CANDU Void Reactivity

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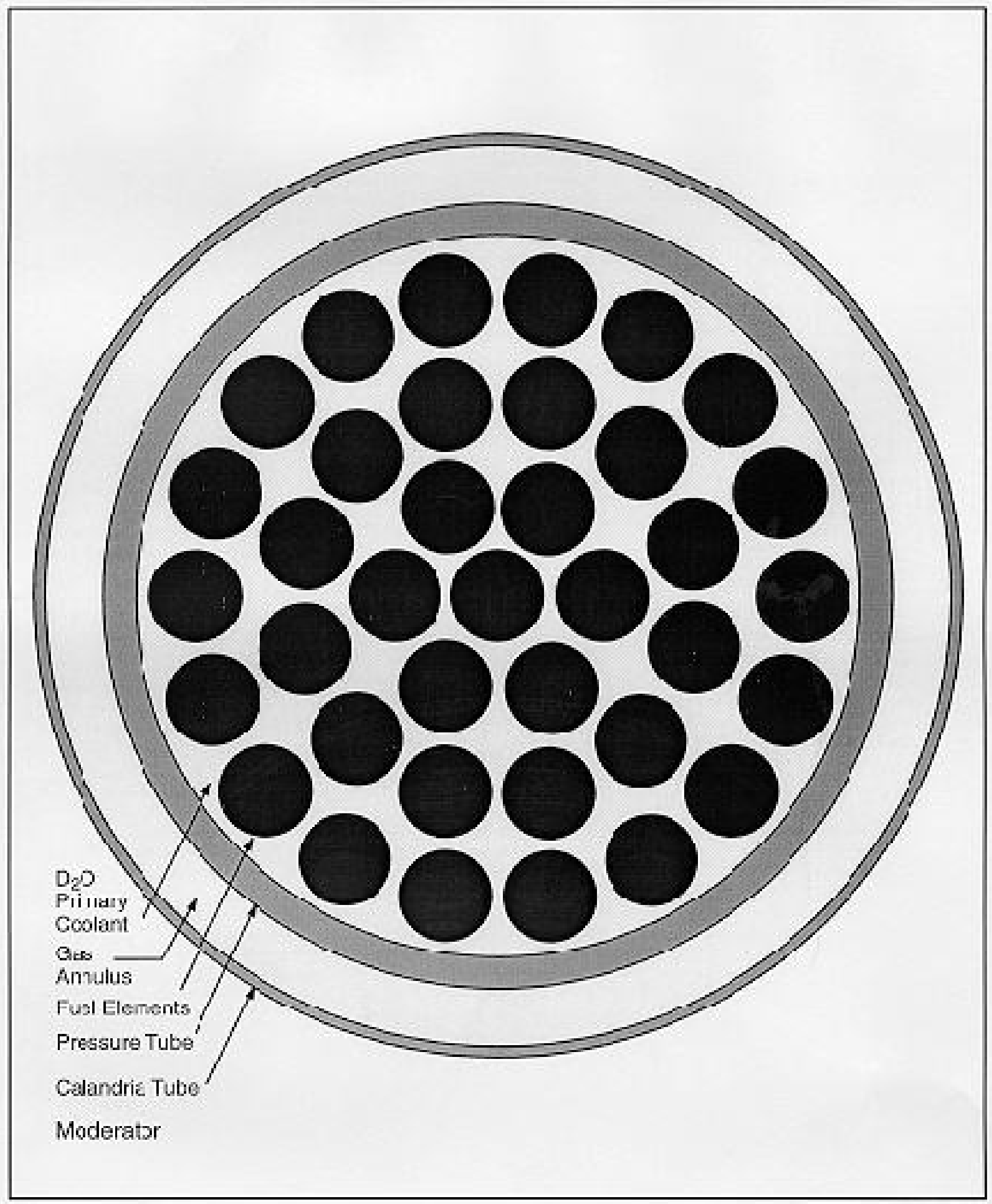
CANDU Coolant-Void Reactivity

- CANDU has positive void reactivity: when coolant is lost, a positive reactivity develops and power tends to increase; this is one of the best-known facts (and criticisms) about CANDU
- Why is it positive?
- Reasons can be traced to pressure-tube design of CANDU, and effects of changes in neutron spectrum (energy distribution)

CANDU Basic Lattice Cell (not to scale)

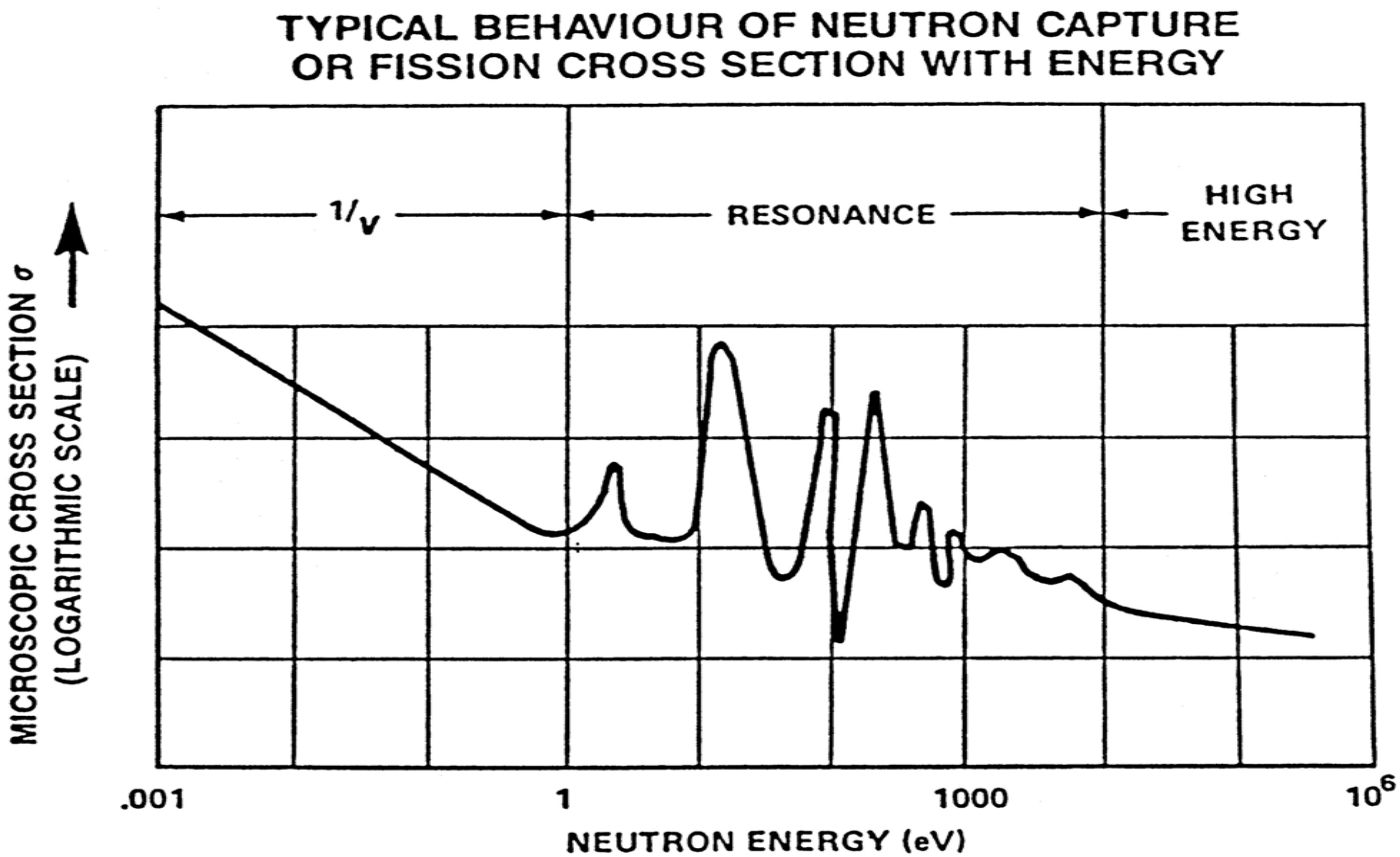


CANDU Coolant-Void Reactivity

First, remember some important facts:

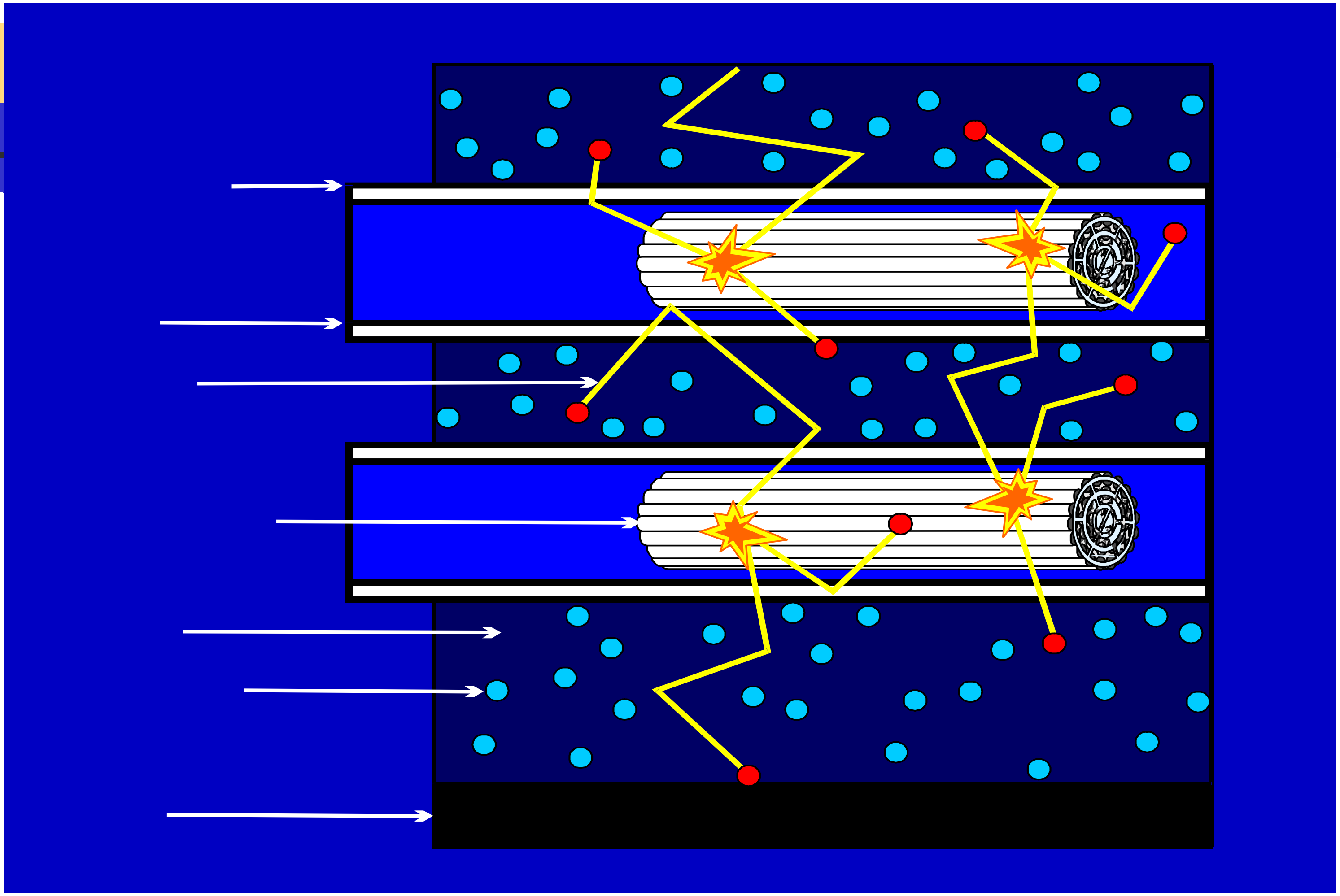
- Neutrons emerging from fission are fast – typical energy ~1 MeV
- The probability of inducing fission in fissile nuclides is much higher at thermal energies (~ 0.025 eV)
- To improve the number of induced fissions, a moderator is used to slow down fission neutrons to thermal energies
- Resonances loom between fast and thermal energies [in range ~ 1 eV-100 keV]; very high peaks
- Most resonances [e.g., U-238] are absorption resonances

Capture or Fission Cross Section vs. Energy (Schematic View)



CANDU Coolant-Void Reactivity

- To maximize resonance escape, fuel is **lumped** into channels separated by volumes of moderator, to allow fission neutrons to escape and be slowed to below resonance energies away from the fuel



Fission Neutrons Slowed in Moderator Region

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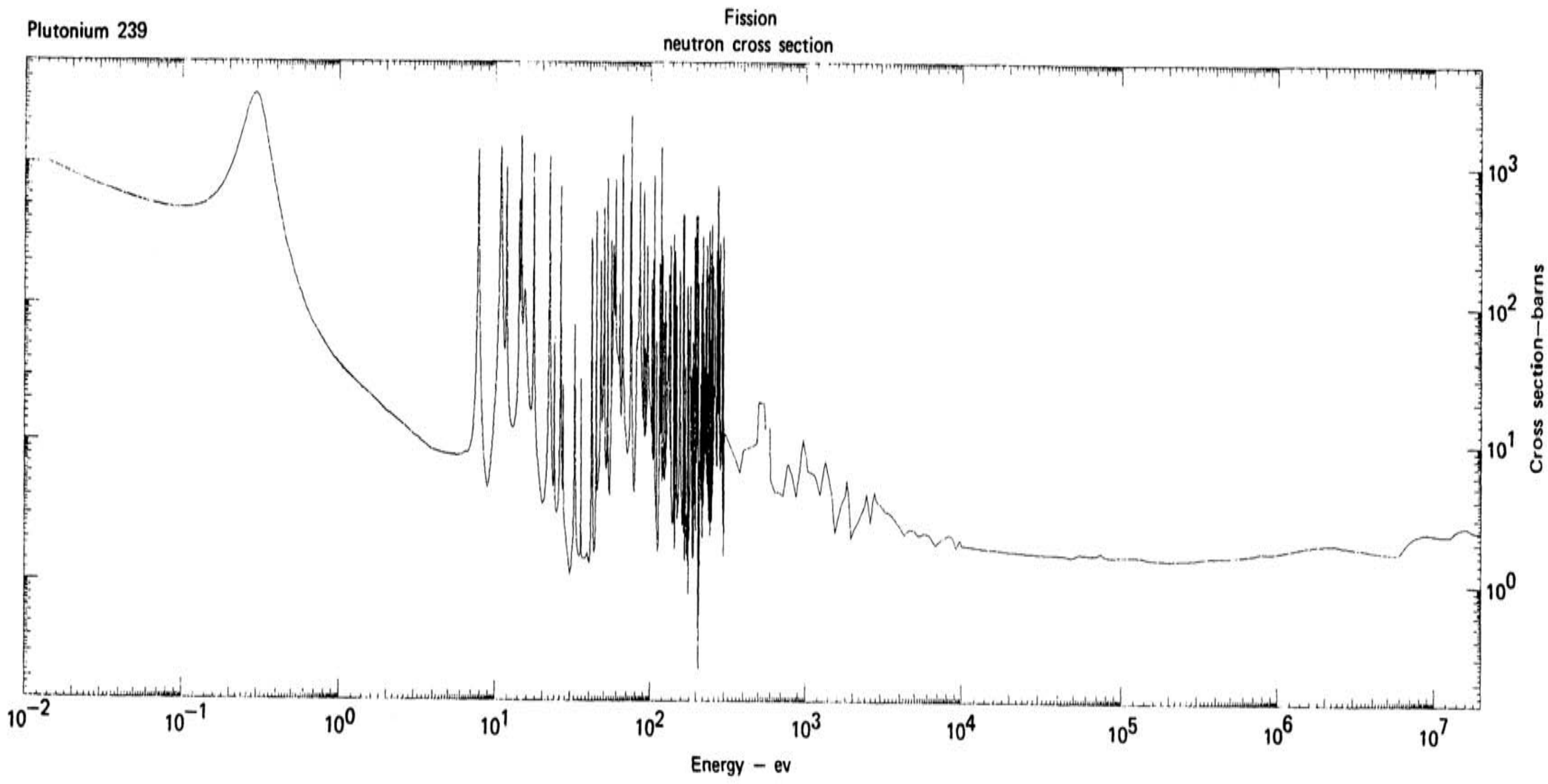
Some background facts (cont'd):

- Some resonances are <u>fission</u> resonances & <u>increase</u> neutron production [e.g., Pu-239 at 0.3 eV]



Low-Lying Fission Resonance in Plutonium-239

CANDU Coolant-Void Reactivity

- CANDU void reactivity is the sum total of several spectral (energy-specific) differential reactivity effects between the cooled configuration and the voided configuration of the lattice.
- Let us consider events which happen to neutrons before they leave the channel where they are born and after they re-enter a channel from the moderator region

cont'd

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<u>Before Escape from a Channel</u>

- Some fission neutrons, before escaping the channel where they are born, are normally slowed by coolant into the resonance energy region and are absorbed.
- Now imagine the coolant is lost. Without coolant, the following will happen:
  - 1) Fewer fast neutrons will be slowed into the resonance region, therefore there will be more opportunities for fast neutrons to induce fission ($\therefore$ more production), and
  - 2) More fast neutrons will escape resonance capture and reach the moderator ($\therefore$ less absorption)
  - Both phenomena increase reactivity cont'd

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After Re-Entering a Channel

- Some thermalized neutrons entering a channel from the moderator are scattered to higher energies; they may suffer resonance capture by hot coolant.
- Now imagine the coolant is lost. Without coolant, scattering to higher energies does not occur, and more neutrons escape resonance capture.
  - This resonance escape gives rise to a **positive** reactivity component from U-238, but
  - To a **negative** reactivity component from Pu-239 (on account of the fission resonance at 0.3 eV)

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Summary of Void-Reactivity Components

- <u>Positive</u> from increased fast fission
- <u>Positive</u> from increased resonance escape at high end of energy spectrum (on way out of channel)
- <u>Positive</u> from increased U-resonance escape at low end of energy spectrum (on way into channel)
- <u>Negative</u> from increased U-resonance escape at low end of energy spectrum (on way into channel)

- Overall result: the **net** coolant-void reactivity is **positive**, but decreases with irradiation (burnup).

CANDU Coolant-Void Reactivity

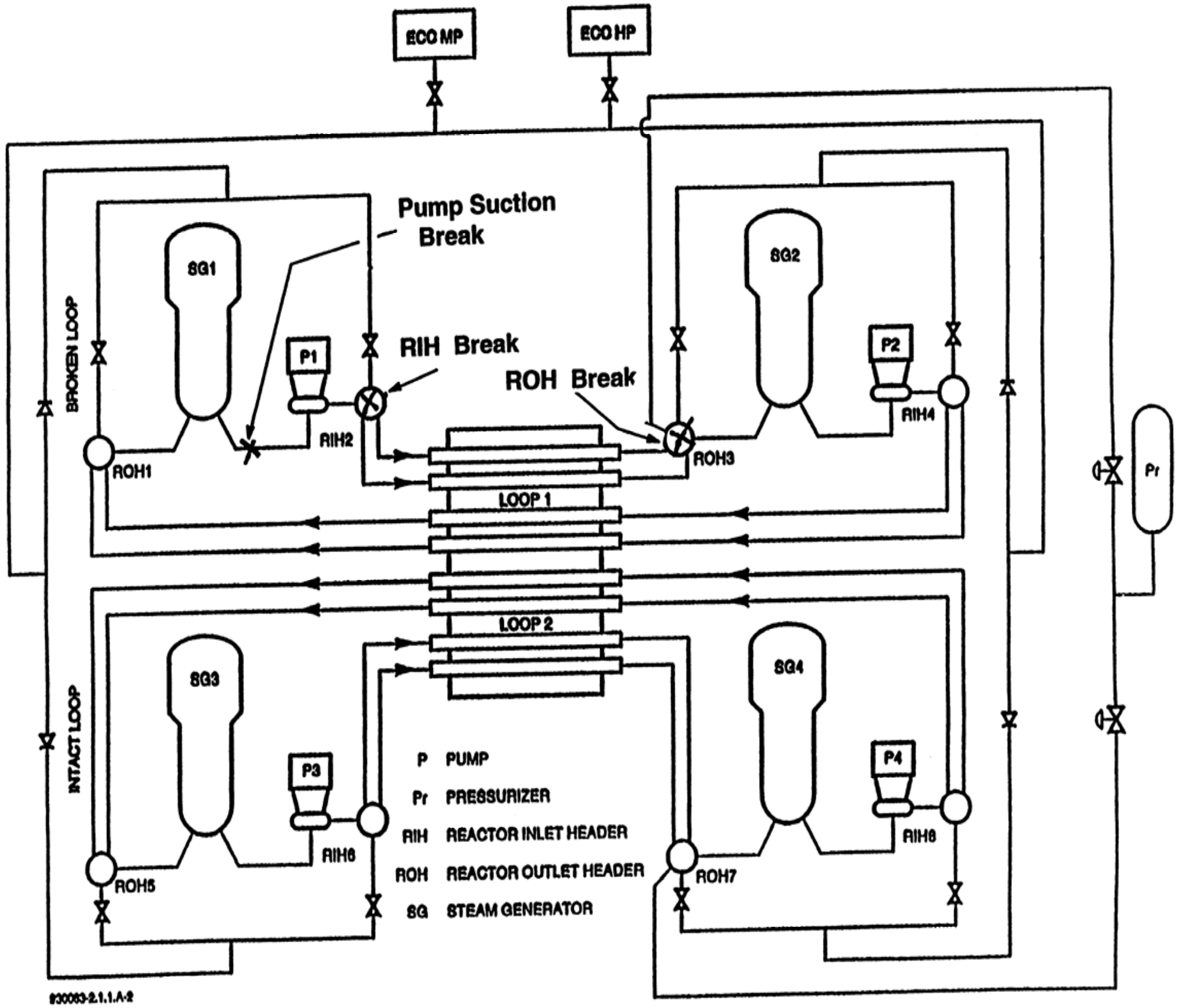
Note:

- This analysis is for the standard CANDU reactors.
- It cannot be generalized: For other lattices (other dimensions, other materials) the differential effects may be, and are often, quite different.

Large LOCA (LLOCA)

- LOCA is the break of a large pipe [see next Figure]
- It is the accident which presents the greatest challenge to CANDU shutdown systems in terms of the **rate** of positive reactivity insertion.

Examples of Break Locations Giving Rise to a Large



Large LOCA

- Reactivity from full-core voiding:
  - ~15-18 milli-k for fresh fuel
  - Reduces to ~10-12 milli-k for equilibrium fuel
- In Bruce, reactivity insertion is ~6 milli-k in the first second after break
- It is typically ~4-5 milli-k in other CANDUs with two-loop design
- Reactivity change on this time scale leads to **fast neutronic transient**
- Power pulse ensues, shutdown system must be actuated in fraction of 1 s to quickly terminate transient.

Large LOCA

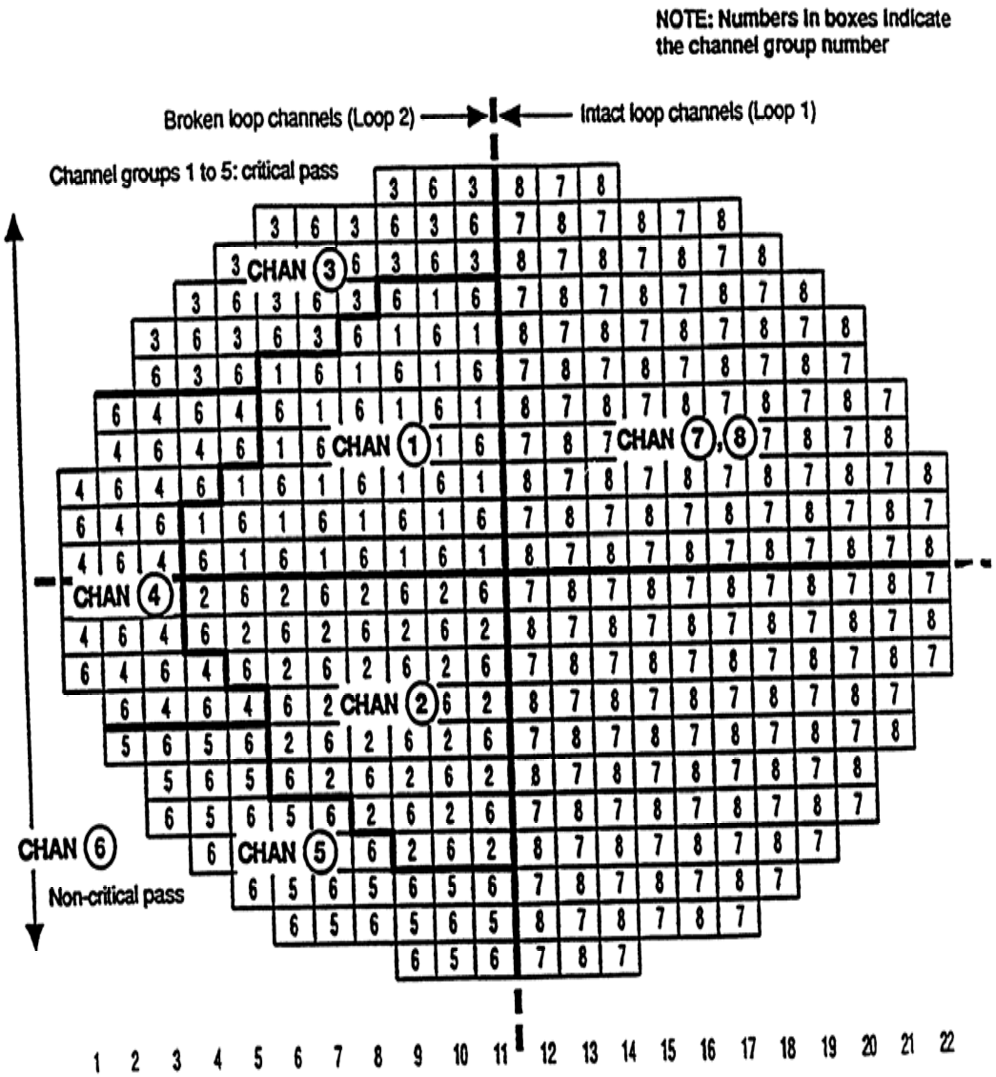
- A LLOCA must be analyzed as a kinetics problem
- The time-dependent diffusion equation, with terms for the delayed-neutron source, must be solved
- This equation is linked to time-dependent equations for the delayed-neutron precursors
- In the early days, point kinetics was used
- In modern analysis, space-time kinetics is used

Large LOCA

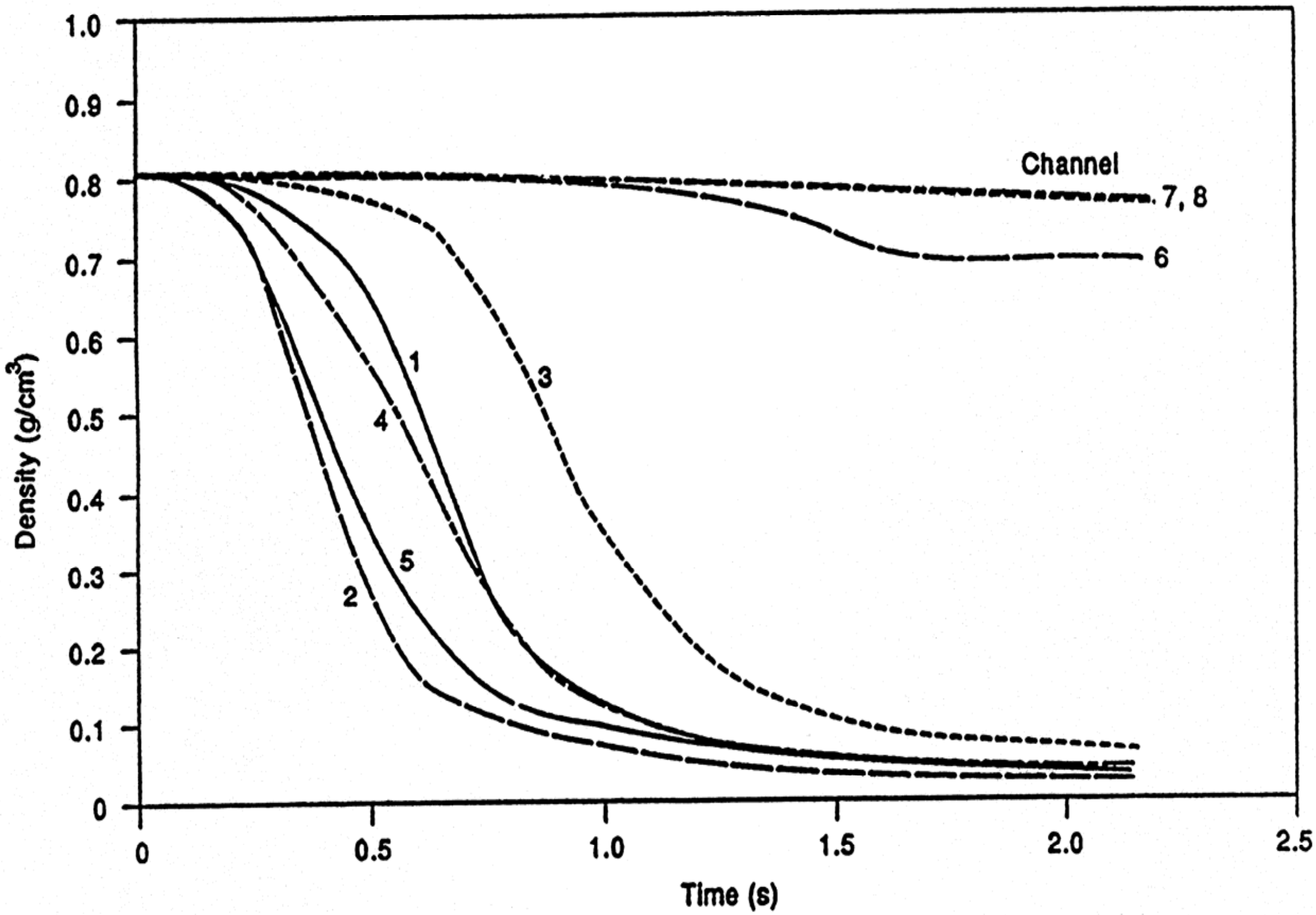
Coupled Neutronics-Thermalhydraulics Analysis

- A multi-channel thermalhydraulics is set up, to give the voiding rate in various channels (high-power inner region vs. peripheral region, elevation of channel in core, different thermalhydraulics loops and passes)
- The voiding rate in the various groups is calculated
- Then the power transient pulse in the various channels is calculated with the kinetics code
- See typical figures in following slides

Example of Thermalhydraulic Channel Grouping for a LLOCA Calculation



Examples of Coolant Densities Calculated for Various Channel Groups



Examples of Power Pulses Calculated for the CANDU-6 for an Individual Bundle and Core Halves - Calculation gives power also for each channel & bundle