present, so is the extra 28 mk from xenon decay
  - both must be offset using poison addition
- After restart, following a long shutdown, Sm burns down faster than Pu
  - giving temporary extra reactivity for a few days

Reactivity Worth of Zones & Rod

Offsetting the Inherent Core Reactivity Effects

Zones

- The zones, if kept near their mid points by judicious fuelling
  - or use of poison addition after excess fuelling

  can compensate for immediate temperature effects on power maneuvers between, say, 50% and 100%
  - they may need to be backed up by adjuster outdrive or control absorber indrive
    - » but this is admission of failure to maintain adequate fuelling
- Adequately sized to limit and then damp out xenon oscillations

Adjusters

- On an SDS #1 trip from full power the xenon transient is likely to make the core so subcritical that it cannot be restarted for 36 hours or so
- The adjusters are sized (typically 15 to 18 mk) to allow over-ride of the transient if the rods can be fully removed in 30 to 40 minutes from the trip (design intent, but not used)
  - Considering the slow speed of the rod drives this means the decision to restart must come about 20 minute after the trip
  - Trip review always takes longer than this

Control Absorbers

- Control Absorbers are typically worth about10 mk
- On a stepback there is a prompt drop from 100% to about 50% (taking account of temperature reactivity increase)
- Subsequently, power drops as the delayed neutrons decay
  - below 10% in a few minutes
- Power can be dropped from 100% to 60% (poison prevent operation) without poisoning out
  - i.e. the transient is low enough that adjuster withdrawal can keep the reactor critical at power through the transient.

Automatic Reactor Regulation

Reactor Regulating System

RRS

Control of the Liquid Zones

- The "empty" part of the liquid zone control compartment, above the H_2O, is filled with helium at pressure, connected to a separate helium circuit for pressure control
  - Helium enters the compartment through a "bubbler" that measures the water level.
- Water is forced out of the zone compartments at a constant rate by helium pressure
- Control valves are held partly open at a bias setting that exactly matches water inflow to outflow

Valve Lift

- The regulating system moves the control valves away from the bias position to raise or lower the water level in the zone
- It is not controlling water level, however, but measured power level
- $(\text{Valve Lift})_i = (\text{Bias})_i + \text{Bulk Lift} + (\text{Differential Lift})_i$
- The label i runs from 1 to 14, labelling each zone
- Each valve is biased about 50% open, but different lengths of tubing give different flow resistances so biases are adjusted individually.

Power Increase

(Valve Lift)$_i$ = (Bias)$_i$ + Bulk Lift + (Differential Lift)$_i$

- Suppose the Operator request a power increase by typing a new power into the control computer.
- This changes the setpoint and there is now a difference (an "error") between the measured value and the setpoint.
- The control system decreases the bulk lift term on all 14 control valves (valves close in proportion)
  - this decrease water inflow while outflow stays constant
  - all 14 zone levels drop and power rises
  - bulk lift $\propto$ error, so the valves return to the bias setting when the error goes to zero.

Temperature Effect on Zone

the advantage of negative feedback

- The zone level will not be the same as it was before the maneuver
  - core reactivity is less because of the higher fuel temperature (mainly) so the zones stay lower
  - on a small, slow maneuver, the zone will simply move slowly down to the new position while the power moves gradually up
    - it is not necessary for the zones to drop to raise power and then return above the original setting to stop the rise, followed by a drop to the original setting to hold power, as they would without temperature feedback

Bulk Xenon Effect on Zone

- At higher power burns out xenon faster than it can presently be replaced
  - power will continue to rise slowly.
- The power error is based on the actual power difference between measured and demanded power, and on the difference between measured and demanded rate
  - this starts the regulating system opening the control valves again to raise zone level as the xenon burns out

Xenon Spatial Effect on the Zones

$$(\text{Valve Lift})_i = (\text{Bias})_i + \text{Bulk Lift} + (\text{Differential Lift})_i$$

- Xenon burnout is not uniform across the core, so some individual zone power measurements deviate from the zone average.
  - the regulating system adjusts the differential lift term for each zone individually to restore the power distribution
  - the differential lift term in the control algorithm is proportional to the difference between the power from the zone and the average power from all the zones.

Spatial Control

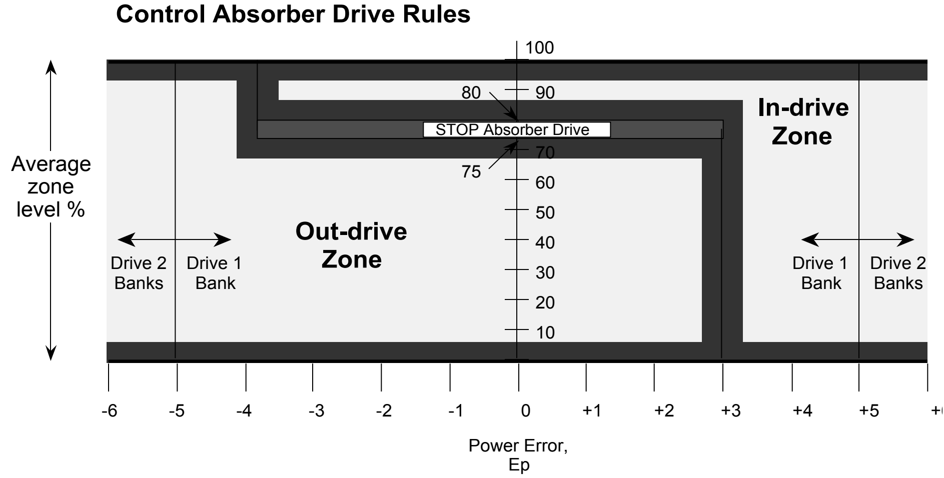
- If a measured zone level is too high or too low, the control system reserves the remaining "room" for bulk power control
- Differential lift is phased out, typically between 80% and 90% and from 10% down to 0%
- RRS tries to prevent level dropping below 5% or above 95%
  - flooding of the helium lines at high level
  - helium blow through of the water lines at low level

  fails the regulating system

Phase Out of Spatial Control

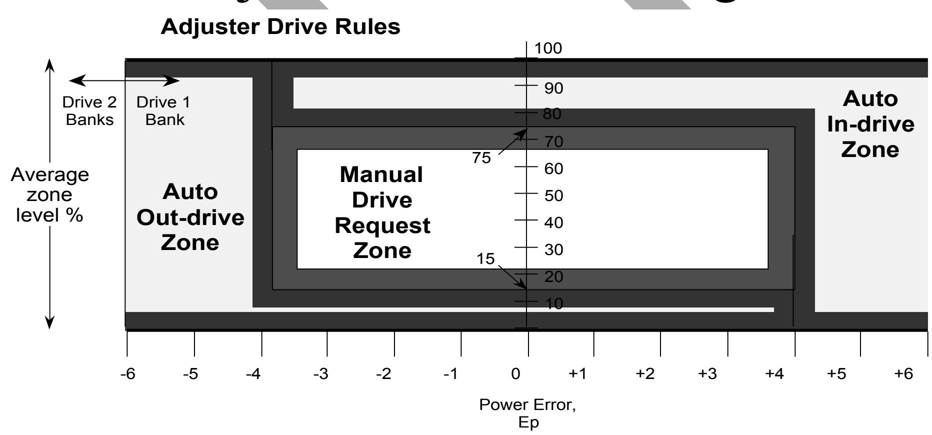
- Spatial control is not needed, and not possible once control passes to the ion chambers
- When power rises on startup, RRS phases in the differential lift term between 15% and 25% full power
- Transfer from ICs to ICDs is phased in between 5% and 15%

Control Absorber Rod Drives Logic



■ RRS is designed to drive the rods automatically when required by this logic diagram

Adjuster Rod Drive Logic



■ Once a bank of adjusters start to drive, it does not stop until it is completely out (or completely in).

Power Error E_p

- **Ep = K_{level} [P(measured) - P(demanded)]**
  + K_{rate} [Rate(measured) - Rate(demanded)]
- **Measurements were described in chapter 10**
- **Demanded values normally come from the boiler pressure control program**
  - BPC asks for reactor power to match the turbine demand.
    - » the operator gives the turbine/generator set a requested power output
  - The request can also come from the operator via the keyboard