SUPPLEMENT TO CHAPTER 12
OF
REACTOR PHYSICS FUNDAMENTALS

This supplement summarizes some key physics principles in the text and expands on the mathematical treatment. You should be familiar with the text material before you study this supplement.

Fast Feedback Reactivity Effects

Physical Effects of Temperature:
thermal expansion
molecular speeds

Effects on Reactivity Factors: η, f, p, ε, (Λ_t & Λ_f)

Fuel Temperature Effect

Moderator Temperature Effect

Coolant Temperature Effect

Core Voiding:
effects on ε & p
possible effect on f
effect on η

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PHYSICAL EFFECTS OF TEMPERATURE

Increasing the temperature in the reactor core has two physical effects, causing three types of change in nuclear processes (in bold print below):

Thermal expansion, Reduced Density of the Heated Materials
Atoms/molecules push further apart from one another, so density decreases, (**THE DENSITY EFFECT**).

Increase is Molecular Speeds
As materials are heated, the kinetic energy of the atoms and molecules increases. The increase in molecular speeds has two nuclear effects, caused because:
the U-238 nuclear targets move faster, (**DOPPLER BROADENING**),
the thermalized neutrons move faster, (**THE NEUTRON SPECTRUM EFFECT**).

Chapter 12 is about reactivity changes caused by temperature changes in the fuel, coolant and moderator. This supplement looks at how each of the factors in the six factor formula, $k = \varepsilon p f \eta \Lambda_f \Lambda_t$, changes with temperature because of these three effects. First, consider these processes one at a time:

1. THE DENSITY EFFECT

Lower density affects macroscopic cross sections. Recall the formulae for reaction rate (R), macroscopic cross section (Σ), and mean free path (mfp):

$$R = \Sigma\phi \qquad \Sigma = N\sigma \qquad mfp = 1/\Sigma$$

Density and N, (the number of nuclear targets per unit volume) decreases as temperature increases. Macroscopic cross sections of the heated material decrease and neutron path lengths increase.

Reaction rates (reactions per cm^3 per second) decrease, but this is not always important. For example, if a fuel bundle expands, the rate of reaction per bundle stays the same.

For example, an increase in neutron path lengths, particularly with moderator heating, increases neutron leakage and resonance capture in adjacent fuel channels, but decreases moderator absorption.

2. DOPPLER BROADENING

The nuclear targets in hotter materials move at higher speeds. This has *one* important effect; U-238 resonance capture of slowing neutrons increases dramatically. Only a **fuel temperature increase** can increase the U-238 vibration, and only **epithermal neutrons** (neutrons in the resonance energy range) are affected. This effect is explained in the text.

The net effect is to reduce resonance peak height and to broaden its energy range. In figure 12.13 (or 3.3) the sharp narrow peaks are made lower as temperature increases, but the valleys between the peaks are filled in. This increases the probability of capture in U-238 throughout the resonance energy range.

3. THE NEUTRON SPECTRUM EFFECT

Thermal neutrons interact with hotter materials, share the energy of their surroundings, and move faster. Microscopic cross sections decrease at higher neutron speeds. This may have two separate effects:

<u>neutron path lengths</u> increase because of the energy dependence of the microscopic cross section, σ.

Recall that most cross-sections behave approximately as $\sigma \propto 1/v$.
Since $\Sigma = N\sigma$ and $mfp = 1/\Sigma$, Σ decreases and mfp increases.

The <u>reaction rate</u> for an induced reaction, $R = \Sigma\phi$, may or may not change.

Recall that $\phi = nv$ and $\Sigma = N\sigma$. An increase in average neutron speed, v, increases the thermal flux, ϕ, while the cross section, σ, decreases with increased neutron speed. In simple words, shifting the neutron spectrum to higher speeds increases the number of thermal neutrons crisscrossing a region, but at the same time decreases the size of the targets in that region. These two effects tend to offset one another.

For a 1/v cross section the decrease in σ exactly offsets the increase in ϕ so the temperature change has no effect on the reaction rate. Fissile materials such as Pu-239 do not have ideal 1/v cross sections, so reaction rates in these materials change with temperature.

While neutrons are slowing down the energy loss per collision is not affected by the temperature of the atoms the neutrons collide with. Reactor core temperature changes cannot affect fast and epithermal neutrons.

Spectrum Effects on η and f

Reproduction Factor, η.

The CANDU temperature coefficients are different for fresh fuel and equilibrium fuel. The difference is mainly caused by η.

Consider how η changes for fresh CANDU fuel as the temperature of the core increases. One *physical effect* is that warmer neutrons enter the fuel. The fission and absorption cross sections of substances in the fuel are different for different neutron energies.

$$\eta_{fresh}^{CANDU} = \frac{\nu\Sigma_f^{U-235}}{\Sigma_a^{U-235} + \Sigma_a^{U-238}} = \frac{\nu\Sigma_f^{U-235} / \Sigma_a^{U-235}}{1 + \Sigma_a^{U-238} / \Sigma_a^{U-235}} = \frac{\nu\sigma_f / \sigma_a}{1 + \Sigma_a^{U-238} / \Sigma_a^{U-235}} = \frac{\eta^{U-235}}{1 + \Sigma_a^{U-238} / \Sigma_a^{U-235}}$$

For pure U-235, $\eta^{U\text{-}235}$, is almost constant in the thermal neutron energy range. (It decreases very slightly with energy. However, the denominator of η^{CANDU} increases for warmer neutrons, so the spectrum effect causes η^{CANDU} to decrease. The rate of absorption in U-235, $\Sigma_a\phi$, decreases for warm neutrons, while the absorption rate in the other materials *in the fuel* is independent of temperature.

For pure Pu-239, η^{239} *decreases* slightly with increasing neutron energy in the thermal neutron energy range. Both σ_f & σ_a decrease much less than 1/v, giving a very strong increase in reaction rates. The rate of absorption in Pu-239 is so strong that it dominates U-235 in equilibrium fuel, so $\eta_{equilibrium}^{CANDU}$ increases as neutron temperature increases.

Thermal Utilization Factor, f.

The thermal utilization factor, f, is defined in terms of cross section ratios, so one also expects it to change with neutron temperature, much as η does. There is, however, an interesting offsetting effect called the thermal disadvantage factor.

$$f = \frac{\phi_{fuel}\Sigma_a^{fuel}}{\phi_{fuel}\Sigma_a^{fuel} + \phi_{\mathrm{mod}\,erator}\Sigma_a^{non-fuel}} = \frac{\Sigma_a^{fuel}}{\Sigma_a^{fuel} + (\phi_{\mathrm{mod}\,erator}/\phi_{fuel}) \times \Sigma_a^{non-fuel}}$$

$$f = \frac{1}{1 + (\phi_{\mathrm{mod}\,erator}/\phi_{fuel}) \times (\Sigma_a^{non-fuel}/\Sigma_a^{fuel})}$$

where the ratio ($\phi_{moderator}/\phi_{fuel}$) is the thermal disadvantage factor.

The effect of a neutron spectrum change caused by a temperature change in the surroundings is, again, accounted for by comparing the reaction rates. In fresh fuel (no Pu-239) $\phi\Sigma_a$(fuel) decreases as neutron temperature increases. With significant Pu-239 present, $\phi\Sigma_a$(fuel) increases as neutron temperature increases. The correction is much larger for Pu-239 than for U-235, so Pu-239 dominates the behaviour of equilibrium fuel.

An increase in neutron absorption in the fuel depresses flux in the fuel, i.e. when
Σ_a(non-fuel)/Σ_a(fuel) decreases, $\phi_{moderator}/\phi_{fuel}$ increases and partly offsets the change. The result is that part of the change in f is similar to the change in η, but not as large.

Thermal utilization, f, is also affected by density changes, so its behaviour is more complicated than the behaviour of η. With poison in the moderator, or with low moderator isotopic, the density dependence (e.g. with a moderator temperature change) is likely to be the dominant effect.

PHYSICAL REASONS FOR CORE TEMPERATURE AND VOID REACTIVITY FEEDBACK EFFECTS

k_{eff}	↑ FUEL TEMPERATURE	↑ MODERATOR TEMPERATURE	↑ COOLANT TEMPERATURE	100% VOID
η	spectrum effect neutrons are hotter ↓ for U-235, ↑ for Pu-239 **large effect,** but always dominated by p effect	spectrum effect neutrons are hotter ↓ for U-235, ↑ for Pu-239	spectrum effect neutrons are hotter ↓ for U-235, ↑ for Pu-239	spectrum effect(loss of re-warming by the coolant) neutrons are cooler **large effect** ↑ for U-235, ↓ for Pu-239
ε	no significant effect depends on U-238 content & fast flux These don't change.	no significant effect depends on U-238 content & fast flux These don't change.	density effect decrease in density - slight increase in fast flux in the channel - small effect.	density effect flux of fast neutrons in the channel increases **major effect**
p	Doppler Broadening vibration of U-238 targets increase so absorption of epithermal neutrons increases. p↓ **major effect**	density effect longer path lengths increase epithermal neutron population in adjacent channels. p↓	density effect Epithermal flux reduces a little in channel of birth, so there is less resonance capture. p↑ - small effect	density effect flux of epithermal neutrons in the channel decreases **major effect**
f	spectrum effect changes like η, but reduced because of the thermal disadvantage factor (ϕ_m/ϕ_f)	density effect less moderator absorption. Spectrum effect may adds to or partly offsets this effect f↑	spectrum & density effect slightly fewer scatters from hotter molecules some reduced absorption because of density effect	density effect reduces absorption. **Large effect**; limited by keeping coolant isotopic high. Also a spectrum effect.
Λ_f	no significant effect depends on slowing down path length and geometry	density effect increases path length so fast neutrons travel further	density effect insignificant increase in path length	density effect small increase in path length
Λ_t	spectrum effect increase in thermal neutron path length because cross sections decrease.	path length increases due to both density effect smaller cross sections	path length increases a little due to smaller cross sections	small increase in path length density effect slightly offset by larger cross sections

COOLANT VOIDING

Void Coefficient is often defined as the reactivity change per % void. The void characteristics of a CANDU core are given by reporting the reactivity change that occurs for 100% voiding of the channels. Most CANDUs have two heat transport system loops that isolate on a loss of coolant. The reactivity change for half core voiding is much smaller than for full core voiding.

For the CANDU core, the biggest contributor to void reactivity is caused by the loss of moderation in the coolant channel. With voiding, fast neutrons from fission, escaping from the fuel, do not begin slowing down in the coolant. This increases the number of very fast neutrons near the fuel, and decreases the number of resonance energy neutrons. As a result, both ε & p increase sharply.

Thermalized neutrons entering the fuel from the moderator do not undergo spectrum warming by interactions with the coolant. This has a large effect too: η increases for fresh fuel and decreases for equilibrium fuel.

Neutron absorption in the coolant decreases when the channels void. This causes f to increase. This increase in thermal utilization is potentially a bigger effect than any of the others, but is kept from being dominant by keeping the coolant isotopic higher than a specified minimum.

Leakage is affected only a little with voiding. Neutrons do not begin slowing down until they reach the moderator so, on average, they travel a bit further from their starting point, increasing leakage.

Typical Components of the Fuel Temperature Coefficient for a CANDU (Nominal Operating Conditions. Units are μk/ C [*])

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**

[*] e.g. a fuel temperature increase of 500 C (typical for a change from zero power hot to full power) for equilibrium fuel results in a decrease in reactivity of about 2 mk.

Component of the Reactivity Change in mk due to Full Core Total Loss of Coolant at Full Power - Typical CANDU values

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**