Advanced Transmutation Reactors

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Yours truly

Transmutation due to neutron interactions
GNEP fuel cycle goal
Fast Reactor Basics
Advanced Burner Reactor
SCALE in academic environment: SABR
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- PhD from Delft University of Technology (The Netherlands), “Improving fuel cycle design and safety characteristics of a Gas Cooled Fast Reactor” (2006)
- Started at GeorgiaTech March 1st 2007 as Assistant Professor
- Research focus: Fast Reactors and Nuclear Fuel Cycle
- (Ultimate) Goal: closing the nuclear fuel cycle

Overview

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The Nuclear Fuel Cycle

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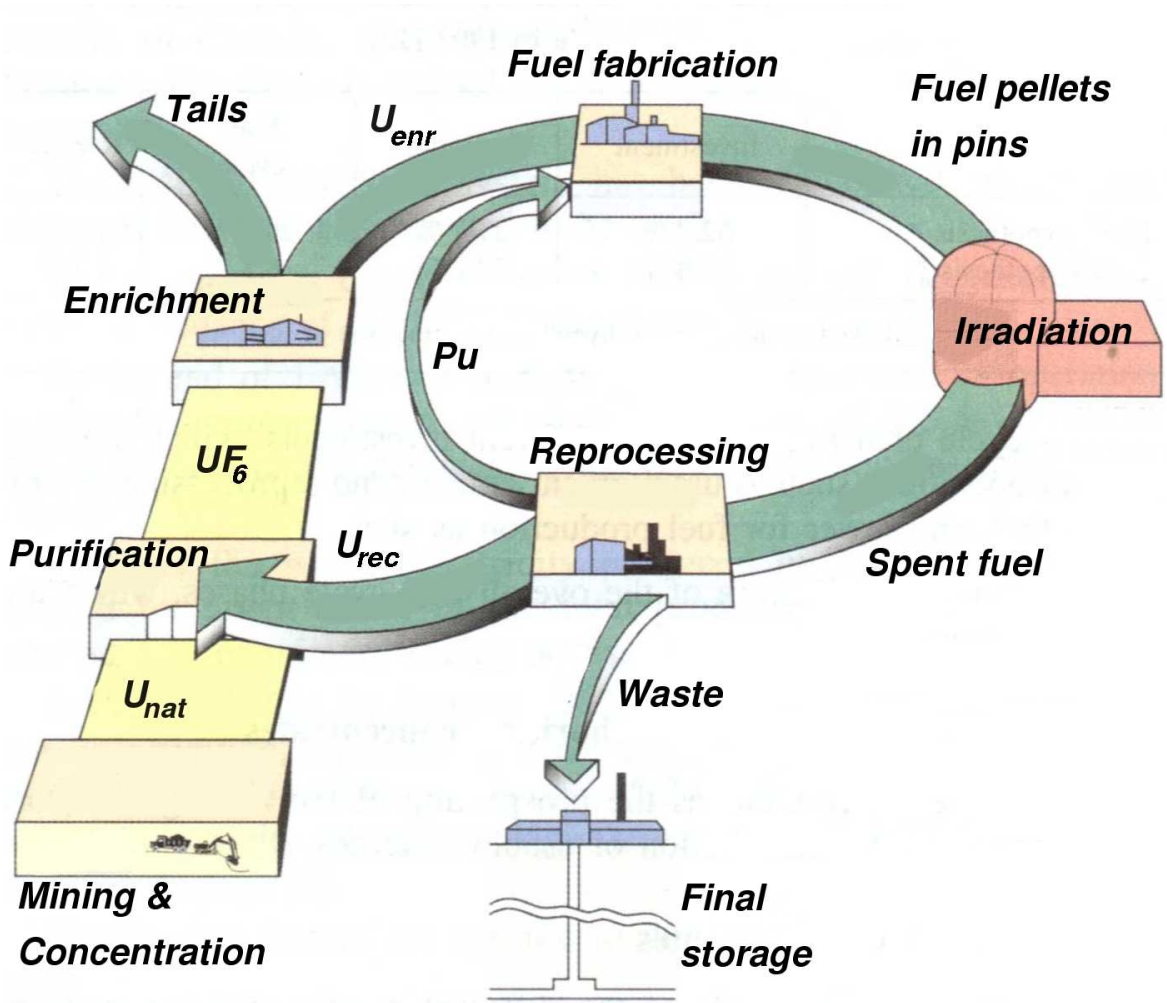

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Transmutation due to neutron interactions

Transmutation equations

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Interaction of a mixture of nuclides with neutrons is described by the transmutation equation:

- time rate of change = production rate - destruction rate + source

$$\frac{dN_i}{dt} = -(\sigma_a \phi + \lambda_i) N_i + \sum_k N_k \sigma_{c,k\to i} \phi + \sum_l \lambda_{l\to i} N_l + \sum_j y_{j\to i} N_j \sigma_{f,j} \phi + q_i$$

$$\bar{\sigma}_x(r,t) = \frac{\int_0^\infty \sigma_x(r,E,t)\phi(r,E,t)dE}{\int_0^\infty dE\phi(r,E,t)dE}$$

Transmutation matrix

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- Transmutation equations form a coupled system, can be written as matrix system.

$$\frac{\partial \vec{N}}{\partial t} = \underline{M}\vec{N} + \vec{Q}$$

- $\underline{M}$: Transmutation Matrix, contains nuclear data (σ, λ) (e.g. from unit cell calculation), and ϕ
- Note that all $\bar{\sigma}_x$, ϕ are *spectrum averaged* values: depletion behaviour depends on reactor spectrum (thermal, epi-thermal, fast).

Depletion of UOx in a PWR

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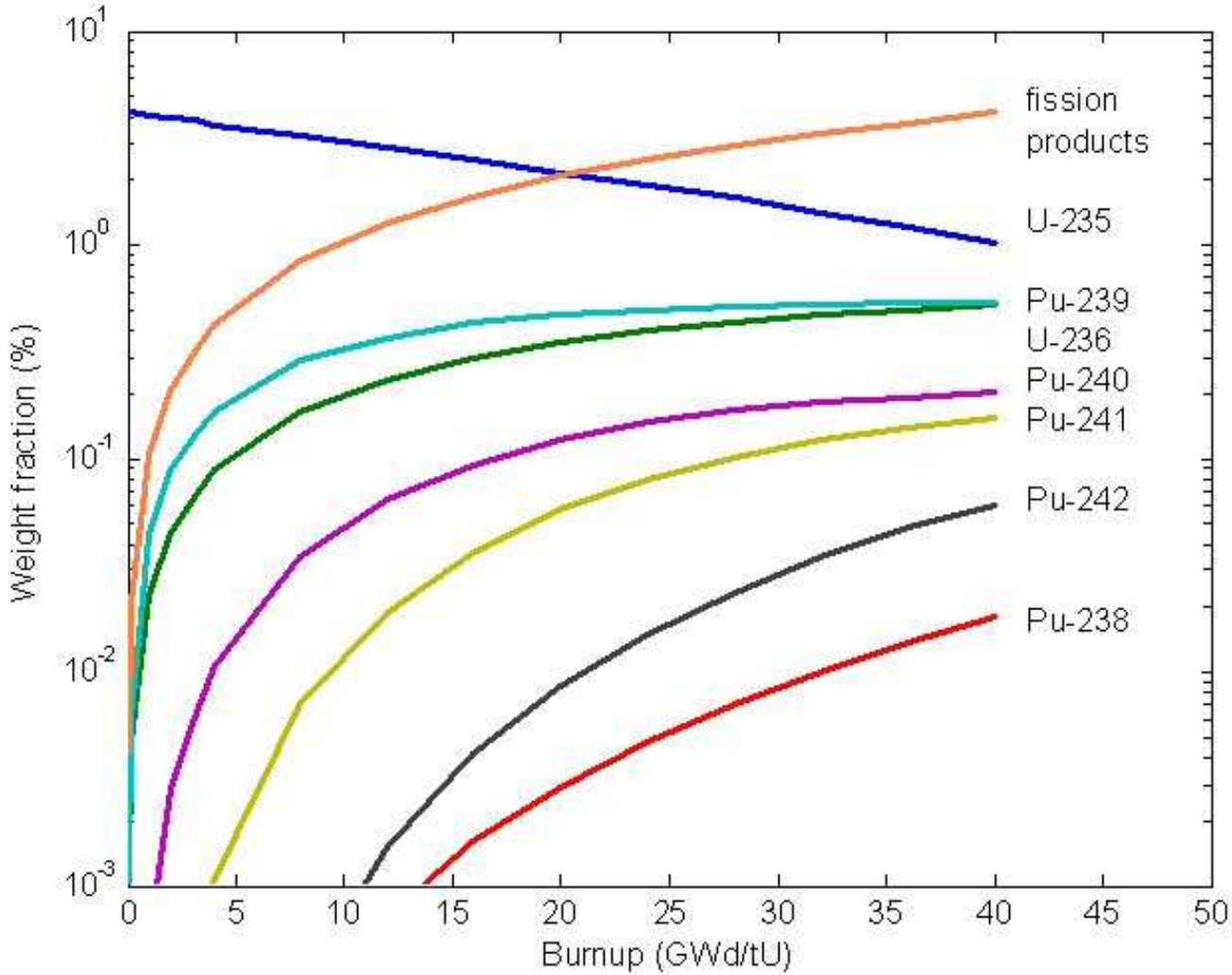

Long term radioactive waste

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Isotopes with a long half life in Spent Nuclear Fuel

- Fission Products: Tc-99, I-129, Cs-135
- Minor Actinides: Np-237, Am, Cm
- But above all: plutonium
- Note: in some cases, long-term radioactivity due to decay products

The canonical numbers

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Production of TRU (Np, Pu, Am and Cm), per TWhe, in a PWR or similar reactor, enriched uranium (4.5%)

- Pu: + 26 kg / TWhe
- Np: + 1.8 kg / TWhe
- Am: + 1.11 kg / TWhe
- Cm: + 0.3 kg/ TWhe

Or, per GWe installed power: 1000 MWe PWR, load factor 91.3%, annual production 8 TWhe, corresponding to 208 kg Pu and 25.7 kg MA, per year.

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- Reduction of long-term repository requirements can be achieved by ’getting rid’ of TransUranic (TRU) material, i.e. by fissioning the TRU isotopes
- Plutonium poses proliferation risk, should not be separated individually
- Uranium is hardly radioactive, fissile fraction in SNF low, poses no problems if separated
- All TRU material to be separated ’en bloc’ from SNF, and put into an Advanced Burner Reactor, for transmutation

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  1. this not a ’cycle’ in the true sense of the word

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  1. this not a ’cycle’ in the true sense of the word
  2. still relies on natural uranium as the source of the fissile isotopes

Properties of transmutation systems - 1

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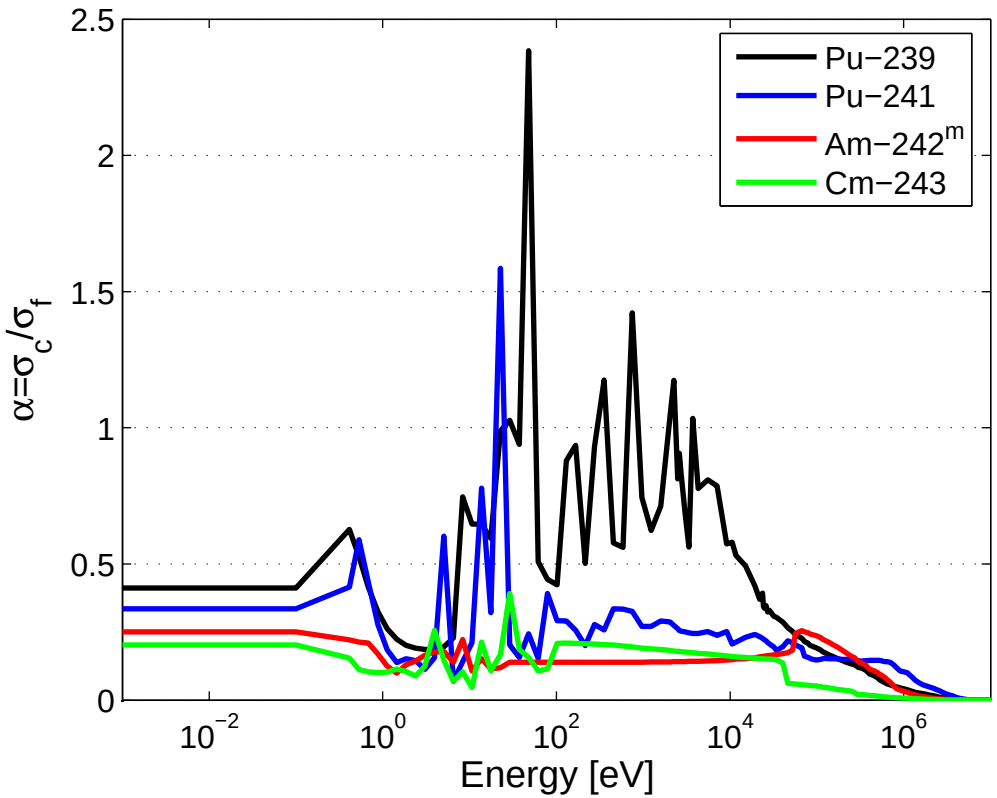
Capture to fission ratio $\alpha = \frac{\sigma_c}{\sigma_f}$



High energy neutrons: fission dominates over capture.

Properties of transmutation systems - 2

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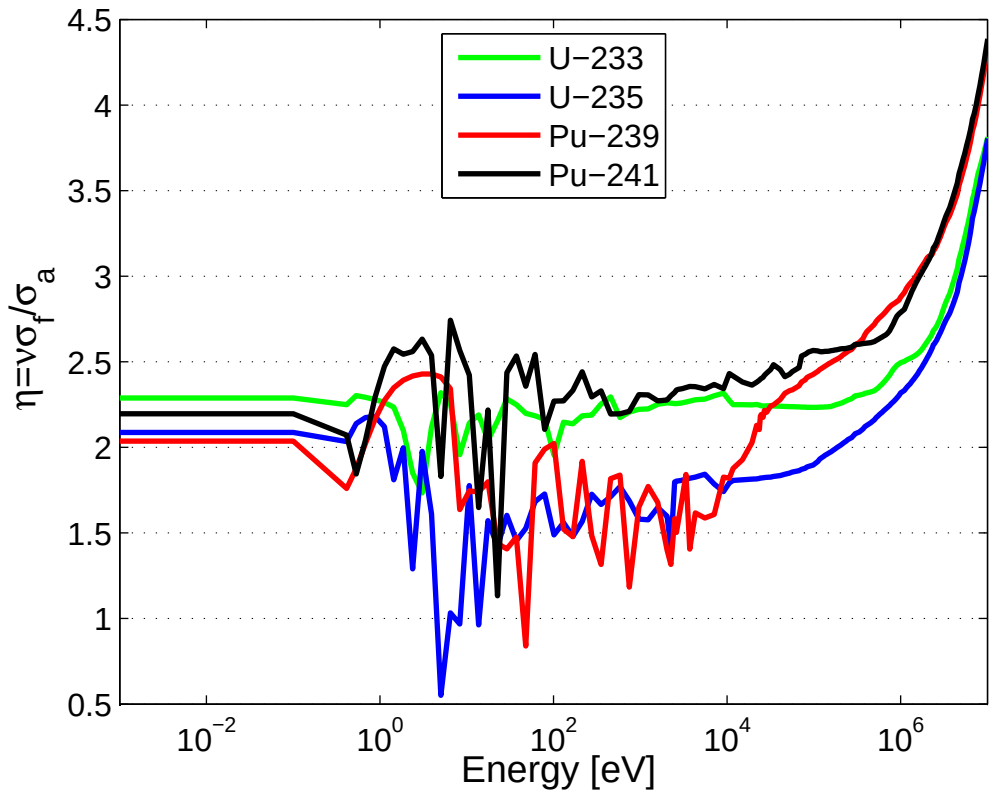
Neutron per fission $\eta = \nu \frac{\sigma_f}{\sigma_c + \sigma_f}$



More neutrons available in high-energy fissions

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- High energy neutrons, $E = 1/2mv^2 \rightarrow$ fast neutrons, fast reactors

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- No moderator, and no optimal fuel to moderator ratio: coolant fraction as small as possible within thermal limits

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- Gas cooling possible: Gas Cooled Fast Reactor (Generation IV system), using helium or (supercritical) CO2
- Cross sections smaller at higher energies, especially fission XS, so usually high enrichment needed: 15% - 30% fissile fraction

Void effect in fast reactors

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Coolant voiding causes four effects:

1. Slightly harder spectrum increases fission yield ν, reduces parasitic absorption in resonances, and increases fissions of threshold fissioners: +ρ
2. Reduced absorption by coolant: + ρ
3. Reduction of scattering by coolat increases leakage: - ρ
4. Reduction of coolant will increase the temperature, in a *properly designed* fuel this should lead to higher absorption due to the Doppler effect: - ρ

Void effect in fast reactors

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Notes:

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1. In practice a high-leakage configuration is chosen, to make sure that effect 3 dominates: low and wide ('pancake') core
2. Void effect has 'spatial dependence', i.e. the location where voiding occurs determines the sign / magnitude of the reactivity effect

The Doppler effect

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$$\bar{\sigma}_\gamma(E,T) = \frac{\sigma_0 \Gamma_\gamma}{\Gamma}\sqrt{\frac{E_0}{E}}\Psi(\xi,x)$$

$$x = \frac{2}{\Gamma}(E - E_0), \qquad \xi = \frac{\Gamma}{\sqrt{4E_0 kT/A}}$$

$$\Psi(\xi,x) = \frac{\xi}{2\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{dy}{1+y^2}\exp\left(\frac{1}{4(x-y)^2\xi^2}\right)$$

Temperature dependence in ξ. Higher T 'broadens' $\bar{\sigma}_\gamma$ but the area under the curve is *constant*

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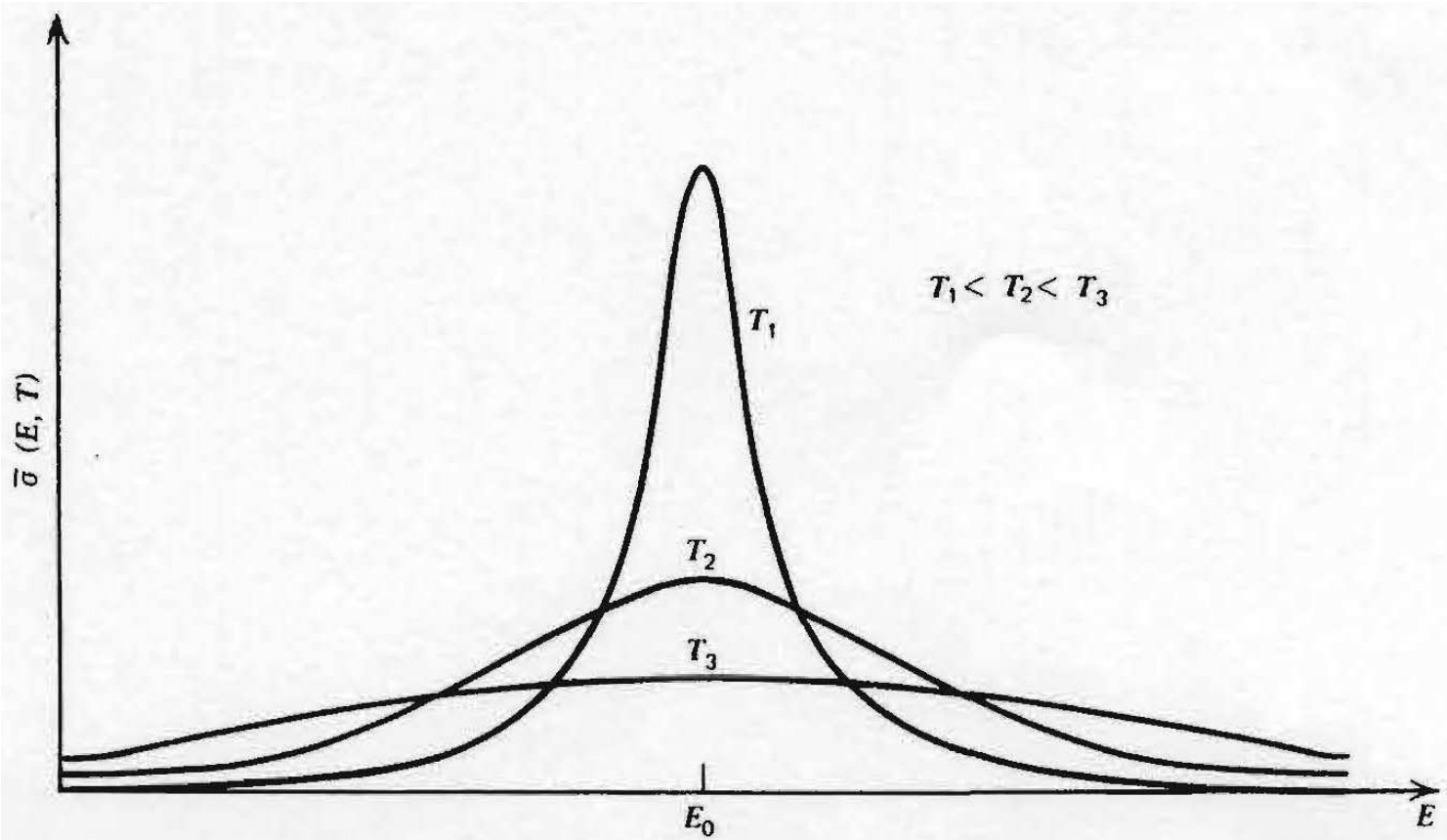

FIGURE 2-14. Doppler-broadening of a resonance with increasing temperature.

The Doppler effect

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Total resonance absorption is given by resonance integral:

$$I = \int \sigma_\gamma(E)\phi(E)dE$$

Increasing T broadens resonance, 'catching' more neutrons.

- This is valid for *all* cross sections, including fission: highly enriched fuel may have positive Doppler-coefficient
- Resonances more effective at low energy (higher flux): fast reactors generally have small Doppler effect
- Need to calculate self-shielding accurately to adequately calculate Doppler effect

The Doppler effect

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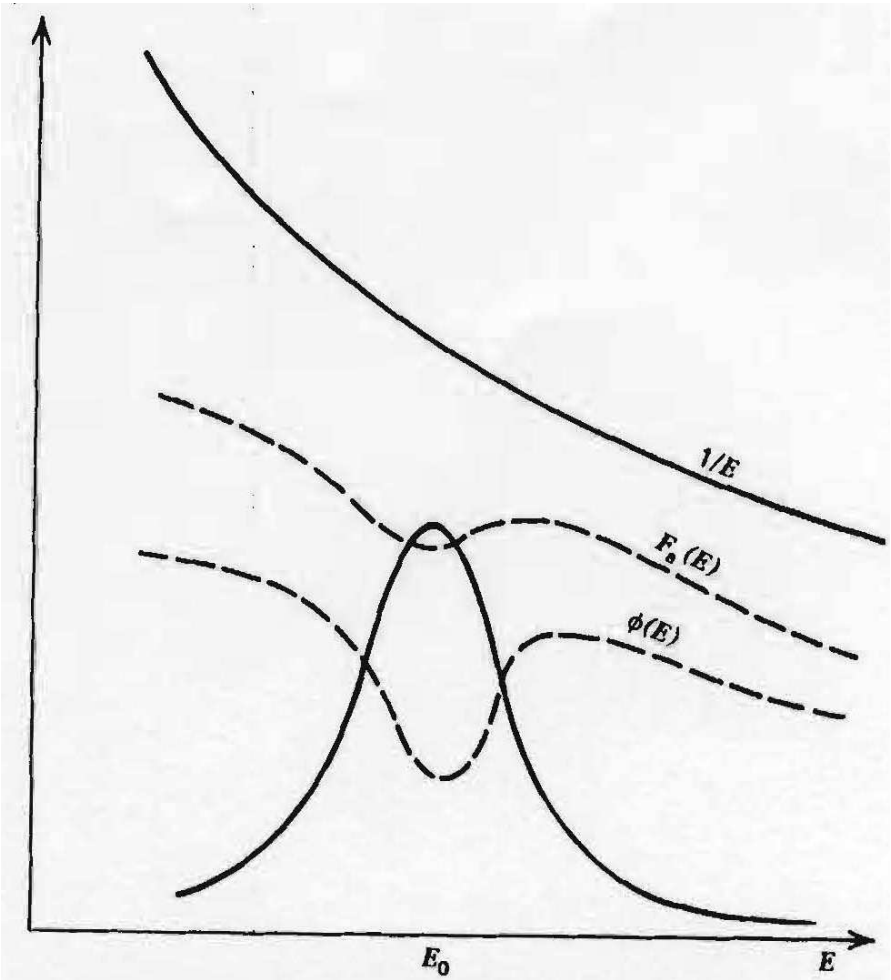

Geometrical effects in fast reactors

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- Core expansion has *negative* reactivity effect (both radial and axial expansion): thermal expansion feedback
- Careful design of fuel pins necessary: for instance thermal effects can cause a more dense fuel configuration, and positive thermal feedback occurs (fuel bowing!)
- Compaction increases reactivity: can cause problems if fuel melts

Kinetic parameters

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For fast reactors point-kinetics is just as (in)valid as for thermal systems

$$\frac{dp(t)}{dt} = \frac{\rho(t) - \beta(t)}{\Lambda(t)} p(t) + \sum_{i=1}^{i=I} \lambda_i C_i(t)$$

$$\frac{dC_i}{dt} = \frac{\beta_i(t)}{\Lambda(t)} p(t) - \lambda_i C_i$$

$$\Lambda \propto \frac{1}{v \nu \Sigma_f}$$

$$\beta(t) = \frac{\langle \phi_0^+, F_d \psi_0 \rangle}{\langle \phi_0^+, F \psi_0 \rangle}$$

Delayed neutron fraction

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- Delayed neutron fraction generally *decreases* with atomic number: heavier elements produces less delayed neutrons
- Delayed neutron fraction generally *increases* with mass number, i.e. Pu-241 produces more delayed neutrons than Pu-239
- Generally, in fast reactors the *effective* β is smaller than β (due to adjoint weighting)
- Delayed neutrons spectrum softer than fission neutron spectrum; if strong thermal absorbers are present in a system, delayed neutrons are more likely to be absorbed than fission neutrons: β_{eff} further reduced

Some illustrations

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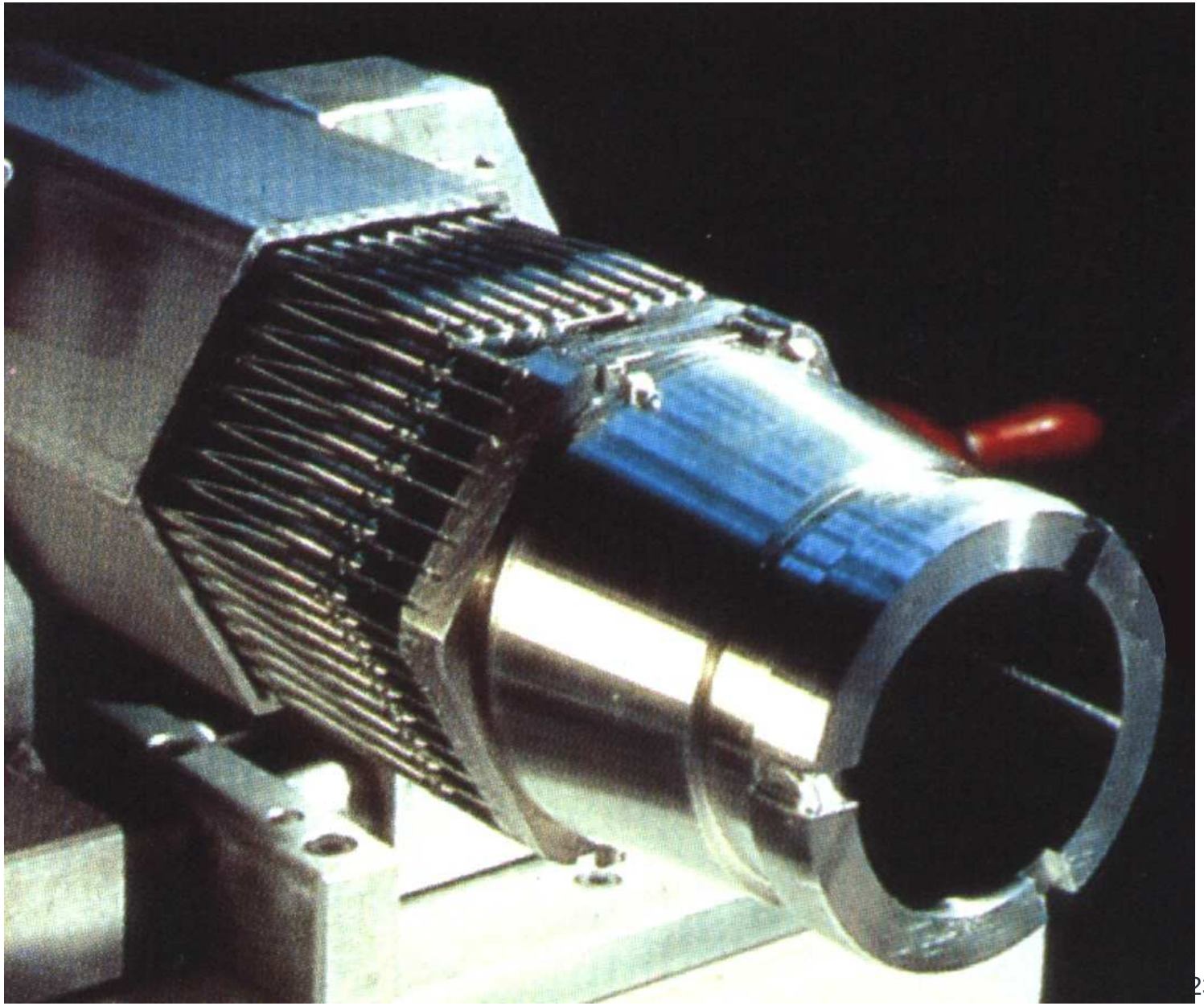

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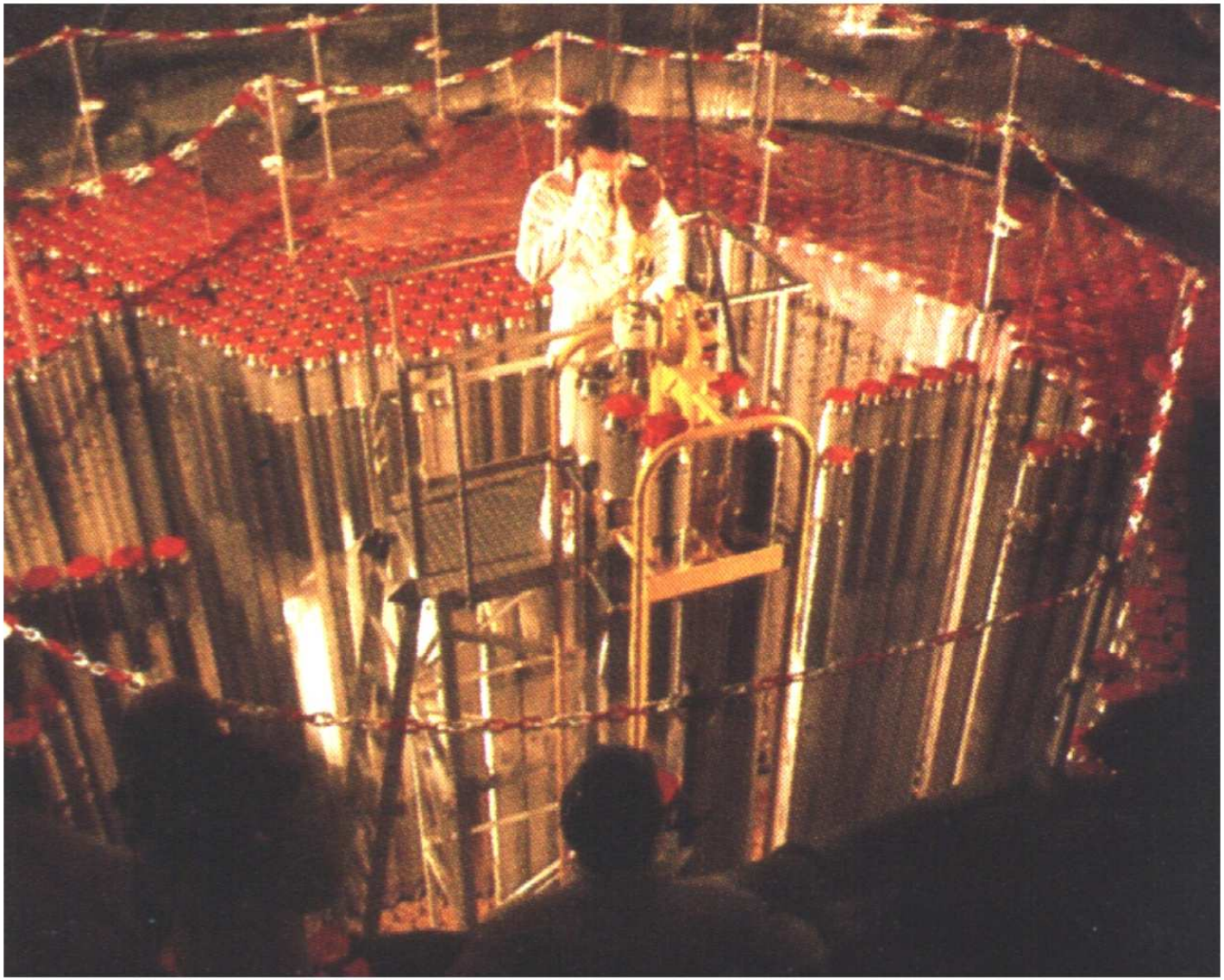

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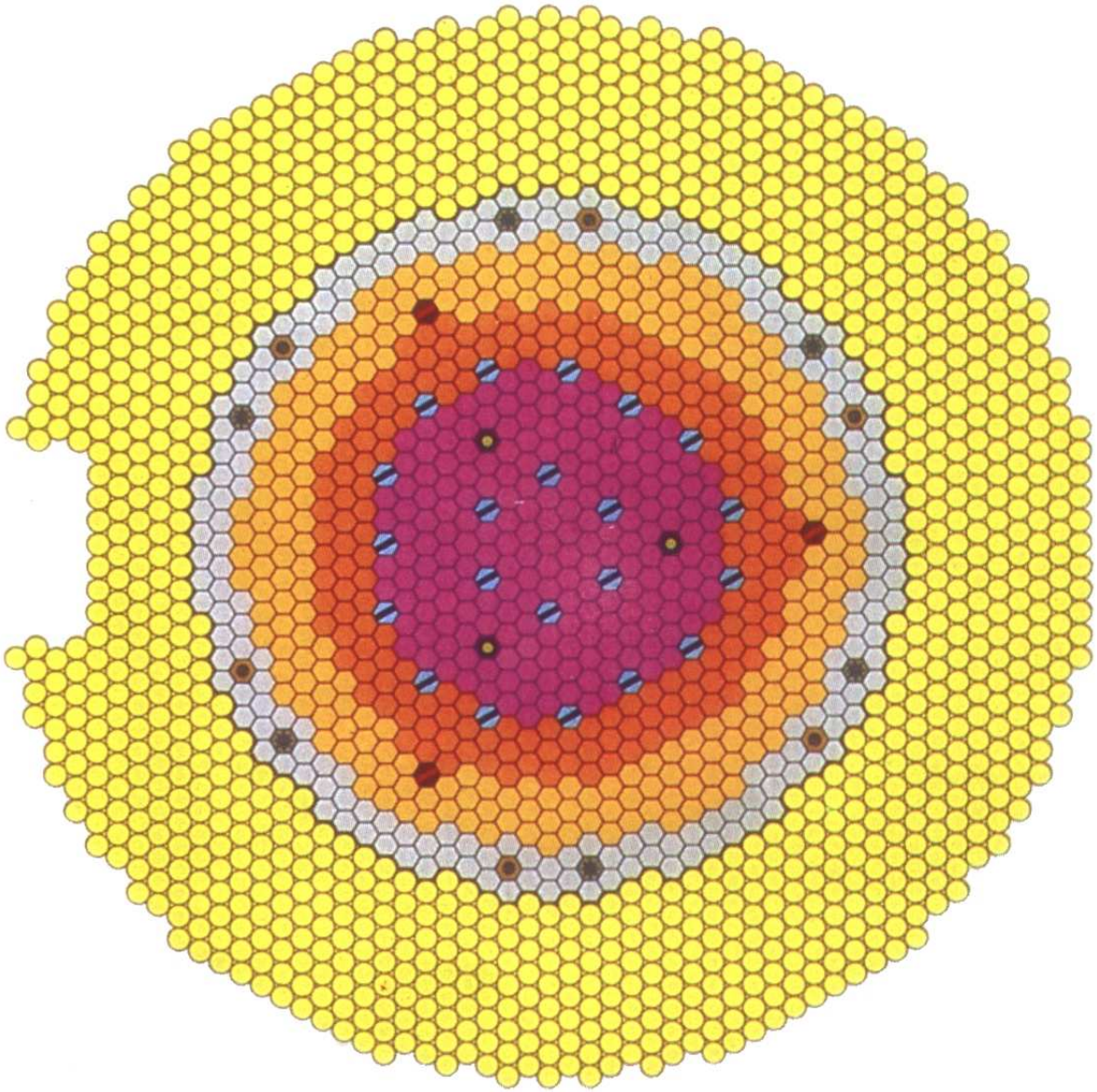

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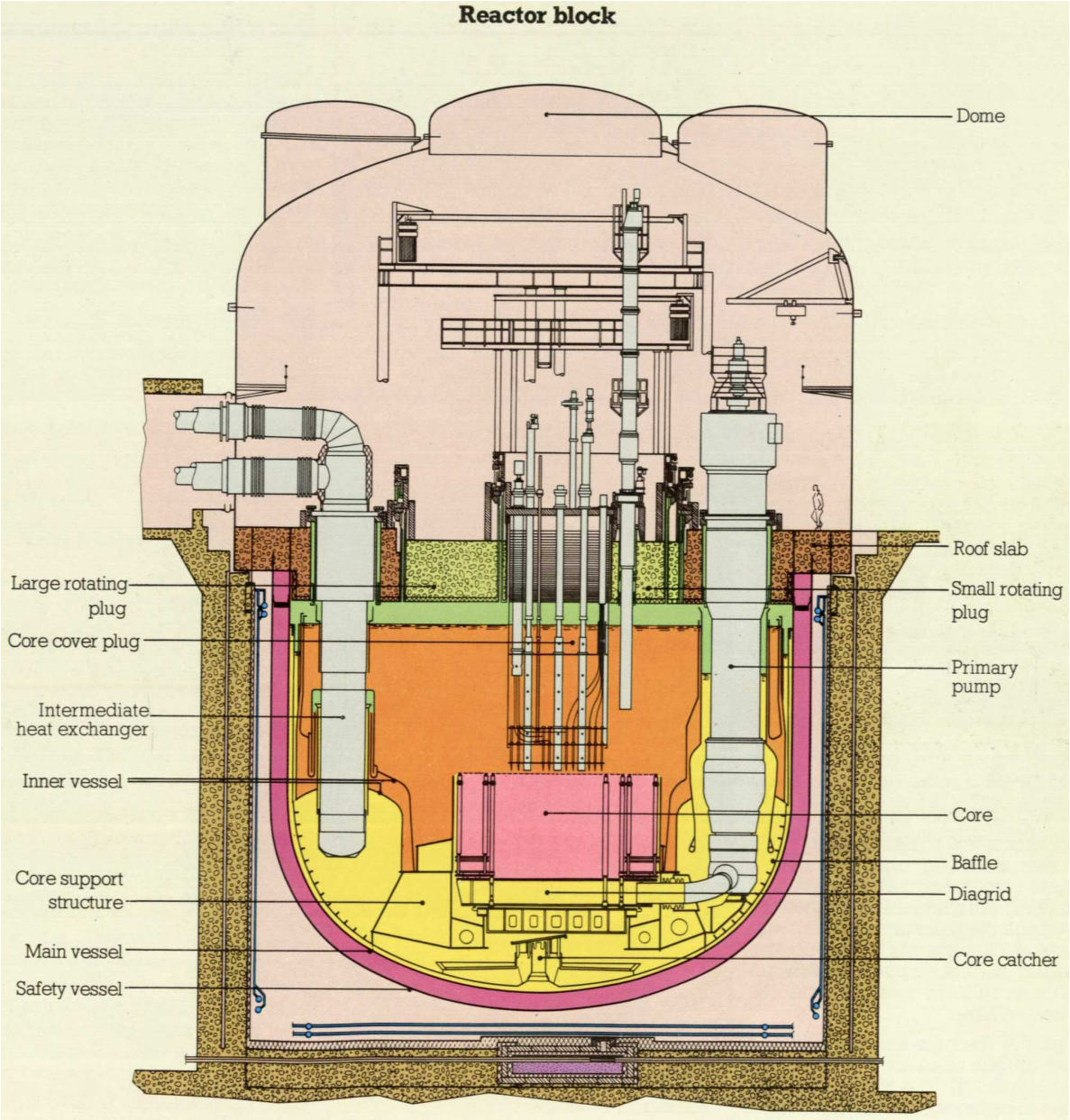

Fast spectra

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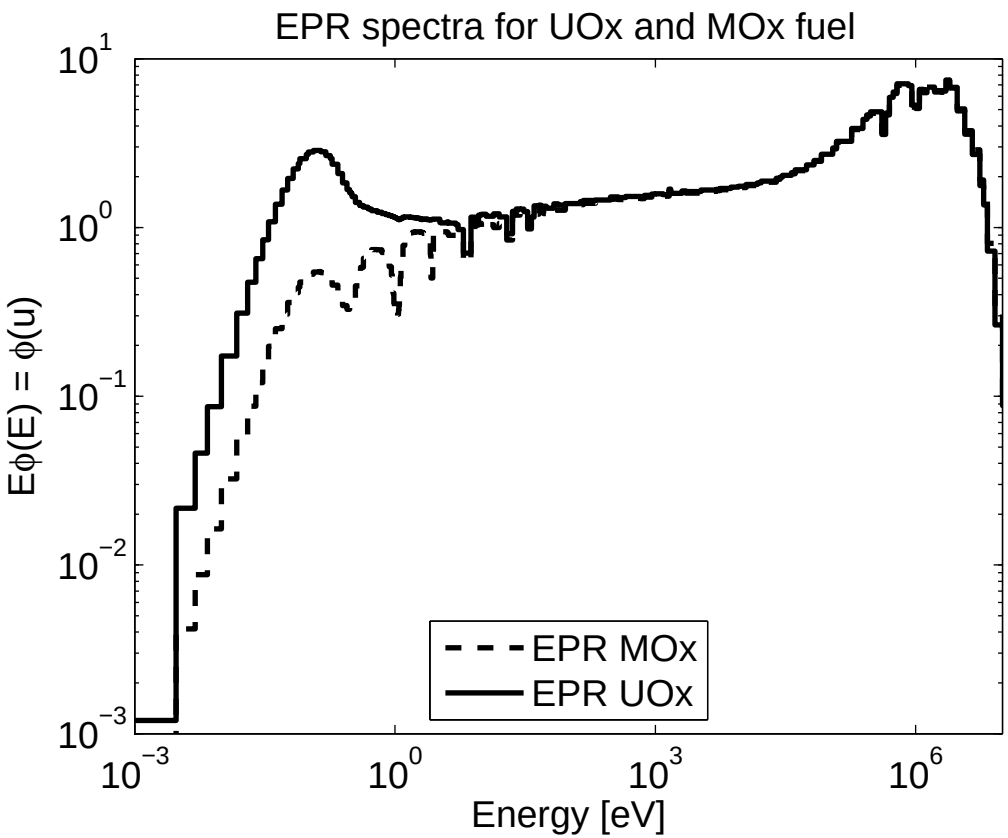

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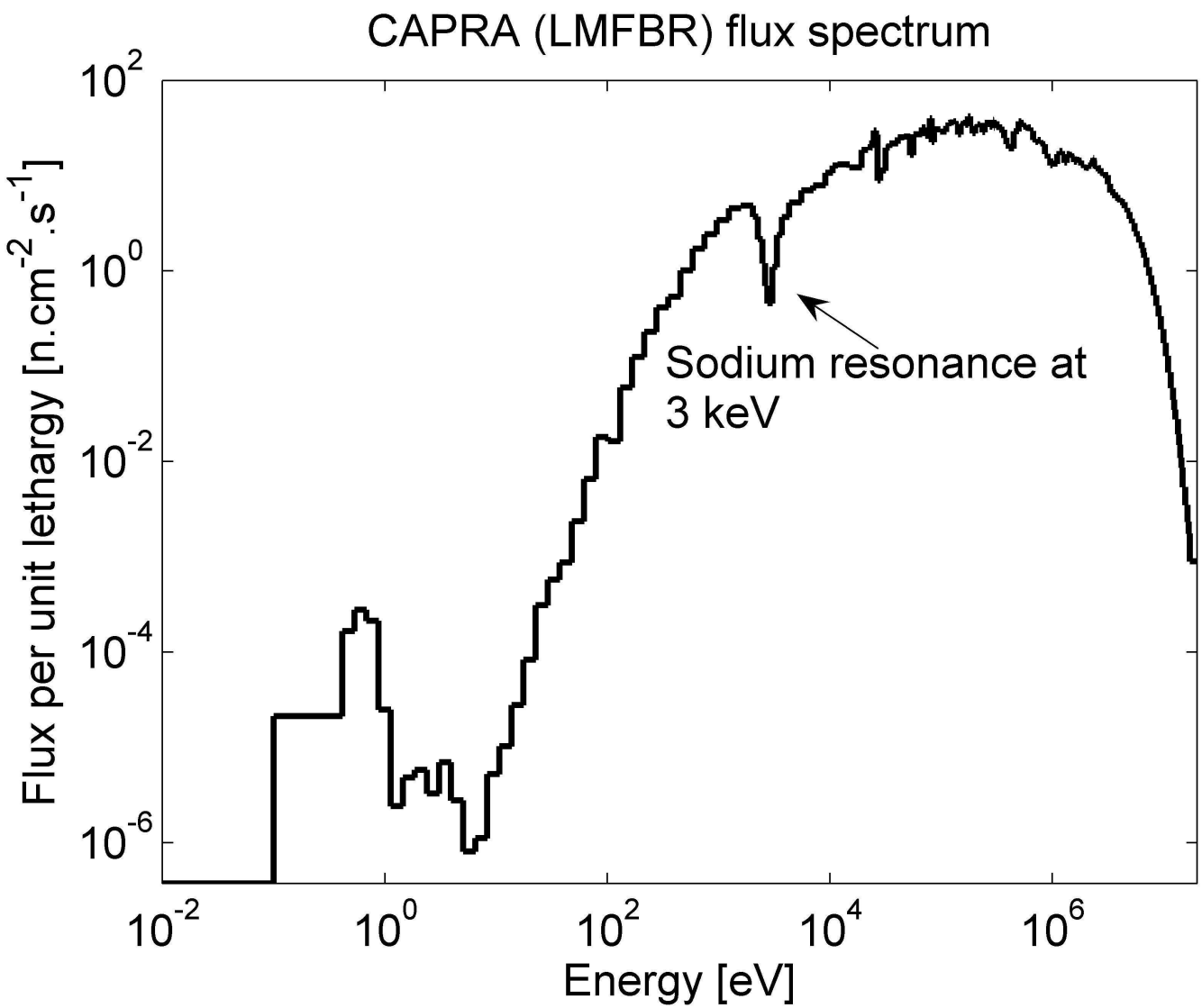

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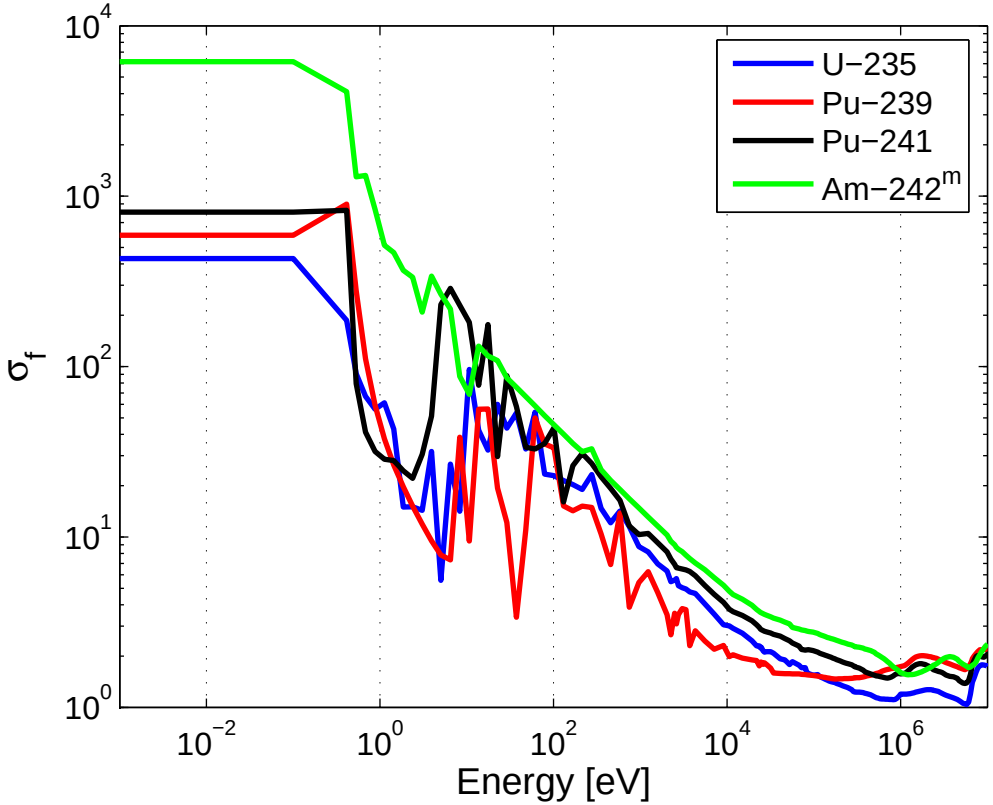

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Advanced Burner Reactor

The ABR 'double strata' fuel cycle

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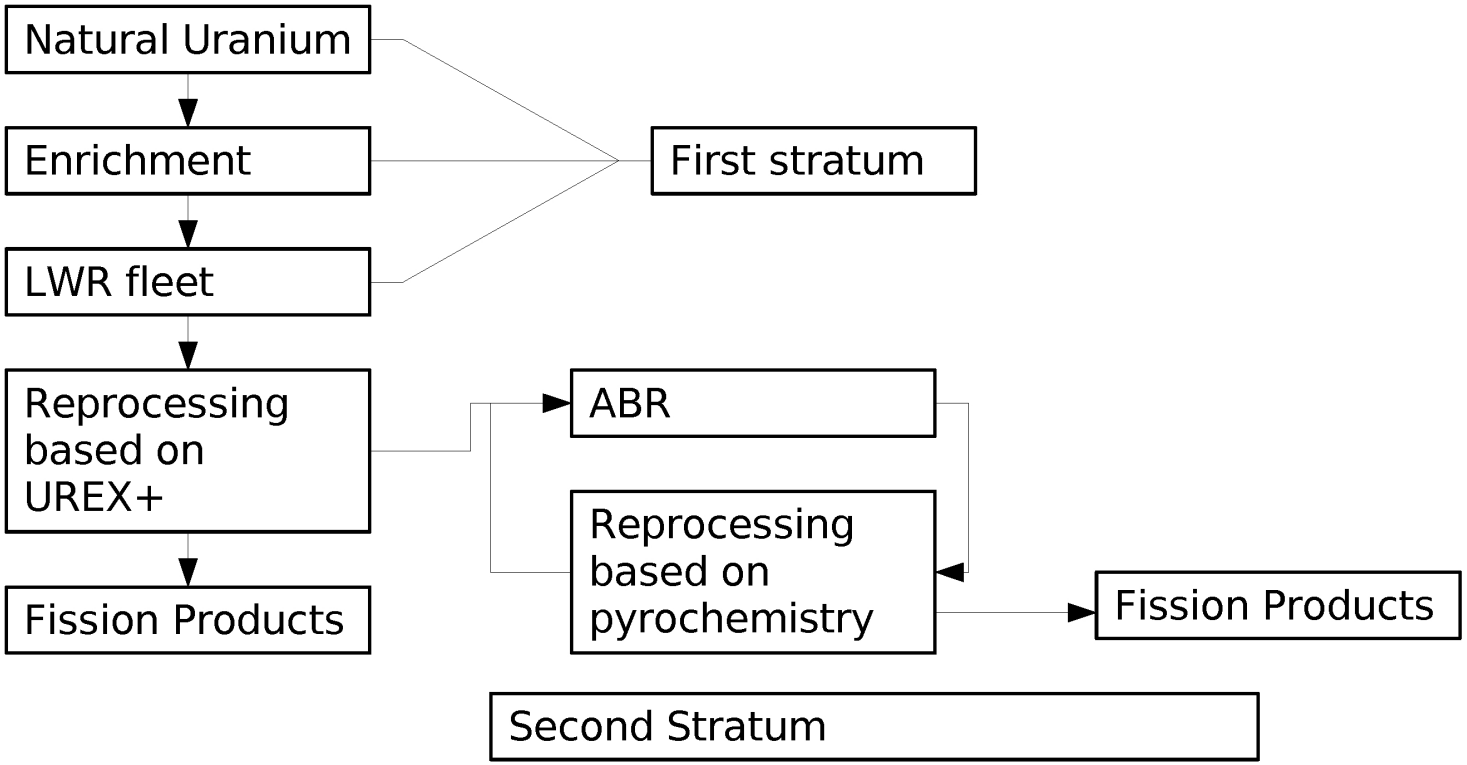
Proposed ABR cycle is an example of a 'double strata' cycle



Simple calculation: for each GWe of PWR power, approx. 900 MWth of ABR power required to destruct TRU (or: ABR installed capacity 30% of total installed capacity)

ABR characteristics

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- TRU-Zr metallic fuel; TRU is mainly reactor grade plutonium, with high fissile fraction: Doppler positive, need Zr for absorption and negative temperature coefficient
- Metallic fuel: high thermal conductivity, high thermal expansion (good for reactivity feedback)
- No uranium: bad for β_{eff}; e.g. Gas Cooled Fast Reactor on UPuC fuel, 16% Pu, 84% U-238: U-238 contributes 51% of β_{eff} (!). U-238 threshold fission, small XS, but large delayed neutron production
- Sodium cooling, but many other system parameters to be determined

Sub-critical transmutation systems

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- Pure transmutation systems (usually) have large reactivity swing: either high overreactivity of fresh fuel, or short irradiation interval (with low burnup)
- Low burnup leads to high mass flow of material in the reprocessing plants
- Sub-critical reactors: criticality is no longer constraint, high burnup possible

$$\frac{dp}{dt} = \frac{\rho - \beta}{\Lambda} p(t) + \sum_{i=1}^{i=I} \lambda_i C_i(t) + S(t)$$

$$\frac{dC_i}{dt} = \frac{\beta_i}{\Lambda} p(t) - \lambda_i C_i$$

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Where does SCALE come into the picture?

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- Georgia Tech has a design class, each year, Spring semester.
- Focus has been on several fusion driven subcritical reactor designs for transmutation
- Several possibilities have been investigated: gas cooling, Pb-Li cooling, Once-Through (deep burn) vs. multiple recycle, metallic fuel vs. coated particles etc.
- This year's class: Sodium-cooled Advanced Burner Reactor: SABR
- Neutronics and fuel cycle mainly based on SCALE 5.1 cross section generation

SABR system layout

Transmutation due to neutron interactions

GNEP fuel cycle goal

Fast Reactor Basics

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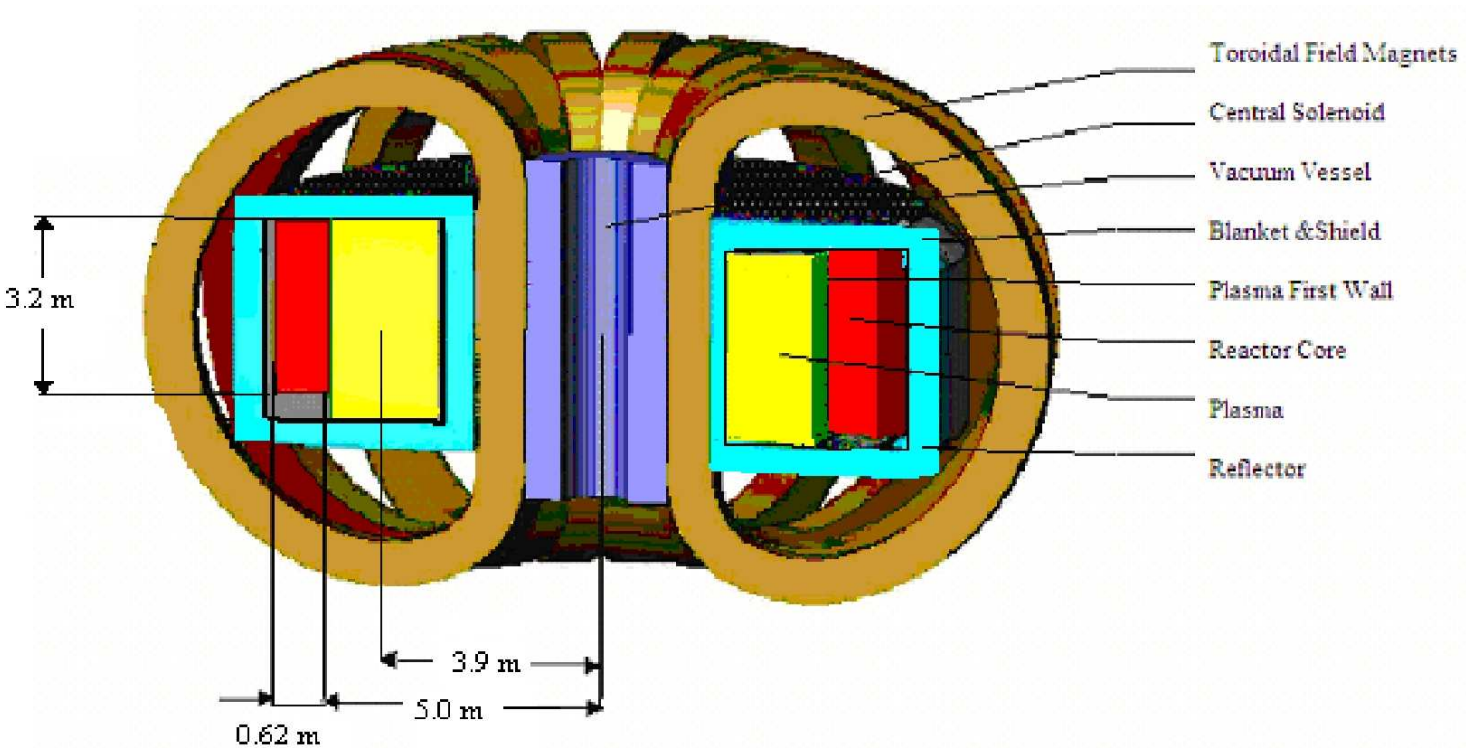

SABR neutronics approach

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- Started out using TRITON and CSAS, but no source options present, switched to EVENT (3-D even-parity code, C. d'Oliveira)
- Cross sections generated using CSAS, collapsed from 238 groups to lower number (application dependent), then use EVENT, fixed source calculation in 3-D annular geometry, to obtain 'k_{eff}', flux spectrum etc.

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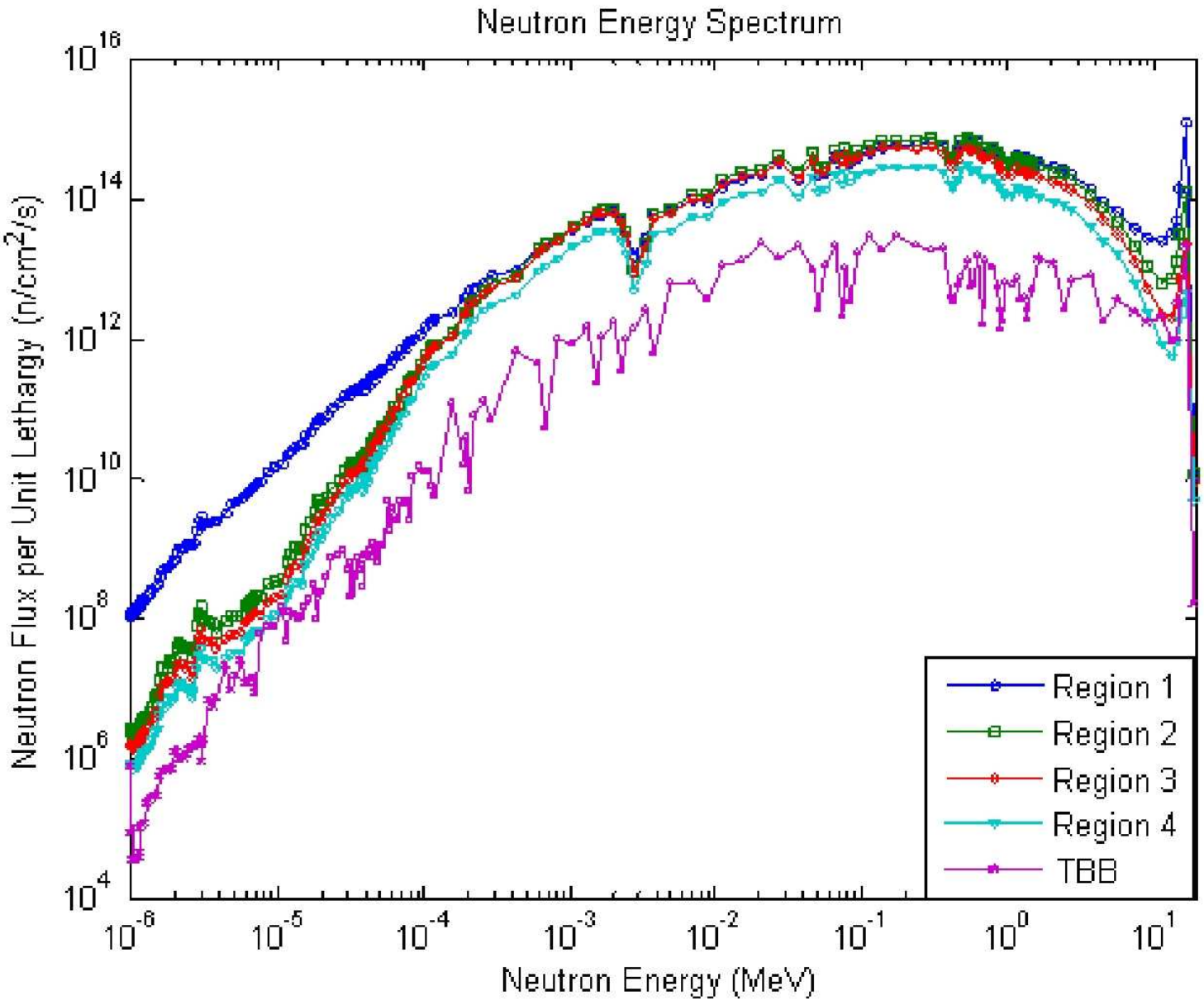

SABR fuel cycle study

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- Use TRITON to do fuel depletion, but TRITON does not have source-driven option
- Solution 1 (simple solution): use EVENT to calculate power densities for several fuel 'batches' (or zones), then use individual TRITON runs to deplete materials
- Disadvantage: spectrum will be slightly wrong because of (lack of) 14 MeV neutrons in TRITON
- Solution 2: use CSAS for XS generation, then XSDRNPM fixed source calculation, then use COUPLE + ORIGEN
- Requires considerable scripting to set up, so option 1 was used

SABR fuel cycle

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- Use CSAS for XS, then perform EVENT calculations to obtain power distributions, then use individual TRITON pin-cell models to do the depletion calculations
- Reshuffle fuel every once in a while, do new CSAS - EVENT - TRITON calculations
- For instance, fresh fuel may be added to the outermost fuel positions, then moved inward ('out-to-in'), or fresh fuel may be added to the inner positions, then moved outward ('in-to-out')
- Surprising result: power densities in fuel zones hardly dependent on fuel shuffling scheme
- Subject of MSc research Mr. C. Sommer (December 2007)

SABR fuel cycle

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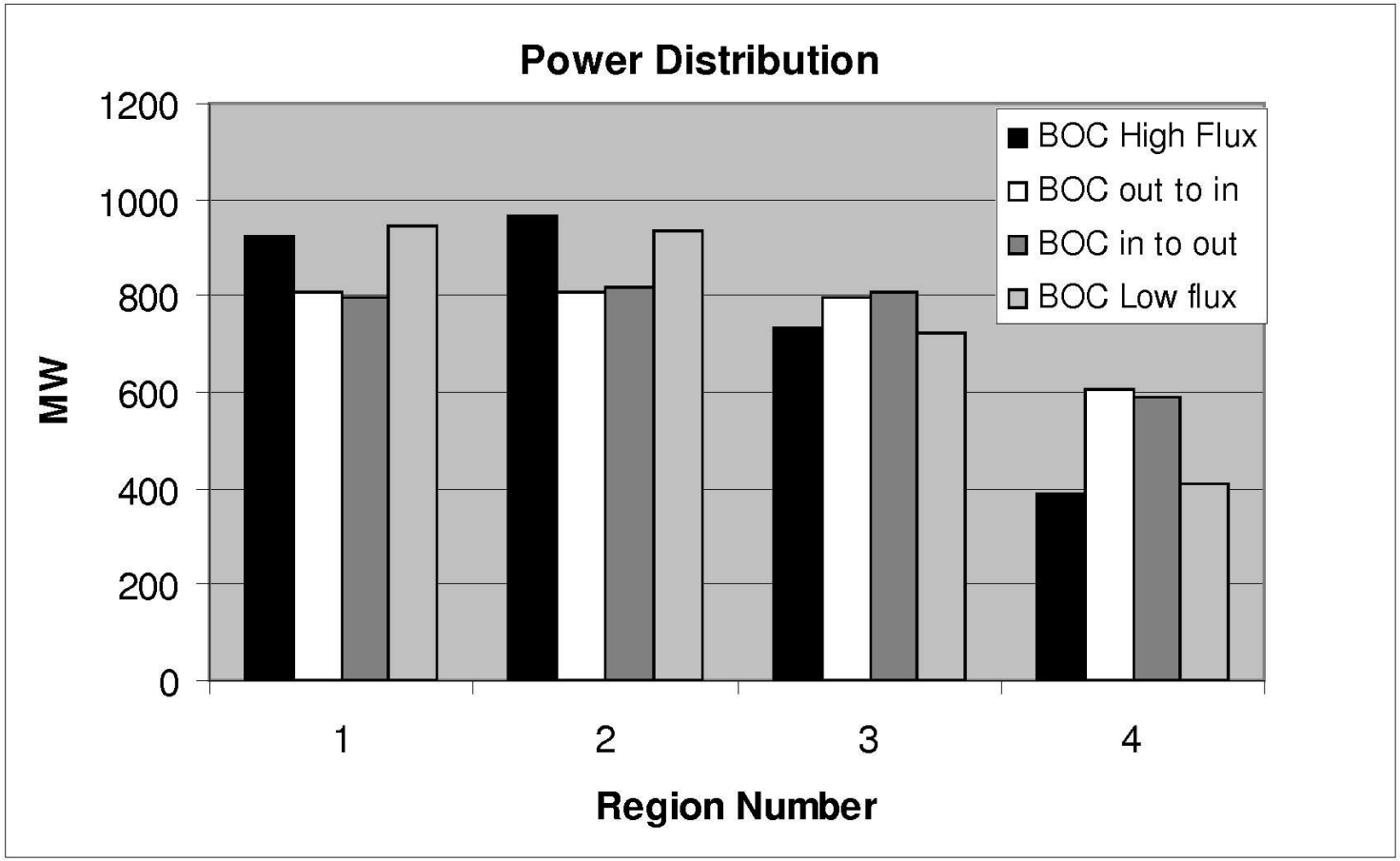

SABR Doppler and void coefficients

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- First approach to Doppler coefficient was with MCNP, but the students soon realized that wasn't ideal: much work to generate libraries with NJOY, long MCNP runs to get adequate statistics
- SABR reactivity coefficients proved to be smaller than MCNP statistics: switched over to TRITON + EVENT
- Doppler coefficient is very small; variational analysis was done on pin-cell model using CSAS and VAREX. Result: positive contributions from Pu-239 and Pu-241 are nearly equal to negative effects of Pu-240 and Zr
- Dynamic analysis (plasma, neutrons, thermal and feedback) subject of MSc thesis Mr. T. Sumner (December 2007)

SABR Doppler and void coefficients

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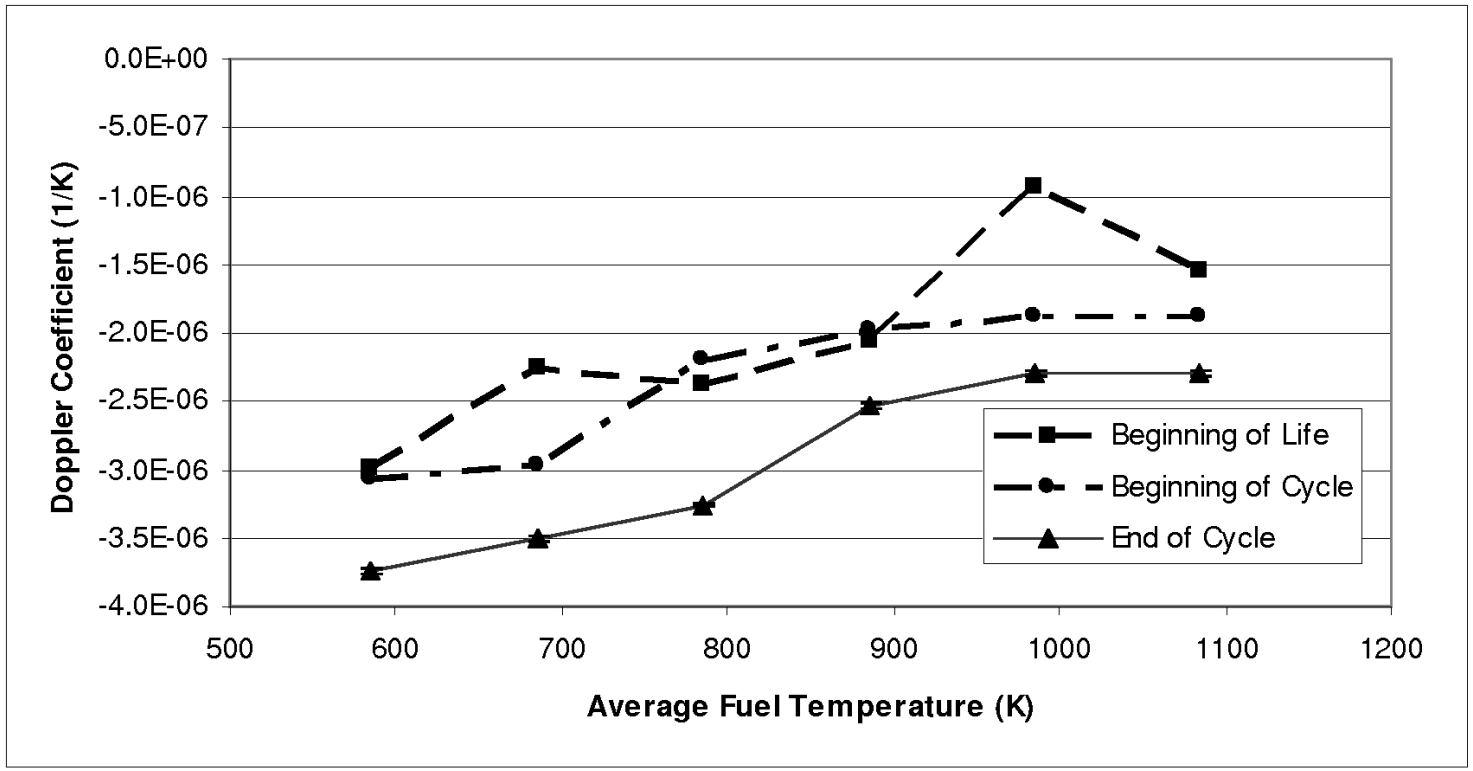

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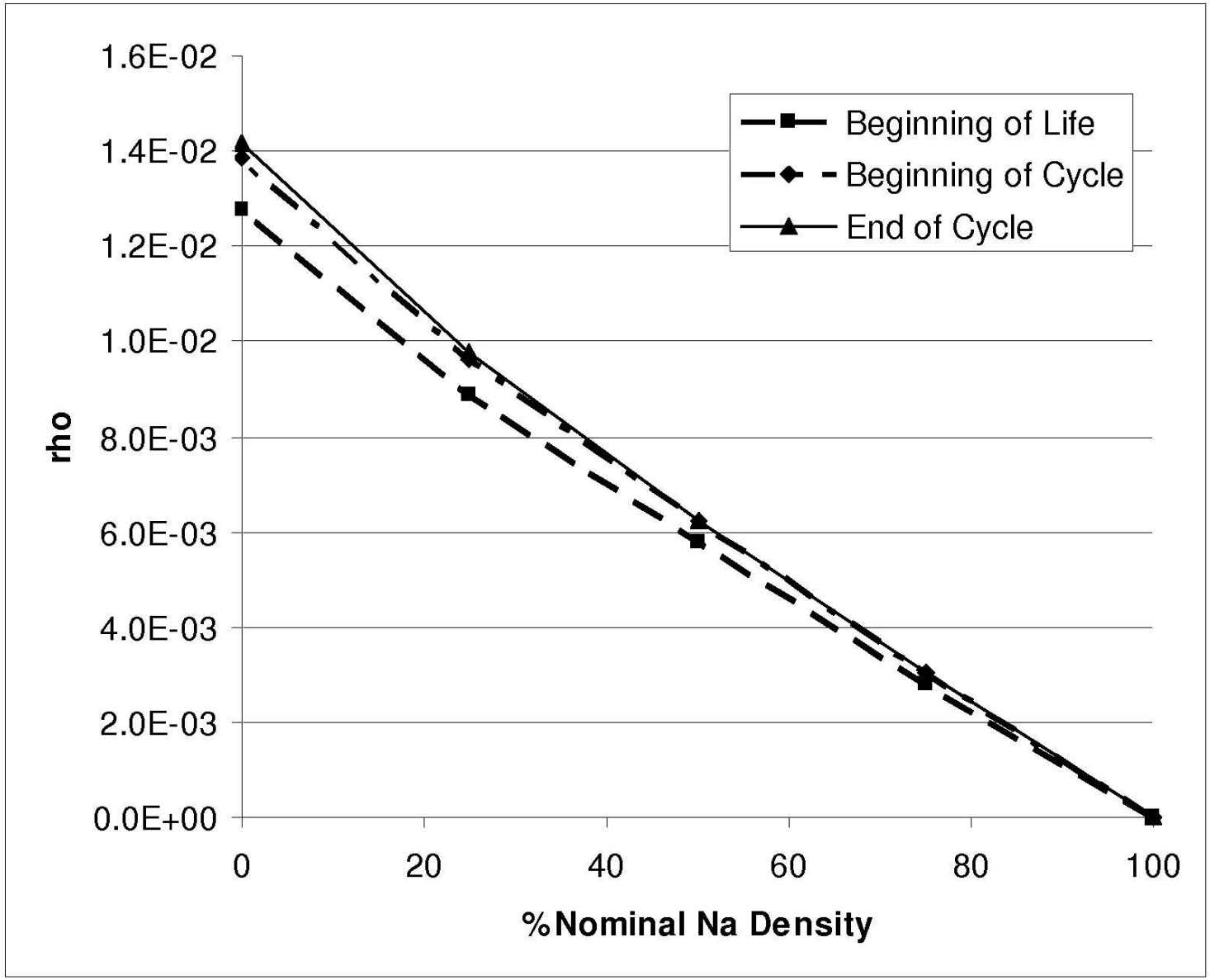

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Gas Cooled Fast Reactor analysis

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- My thesis research (2002) started out by making a TRITON-substitute using SCALE 4.4a + Perl, for closed fuel cycle analysis of coated particle Gas Cooled Fast Reactor (Nuclear Technology, Sept. 2005)
- Later switched to GFR600 reactor which has plate fuel; TRITON (NEWT) in SCALE 5 could not handle this geometry, and although Mark Dehart helped me out as much as he could, I switched back to my old code
- One MSc and one BSc graduated with reports based on this code

Gas Cooled Fast Reactor analysis

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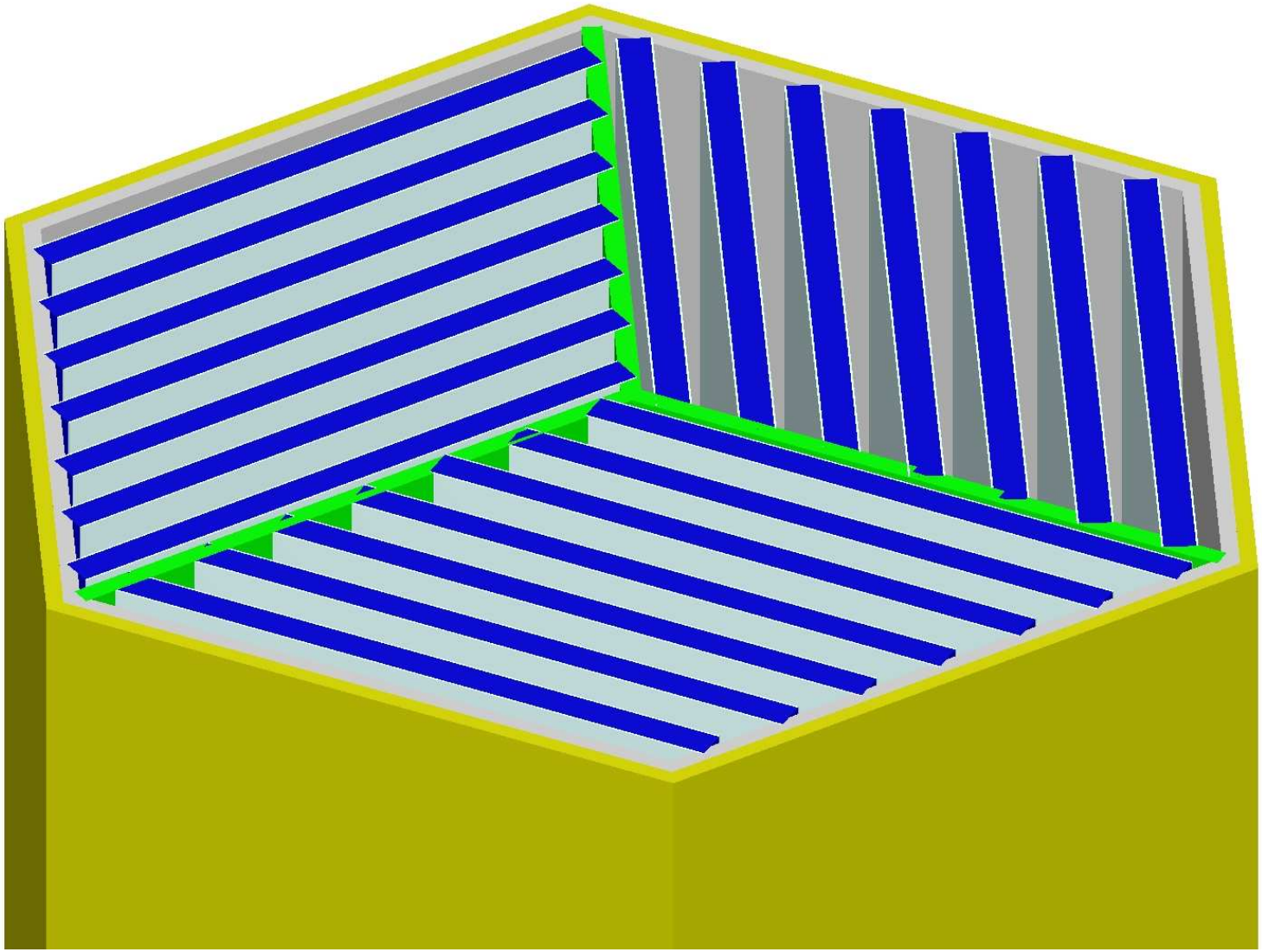

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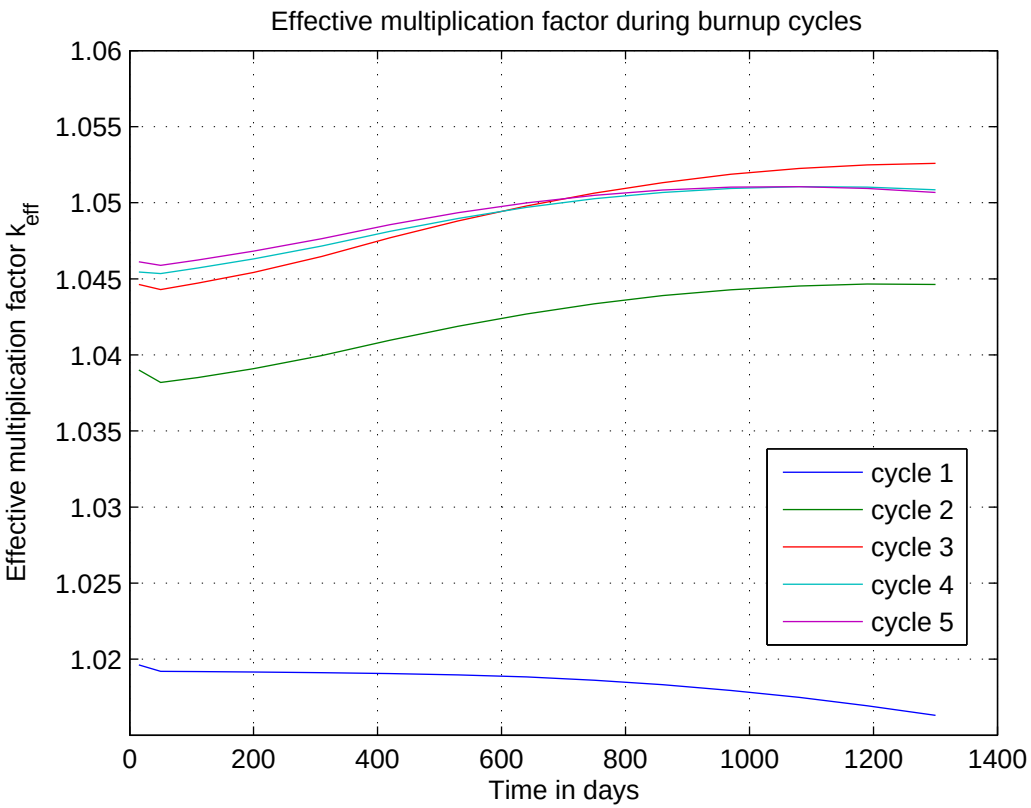

Reactivity weighting for GCFR

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$$w_i \equiv \frac{\Delta\rho}{\Delta N_i} = \frac{\langle \phi_0^*, [\lambda_0 \frac{\partial P}{\partial N_i} - \frac{\partial L}{\partial N_i}]\phi_0 \rangle}{\langle \phi_0^*, P_0 \phi_0 \rangle} \tag{1}$$

- Reactivity weight w_i correspnds to change of reactivity of reactor upon small addition of an isotope i
- Calculated using TSUNAMI-1D for GFR600 fuel slabs (Nucl. Sc. Eng. Oct. 2007)

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Step 1: design an ABR

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- Obviously the first step
- Expected results: large reactivity swing, low burnup, very low β_{eff}, very small Doppler coefficient (probably positive)
- Metallic fuel (TRU-Zr or similar), high thermal expansion, improving feedback; pancake core to enhance leakage (which will also increase transmutation - consider as an example the Korean PEACER design, which has a core height of 0.5 m and diameter of 5 m (!))
- If the reactivity swing is too large, and Doppler coefficent and β_{eff} are too low, one may opt for a sub-critical system
- Maximum power of sub-critical system determined by k_{eff} and source strength: Accelerator Driven System is low-power due to beam-line limitations
- Fusion driven sub-critical system does not have this limitation, but an adequate fusion source may take some development time

Calculational tools for ABR design

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- Accurate cell calculations. Fine-group approach seems necessary (ERANOS: 1968 groups collision probabilities, MC2: 1740+ groups): CENTRM should be fine
- The Doppler coefficient may be improved by including moderator pins in the fuel assemblies, thus 2-D cell calculations will be required (moderator pins are commonly used in TRU reactor designs to increase flux in the resonances)
- (Distribution of) Void effect can be estimated using Equivalent Perturbation Theory (or Extended PT); geometry effects can be estimated with variational analysis; Requirement of solving (generalized) adjoints, especially on a core-wide level
- Core-reflector interaction can be considerable in fast reactors, especially for stainless steel reflectors due to resonances in iron: need to perform detailed homogenization calculations for reflectors and 'diluent assemblies'

Moderated targets

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- Moderated targets: introduction of MA (Am, but Cm also considered) into special assemblies, with moderator. Target is to benefit from high flux level typical for fast reactor, combined with larger XS at thermal energies to obtain large depletion rates
- May seem counterproductive from $\alpha = \sigma_c/\sigma_f$ considerations
- The idea is to introduce only transmutation target material (esp. Am), and allow it to capture neutrons to form highly fissile isotopes (Am-242, Cm-243)
- Only beneficial if high burnup can be reached in one irradiation campaign (90%) so that targets are candidates for direct disposal
- Moderated targets can only be accurately calculated using fixed source calculations
- Promising option, several irradiations currently ongoing in French Phénix reactor; important question is the material throughput in these targets

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This presentation is merely an overview of some aspects reactor physics. I'd like to hear your comments!