



CANDU Safety

#3 - Nuclear Safety Characteristics

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What Makes A Safe Nuclear Design?

- λ inherent nuclear safety is ideal
 - all transients terminated safely by inherent negative neutronic feedback without any moving parts or fluids
 - SLOWPOKE research reactor is in this category (20kW)
- λ passive nuclear safety is nice
 - all transients terminated safely by inherent neutronic feedback and/or movement of fluids, without any external motive power or valves
 - PIUS mostly in this category
- λ none of the major power reactors are of these types because of economics & power density requirements



Neutronic Time-scales

- λ prompt neutron lifetime
 - λ 10^{-4} seconds (LWRs)
 - λ 10^{-3} seconds (CANDU)
 - λ *cannot* control on prompt neutrons
- λ delayed neutrons (0.6% of all neutrons)
 - λ lifetimes range from tenths to tens of seconds
 - λ basis of safe control



Other Time-scales

- λ fuel temperature feedback - milliseconds
- λ coolant temperature feedback - ~7 seconds
- λ moderator temperature feedback:
 - ~7 seconds in LWRs
 - minutes in CANDU
- λ practical control system response - few seconds
- λ practical shutdown system response - 2 seconds



Sign of Reactivity Coefficients

<i>Coefficient</i>	<i>CANDU</i>	<i>LWR</i>
<i>Fuel Temperature</i>	(-)	-
<i>Coolant temperature</i>	+	-
<i>Coolant density</i>	-	+
<i>Moderator temperature</i>	+	-
		+ if highly poisoned



Power Coefficient

- λ power coefficient
 - reactivity change following a change in reactor power
 - combination of fuel, temperature and moderator reactivity
 - near zero for CANDU, negative for LWRs
- λ negative power coefficient is convenient since it simplifies the control system
- λ negative power coefficient is *not* required for safety in CANDU
- λ a large positive power coefficient would be unsafe since it would require a very fast control system for stability
- λ a large negative power coefficient requires “deep” shutdown systems to hold the reactor shut down



Response to Accidents

<i>Accident</i>	<i>CANDU</i>	<i>LWR</i>
<i>Withdrawal of control rod - prompt feedback</i>	Small, negative	Negative
<i>Withdrawal of control rod - long-term feedback</i>	Slow power increase terminated by shutdown or control systems	Power increase stabilizes at higher power level; may require shutdown system
<i>Loss of coolant (rapid decrease in coolant density)</i>	Fast rise in power requiring shutdown systems	Drop in power, shutdown required in longer term
<i>Cold H₂O injection (decrease in coolant temperature & purity)</i>	Drop in power, H₂O is a neutron absorber	Increase in power, cold water must be borated
<i>Steam Line Break (decrease in coolant temperature & density)</i>	Drop in power, shutdown required in longer term	Increase in power requiring shutdown
<i>Control rod ejection</i>	Not physically possible	Rapid rise in power above prompt critical, stopped by fuel temperature feedback and eventually shutdown system

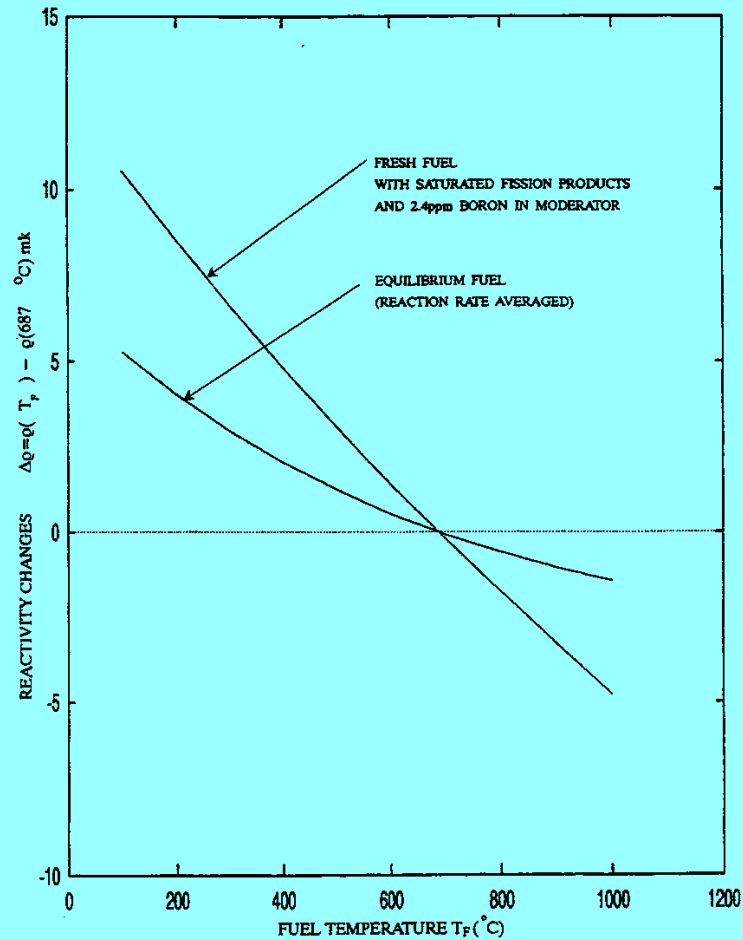


Other Neutronic Safety Characteristics

- λ avoid large amounts of reactivity compensation
 - CANDU achieves this via on-power refueling
 - LWRs compensate by using boron in coolant, recent designs use burnable poisons in fuel
- λ avoid large and fast positive reactivity insertions:
 - CANDU - large LOCA
 - LWR - rod ejection, steam line break
- λ ensure shutdown systems are effective for any core state possible during operation (major lesson from Chernobyl)

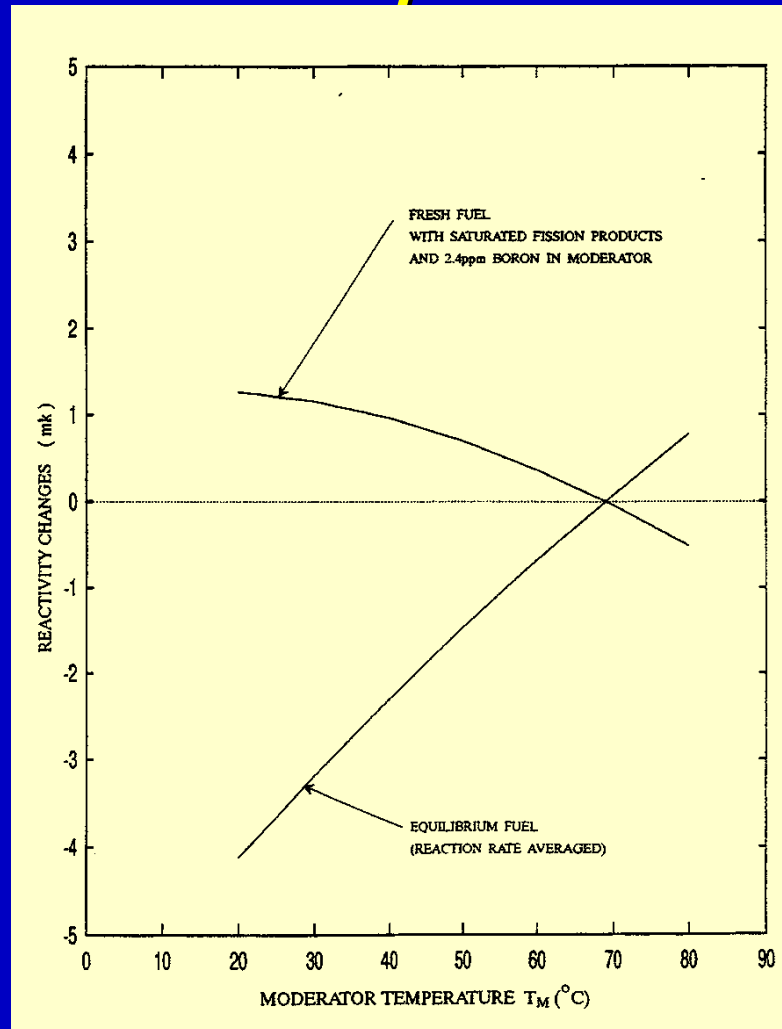


CANDU Fuel Temperature Reactivity



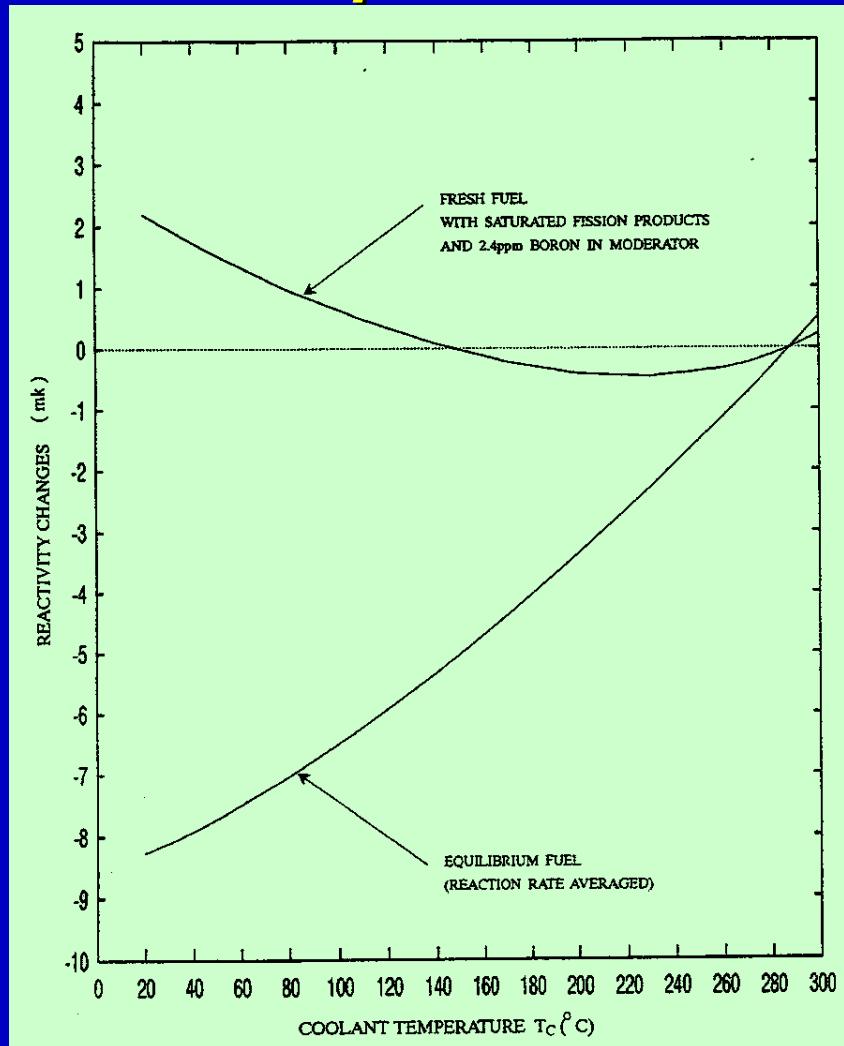


CANDU Moderator Temperature Reactivity



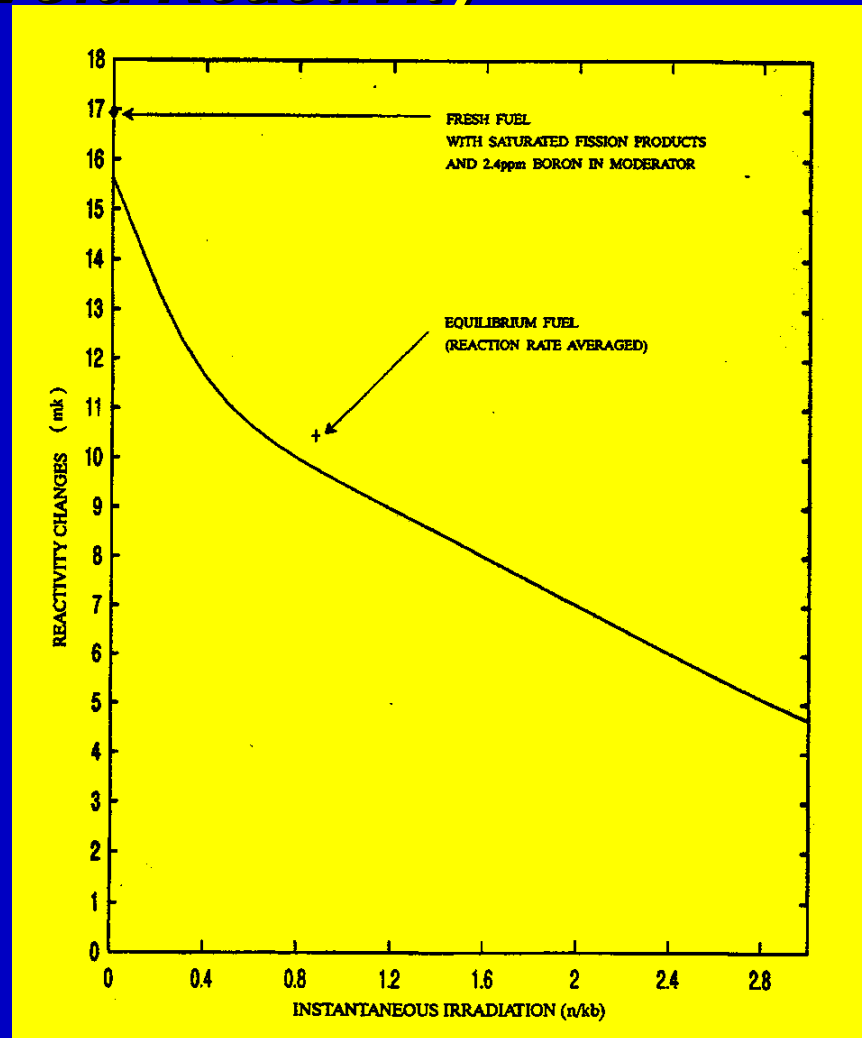


CANDU Coolant Temperature Reactivity



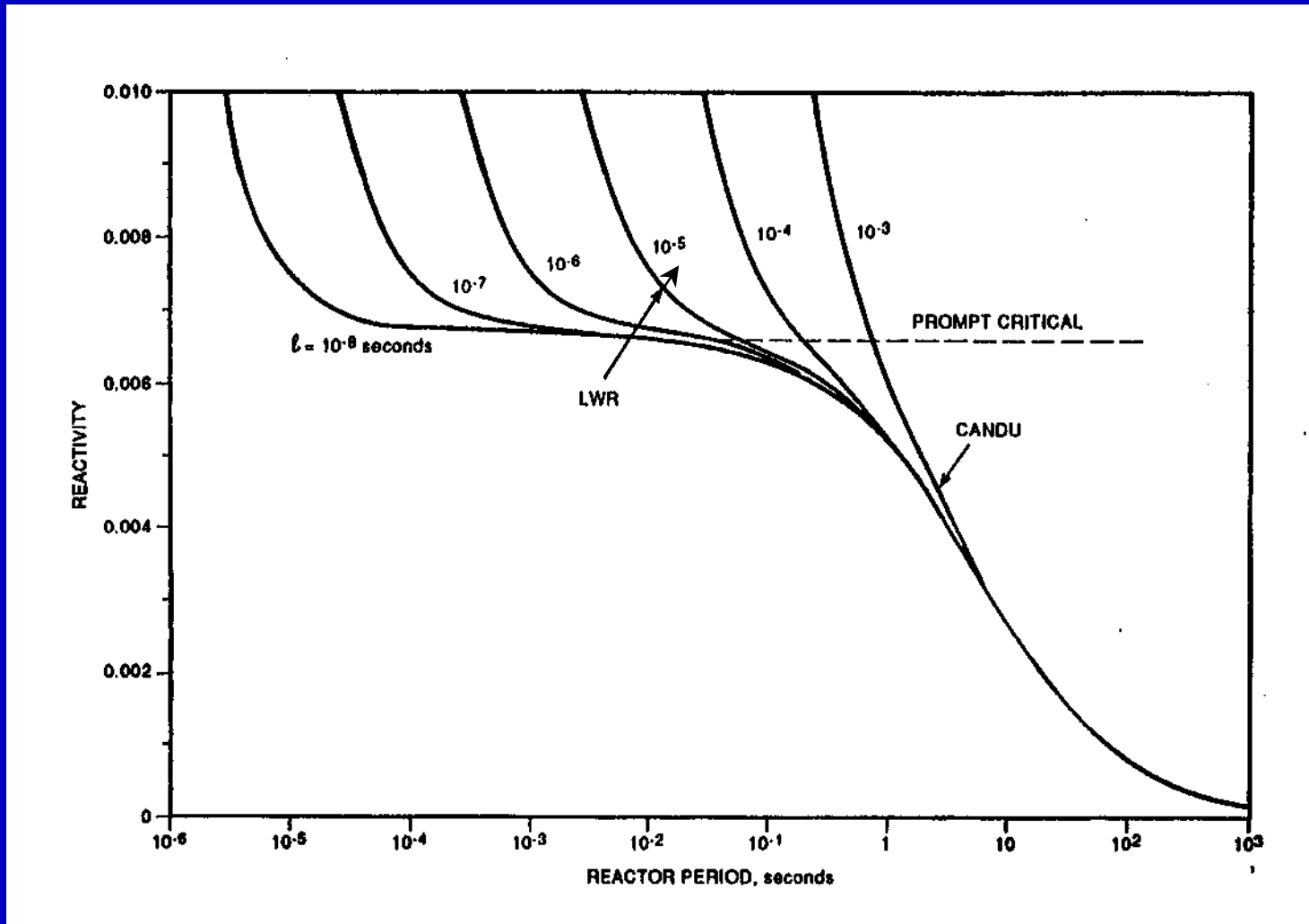


Coolant Void Reactivity





Reactor Period and Reactivity for Varying I^*





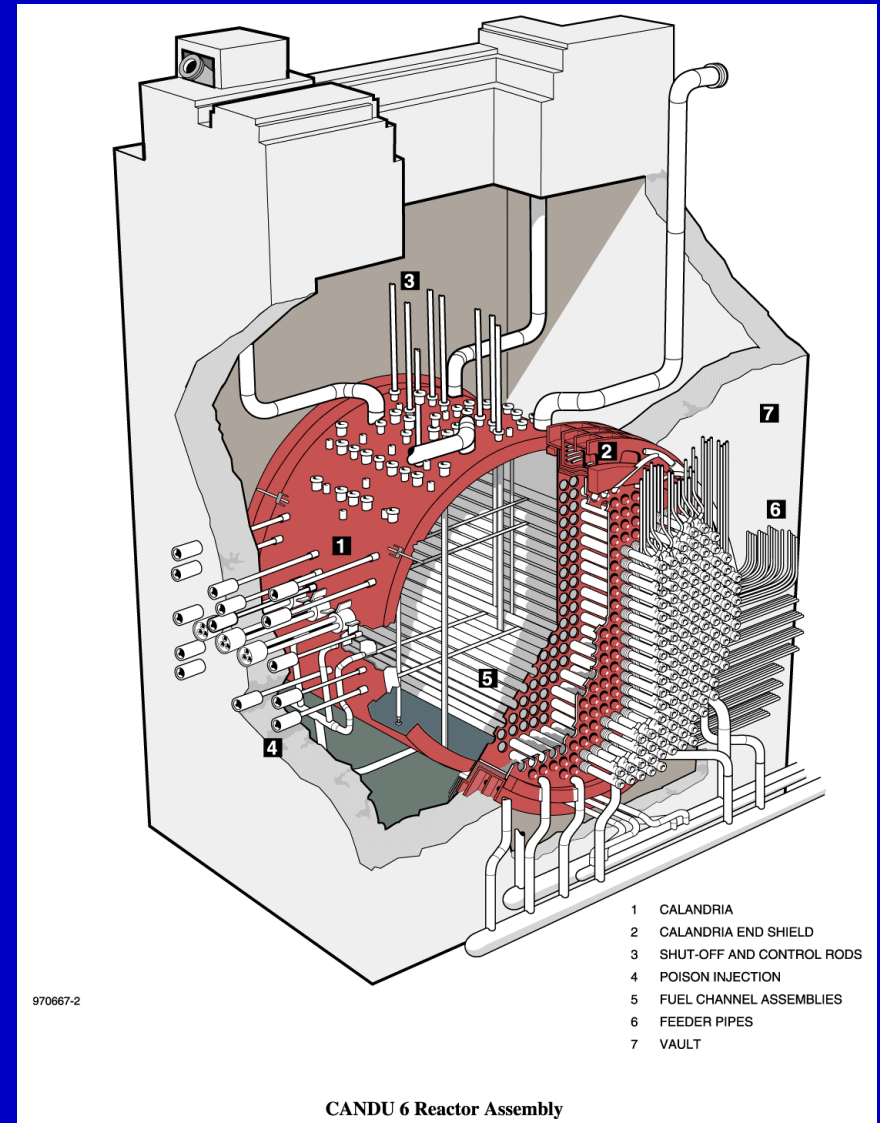
Reactivity Control

- λ primary short term control: light-water zone compartments
 - spatial and bulk power control
- λ flux shaping & xenon override: adjuster rods (normally inserted)
- λ rapid control power reduction on upsets: absorber rods (normally out of core)
- λ long term control: on-power refueling
- λ fresh fuel reactivity compensation: boron / gadolinium in moderator
- λ emergency shutdown: rods and poison injection



Reactivity Control

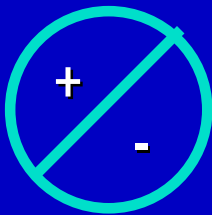
- λ zone controllers, absorber and adjuster rods come in from the top of the core into the moderator
- λ shutoff rods also come in from the top
- λ liquid poison injection (shutdown system 2) comes into the moderator from the side



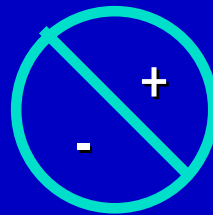


Xenon

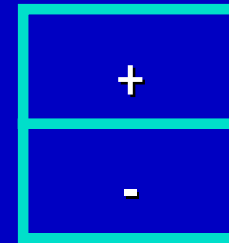
- λ CANDU is a large reactor (6m. long cylinder by 7.6m diameter)
- λ potential for spatial instability due to xenon decay (28mk)



First Azimuthal A
-16.2 mk



First Azimuthal B
-16.9 mk



First Axial
-27.1 mk

Subcriticality



Spatial Control

- λ xenon instabilities (first azimuthals) can occur; they are slow (hours) but require spatial detection and control
- λ spatial control also needed for local flux variations due to refueling (~8%) and global flux tilts due to asymmetric refueling