Reactivity Feedback - Examples

In this section we will discuss a couple of examples of reactivity feedback mechanisms: void-reactivity feedback and fuel-temperature feedback.

A. Coolant-Void Reactivity

A.1 Definition

The loss of coolant is an important scenario to study in CANDU safety analysis, because it introduces positive reactivity and therefore promotes a power rise.

The reactivity change brought about by the complete loss of coolant is called the coolant-void reactivity (or just void reactivity). It is sometimes called "void feedback" because it represents an incremental reactivity fed back into the system upon a change in lattice conditions, in this case a loss of coolant. The term coolant-void reactivity can (as any reactivity component) refer to an "infinite-lattice" value or to a "finite-core" value, depending on the context or the type of calculation. Of course the more relevant perspective for a real reactor is that of the finite core, but the infinite-lattice value is sometimes useful to consider for discussion purposes.

Here I would like to investigate the physical basis of the positive coolant-void reactivity.

A.2 Background Facts

Let us first review some background facts:

- Neutrons from fission are fast (energy distribution with maximum at ~1 MeV).
- We want to slow the neutrons down to thermal energies (~0.025-eV range), where the probability of inducing fission in fissile nuclides is many orders of magnitude higher.
- Between fast and thermal energies, resonance capture can remove a large number of neutrons from circulation. Capture in most resonances [e.g., in U-238] is non-productive of new neutrons. While some resonances are fission resonances [e.g., one in Pu-239 at 0.3 eV] & increase neutron production, resonance capture represents a large net negative drain on the chain reaction.In order to reduce resonance absorptions, fuel is lumped into channels surrounded by moderator, to encourage neutron thermalization away from the fuel.

A.3 Why is CANDU Coolant-Void Reactivity Positive?

A.3.1 Not a Pressure-Vessel Reactor; Spectrum Changes

CANDU is a pressure-tube, not a pressure-vessel, reactor. The coolant is therefore physically separate from the moderator.

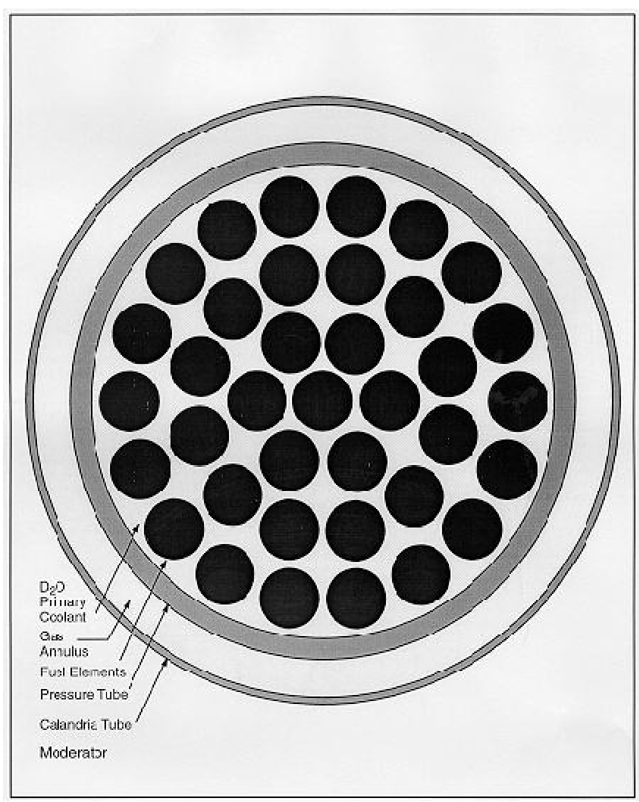
In thermal reactors (reactors which are based on a thermal or near-thermal spectrum – i.e., all commercial reactors except for prototype fast reactors), the moderator is necessary to sustain the chain reaction. In a pressure-vessel reactor, one liquid serves as both coolant and moderator, and a loss of coolant is also a loss of moderator; the coolant-void reactivity will then be negative.

In pressure-tube reactors, the loss of coolant is not accompanied by a loss of moderator. If we now look at relative volumes in the basic lattice cell in current CANDU reactors, we realize that the coolant volume is a very small fraction of the moderator volume: the reduction in moderation is much too small to guarantee a negative coolant-void reactivity.

In fact, subtle spectrum changes upon loss of coolant in current CANDU are at the root of a positive coolant-void reactivity. Let us now look at the differential effects of these spectrum changes. It’s important to realize that these are subtle, not huge differences, but in feedback issues it is relative effects which count.

A.3.2 Fast-Fission Factor

We would like fission neutrons, born in the fuel, to escape from the channel as quickly as possible to be slowed down in the moderator. However, a certain fraction of fast neutrons are slowed down by the coolant before escaping the channel.



What happens when the coolant is <u>present</u>: a fraction of fission neutrons, those with energy above 1.2 MeV, which collide with fuel before escaping the channel, may have an opportunity to induce "fast fission" in U-238. But those slowed by the coolant below 1.2 MeV do not have enough energy to cause fast fission, even if they interact with fuel.

What happens when the coolant is <u>absent</u>: fewer fission neutrons lose energy in the channel, and more fission neutrons will therefore have an opportunity to induce fast fission in U-238. The fast-fission factor increases. This contributes a **positive component** to the coolant-void reactivity.

A.3.3 Resonance Escape Before Leaving the Fuel Channel

A certain fraction of fast neutrons are slowed down into the high resonance-energy range (from higher energies) by the coolant before escaping the channel.

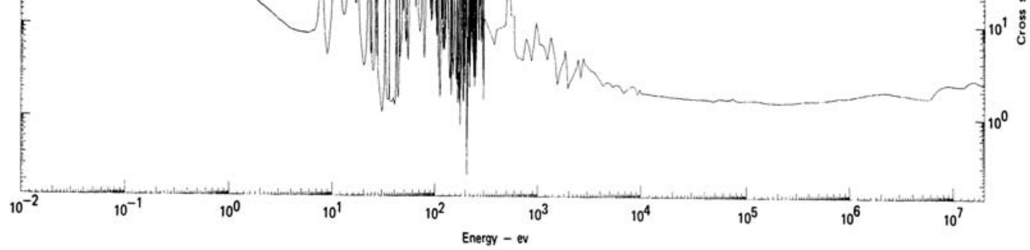
What happens when the coolant is <u>present</u>: some of the neutrons slowed into the resonance-energy range may interact with the fuel, and be non-productively captured in U-238 resonances, before escaping the channel.

What happens when the coolant is <u>absent</u>: fewer fission neutrons are slowed into the resonance-energy range, and more neutrons will therefore escape resonance absorption before exiting the channel. This resonance escape (from above) contributes a **positive component** to the coolant-void reactivity.

A.3.4 Resonance Escape on Re-Entry into a Fuel Channel

Neutrons thermalized in the moderator will eventually (we hope) re-enter a fuel channel.

What happens when the coolant is <u>present</u>: A certain fraction of thermalized neutrons re-entering a fuel channel are up-scattered into the low resonance-energy range (from thermal energies) by the hot coolant. Some of these neutrons may interact with the fuel and be captured in resonances. Captures into U-238 resonances are non-productive. But if Pu-239 is present (i.e., as the fuel burns and plutonium is created), captures into the Pu-239 low-lying fission resonance at 0.3 eV (see figure) may produce more fissions.



What happens when the coolant is <u>absent</u>: fewer thermalized neutrons are up-scattered into the resonance-energy range on entering the fuel channel, and therefore fewer will be captured into resonances resonance absorption. The escape from U-238 resonances is a **positive component** to the coolant-void reactivity; the escape from the Pu-239 resonance is a negative component. The net effect on void reactivity is positive, but one which decreases as burnup increases (and plutonium builds up).

A.4 Value

The differential effects discussed above are not huge, a few parts per thousand.

The net coolant-void reactivity for fresh fuel is about 15-20 mk. It varies, depending on various lattice conditions or parameters:

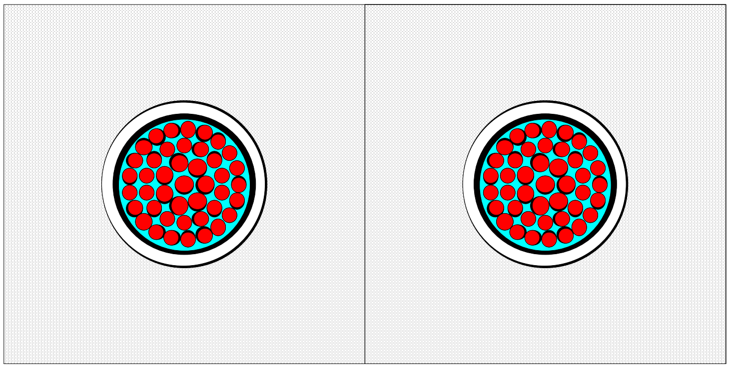
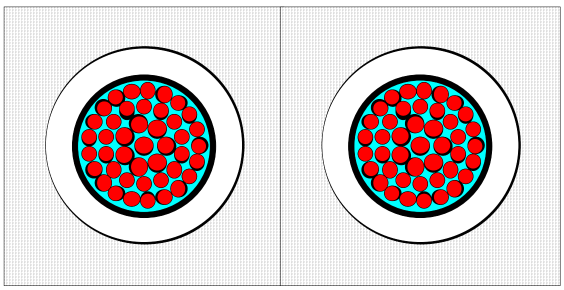
- Coolant purity: Void reactivity is higher when D_2O coolant purity is lower (greater absorption by coolant, lost on voiding)
- Moderator poison: Void reactivity increases with poison concentration (absorption in poison decreases due to neutron-flux redistribution on voiding)
- Pressure-tube creep: Void reactivity is greater with larger-diameter pressure tube.

Also, different computer codes may give different values of void reactivity. For instance, WIMS-IST gives a higher (more positive) value than does POWDERPUFS-V; the WIMS value tend to agree better with measurements.

The void reactivity can, however, be reduced by:

- reducing the lattice pitch; this increases the relative moderating effect of the coolant
- increasing the gap between calandria and pressure tubes; this also increases the relative moderating effect of the coolant
- adding poison at the centre of the fuel bundle. On coolant voiding, the thermal neutron flux increases at the centre of the cell; this increases absorption in the poison and reduces void reactivity.

Void reactivity can even be made negative by a combination of these measures; e.g., as in the Advanced CANDU Reactor:

	37-Element Bundle Natural-Uranium Fuel No Poison in Fuel
	CANFLEX Bundle Enriched Fuel Smaller Lattice Pitch; Larger Gap Between Pressure and Calandria Tubes; Dy Poison in Centre Pin

A.5 Impact of Coolant-Density Reactivity on Other Reactor Parameters

Coolant-void reactivity is the effect of an extreme scenario: the complete loss of coolant. However, even smaller, fractional changes in coolant density will have a reactivity effect. The following are possible manifestations of such effects:

A.5.1 Coolant Boiling in Channels

There may be coolant boiling in some high-power channels in some reactors, depending on the pressure in the primary heat-transport system and the amount of subcooling. Boiling in the channel will occur in some fraction of the channel, at the coolant-outlet end. If boiling occurs, then the local reactivity will be higher at the outlet end of the channel than it would be without boiling. This higher reactivity will promote a higher flux at the channel end. For accurate flux calculations, especially in safety or ROP calculations, the local coolant density and its local reactivity effect need to be modelled - an example of a situation where coupled neutronics-thermalhydraulics calculations may be required.

A.5.2 Power Coefficient

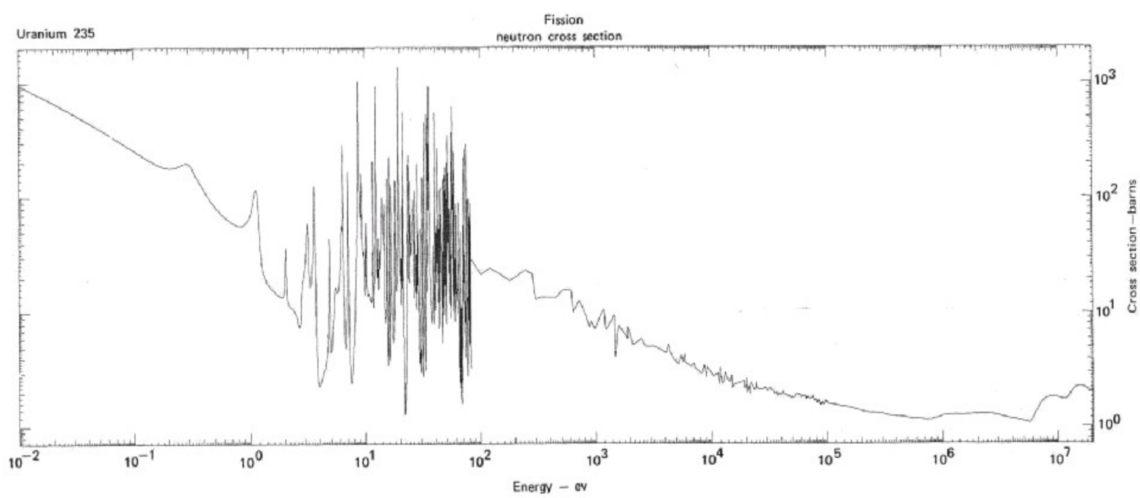
The power coefficient of reactivity is the expected change in system reactivity per unit change in reactor power. One effect of a change in power is a change in fuel temperature, so the reactivity effect of the latter is an important ingredient in the power coefficient. However, a change in reactor power may well result also in a change in the amount of coolant boiling in the core, so that the reactivity effect of coolant density will also enter the power coefficient. Once again, coupled neutronics-thermalhydraulics calculations are normally required to get an accurate estimate of this effect.

B. Fuel-Temperature Feedback and the Doppler Effect

Another type of feedback is fuel-temperature feedback; that is, the reactivity effect of a change in fuel temperature. This is a major component of the power coefficient of reactivity, since fuel temperature is directly linked to reactor power. One phenomenon at play in fuel-temperature feedback is the Doppler broadening of resonances.

Doppler broadening of resonances is explained as follows:

Let's look at the plot of a nuclear cross section as a function of neutron energy. If we consider the independent variable to be neutron speed instead of neutron energy, we immediately realize that what really counts is the speed of the neutron <u>relative</u> to the nucleus. If the nucleus is in motion, then this motion should be taken into account.



Fission Cross Section of ^{235}U versus Neutron Energy (Source: Duderstadt)

Now of course nuclei are not at rest – they are in fact always in motion, thermal motion as a result of the ambient temperature. If the temperature increases, then the thermal motion of the atoms and nuclei increases. This motion means that a neutron has a greater probability of being within "striking distance" of a resonance, since the greater speed of the nucleus can "add to" or "subtract from" the neutron's speed (depending on relative directions of motion). This translates into an effective "broadening" of the resonance, called the Doppler broadening.

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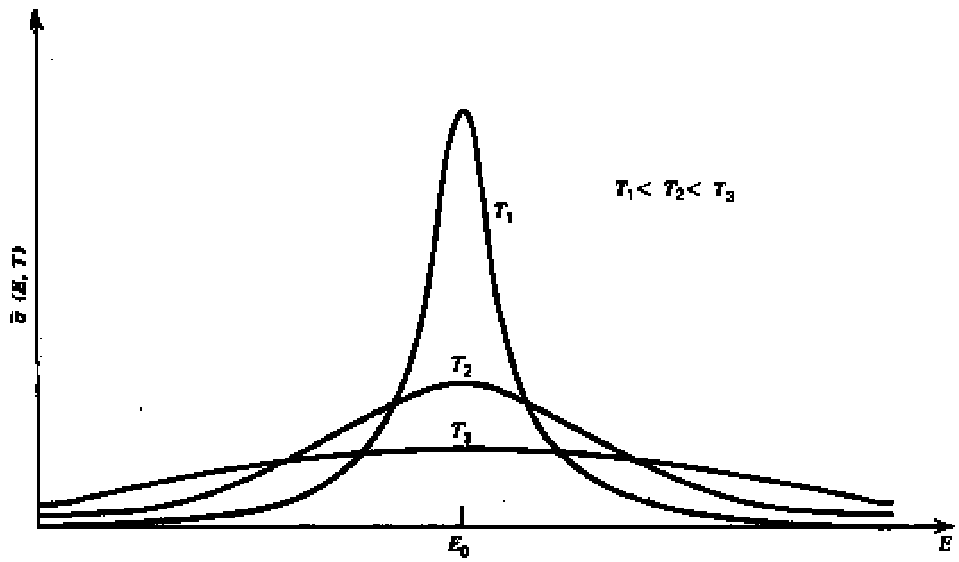

Doppler Broadening of Resonance with Temperature
[from **Nuclear Reactor Analysis**, by James J. Duderstadt and Louis J. Hamilton, John Wiley & Sons, 1976]

Doppler broadening "extends" the range of a resonance, and results in increased capture in the resonance. Increased capture in U-238 resonances is a **negative** reactivity effect, leading to a **negative fuel-temperature reactivity coefficient**. However, when Pu-239 is present, the low-lying fission resonance at 0.3 eV must also be considered. In this case, increased capture is a **positive** reactivity effect. The fuel-temperature coefficient then becomes **less negative as burnup increases**. At some value of burnup, the fuel-temperature coefficient of natural fuel changes sign and becomes positive.

C. Possible Exercises

C.1 Select a reasonable concentration of moderator poison (say, boron). Or, determine the concentration of moderator poison which would just replace the negative reactivity of the steady-state xenon load. Determine the effect of such poison concentration on void reactivity at, say, an average exit irradiation of 1.8 n/kb.

C.2 Determine how void reactivity changes for a change in moderator purity.