CANDU Safety
#3 - Nuclear Safety Characteristics

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Safety & Licensing

What Makes A Safe Nuclear Design?

- 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)
- 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
- none of the major power reactors are of these types because of economics & power density requirements

Neutronic Time-scales

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

Other Time-scales

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

Sign of Reactivity Coefficients

Coefficient	*CANDU*	*LWR*
Fuel Temperature	(–)	–
Coolant temperature	+	–
Coolant density	–	+
Moderator temperature	+	– + if highly poisoned

Power Coefficient

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

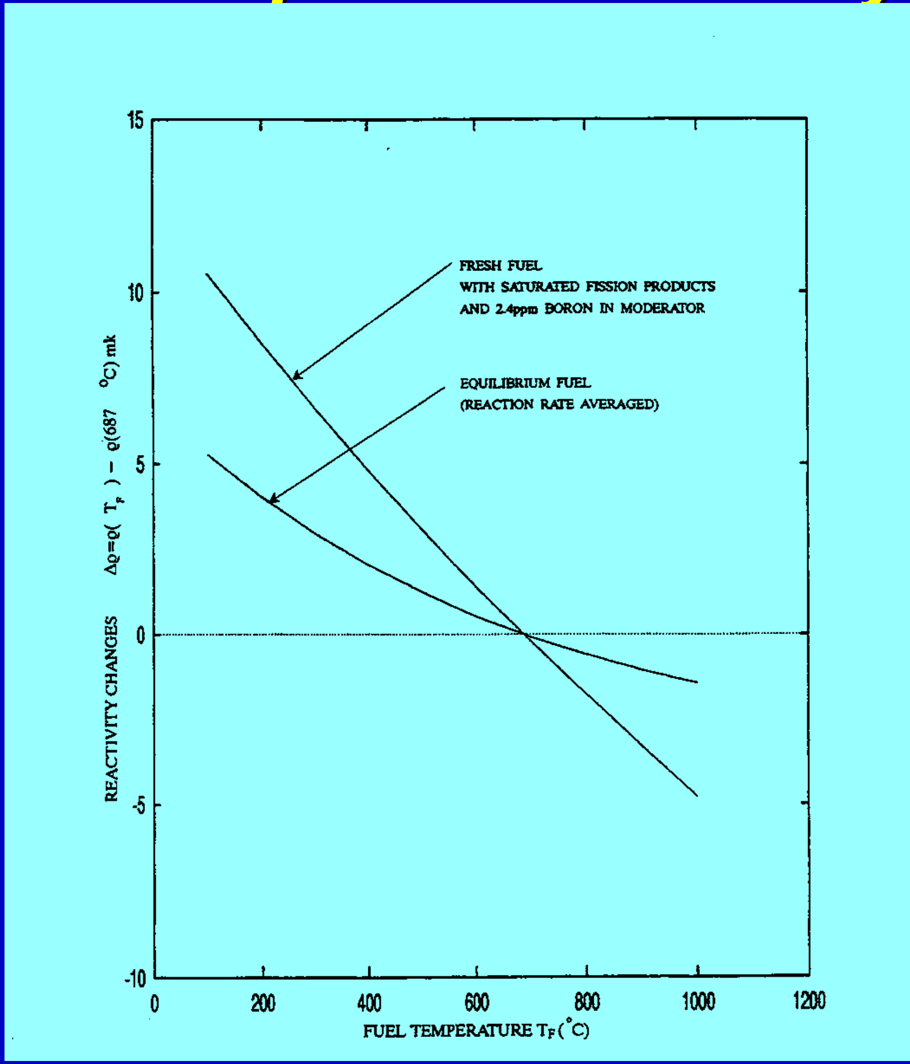
Response to Accidents

Accident	*CANDU*	*LWR*
Withdrawal of control rod - prompt feedback	**Small, negative**	**Negative**
Withdrawal of control rod - long-term feedback	**Slow power increase terminated by shutdown or control systems**	**Power increase stabilizes at higher power level; may require shutdown system**
Loss of coolant (rapid decrease in coolant density)	**Fast rise in power requiring shutdown systems**	**Drop in power, shutdown required in longer term**
Cold H_2O injection (decrease in coolant temperature & purity)	**Drop in power, H_2O is a neutron absorber**	**Increase in power, cold water must be borated**
Steam Line Break (decrease in coolant temperature & density)	**Drop in power, shutdown required in longer term**	**Increase in power requiring shutdown**
Control rod ejection	**Not physically possible**	**Rapid rise in power above prompt critical, stopped by fuel temperature feedback and eventually shutdown system**

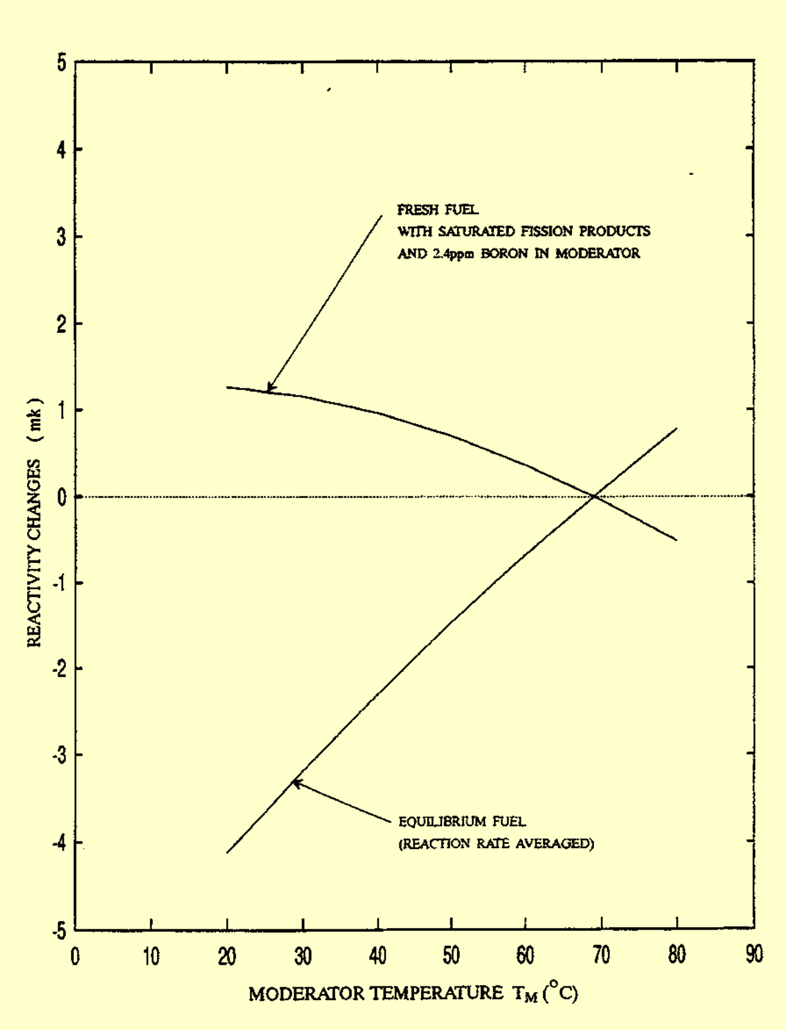
Other Neutronic Safety Characteristics

- **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**
- **avoid large and fast positive reactivity insertions:**
  - **CANDU - large LOCA**
  - **LWR - rod ejection, steam line break**
- **ensure shutdown systems are effective for any core state possible during operation (major lesson from Chernobyl)**

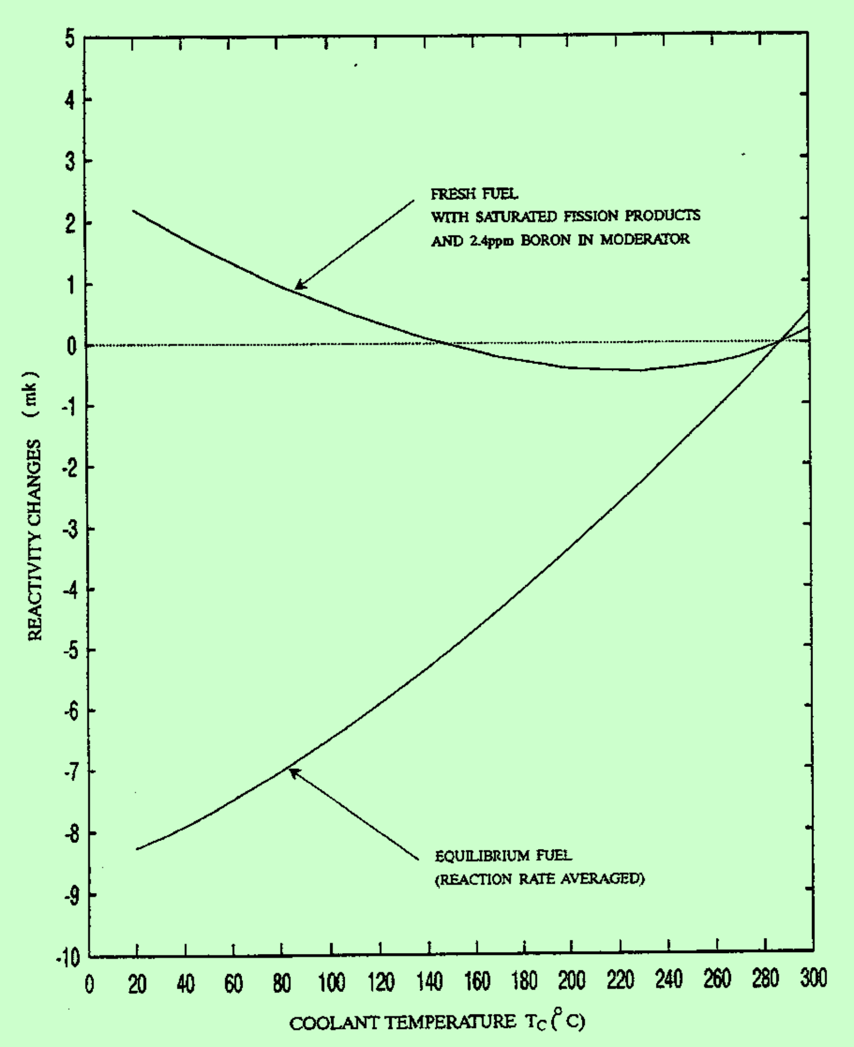
CANDU Fuel Temperature Reactivity



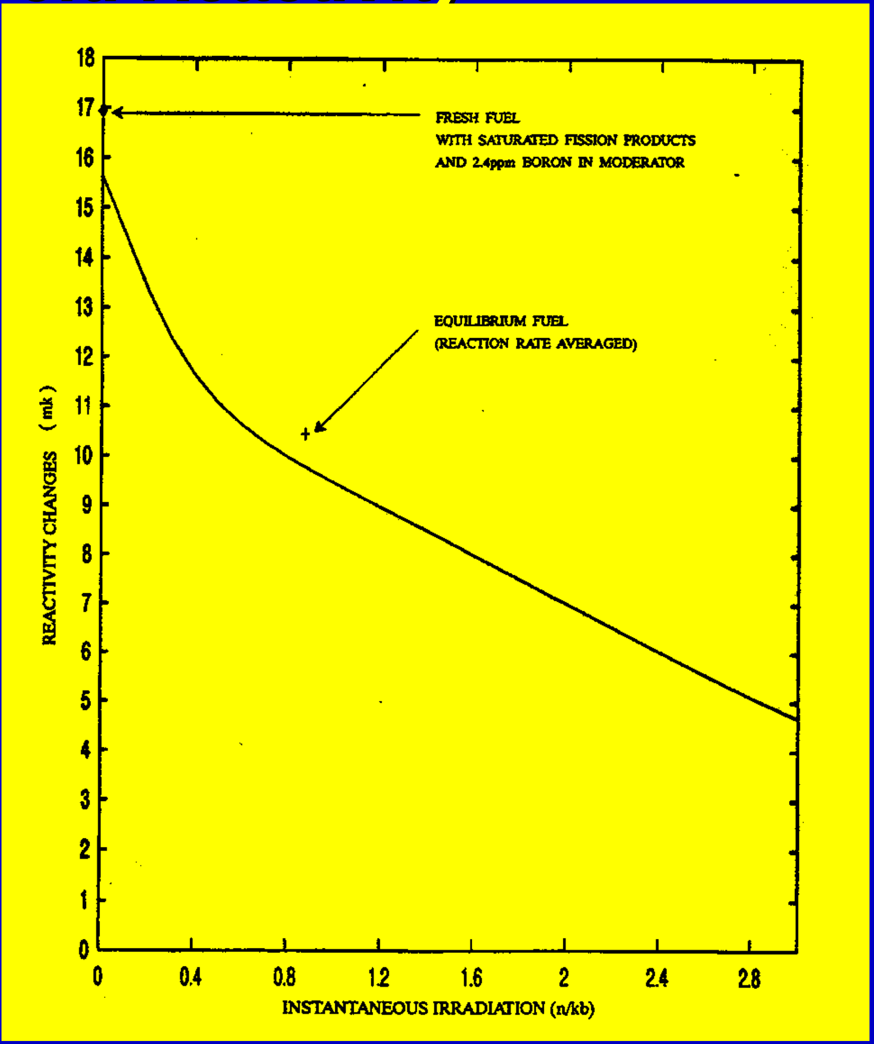
CANDU Moderator Temperature Reactivity



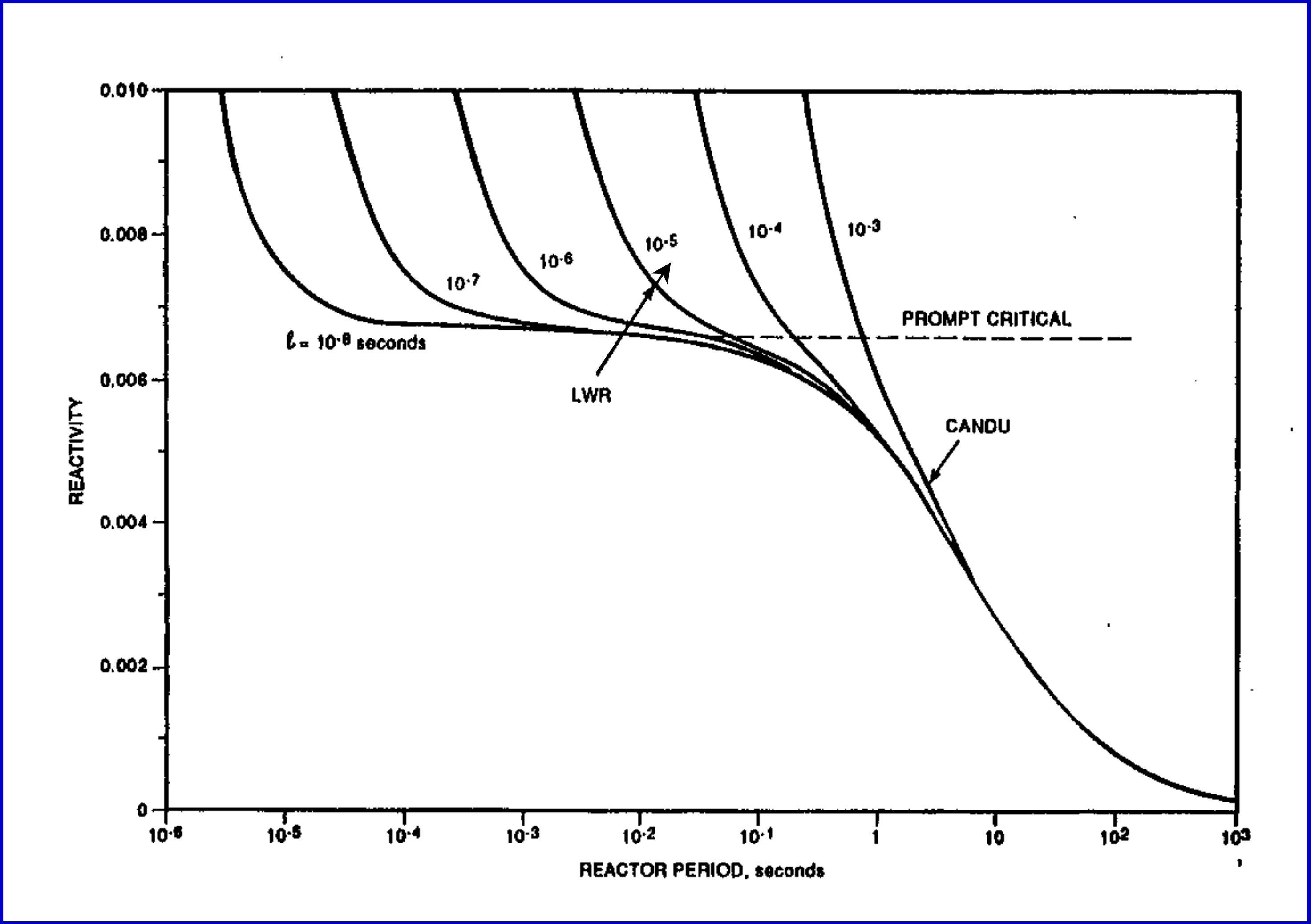
CANDU Coolant Temperature Reactivity



Coolant Void Reactivity



Reactor Period and Reactivity for Varying l*

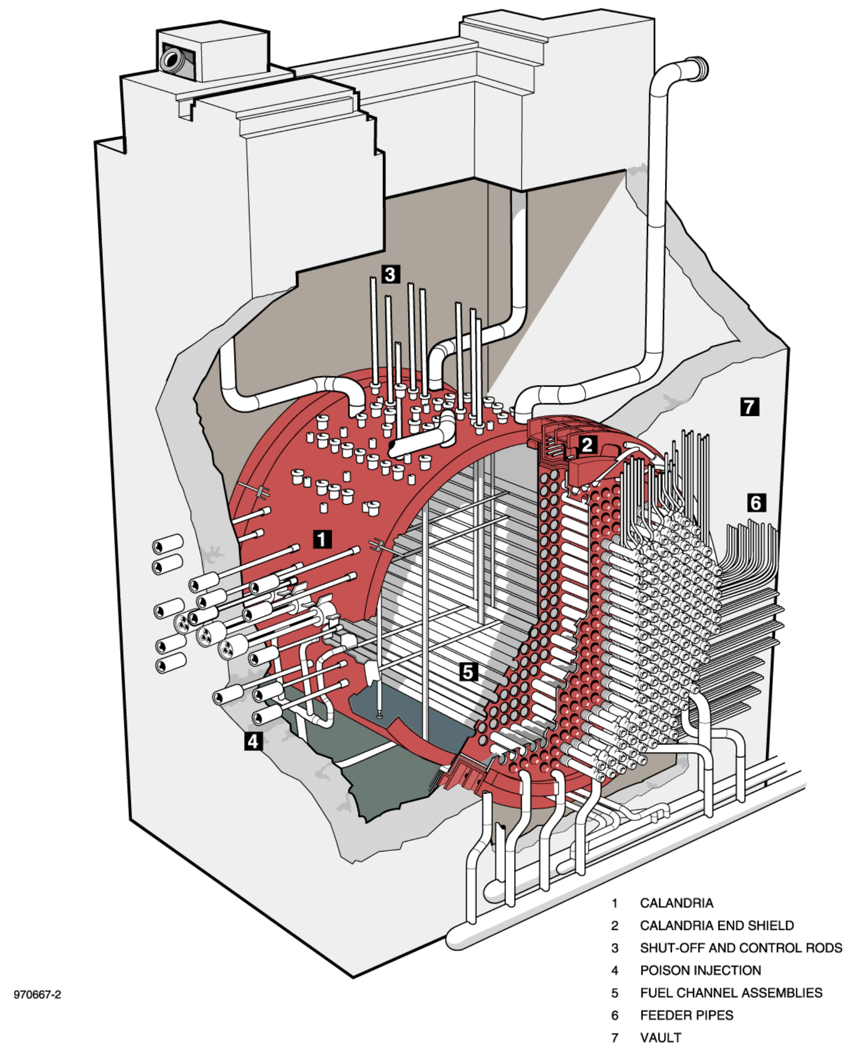


Reactivity Control

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

Reactivity Control

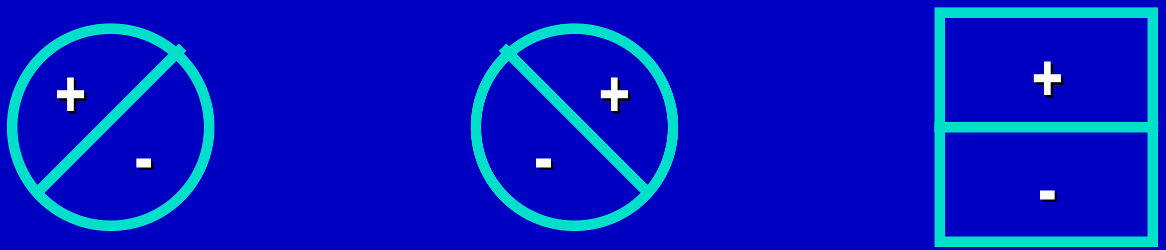
- zone controllers, absorber and adjuster rods come in from the top of the core into the moderator
- shutoff rods also come in from the top
- liquid poison injection (shutdown system 2) comes into the moderator from the side



CANDU 6 Reactor Assembly

Xenon

- CANDU is a large reactor (6m. long cylinder by 7.6m diameter)
- 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

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