# CHAPTER 3: ELEMENTARY PHYSICS OF REACTOR CONTROL

# MODULE C: REACTIVITY FEEDBACK DUE TO TEMPERATURE AND VOID EFFECTS

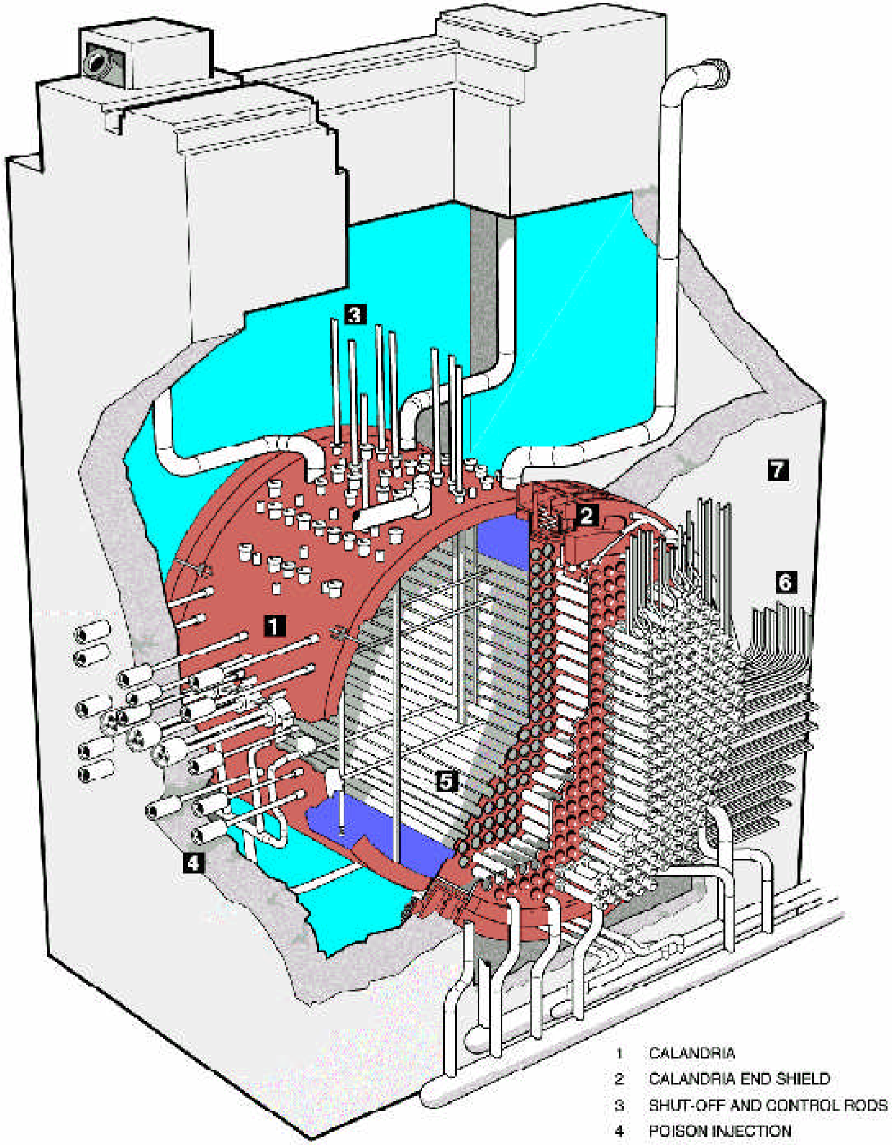
## MODULE OBJECTIVES:

**At the end of this module, you will be able to describe:**

1. **reactivity as a function of reactor power**
2. **the physics basis for the temperature effects of reactivity, including**
   - **(1) density effects**
   - **(2) neutron energy spectrum effect**
   - **(3) doppler broadening effect**
3. **the temperature coefficients and the six factor formula**
4. **the fuel, moderator and coolant temperature coefficients**
5. **the power coefficient of reactivity**
6. **effects due to void formation**

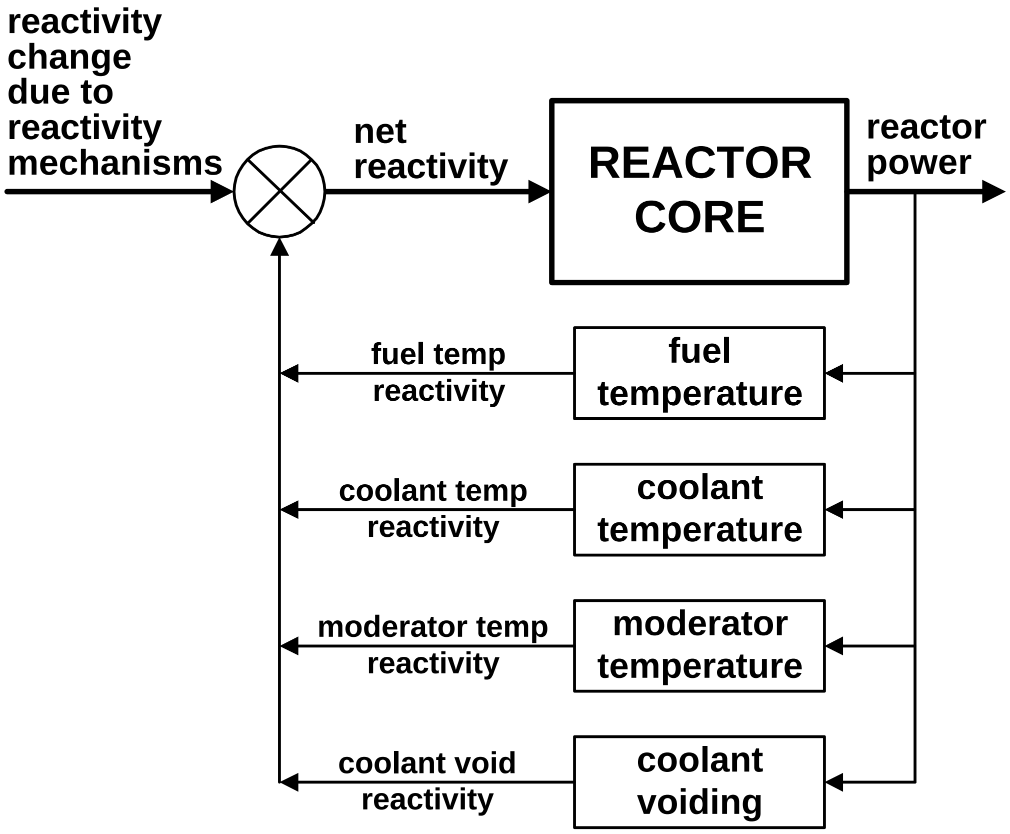
## 1. INTRODUCTION

- **so far in this chapter we have considered how a nuclear chain reaction can be maintained and its level changed, in terms of the creation of neutrons from fission, and their absorption in the fuel and other materials, as well as their escape from the reactor core**
- **reactivity has been defined in terms of the deviation of the neutron multiplication from critical, and equations developed that relate the time dependent change of the neutron population to reactivity**
- **in this course we are concerned about controlling reactor power, which is done by controlling the reactivity of the core**
- **before we consider the means of changing the core's reactivity by external means, we need to look at reactivity effects internal to the reactor**
- **in the previous module reference was made to changes in core reactivity as the composition of the fuel changes with 'burnup'**
- **in this module we look at the effects on reactivity of changes in the temperatures of the many materials that are present in the reactor core, and the effects of any voids that may form in the coolant and the moderator if these liquids were to boil**



## 2. REACTIVITY AS A FUNCTION OF REACTOR POWER

- **when reactor power changes, the temperatures of the various reactor components and the amount of void (if any) in the reactor coolant, will change**
- **for example, on a power level increase, the respective temperature of the fuel, coolant, and moderator will each rise**
- **these temperature changes will alter one or more of the factors in the in the six factor formula, resulting in reactivity changes**
- **since a reactivity change that is due to the action of the reactor control system that results in a power level change will cause a temperature (and/or void) change which will then alter the reactivity of the core, the reactivity changes due to temperature (and/or void) take the form of a reactivity feedback effect**
- **the reactor control system must therefore continually adjust the reactivity control mechanisms during a demanded power level change to keep the actual power changing at a rate that corresponds to the setpoint change**
- **positive feedback will tend to cause instability**
- **large negative feedback would oppose any power level change**
- **small negative feedback has a ‘self regulating’ effect, resulting in an ‘inherently safe’ reactor**



## 3. PHYSICS BASIS FOR THE TEMPERATURE EFFECTS OF REACTIVITY

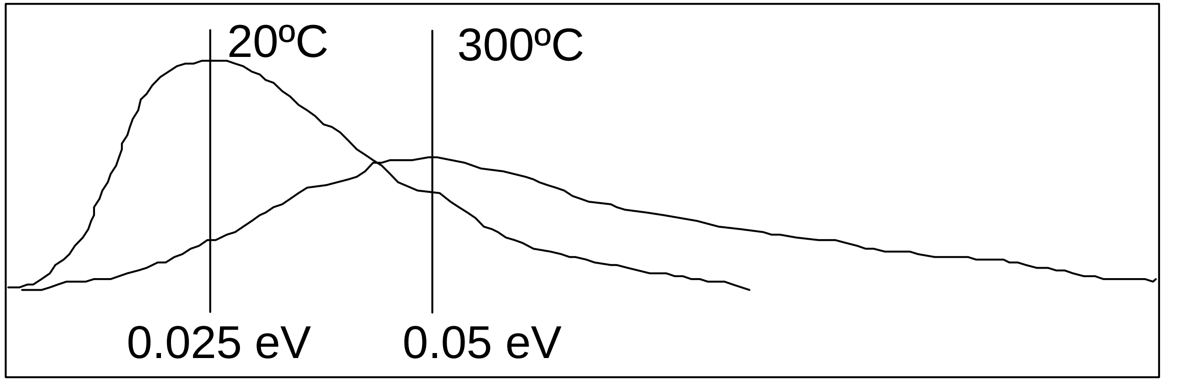
- **recall that the reaction rate for a given nuclide in the reactor is given by: $R = \phi\Sigma = \phi N\sigma$, where N is the number of a particular nuclei per unit volume, and $\sigma$ refers to either the fission or absorption cross section of the corresponding nuclei**
- **the reaction rate will change as a function of temperature for one of the following reasons:**
  - ⇒ **thermal expansion of the material will reduce its density, and hence N decreases**
  - ⇒ **changes in the energy spectrum of the thermal neutron flux will alter $\sigma$**
  - ⇒ **the nuclei move at higher speeds, increasing the probability of resonance capture of epithermal neutrons (Doppler effect, Doppler broadening, Resonance broadening)**

### 3.1 Density Effects

- **as the temperature of the moderator or coolant increases, its density decreases**
- **since the number of atoms per unit volume are fewer, neutrons will travel further between collisions and therefore have an increased chance of leaking out of the core, hence both the fast ($\Lambda_f$) and the thermal ($\Lambda_t$) non-leakage probabilities will decrease, therefore decreasing reactivity**
- **the reduction in atomic density will lower $\Sigma_a$ for the moderator and the coolant, which will therefore increase the thermal utilization (f) i.e. increasing reactivity**
- **if there is poison in the coolant and/or the moderator, the reactivity effect of a density change is magnified (for PWR and BWR the poison is in the common coolant/moderator; for CANDU poison is only added to the moderator)**
- **since the fuel is in the form of a ceramic material with high crystalline stability, there are no significant density changes due to temperature, as long as the temperature of the fuel is kept below its melting point**

## 3.2 Neutron Energy Spectrum Effect

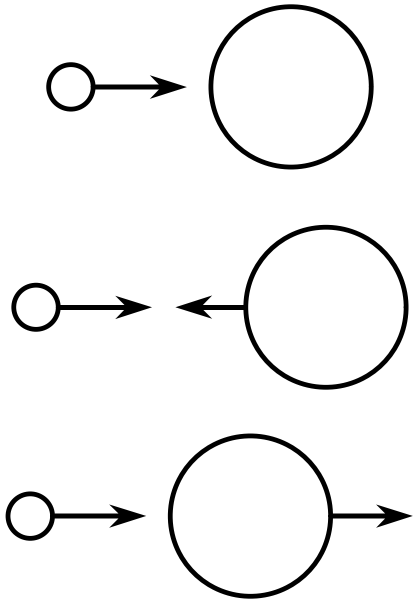
- **changes in the temperatures of the various materials in the core with which the neutrons interact, will alter the energy distribution of the thermal neutrons (also called the 'neutron temperature')**
- **the thermal spectrum of the neutrons changes as shown on the diagram: the peak of the thermal neutron spectrum decreases, the average and most probable energies increase,**




- **the change in thermal energy spectrum with temperature will alter the balance between the fission and absorption rates in the core since these are functions of the neutron energy**
  - ⇒ **'spectrum hardening' refers to 'hotter' neutrons**
  - ⇒ **'spectrum softening' refers to 'cooler' neutrons**
- **the parameter that is most effected is the reproduction factor $\eta$.**

## 3.3 Doppler Broadening Effect

- **the Doppler effect arises when the temperature of the fuel changes, because an increase in fuel temperature will increase neutron capture in U-238 as they pass through the resonance range**
- **absorption at the resonance peaks is a function of the speed of the neutron relative to the speed of the U-238 nucleus, and since a higher fuel temperature means result in the U-238 atoms vibrating more vigorously, there is a wider range of neutron speeds that can coincide with the absorption peaks of U-238**
- **the range of energies at which neutrons are captured increases**
- **although the capture cross section at the resonance peak is reduced, the overall probability of capture is increased**



**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**

- **the overall effect is a reduction in the resonance escape probability (p) and hence a decrease in reactivity**

## 4. TEMPERATURE COEFFICIENTS AND THE SIX FACTOR FORMULA

- **the temperature coefficient of reactivity is defined as the change in reactivity per unit change in temperature, with units of mk/°C or μk/°C**
- **mathematically the temperature coefficient is written as**

**recall that** $k = \eta f p \varepsilon \Lambda_f \Lambda_t$

**taking logs of both sides** $\ln k = \ln \eta + \ln f + \ln p + \ln \varepsilon + \ln \Lambda_f + \ln \Lambda_t$

**and differentiating, we get**

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

- **Typical components of the fuel temperature coefficient (μk/°C) for a CANDU are:**

| FACTOR | 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 |

## 5. FUEL, MODERATOR AND COOLANT TEMPERATURE COEFFICIENTS

- **the effects of density, neutron temperature and Doppler broadening alter the components of the six factor formula in various ways and their values are also a function of the 'age' of the fuel**
- **since the temperature of the fuel, moderator and coolant can be varied independently from one another (within certain limits), the reactivity coefficient of each of these effects needs to be known**

| Values for CANDU near full power operating conditions | Unit of $\mu$k/ ºC | $\Delta$T from zero power hot to full power |
|---|---|---|
| Fuel temperature coefficient | - 4.5 | 530 |
| Coolant temperature coefficient | +30 | 25 |
| Moderator temperature coefficient | +70 | 5 |

- **it was noted in section 2 that a reactor will be potentially unstable if it has a large positive temperature coefficient of reactivity: is the reactor with the parameters in the above table unstable?**
- **in analyzing the stability of a feedback control system both the gain and the phase of the feedback signal had to be considered**
- **for a reactor undergoing a power level transient the temperature change for the fuel will be much larger and occur much more rapidly than for the coolant and the moderator , so as long as the fuel temperature coefficient is negative, the reactor will be stable**

## 6. POWER COEFFICIENT OF REACTIVITY

- **the Power Coefficient is defined as the reactivity change due to all the temperature effects as the reactor power changes from hot shutdown to 100%FP**
- **note that this is not a reactivity change per unit of temperature as the previous temperature coefficients were defined, but the total reactivity change between the two operating states**
- **it can be assumed that the reactivity effect is a linear function of the power level between 10% and 100%FP**
- **for CANDU reactors the Power Coefficient is between – 2 mk and – 6 mk, depending on the design of the fuel bundle and the amount of burn-up**

## 7. EFFECTS DUE TO VOID FORMATION

- **voids will be formed in the core if the temperature of moderator or the heat transport system fluid reaches the boiling point**
- **note that for BWRs boiling of the common moderator and reactor coolant will take place under normal operating conditions**
- **for CANDUs the moderator system is not expected to reach boiling, while some boiling in the heat transport system is expected to take place near full power operations**
- **the two events that could cause voiding are:**
  - ⇒ **large Loss Of Coolant Accident (LOCA), such as a header rupture and depressurization**
  - ⇒ **fast Loss Of Regulation resulting in excessive power generation**
- **Components of the void reactivity in case of full core voiding are given in the Table in mk**
- **Safety Analysis must demonstrate that either Reactor Shutdown System acting alone could limit the power increase to safe levels in case of such an accident**

| 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 |