chapter 12

Fast Feedback Effects of Reactivity

Fuel Temperature
Coolant Temperature
Moderator Temperature
Core Voiding

Feedback -
The Reactivity Changes as Power Changes

- When Power changes, the temperatures of reactor components change.
- In Particular, on a power increase:
  - fuel, coolant, & moderator temperatures rise
- Each of these has effects on the 6 factors in the six factor formula
- The control system must continually adjust its reactivity during a power ramp to keep the rate of rise at the demanded value

Disadvantage of Positive Feedback

- Positive Feedback makes control difficult.
  - a small reactivity addition increases reactivity so power rises faster
    - this increases reactivity and rate of rise even more
  - the control system responds with a large negative Δk insertion to limit rise
    - power decreases a little and causes a decrease in reactivity, triggering a faster and faster drop
  - the system is inherently unstable
  - a fast, responsive control system with large Δk insertion capability is essential

Large Negative Feedback is also a Problem

- The control system must fight core reactivity changes to have any effect
  - to raise power the control system must insert large positive reactivity:
    - to give the required rate of increase
    - to overcome the reactivity lost during the increase
  - on a power decrease, reactivity increases:
    - making it difficult to drive the power down in an emergency
  - the control system must have the capability of adding large amounts of reactivity quickly

The Inherently Safe Reactor

This has not yet been designed

- Ideally the reactor should be "self regulating" under all circumstances
- A small negative feedback causes the rate of power rise to decrease naturally as power rises to the demanded level
  - only gentle control system intervention is required, and "runaway" is impossible
- The increased reactivity on a power drop is small enough that shutdown is easy.
- CANDU has some of these features.

CANDU Temperatures: control

Fuel

Coolant

Moderator

Fuel Temperature -800°C (full power)

- The ceramic UO_2 fuel pellet is not a good heat conductor
  - at full power the hottest fuel elements have center line temperatures near 1800°C
  - for adequate transfer from fuel to coolant, the sheath temperature is 50°C greater than the coolant temperature (approx.)
  - "Average" fuel temperature is over 700°C,
  - dropping on shutdown to about 10°C higher than coolant temperature
    - because of decay heat

Coolant Flow

- Heavy Water coolant flows through the fuel channels at about 25 kg/s
  - speed is near 10 m/s
- This highly turbulent flow maximizes heat transfer from the fuel
- 4 large Heat Transport System pumps maintain circulation fairly constant:
  - Coolant density changes from, approx.
    - 1.1 g/cm^3 (cold) to 0.86 g/cm^3 (hot)
  - Flow resistance changes a little with onset of boiling (some channels) at high power.

$T_{coolant} \approx$ 290°C (hot) - (average T)

- The coolant transfers heat to the boilers
  - the boiler steam/water saturation pressure is held constant (almost 260°C, 4.5 MPa)
- As power increases, most of the extra heat is transferred to the boilers
  - $T_{coolant}$ (boiler outlet, reactor inlet) $\approx$ 260°C - 270°C
  - $T_{coolant}$ (reactor outlet, boiler inlet) $\approx T_{sat}$ (D_2O)
    At full power $P_{sat} \approx$ 10 MPa, T_{sat} (D_2O) $\approx$ 310°C
    - depends on the heat input from the fuel
    - $\Delta T \approx$ 40°C from inlet to outlet at full power

Moderator Heat Load and Cooling

- Heat input to the moderator is about 5% of the total fission heat (about 100 MW)
  - from thermalizing neutrons
  - from γ ray absorption
  - transfer from the hot pressure tubes
- Moderator Heavy Water is pumped through two large heat exchangers
  - flow is constant
- Cooling water flow to the shell side of the heat exchanger is controlled
  - to keep moderator temperature constant

Moderator Temperature Control

- Control Systems Vary
  - simple: only moderator T_{outlet} is measured
  - complex: moderator T_{inlet}, T_{outlet}, $T_{cooling\ water}$, & Power are all used for control variables
- $T_{moderator}$ is dominated by mixing of cooled inlet water with calandria water
  - at low power, forced (pumped) circulation dominates
  - at high power natural (convection) circulation dominates.

Moderator Temperature T ≈ 70°C (hot)

- Even with the moderator T_{outlet} held constant, bulk moderator temperature varies with power
  - Thermal Expansion causes D_2O to rise into the overflow ducts as power rises.
  - Moderator Level drops as power falls.
- The control systems will keep the bulk temperature within 60°C to 70°C range
  - unless shutdown and cooled down

CANDU “Benchmark” Temperatures

(typical average values)

SUMMARY	Cold, Shut Down	Zero Power Hot	Full Power
Fuel	30°C	270°C	800°C
Coolant	30°C	265°C	290°c
Moderator	30°C	65°C	70°C

Physical Effects of Temperature

Molecular Speed

Thermal Expansion

Thermal Expansion

- Recall the formula for
  macroscopic nuclear cross section, Σ (cm^{-1})
  - $\Sigma = N\sigma$
    - σ is microscopic cross-section (cm^2) - "target size"
    - N is nuclear target density ($\#/cm^3$)
  - Σ is the "probability" of a neutron interaction with a nuclear target per cm of travel
- When materials expand on heating, the nuclei are pushed further apart
  - N decreases so Σ decreases

Nuclear Effects of Thermal Expansion

- path lengths between neutron interactions increase
  - mean free path (mfp) = Σ^{-1}
- Rate of Interaction, $R = \Sigma\phi$, decreases
  - flux, ϕ, is (loosely) the number of neutrons criss-crossing a region each second [neutron path length "layed down" in each cm^3 each second ($cm/cm^3 \cdot s = cm^{-2}\, s^{-1}$)]
  - R is the number of nuclear reactions per cm^3 of material each second ($cm^{-3}\, s^{-1}$)

Increase in Molecular Speeds

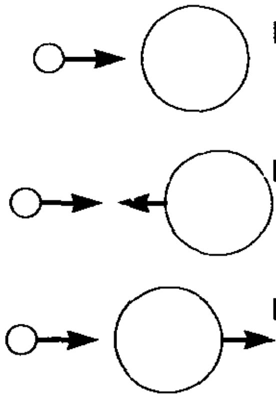
Two Important Effects

- Thermalized neutrons are in thermal equilibrium with their surroundings
  - As core materials heat up, molecular speeds increase, increasing thermal neutron energy
  - nominal energy is 0.0253 eV at 20°C
    - corresponds to neutron speed 2200 m/s
- Nuclear Targets move at higher speeds
  - This increases resonance capture of epithermal neutrons
  - U-238 is the only nucleus in the core with: (1) significant resonances, (2) large quantity

Some Terminology

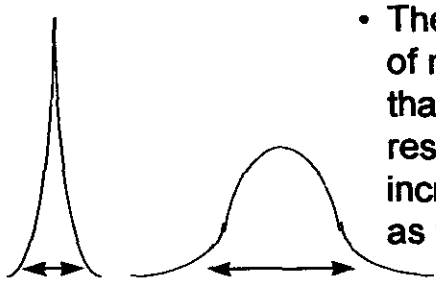
- Effects caused by density changes are known simply as *Density Effects*
- Resonance Broadening which causes increased epithermal neutron capture in U-238 is called *Doppler Broadening* or the *Doppler Effect* or *Resonance Broadening*
- Effects caused by thermal neutron speed changes are known as *Spectrum Effects*
  - *spectrum hardening* refers to "hotter" neutrons
  - *spectrum softening* refers to "cooler" neutrons

The Doppler Effect - Nuclear Targets in Motion



- **Nucleus at Rest**
  - only neutrons at the resonance energy are absorbed
- **Nucleus moves towards neutron**
  - neutrons below resonance energy are absorbed
- **Neutron catches up to nucleus**
  - neutrons above resonance energy are absorbed
- Fewer neutrons at resonance energy are absorbed,
- The range of neutron energies absorbed increases.

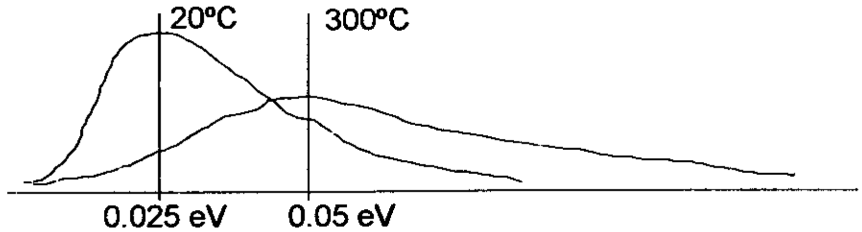
Doppler Broadening - resonance energy



- The increase in range of neutron energies that can be absorbed results in a sharp increase in absorption as the fuel heats up

- The U-238 resonances are so high that there is a near certainty of absorption of neutrons near the peak energy if they enter the fuel, whether or not the peak is lower

The Spectrum Effect



- As the core materials heat up, the thermalized neutrons share in this energy.
- The most probable & average energies increase
  - The peak of the neutron spectrum comes down and more neutrons are shifted to higher energies, but
  - not into the epithermal (resonance) energy range.

Nuclear Effects of Spectrum Hardening

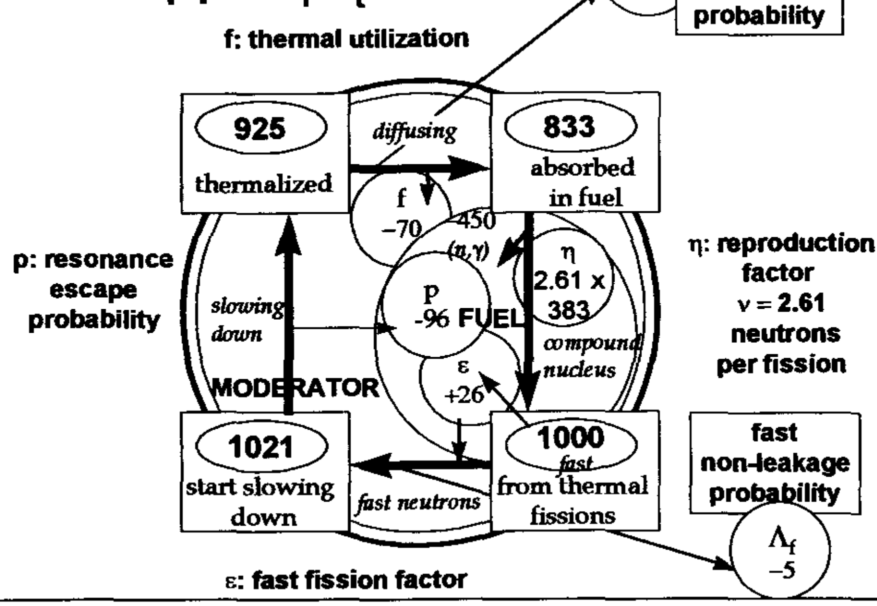
(hotter thermalized neutrons)

- The microscopic cross sections (σ) for thermal neutron interactions with nuclei vary with neutron energy
  - they decrease as neutron energy increases
  - well behaved cross sections have $\sigma \propto (1/v)$
- $\Sigma = N\sigma$ decreases, which has two effects:
  - path lengths (mfp = Σ^{-1}) increase
    - as with density decrease, but only for thermal neutrons
  - the # of Reactions/s per cm^3 ($R = N\sigma\phi$) decrease
    - this doesn't affect the number of reactions in the whole core if materials stay within the core.

Effect of Temperature Change on Reactivity

Fuel, Coolant and Moderator Temperature Changes and How They Affect $k = \eta f p \varepsilon \Lambda_f \Lambda_t$

$k = \eta f p \varepsilon \Lambda_f \Lambda_t$



$k = \eta f p \varepsilon \Lambda_f \Lambda_t$: density effect

For Moderator or Coolant Temperature Increase

- the next slide discusses path length increase due to decreased mfp = Σ^{-1}
- $R_a \downarrow$ as smaller Σ_a reduces the amount of absorption in moderator and coolant.
  - Density of absorbers (H_2O, reactivity control poisons) decreases with thermal expansion
- Thermal expansion of heavy water means there is less of it in the core.
  - fuel bundles accommodate pellet thermal expansion so total # of reactions unchanged.

$k = \eta f p \varepsilon \Lambda_f \Lambda_t$: path length effect

For Moderator Temperature Increase

- Increase in path lengths makes the reactor and the spacing between the channels (lattice pitch) seem smaller.
- Non-Leakage Probabilities (Λ_f & Λ_t) $\downarrow$
  - neutrons travel further and are more likely to reach the edge
  - bigger effect for thermal neutrons
    - both density effect and spectrum effect
- Resonance Escape Probability (p) $\downarrow$
  - unthermalized neutrons are more likely to reach adjacent channels

Doppler Broadening Effect

For Fuel Temperature Change

- Increase in fuel temperature increases resonance capture of neutrons that are slowing down through the resonance energy range. p ↓ as T ↑
- This dominate every other effect on a power changes
  - big effect: there is a large amount of U-238
  - large, fast fuel temperature change

Spectrum Hardening - Changes in Fuel and/or Moderator and/or Coolant Temperature

- Any temperature increase results in some spectrum hardening
- Only thermal neutrons are affected
  - i.e. only f, η & Λ_t in the 6 factor formula
- Λ_t decreases a little because of increased path length

$$f = \frac{\Sigma_a^{fuel}\phi^{fuel}}{\Sigma_a^{fuel}\phi^{fuel} + \Sigma_a^{nonfuel}\phi^{nonfuel}} \qquad \eta = \nu\frac{\Sigma_f\phi^{fuel}}{\Sigma_a\phi^{fuel}}$$

- f and η are descussed on the next slides

Spectrum Effect on 1/v Cross Sections

- neutron speeds increase with rising temperature
  - $\phi = nv$ increases in proportion to v
  - $\sigma = \sigma_{thermal}(v_0/v)$
  - $R = \sigma\phi$ doesn't change with temperature
- "The # of neutrons crossing the region increase, but the targets get smaller."
- This is true for 1/v cross sections even for a Maxwellian temperature spectrum with a distribution of neutron energies.

Fissile Isotopes are non - 1/v

- Neutron spectrum changes will only affect cross sections that are not 1/v
- The only important non 1/v cross sections in the core are the fissile isotopes
  - U-235
  - Pu-239

What about other stuff in the core?

- Many fission products in the core could also be non 1/v, but their effects will cancel each other out
  - there are a very large number of different types, each in small quantities

U-235 and Pu-239 Cross Sections

- Absorption and fission cross sections for U-235 both decrease faster than 1/v
  - rate of fission and of absorption each decrease somewhat with spectrum hardening
- Absorption and fission cross sections for Pu-239 decrease much less than 1/v
  - rate of fission and of absorption each increase significantly with spectrum hardening

"U-235 likes cold neutrons
Pu-239 ***really*** likes warm neutrons"

Spectrum Hardening: η $\quad \eta = \nu \frac{\Sigma_f \phi^{fuel}}{\Sigma_a \phi^{fuel}}$

- The absorption and fission cross sections both change as neutron temperature changes
- The behaviour of η for the fissile isotopes is well known
  - for U-235, η_{235} is nearly constant
    - it decreases slighty with increasing temperature
  - for Pu-239, η_{239} decreases a little as neutron temperature increases
    - even though both absorption and fission rates increase strongly with increasing temperature

CANDU fuel: η_{CANDU} $\quad \eta = \nu \frac{\Sigma_f \phi^{fuel}}{\Sigma_a \phi^{fuel}}$

- Absorption in real fuel includes absorption in materials other than the fissile isotopes
  - mainly U-238 and fission products, which show almost no net temperature dependance
- For U-235, as neutron temperatures increase, the numerator in η_{CANDU} decreases faster than the denominator
- For Pu-239, as neutron temperatures increase, the numerator in η_{CANDU} increases much faster than the denominator

CANDU: Fresh and Equilibrium Fuel

- U-235 is the only fissile isotope in Fresh Fuel
  - η_{CANDU} decreases with increasing neutron temperature for Fresh Fuel
- Equilibrium fuel contains U-235 and Pu-239. Because Pu-239 has much stronger temperature dependent cross sections than U-235, its effect dominates
  - η_{CANDU} increases with increasing neutron temperature for an Equilibrium Fuelled CANDU

Another Way to Look At It: Fresh Fuel

$$\eta_{CANDU} = \nu \frac{\Sigma_f \phi^{fuel}}{\Sigma_a^{fuel} \phi^{fuel}} = \nu \frac{\Sigma_f^{235} / \Sigma_a^{235}}{1 + \frac{\Sigma_a^{other}}{\Sigma_a^{235}}} = \nu \frac{\eta^{235}}{1 + \frac{\Sigma_a^{other}}{\Sigma_a^{235}}}$$

- η^{235} is nearly constant with temp. increase
- The rate of absorption in U-235 decreases while the rate of aborption in "other" is not temperature dependents
- Consequently, η_{CANDU} decreases as temperature increases

Have We Forgotten f?

- f is also the ratio of cross sections
- Similar analysis shows that it behaves very much like η as far as the spectrum effect is concerned
  - just not as big an effect
- Full analysis is much more complicated
  - f is also affected by path length changes and density changes

Collecting up the Bits & Pieces

Fuel Temp

Coolant Temp

Moderator Temp

Additive Effects of the 6 Factors

- $k = \eta f p \varepsilon \Lambda_t \Lambda_f$
- $\ln k = \ln \eta + \ln f + \ln p + \ln \varepsilon + \ln \Lambda_t + \ln \Lambda_f$

$$\frac{d\ln k}{dT} = \frac{1}{k}\frac{dk}{dT} = \frac{1}{\eta}\frac{d\eta}{dT} + \frac{1}{f}\frac{df}{dT} + \frac{1}{p}\frac{dp}{dT} + \frac{1}{\varepsilon}\frac{d\varepsilon}{dT} + \frac{1}{\Lambda_f}\frac{d\Lambda_f}{dT} + \frac{1}{\Lambda_t}\frac{d\Lambda_t}{dT}$$

- The fractional change in k per °C change is the

  Temperature Coefficient of Reactivity

- It is the sum of the individual contributions

Typical Components of the Fuel Temperature Coefficient for a CANDU

TERM	FRESH FUEL	EQUILIBRIUM FUEL
$(1/\varepsilon)d\varepsilon/dT$	0.0	0.0
$(1/p)dp/dT$	-9.3	-9.3
$(1/f)df/dT$	-0.8	+0.3
$(1/\eta)d\eta/dT$	-4.0	+5.3
$(1/\Lambda_f)d\Lambda_f/dT$	0.0	0.0
$(1/\Lambda_t)d\Lambda_t/dT$	-0.8	-0.4
TOTAL	**-15**	**-4**

(Nominal Operating Conditions.
Units are μk/°C *)

• e.g. for a 500°C increase in fuel temperature for equilibrium fuel, there is a reactivity decrease of about 2 mk

Fuel, Moderator & Coolant Temperature Coefficients

Values near full power operating conditions	Unit of mk/^{o}C	ΔT from zero power hot to full power
Fuel temperature coefficient	-4.5	530
Coolant temp. coefficient	+30	25
Moderator temp. coefficient	+70	5

- Typical Values, giving a net small prompt negative feedback effect

Summary of the Fuel Temp Effect

- The biggest single effect is increase in resonance capture due to Doppler Broadening
- The only other large contribution is from η,
  - which is adds to the resonance capture effect for fresh fuel, and,
  - partly offsets it for equilibrium fuel

Moderator Temperature Effect

- Increased temperature increases path lengths
  - p ↓ for fresh & equilibrium fuel, but f ↑ more (eqb^{m})
    - because the core is over-moderated
    - giving a small gain in reactivity for equilibrium fuel
  - f ↑ strongly in a fresh core, which must be heavily poisoned to keep k near 1
    - this dominates the decrease in p
  - there is a small increase in leakage
- η increases very strongly for equilibrium fuel
- η decreases somewhat for fresh fuel U-235

Net Effect For Moderator Temperature

- For a 10°C rise in moderator temperature, in the typical operating range of 60°C to 70°C, there is a net gain of less than +1 mk for both fresh and equilibrium fuel
- Moderator temperature control should limit this to about +0.5 mk in going from zero power hot to full power
- This small effect will appear gradually. With over 250 Mg of moderator the temperature rise is relatively slow.

Coolant Temperature Effect

- The coolant temperature effect is smaller still than the moderator temperature effect
  - and there is no control of coolant temperature independent of fuel temperature
- A temperature increase of about 25°C will increase reactivity about +0.5

Power Coefficient: definition

- Power Coefficient is the reactivity change in going from the Hot Shutdown state to Full Power
- When maneuvering power slowly in the linear power range (from about 10% F.P. to 100% F.P.) it is helpful to know how much change in reactivity is required.
- A rough rule of thumb is to take a fraction of the power coefficient
  - this assumes the reactivity change is linear over the power range, a good assumption

CANDU Power Coefficient
equilibrium fuel

- For CANDU reactors the Power Coefficient is about - 2 mk to - 6 mk
  - depending on the design and on fuel burnup achieved by the design
    - sensitive to fuel temperature
- This gives 0.02 to 0.06 mk per %
  - 5% to 10% zone level decrease for 10% power increase

Core Voiding

Fast Positive Feedback!

How much reactivity is added by voiding?

- Early estimates of the Chernobyl accident said that something like + 30 mk was inserted into the core when the coolant turned to steam.
  - this would have made the core something like 25 mk super prompt critical
- Full core voiding for CANDU with equilibrium fuel is much smaller, and most CANDU reactors have two coolant loops, limiting voiding to only ½ core.

What could cause voiding?

- Two kinds of events are considered
  - Large Loss of Coolant (LOR)
  - Fast Loss of Regulation (LOR)
    - The first could be triggered by a large pipe break followed by rapid depressurization.
    - The second may entail a failure of the regulation system, with excess reactivity added, causing boiling in the coolant followed by pipe rupture and depressurization.
- Safety Analysis must demonstrate that either SDS acting alone could limit power rise in these accidents.

Couldn't some less dramatic event cause core voiding?

- In principle, yes, but gradual replacement of coolant with steam gives the regulation system, alarms, power reduction mechanisms etc. lots of time to act.
  - It would take multiple simultaneous failures of defense in depth plus operator negligence.
- The fast LOR and the large LOCA are the accidents that challenge the safety systems the most, and establish the strictest requirements on their design.

Component of the Void Reactivity

Change in mk for Full Core Voiding (Bruce B)

TERM	FRESH FUEL	EQUILIBRIUM FUEL
$\Delta\varepsilon/\varepsilon$	5.0	5.0
$\Delta p/p$	6.0	6.0
$\Delta f/f$	3.0	2.5
$\Delta\eta/\eta$	2.3	-2.5
$\Delta\Lambda_f/\Lambda_f$	-0.8	-0.8
$\Delta\Lambda_t/\Lambda_t$	-0.3	-0.3
TOTAL	**15**	**10**

CANDU 6 Void Reactivity is a little less than this, and it is a two loop system

Notice the relative sizes of the various contributions.

Contributions to Voiding - ε & p

fast fission factor and resonance escape propability

- Neutrons escaping from the fuel often encounter D_2O in the fuel channel before reaching the moderator.
  - a single collision with a deuterium nucleus may reduce the typical fast neutron energy (2 MeV) to below the threshold for fast fission in U-238
  - a couple of collisions can put fast neutrons into the resonance energy range.
- Without this early moderation in the channel,
  - there are more fast fissions (more fast neutrons)
  - less resonance capture (fewer epithermal n)

Contributions to Voiding - η reproduction factor

- The coolant temperature is near 300°C while the moderator temperature is closer to 70°C.
- When well thermalized neutrons enter the fuel channel on their way into the fuel they often encounter heavy water coolant
  - this re-warms them from 70°C to a higher temperature.
- Without this rewarming (after voiding) the neutrons are much cooler, this makes:
  - fresh fuel more reactive and
  - equilibrium fuel less reactive

Contributions to Voiding - f

thermal utilization

- The f contribution to voiding is nearly the same size as the η contribution
- It could be much worse than this
  - administrative procedures limit the minimum coolant isotopic to about 97.5%
    - i.e. 97.5% D_2O or more; less than 2.5% H_2O
- There is some absorption of neutrons by the H_2O impurity. When the core voids this absorptions stops and f increases.
  - this was the main contribution to void reactivity at Chernobyl

What about a large negative void reactivity?

- A large negative void reactivity is a bad idea. (Small negative would be ideal).
  - Consider an accident where voiding occurs gradually, with the regulation system keeping everything under control
  - Then protective action by a safety system or operator actions causes the voids to collapse.
- The void collapse accident also leads to catastrophe.