Chapter 10

Power Measurement

Thermal, Neutron, and Fission Power
Rate of Change of Power
Power Rundown

Why do we Measure Thermal Power?

- Nuclear Reactors are expensive, complex devices for making hot water.
- The reactor ÒsellsÓ heat to the steam generators which, in turn, ÒsellÓ steam to the turbine/generator set.
- Economics (and engineering) demand regulation to match heat to requirements.
  - There are good safety reasons too (next slide)

Safety Importance

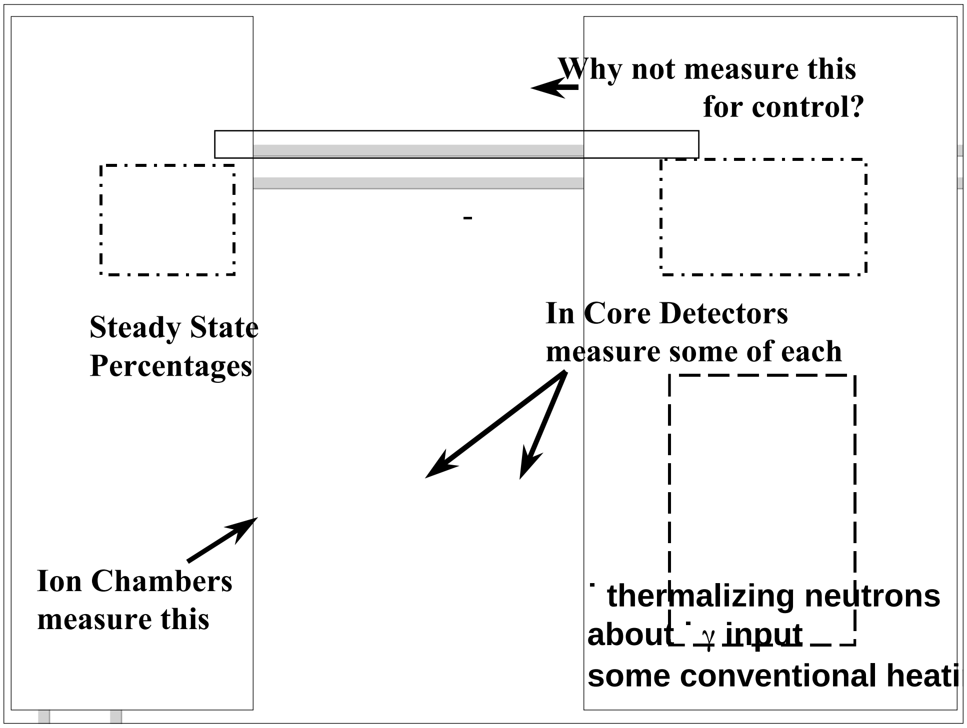
- An operating reactor contains a huge inventory of deadly radioactive stuff.
- Even with the reactor shut down, the Heat Output, if not controlled, could destroy the core and disperse the inventory.
- It is essential to have a heat sink in place, and to measure the heat produced.
  - An independant backup heat sink is poised.

Control: License Requirements

- Legal obligations of the license are:
  - ability to regulate **bulk power** at any power
    - or go to the GSS (Guaranteed Shutdown State)
  - ability to regulate the **spatial distribution** of power when at high power
  - 2 independent **emergency shutdown systems**
    - must be fully available, poised, or go to the GSS
  - ability to **monitor neutron flux and rate of change of neutron flux** whenever there is fuel in the reactor

What do we mean by ÒPOWERÓ?

- **Neutron Power**
  - proportional to fission rate,
    - excludes decay heat (& conventional heating)
- **Reactor Thermal Power**
  - the useful heat, heat transferred from the reactor to the boilers to generate steam
    - includes pump heat (friction heating)
- **Fission Power**
  - the total heat from all nuclear processes in the fuel, including waste heat.
    - excludes pump heat, or other conventional heat



Why not measure this for control?

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Steady State Percentages

In Core Detectors measure some of each

Ion Chambers measure this

˙ thermalizing neutrons
about ˙ γ input
some conventional heati

Thermal and Neutron Power are Not Proportional

Neutron Power measures only this

- When + reactivity is added to the core and thermal power increases:
  - Neutron Power (fission) increases immediately
    - heat from fission (93%) increases immediately
  - Decay heat (6%) increases gradually
    - it must wait for the buildup of more fission products
  - Heat input from the pumps and ambient losses stay the same (net about 1%):
    - decreases if main pumps are shut off after shutdown
    - small change in losses if coolant temperature changes

Why not use thermal measurements for control?

- Rate of Response is too slow
- Inadequate Range:
  - at high power, temperature stops increasing as power rises because boiling sets in;
  - at low power, temperature measurements donÕt respond to change in fission rate because of heat from radioactive decay.
- Its difficult to measure spatial distribution of power,
  - especially where needed (at high power)
  - at best, channel by channel measurements give only the radial power distribution

Core Monitoring Scheme

- Nuclear Measuring Devices (**i**on **c**hambers and self powered **i**n-**c**ore **d**etectors)
  give primary measurements:
  - they have fast response
    - the ICD prompt response is not entirely accurate
  - they are sensitive over the whole power range
    - ICDs above 5%, ICs from 10^{-7} to 150% F.P.
  - ICDs are distributed within the core
    - to allow spatial control

Thermal Power Calibration

(continuous, on-line for regulationıRRS)

- Accurate Thermal Power Measurements are used to calibrate fast nuclear instruments
  - in the high power (normal operating) range.
- On very slow power changes, thermal power lags neutron power only a little
  - calibration factors are nearly up to date (accurate).
- On faster transients the regulation system begins a correct response immediately.
  - as regulation adjusts power to the demanded level, calibration catches up, allowing accurate regulation.

Neutron Flux Monitoring

- The primary measurement response is to the rate of fission, for both ICs and ICDs
- Thermal Calibration factors are not updated as thermal power drops into the decay heat range, leaving response $\propto \phi$
- Ion-chambers remain sensitive to neutron flux as power drops lower and provide the necessary monitoring capability to 10^{-7} F.P.

Startup Instruments

- For power below about 10^{-7} F.P. sensitive ion chambers filled with He-3 or BF_3 gas are installed when needed.
  - Èfor first startup other instruments are used too
- These are connected to ÒcountersÓ and:
  - ¸ used for monitoring power for manual startup;
  - ¸ connected to SDS#1 for emergency shutdown if power goes above a preset level
- More on Startup in Chapter 14

Control: License Requirements

IN SUMMARY: REVIEW REQUIREMENTS

- Legal obligations of the license are:
  - ability to regulate **bulk power** at any power
    - or go to the GSS (Guaranteed Shutdown State)
  - ability to regulate the **spatial distribution** of power when at high power
  - 2 independent **emergency shutdown systems**
    - must be fully available, poised, or go to the GSS
  - ability to **monitor neutron flux** whenever there is fuel in the reactor

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Core Monitoring

Survey of

Instruments Used for Nuclear and Thermal Power Measurements

CANDU-6 Thermal Measurements
(typical)

- Heat Input to the Boilers
- accurate at high power, (P > 50%)
  - Measure:
    - steam flow & saturation pressure (∴ temperature)
    - feedwater flow and temperature.
- Individual Reactor Fuel Channel Powers
  - good if there is no boiling (P < 80% or so)
    - Reactor Inlet Header Temperature and Fuel Channel Outlet Temperatures
    - Channel Flows known from design

Other CANDUs I FINCH

- The Ontario Hydro CANDUs also have Fully Instrumented Channels to assist in calibrating the regulating system detectors.
- These measure inlet flow, outlet flow, and temperature increase from inlet to outlet.
  - flow differences measure steam quality
- Typically 22 such channels provide a distributed ÒsampleÓ of 480 fuel channels.

Nuclear Measurements

- Both Ion Chambers and self powered In-Core Detectors are used.
  - these respond immediately to a change in fission rate
  - ion chambers are useful over the whole range from 10^{-7} full power to 100% (and higher)
  - in-core detectors are good above about 5% full power and are distributed in the core.

Ion Chambers (9 in total)

- The Power Regulating System, SDS#1, and SDS#2 each have 3 ion chambers.
  - they sit against the outside of the calandria where they measure leakage flux
  - they are shielded against γ-rays, and made sensitive to neutrons by coating the electrodes with boron.

Uses of Ion Chambers: rate

- Rate of Power Increase is measured at all power levels
  - The Safety Shutdown Systems trip the reactor on high rate
    - 2 out of 3 measurements high vote for a trip
  - The Regulating System uses the rate measurement to anticipate required changes in zone level, to allow smooth control
    - median signal of 3 is used

Uses of Ion Chambers: power level

- The regulating system uses the median signal of 3 for bulk power control below 5% full power.
  - The Shutdown Systems do not use IC signals for any trip in normal operation, but:
    - a special low level trip is put in place, using the ICs, when the reactor is shut down
    - some trips (e.g. low HTS pressure) are automatically disabled at low power, where they are not needed, using an IC signal.

In-Core Detectors

- An emitter electrode is surrounded by insulating material that separates it from a grounded conducting sheath (the collector).
- Radiation (neutrons & γ) interact with the emitter and eject electrons that travel across the insulator to the collector.
  - creates a voltage difference
- Electrons ÒleakÓ from ground back to the emitter via connecting wires and amplifier.
  - amplified signal is proportional to radiation

In-core Detector Measurement

- The in-core detectors respond to:
  - neutrons from fission (prompt)
  - γ rays from fission (prompt)
  - γ rays from fission product decay (delayed)
- prompt radiation $\propto$ to neutron power; delayed radiation $\propto$ to decay heat; but:
- the instruments do not have a balanced response to n and γ.

In-core Instruments - characteristics

- Typical instruments under-respond to n and over-respond to γ
  - prompt response not enough,
  - delayed response too much
- They respond immediately
- But, they donÕt directly measure neutron power or thermal power
    - Èthey are somewhere in between

In-core Instruments: uses (RRS)

- The regulating system has 14 pairs of in-core detectors, one pair in each zone.
- The average of all the detectors gives the bulk power.
- Each pair measures zone power for regulating the spatial distribution of power.
- ICDs used for bulk and spatial power level only, not for rate measurements.

In-core Instruments: uses (SDS)

- Each SDS has 3 overlapping arrays of in-core instruments distributed in the core.
    - Èeach array able to measure any local high power
- High regional power sensed on 2 out of 3 arrays produces a reactor trip.
- The trip setpoints and calibration process ensure that no fuel bundle in any fuel channel reaches ÒdryoutÓ
    - Èto make sure there is no fuel center-line melting

In-core Vanadium Detectors

CANDU-6

- Vanadium emitter in these detectors capture neutrons by V-51(n,γ)V-52
    - ¸ V-52 decays by (β^-,γ) with T· = 3.76 m
    - ¸ energetic β^- (electrons) cross to the collector
- Detectors are physically quite small
    - ¸ give very localized reading
- Almost 100% neutron sensitive, but
    - ¸ like thermal, too slow for direct control.

Uses of In-core Vanadiums

CANDU-6

- An array of these detectors, feeds a large number of local flux readings to the regulating computer.
- An on-line program calculates the flux shape across the core, a ÒFlux MapÓ
  - Èan accurate map lags a sudden change by 20 min.
- Used to calculate how much of the measured bulk thermal power comes from each reactor zone
  - Èfor on-line calibration of RRS detectors

Return to Reactor Physics!

Rate of Increase:

Rate Log, Linear Rate and all that.

Heat Transfer Times

- Coolant flows from inlet to outlet of the fuel channel at almost 10 m/s, so it takes less than 1 s to cross the core.
  - this is very turbulent flow over the bundles to maximize heat transfer
    - it takes about 40 s or so to do a complete loop back to the starting point.
- Conduction from the fuel into the coolant and from the coolant into the temperature sensing device takes several seconds

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Device Measuring Times

- Thermocouples are used:
- These are slow to respond
  - instruments are inherently slow
  - they are strapped to a Òthermo-wellÓ on the exterior of the piping
  - conduction through the piping to the thermo-well is slow
  - heat capacity of the thermo-well delays temperature rise
  - signals are noisy, so are ÒfilteredÓ, making them slower still.

How important are fast measurements?

- Suppose a temperature measurement lags a power change by 10 s
- Suppose the liquid zone control system fails and adds reactivity at the maximum rate of 0.1 mk/s for several seconds
  - weÕll simplify to + 0.5 mk step addition,
  - $\Delta k/\beta = 0.0005/0.005 = 0.1$ (equilibrium fuel)
- Power increases unacceptably before the instruments detect it, and response time of the control devices extends the delay.

Unacceptable Power Rise

This in not as dramatic an example as the one in the text, but it is still completely unacceptable for safe control

Net increase 1.11 x 1.12 = 1.24 This is a 24% increase before the instruments respond. Rate of increase is $\boxed{1/\tau = 1.1\% \text{ present power/s}}$

Where did that formula for Rate of Power Rise come from?

- The next few slides finish up some details left over from Chapter 8
- Compare the power at two different times after a step addition of Δk.

As expected, power rises exponentially after the prompt jump.

x t_2

x t_1

The Rate Log Signal:

a handy formula

- The same result can be obtained by taking a time derivative of

  ln P(t) from the prompt jump equation.

This graphs as a straight line.

This is the formula for the rate of change of Log_e Power

Linear Rate and Rate Log

- The relation between linear rate and rate log is a standard calculus result.

Control Room Power Indications

- The ion chambers mostly cover a range of 6 decades from 10^{-7} to 10^{-1} of full power
- The in-core detectors mostly cover the last decade of power from 10% to 100%.
- Control room linear power meters give power as % full power (the linear meters)
- Control room log power meters give the power output in ÒdecadesÓ.
  - e.g. - 3.3 decades is $10^{-3.3} = 5 \times 10^{-4}$ of F.P.

So what is the Rate Log about?

- Rate: change in power per second.
- The linear rate (which is not measured) is % of F.P. change per second
- The rate log is 1/P x the linear rate:
  - it is the fractional change per second
- The rate log (measured by ion chambers) is the % Present Power/s
- $1/\tau$ = % P.P./s = (1/P) % F.P./s

Calibration

RRS Detectors

(corrected by computer software)

SDS#1 & SDS#2 Detectors

Compensation and Calibration

RRS - Example: A Power Increase

- **The raw detector signal is multiplied by, for example, 1.04.**
  - **This compensates for the under response of the detector to prompt radiation.**
- **The difference between the thermal power measurement and the neutron power at an earlier time is added to the signal.**
- **The time shift in nuclear power signal equals the natural delay in thermal measurements**
  - **the difference is an accurate correction to the detector signal several minutes ago.**

Calibration

$P_{ic} = 1.04\text{€} P_i + (P_{th} - 1.04\text{€} P_{i\ delayed})^{filtered}$

- If power, P_i, is not changing,
  - $P_{ic} + P_{th}$ and the regulating system is actually controlling on thermal power.
- If power is changing slowly (as happens e.g. as xenon decays - Chapter 11)
  - the correction several minutes ago is almost the same as the correction now.
- On a fast transient RRS respond quickly
  - $1.04\text{€}P_i$ changes quickly, $(P_{th} - 1.04\text{€}P_i)_{delayed}$ catches up gradually

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An Alternate Viewpoint

$P_{ic} = P_{th} + 1.04\text{€} (P_i - P_{i\ delayed})$

- This re-arrangement ignores some signal noise filtering (an oversimplification)
- The control system appears to control on thermal power, and,
  - to correct for the slow thermal response, it adds the difference between the neutron measurement now and what it was when the thermal measurement was made.

SDS Detectors

- The safety systems are completely independent of the regulating system
  - they cannot use the computer
- Compensations is added by a Òblack boxÓ.
- Over-response to decay γ after a power change is corrected by a series of filters with time constants = the decay constants of the main fission products.

Power Rundown

Neutron Power

Thermal Power

Neutron Power Rundown

- Decrease in neutron power after a trip can be considered in 3 phases:
  - the prompt neutron population collapses
    - less than few seconds
  - neutrons from subcritical multiplication of the delayed neutrons decrease rapidly as the delayed neutron precursors decay
    - about 5 minutes
  - long gradual decrease in neutrons from subcritical multiplication of the photo-neutron source as fission product energetic γ emitters decay.

Modelling the Power Rundown

- The dynamics equation from the Chapter 8 lesson can be used to model the power rundown after a trip.

- Assume 100 mk ($\Delta k = -0.100$) is suddenly added to the core

Size of the Prompt Drop

- É is 0.005/(0.005 + 0.100)
- É = 5%
- This is the observed flux from subcritical multiplication of the delayed neutrons.
- The observed flux will fall gradually over the next 5 minutes as the various delayed neutron precursors decay.

The Prompt Drop: drop time

- The equation models the prompt drop well
  - ¸ time constant τ_R is about 0.001/0.100 = 0.01s for a -100 mk reactivity addition.
  - ¸ the prompt population collapses in a few lifetimes, less than 0.1 s
    - È leaving power at the 5% level

Rundown Following the Prompt Drop

- The gradual rundown following the prompt drop
  is less well modelled
  - (τ is negative for - Δk)
- This equation assumes all delayed neutrons have the same lifetime
- Instead, imagine a sequence of such exponentials as each of the short lived fission products decay.

Long Term Rundown

- For Power Rundown, the photoneutrons are not very different from the delayed neutrons
  - they have lower concentration
    - so their effect is not seen till the d.n.s decay
  - they have longer half lives so the rundown will be much slower and take longer

Thermal Power Rundown

- On a reactor trip, the fission heat drops almost immediately to 5% or so of F.P.
- At the moment of shutdown, the % heat from each source other than fission heat, is the same as shown at the beginning of this lesson
- 6% decay heat and 1% pump heat
- Decay heat drops to about 3% in 3 min.
  - most of the backup heat sink equipment is sized to handle a little more than 3% F.P.