Reactor Physics:
Design Parameters for GFRs

22.39 Elements of Reactor Design, Operations, and Safety

Fall 2006

Chris Handwerk

Massachusetts Institute of Technology

Outline

- Background
- Design Philosophy
- Traditional breeder designs and traditional safety concerns
- Reactor physics design in relation to Gen IV goals
  - Sustainability/Proliferation Resistance
  - Economy
 - Safety
    - ◆ Self-controllability

Portions of this presentation are derived from the Fall 2005 version by Dr. Pavel Hejzlar

Why the renewed interest in GFRs?

- Extensive work done in 1970's
- Carter administration ban on reprocessing
- Generation IV International Forum
  - Safety
  - Non-proliferation
  - Economics
  - Sustainability
    - Resources
    - Waste
- 6 Candidate Designs
  - ***GFR***
  - VHTR
  - SCWR
  - SFR
  - LFR
  - MSR

A Technology Roadmap for Generation IV Nuclear Energy Systems
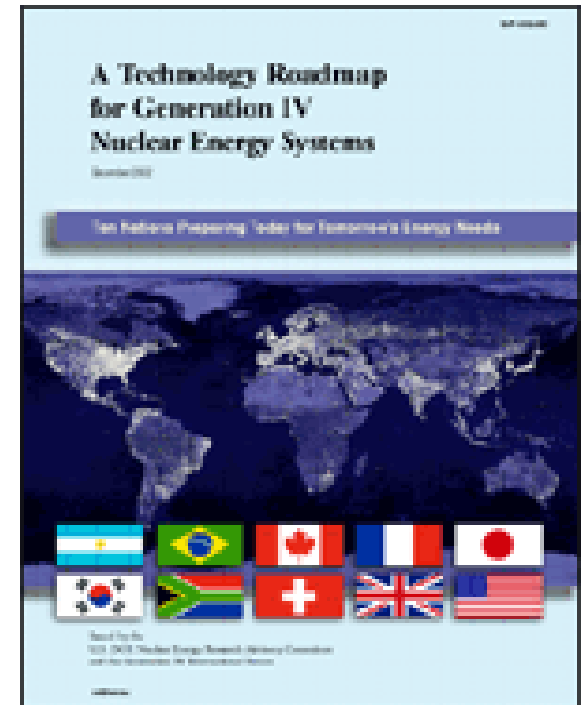
Reactor physics and Gen IV goals
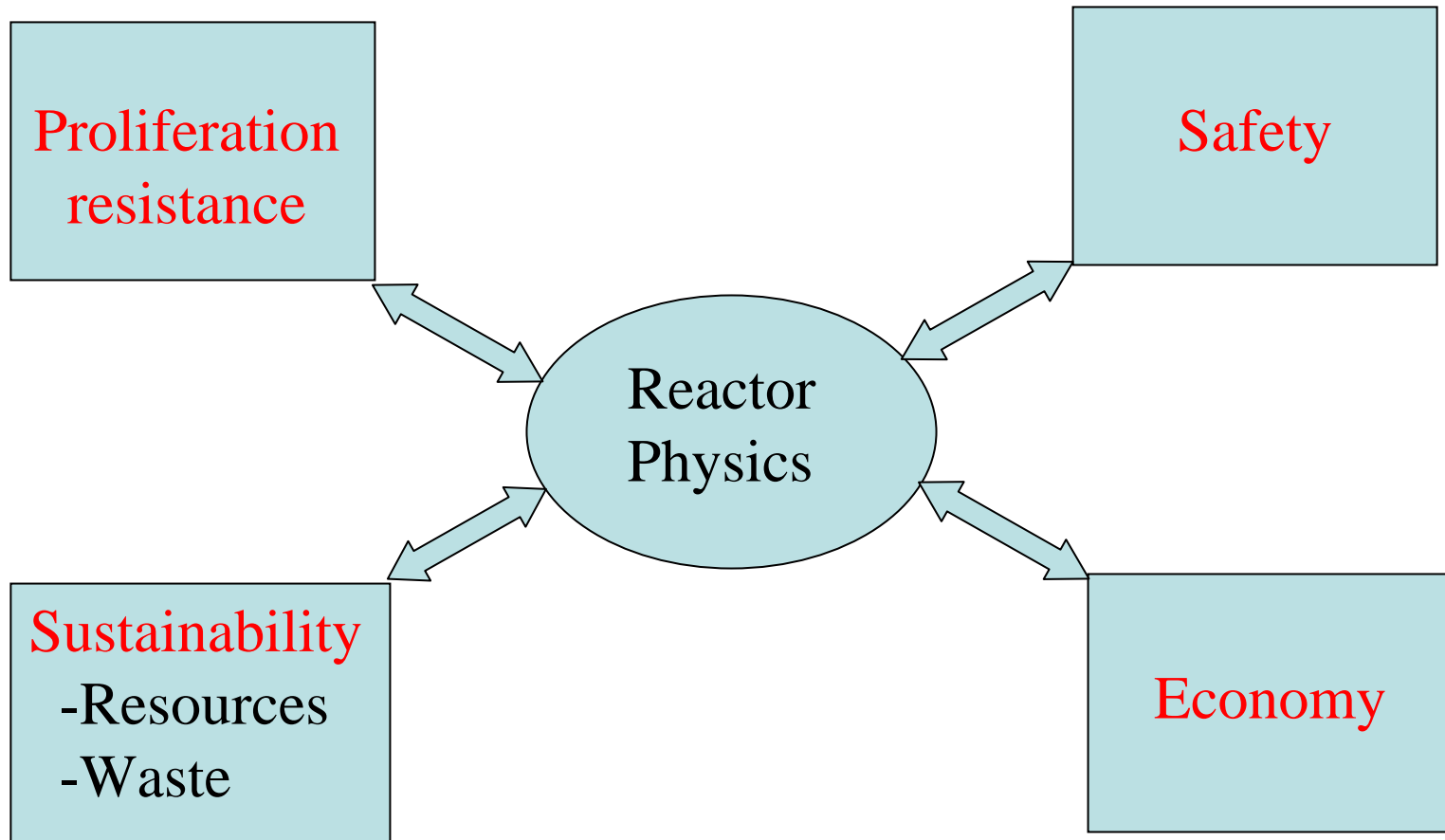
The Engineering Pinwheel
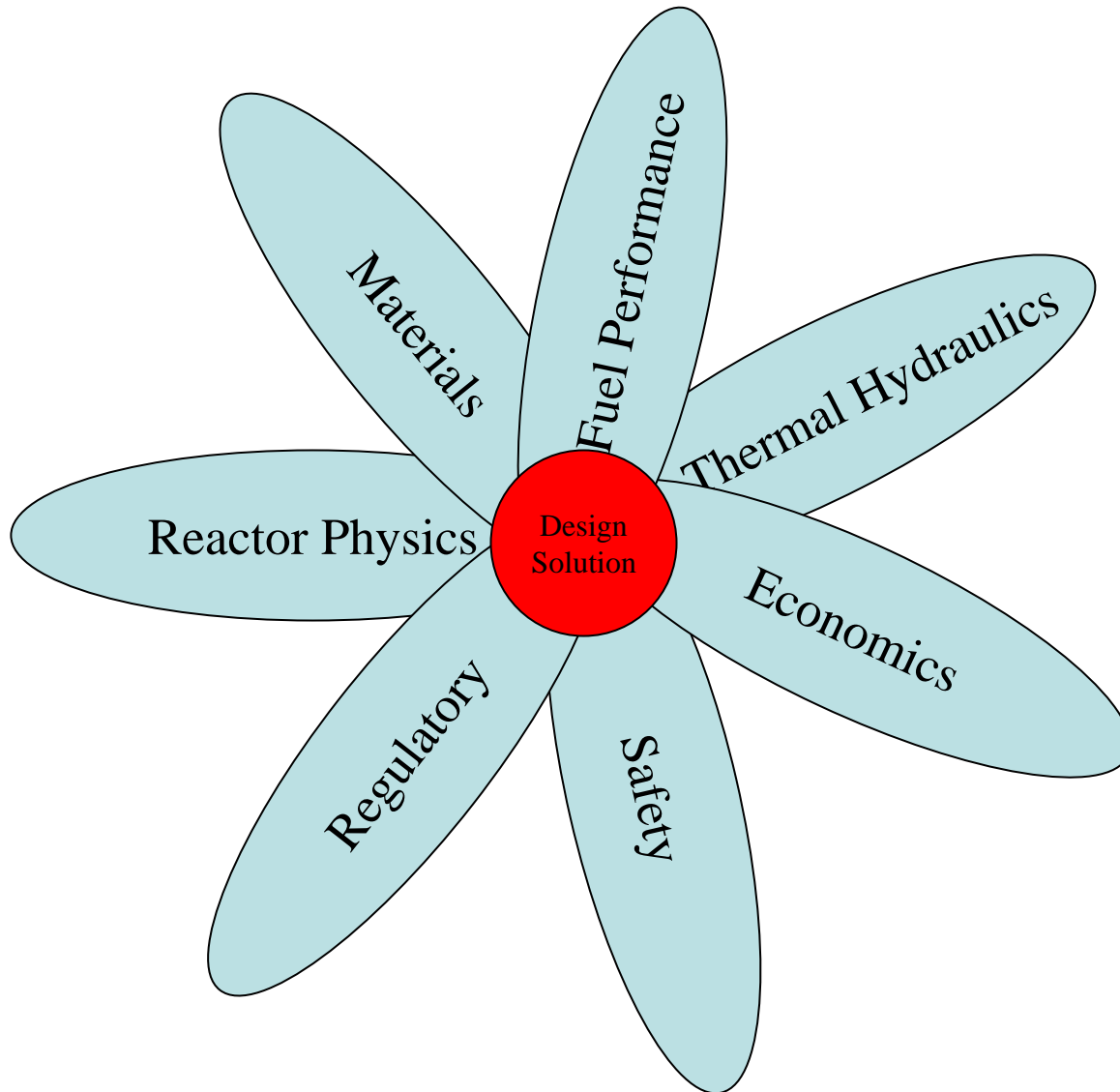
Fast Reactor Fundamentals

- The neutrons are fast
- No moderator (most of the time)
- Coolant is non-moderating
  - Liquid metal
  - Gas
- Neutronic behavior governed mostly by Pu and TRU
  - Much lower β than LWRs (0.0035 v. 0.0065)
- Shorter prompt neutron lifetime
- Tighter lattice than LWRs
- A LOCA will insert positive reactivity
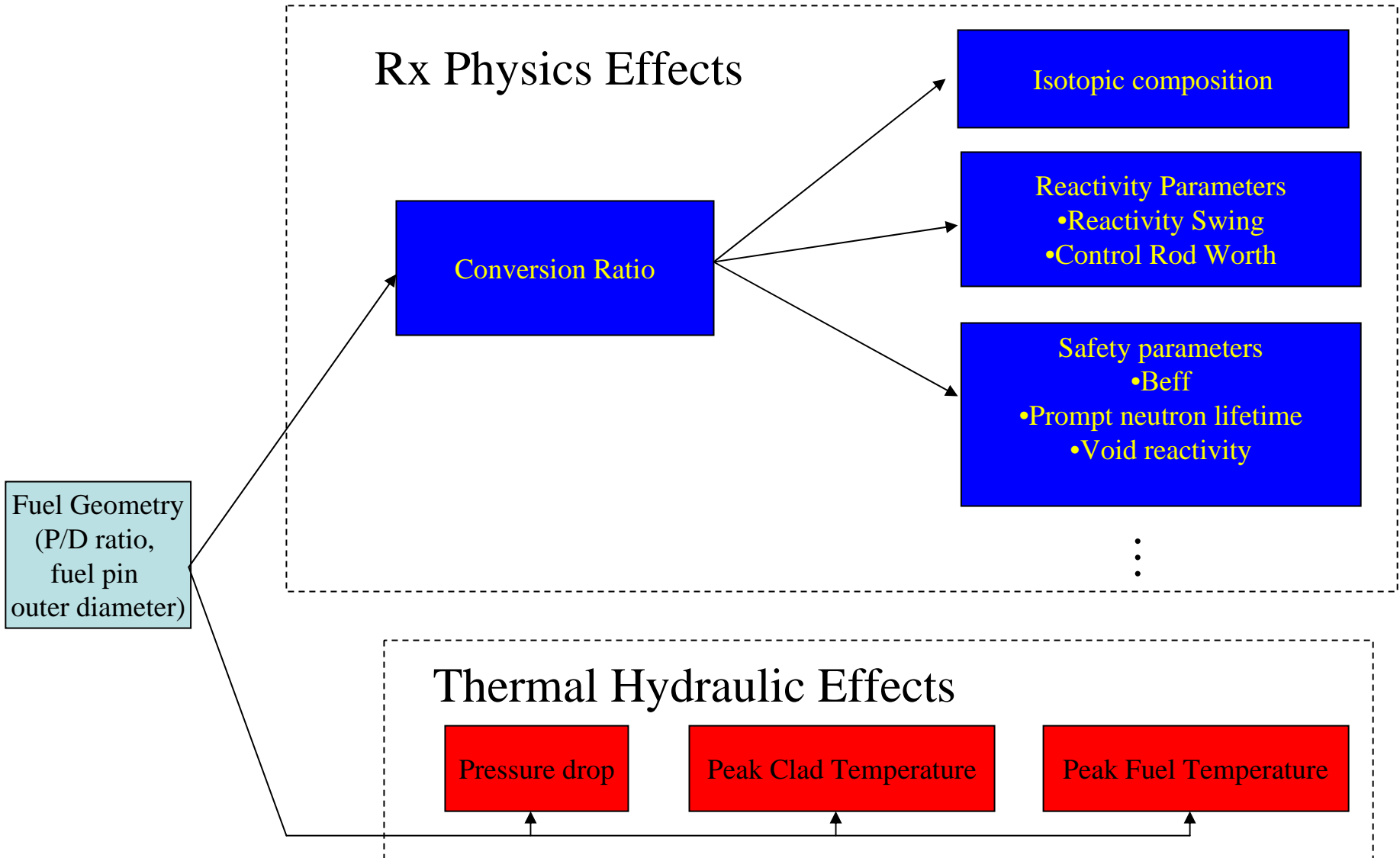- MTC not the chief reactivity coefficient of concern as in LWRs

Steady State Reactor Physics Parameters

Parameter	Design Philosophy

Power Peaking
  ■Intra-assembly, i.e. pin-to-pin
  ■Radial
  ■Axial
	Provide sufficient margin to thermal hydraulic limits

Reactivity limited lifetime	Achieve burnups such that the design (1) is **cost competitive** and (2) has **fluence that is not excessive** when compared to other options
Isotopic Composition	Minimize the volume and radiotoxicity of spent fuel while providing enough Actinide inventory to act as fuel for current and future cycles

Active Reactivity Control
  ■Reactivity Swing
  ■Control Rod Worth
	Keep the reactivity swing low enough such that control rod worth does not become excessive (i.e. significantly beyond current experience, within rod ejection and stuck rod limits)

Steady State T/H Parameters

Parameter	Design Philosophy
Peak Centerline Temperature	■Fuel melting ■Fission gas release ■Doppler
Peak Cladding Temperature	Mechanical properties/ integrity of cladding ◆Creep ◆Stress/Strain
Pressure Drop	■Circulator Work ■Natural Circulation/DHR

The Relation between Rx Physics and T/H Design Constraints

Rx Physics Effects

- Conversion Ratio
- Isotopic composition
- Reactivity Parameters
  - Reactivity Swing
  - Control Rod Worth
- Safety parameters
  - Beff
  - Prompt neutron lifetime
  - Void reactivity

Fuel Geometry (P/D ratio, fuel pin outer diameter)

Thermal Hydraulic Effects

- Pressure drop
- Peak Clad Temperature
- Peak Fuel Temperature

Selection of a coolant

- Chemical compatibility
- Neutronic properties
- Thermal Properties
    - Boiling/Melting Point
    - Heat removal capability
        - High thermal conductivity
        - Large heat capacity
- Density
    - Natural Circulation capability
    - Required Pumping Power
- Availability/cost
- Other….

Coolant Case Study: S-CO$_2$

- Power Conversion System (PCS) work begat the neutronics work
  - High efficiency Brayton cycle (45-50%) v. Rankine (33%)
  - Allows for a direct cycle
- Can provide better natural circulation capability than He
- Can do it all at lower temperatures (650°C) than Helium (850°C)
- Requires a higher pressure for Decay Heat Removal and cycle efficiency (20 MPa v. 8 MPa)
  - What integrated engineering design challenges does this pose?

Traditional sodium FBR designs

- Large power rating (~3000MWt)
- Very high power density (~300kW/l)
  - To reduce fuel cycle cost
  - To minimize doubling time
- Short doubling time (~25 years)
- Oxide fuels - UO2-PuO2 driver fuel, use of UO2 blankets
- Breeding ratio >1 (1.25)
- Pool type reactor
- Active safety
- Intermediate loops
- Rankine cycle
- Difficult maintenance (opaque coolant)
- Complex and expensive

Diagram of reactor removed due to copyright restrictions.

Traditional reactor physics (safety) concerns for early liquid metal cooled FBRs

- Small effective delayed neutron fraction
    - Small value of dollar unit for reactivity, hence concern that prompt critical state can be easier to reach
- Short prompt neutron lifetime
    - Concern over extremely rapid power rise if reactivity increase exceeds prompt critical value
- Hypothetical core disruptive accidents
    - Core geometry not in most reactive configuration
    - Loss of core geometry may hypothetically lead to reactivity increase and large energy generation
    - Although of extremely low probability, these scenarios received substantial attention
- Reactivity insertion > \$1 from coolant voiding
    - Local voiding is also a concern
- External blankets required for breeding

Gen IV Goals 1 & 2: Sustainability/Proliferation Resistance

- Traditionally – high utilization of resources (motivated early development of fast reactors with high breeding ratio - blankets)

- Emphases in Gen IV
  - High resource utilization
  - Waste minimization ⎫
  - Proliferation resistance ⎬ new

- To reduce waste long-term radiotoxicity to that of natural U in <1000yrs – full recycling of TRU (including MA) with losses <0.1% needed

- Enhanced proliferation resistance favors elimination of depleted U blankets, avoidance of Pu separation and maintenance of dirty plutonium isotopics throughout the cycle
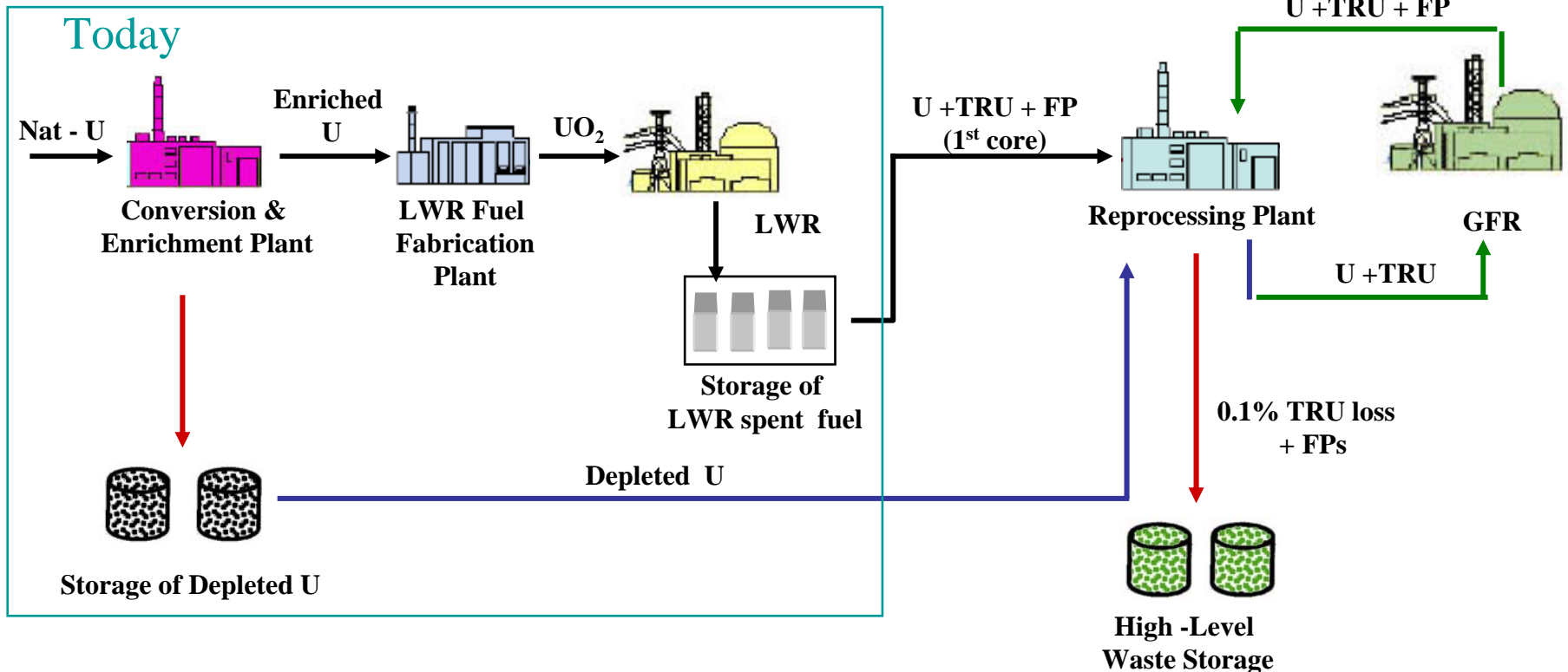
Impact of recycling TRUs

Impact of Removing & Transmuting Actinides
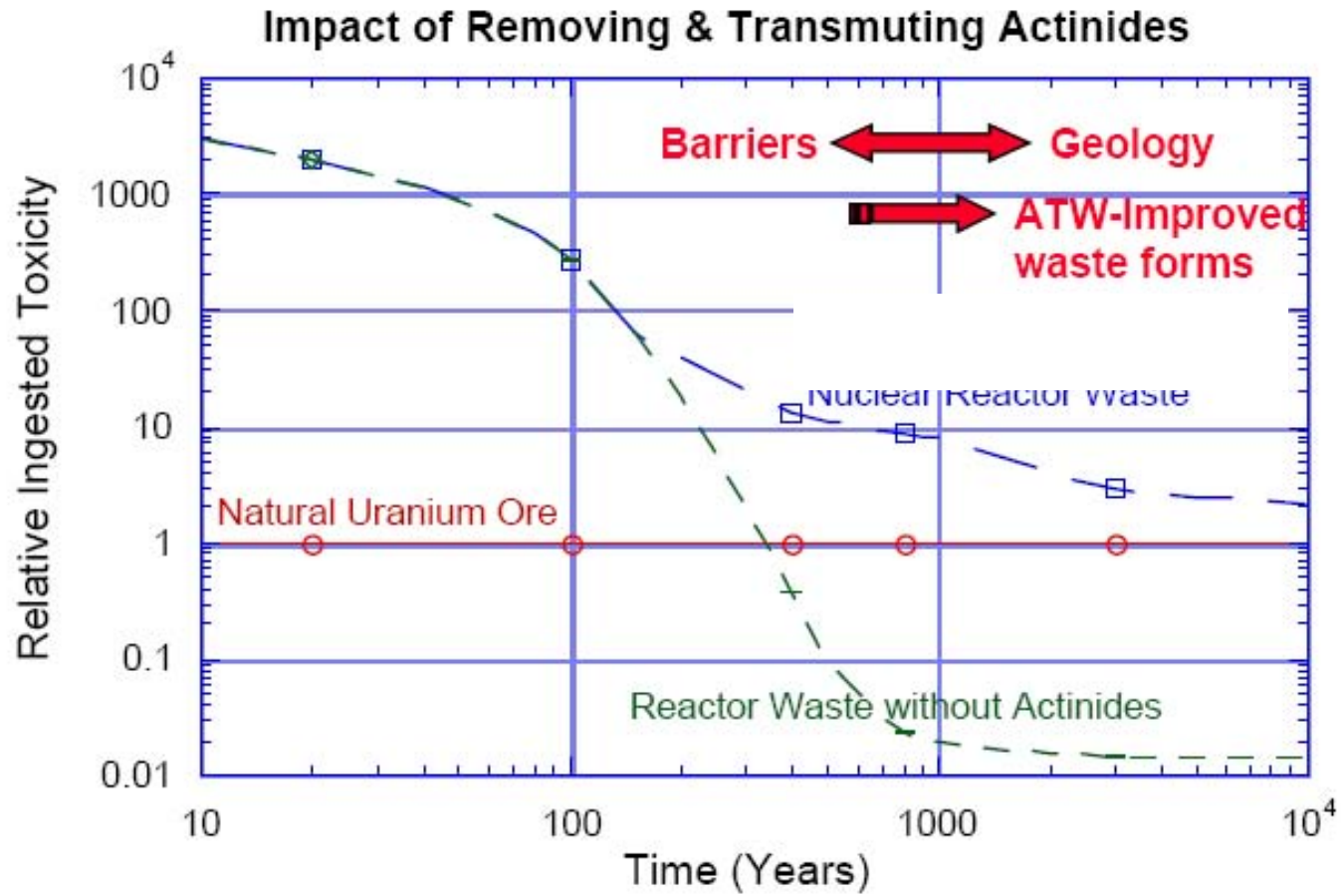
Sustainability-driven design choices

GFR for both waste management and resource utilization

- Use accumulated TRU from spent LWR for 1st FR core
- Design GFR with BR=1, no blankets to avoid clean Pu
- Recycle TRU without Pu separation, Depleted U feed
- If enough GFRs deployed, LWR legacy TRU inventory eliminated
- After full transition to GFR, enrichment could be eliminated

Today

Nat - U

Conversion & Enrichment Plant

Enriched U

LWR Fuel Fabrication Plant

UO$_2$

LWR

Storage of LWR spent fuel

Depleted U

Storage of Depleted U

U +TRU + FP (1st core)

Reprocessing Plant

U +TRU + FP

U +TRU

GFR

0.1% TRU loss + FPs

High -Level Waste Storage

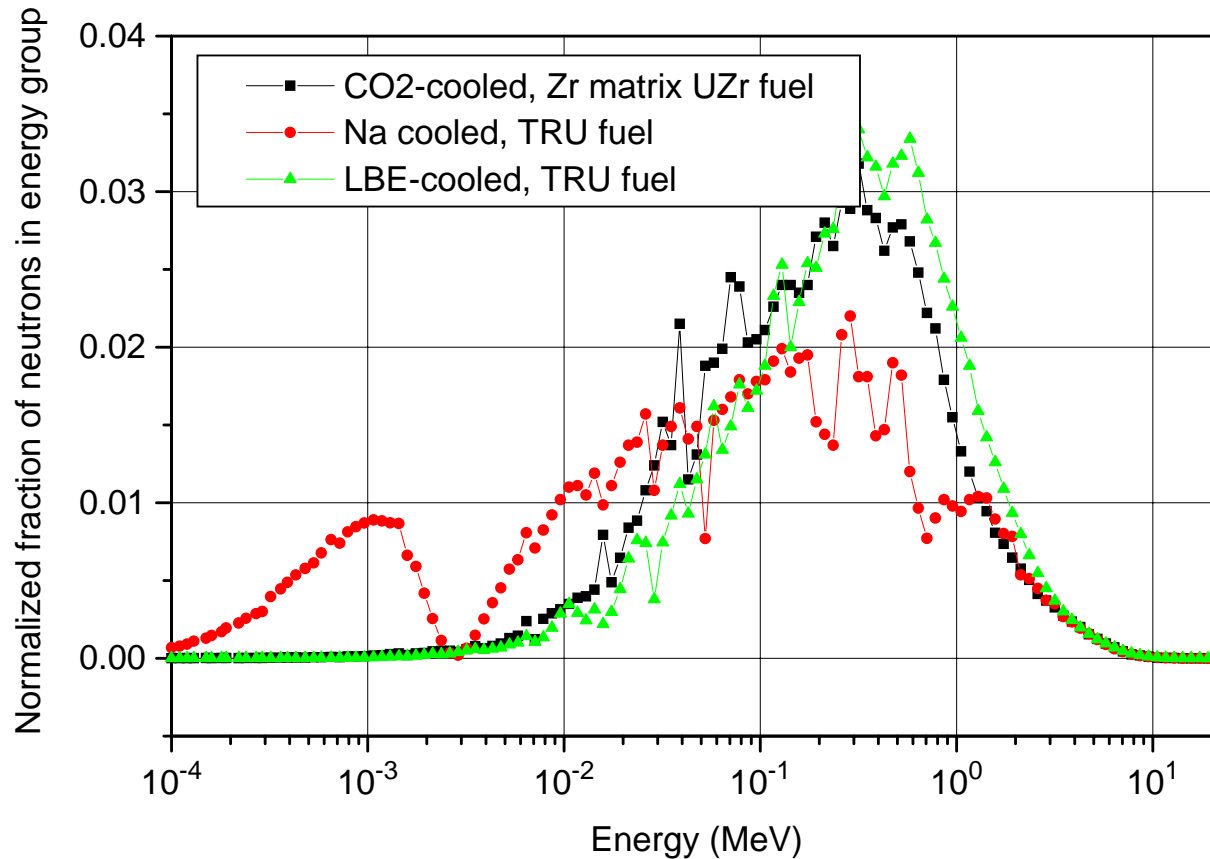# Consequences of sustainability-driven choices

- **Small effective delayed neutron fraction**
  - TRUs have small β
  - TRUs in LWR spent fuel 49%Pu239, 23%Pu240, 7%Pu241, 6.6%Np237, 5%Pu242, 4.7%Am241, 2.7%Pu238
  - Smaller margin to superprompt criticality, hence reactor control more challenging
  - What can be done to increase βeff?
    - Not much
    - Harden spectrum to fission more U238, but this worsens coolant void worth
    - Increase leakage, but this hurts neutron economy

Graph removed due to copyright restrictions.

Consequences of sustainability-driven choices (Cont')

- **Increased positive coolant void worth**
    - Safety issue
    - Typically much smaller in GFR than in LMRs
    - Can be fast
    - Smaller β makes coolant void worth larger in terms of reactivity in dollars
    - More positive coolant void worth is due to TRU loading (primarily Pu239, Np237 and Am241)
    - Why?
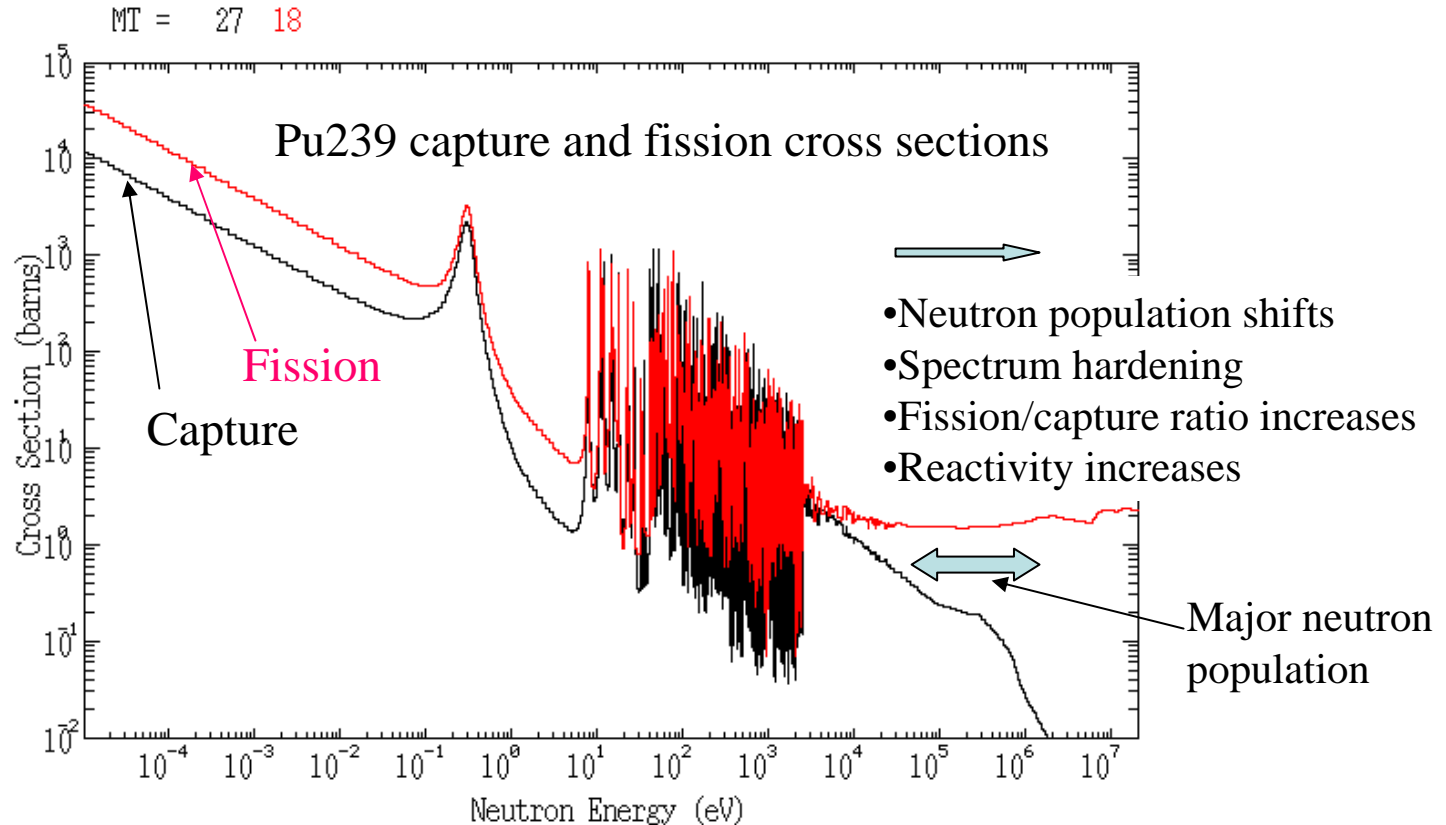
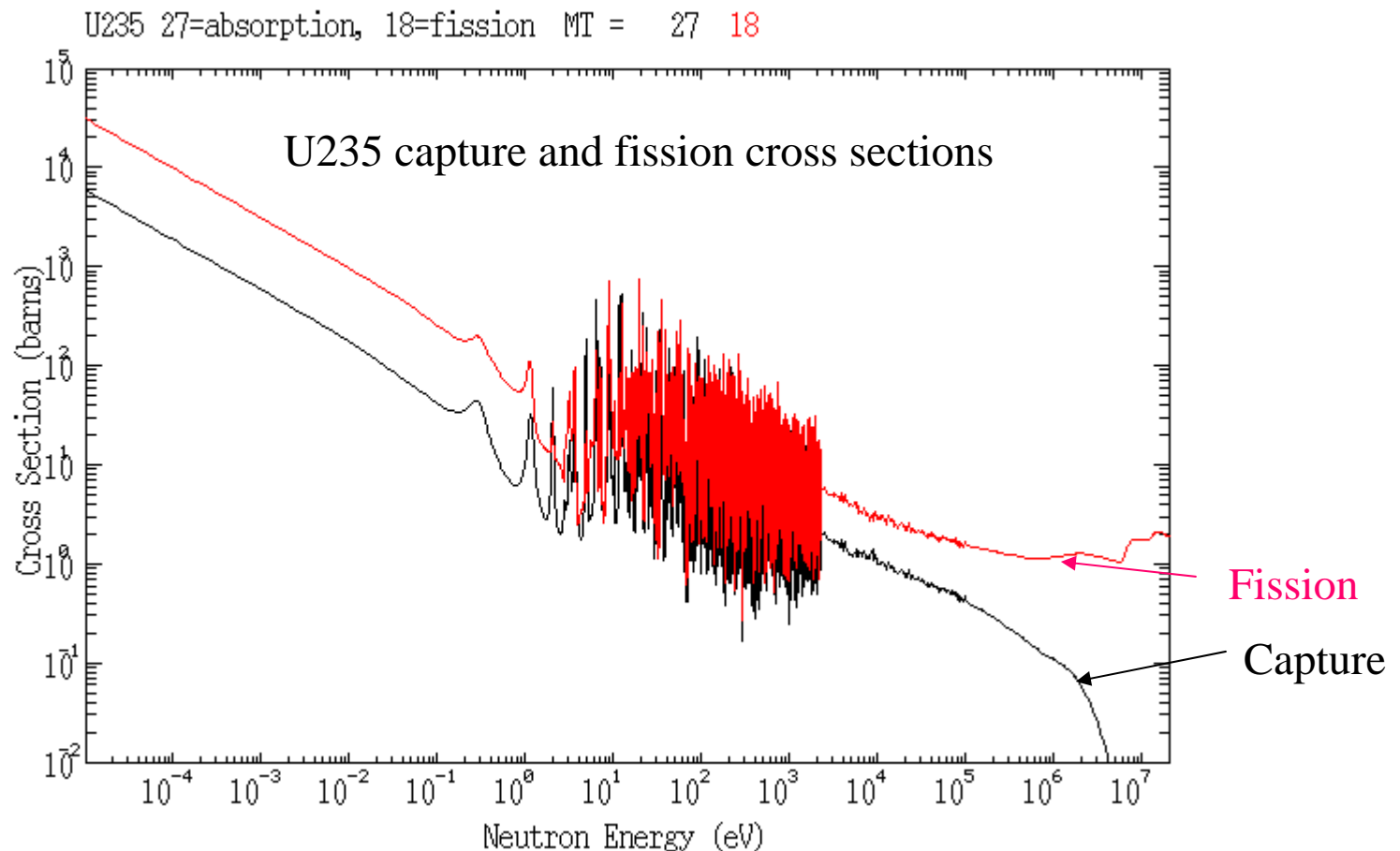# Neutron spectrum in GFR

Positive coolant void worth in FRs
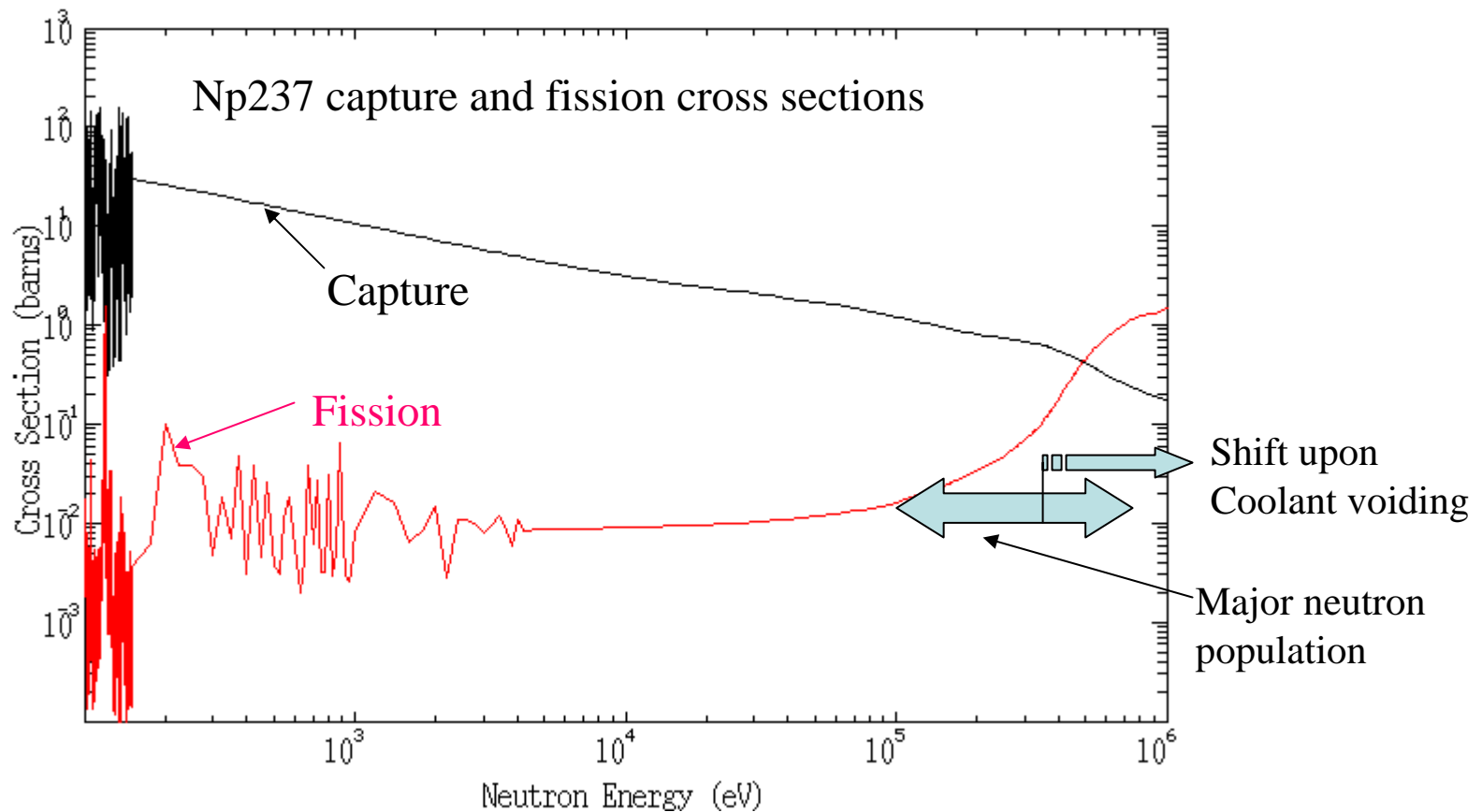
Three components of coolant void worth

1. Spectrum hardening

Pu239 capture and fission cross sections

Fission

Capture

- Neutron population shifts
- Spectrum hardening
- Fission/capture ratio increases
- Reactivity increases

Major neutron population

Positive coolant void worth in FRs

- This differs from U235, hence much lower void worth for U235 fueled core

U235 27=absorption, 18=fission MT =   27 18

U235 capture and fission cross sections

Fission

Capture

Positive coolant void worth in FRs

Minor actinides (mainly Np237 and Am241) exacerbate the problem

Np237 capture and fission cross sections

Capture

Fission

Shift upon Coolant voiding

Major neutron population

- Am 241 same behavior
- What about U238? Also an issue but σ_f comes up after 1MeV and only to 0.5barn

Positive coolant void worth in FRs (cont)

2. Coolant absorption

- Less coolant $\rightarrow$ smaller parasitic absorption, hence reactivity increases (same for over-moderated LWRs)
- Small for GFR but can be significant for LMRs – coolants with higher absorption cross section worse

3. Neutron leakage

- Less coolant $\rightarrow$ increased neutron leakage, hence reduced reactivity
- Smaller or pancake cores have lower coolant void worth
- Coolants with larger scattering cross section have larger reactivity reduction from leakage

Ways to reduce CVW in GFRs

- Although CVW is small (in comparison to LMRs), its reduction is difficult. Why?
- Leakage component is very small (negligible for some gases, such as He)
- Possibilities:
    1. Use core and reflector materials that exhibit an increase in absorption cross section/reduction in reflection upon spectrum hardening
    2. Use gas that has high scattering macroscopic cross section to increase benefit of leakage effect
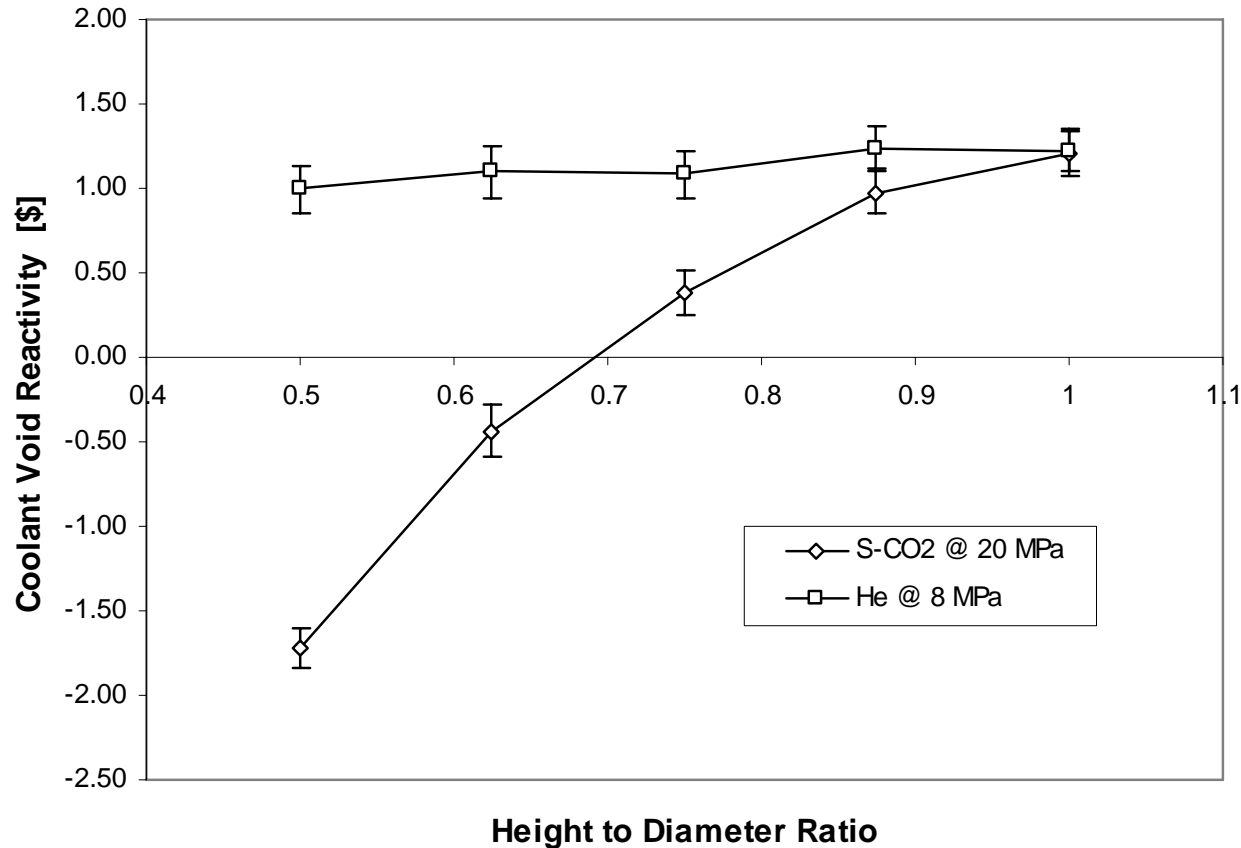   3. Minimize coolant fraction in the core
    4. Soften the spectrum

1. CVW solution: Titanium reflector
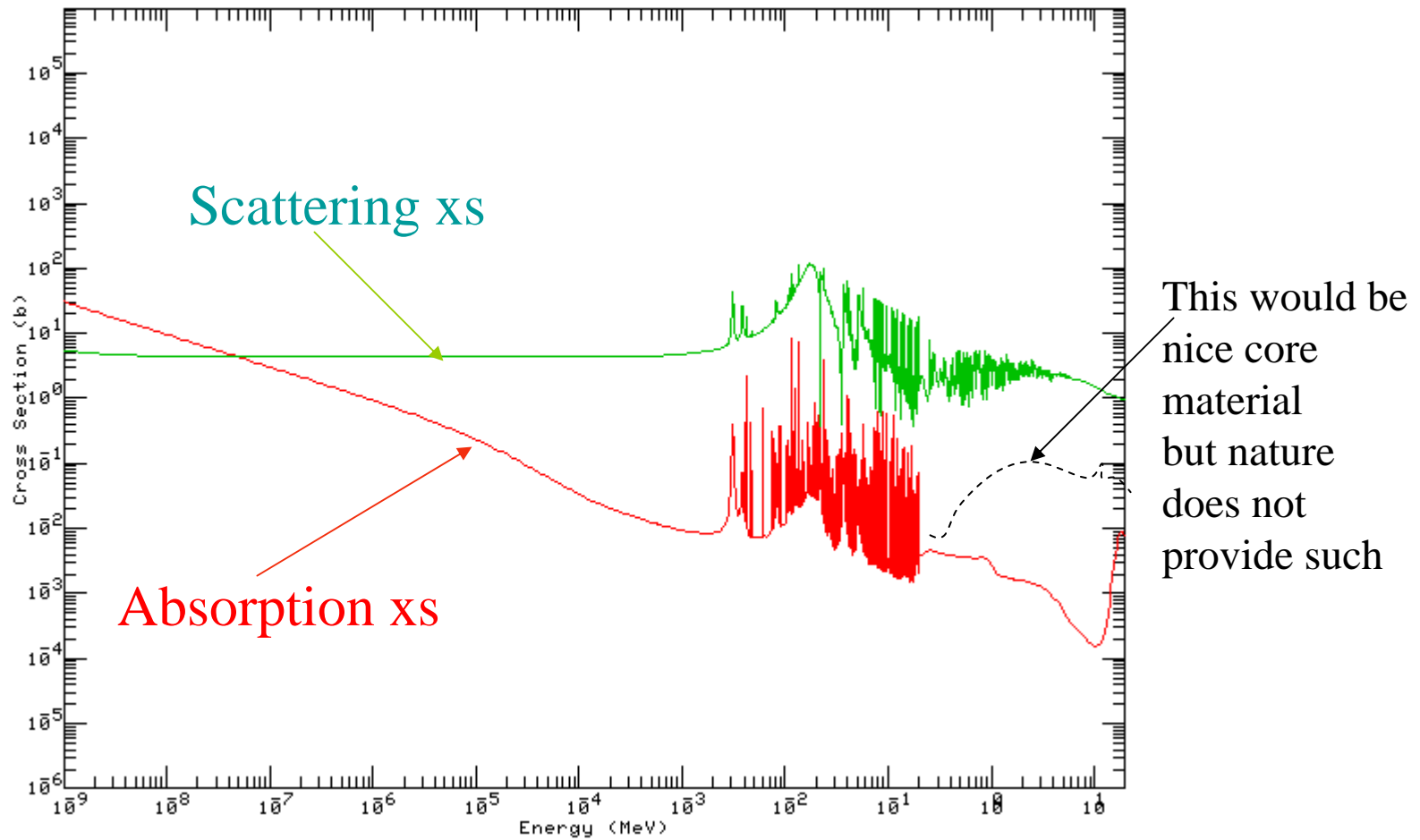


Ti capture and scattering cross sections

2. CVW Solution:
Leakage effect for He and SCO$_2$

Coolant void reactivity for (U-TRU)C pin fuel with Ti cladding and Ti reflector

3. CVW solution:
Tube-In-Duct (TID) Fuel Assembly

- Hexagonal duct with coolant tubes
- Compatible with vibrationally compacted (VIPAC) or specially formed "hexnut" pellet fuel
- Vented to reduce pressure-induced stresses in cladding and duct wall (as in GCFR of 1970's)
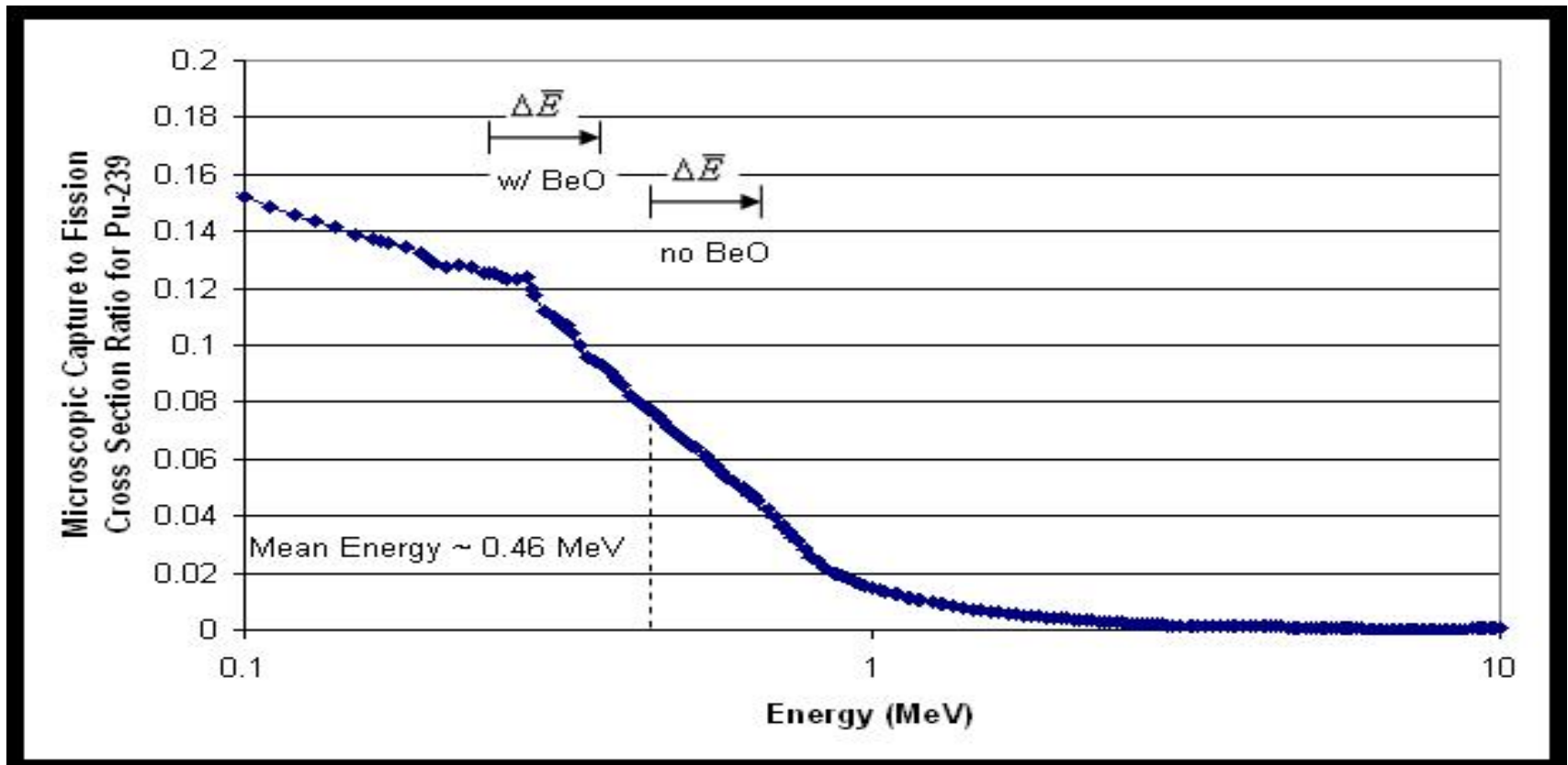- Very high fuel volume fraction (~63%) with tolerable core pressure drop.

Duct Wall

Cladding (ODS MA956)

Coolant Channels
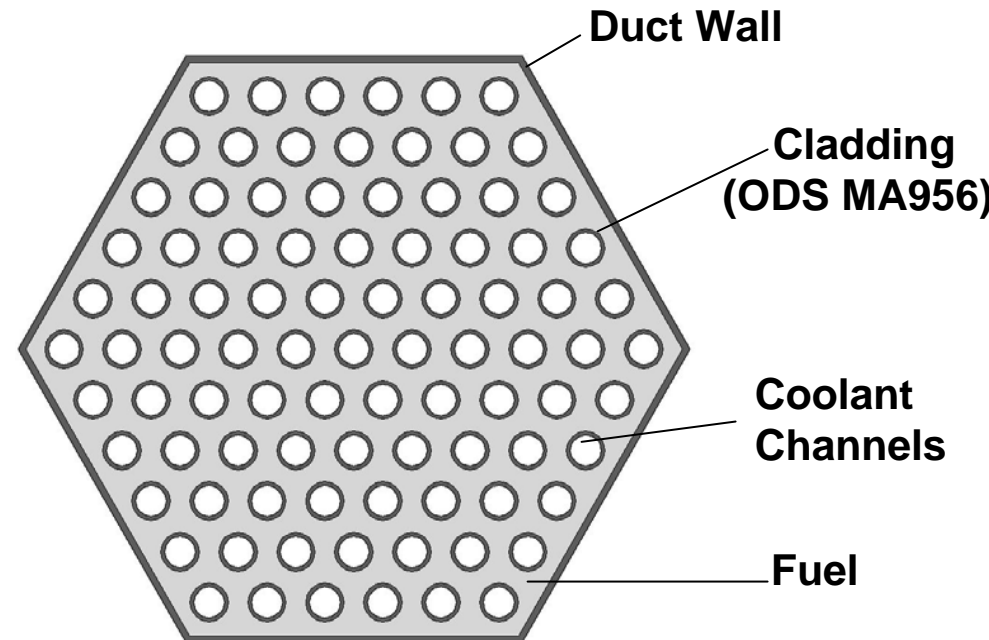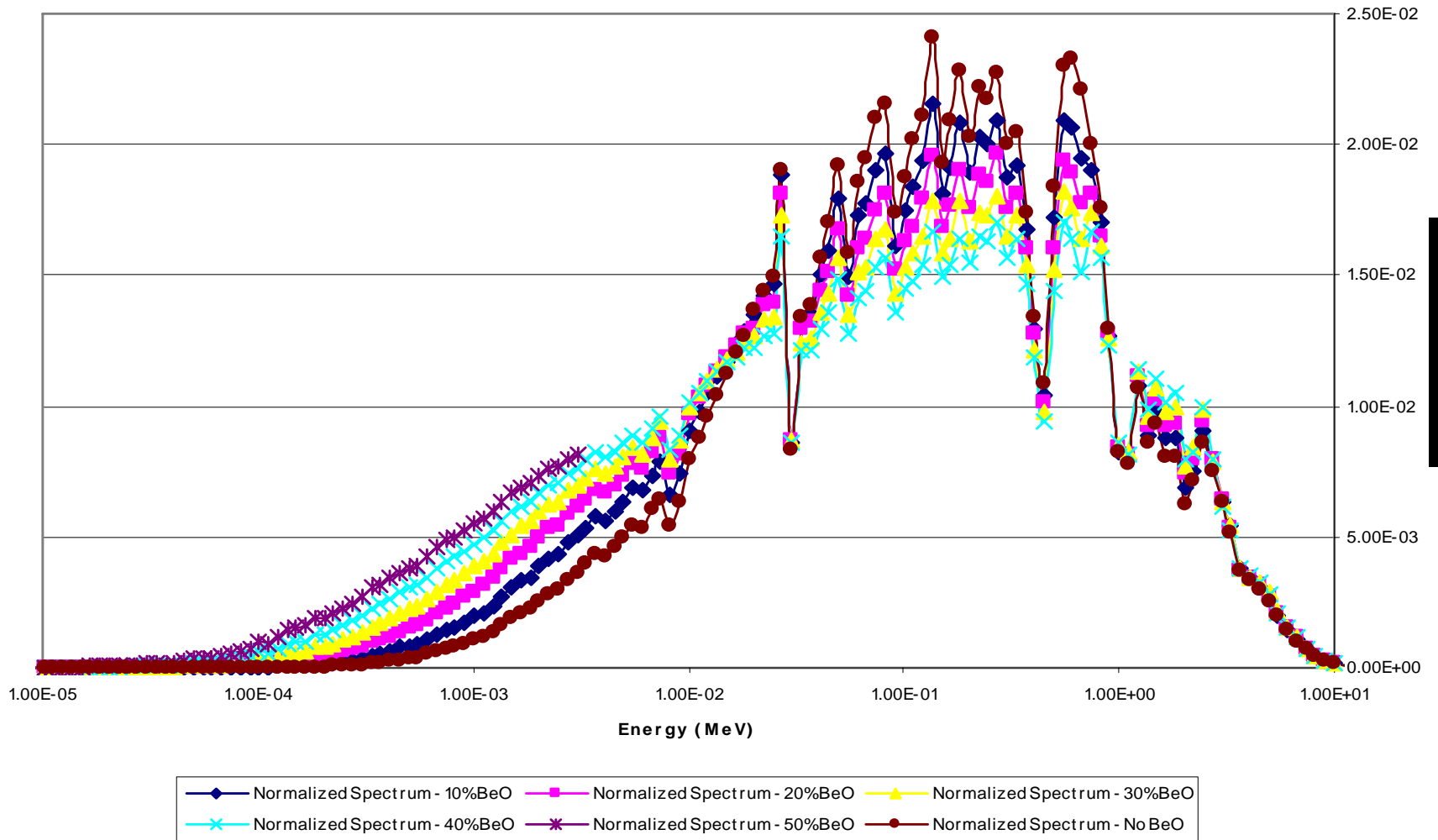
Fuel

(Horizontal Cross Section)

Courtesy of CEA Cadarache. Used with permission.

4. CVW solution:
Use of diluent to soften spectrum

$$\Delta\rho_{VOID}\ \alpha\left(\frac{\sigma_c}{\sigma_f}\right)_{UNVOIDED} - \left(\frac{\sigma_c}{\sigma_f}\right)_{VOIDED}$$

Neutron Energy Spectra of Fuel with BeO Diluent

Legend: Normalized Spectrum - 10%BeO, Normalized Spectrum - 20%BeO, Normalized Spectrum - 30%BeO, Normalized Spectrum - 40%BeO, Normalized Spectrum - 50%BeO, Normalized Spectrum - No BeO

The Diluent Approach

- Without diluent, enrichment zoning
  - BOL CVW=1.6$, radial peaking =1.56
- With BeO diluent, enrichment and diluent zoning
  - BOL CVW=0.5$, radial peaking =1.15
- Diluent can also reduce axial peaking
- Shapes power by:
  - Displacing fuel
    - Minor effect
  - Softening neutron energy spectrum
    - Reduces neutron energy below fast fission threshold
    - Dominant effect
- BeO
  - Moderating effect
  - Thermal conductivity enhancement
  - Best CVR reduction among candidate options
- Other candidates
  - SiC
  - TiC

Radial Power Shaping Using BeO
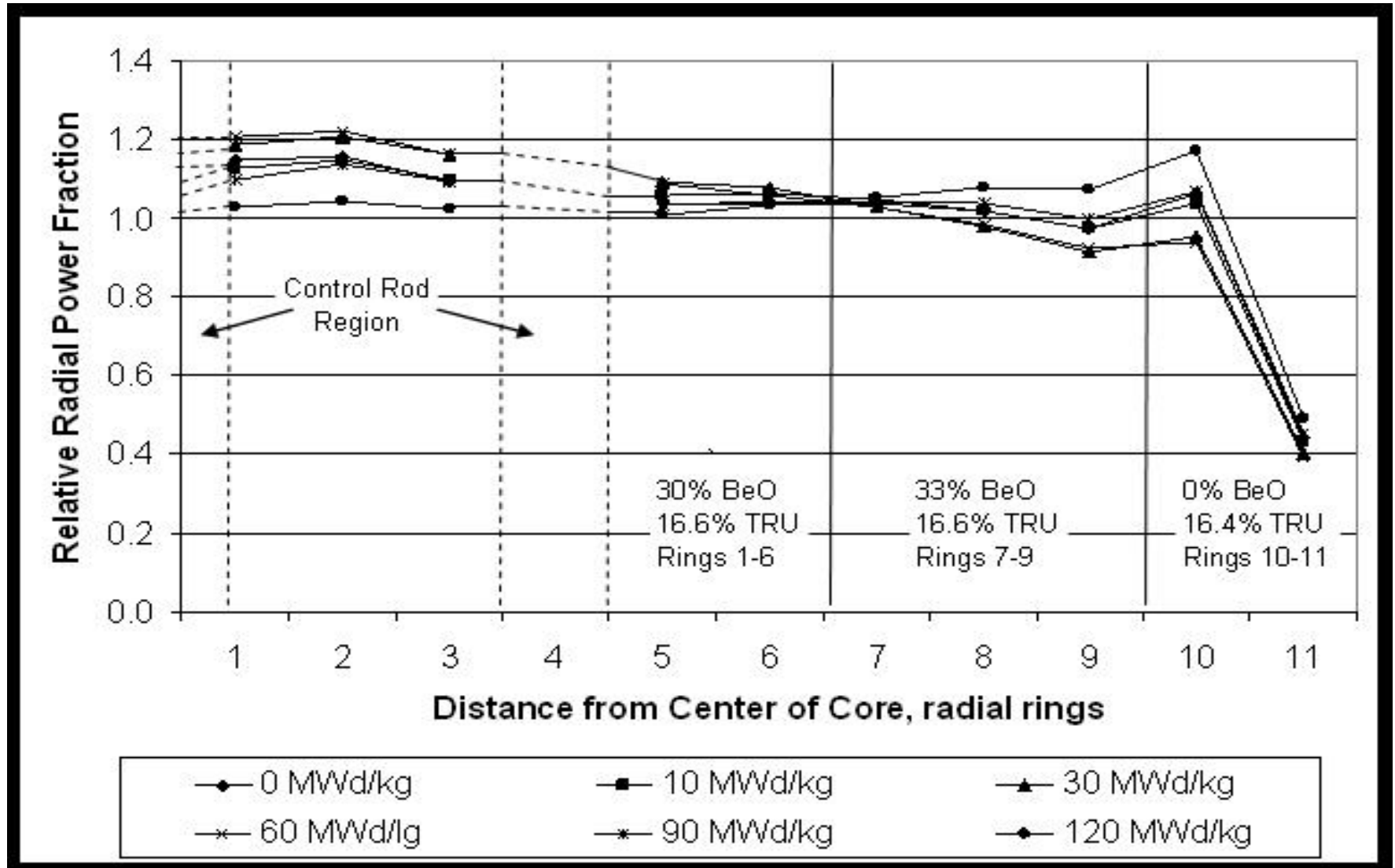
Other effects of diluent
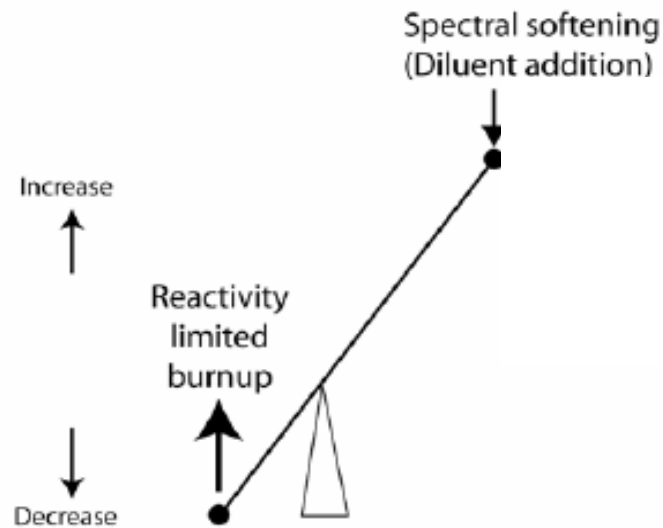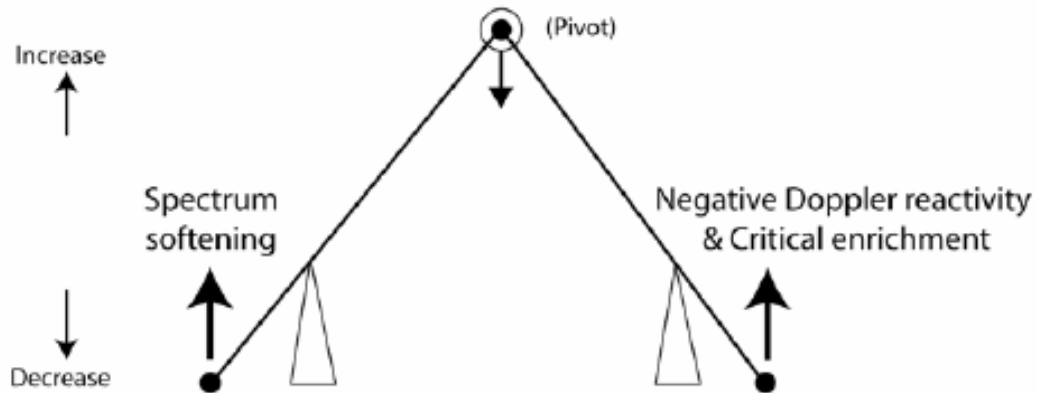
Consequences of sustainability-driven choices (Cont')

- **Difficult to achieve conversion ratio (CR) of 1.0 in the absence of blankets**
  - Balance between leakage/neutron economy and CVW
  - Balance thermal hydraulics and neutronics through coolant and fuel volume fractions

Why high heavy metal density?

- Unit cell calculations

- U fuels

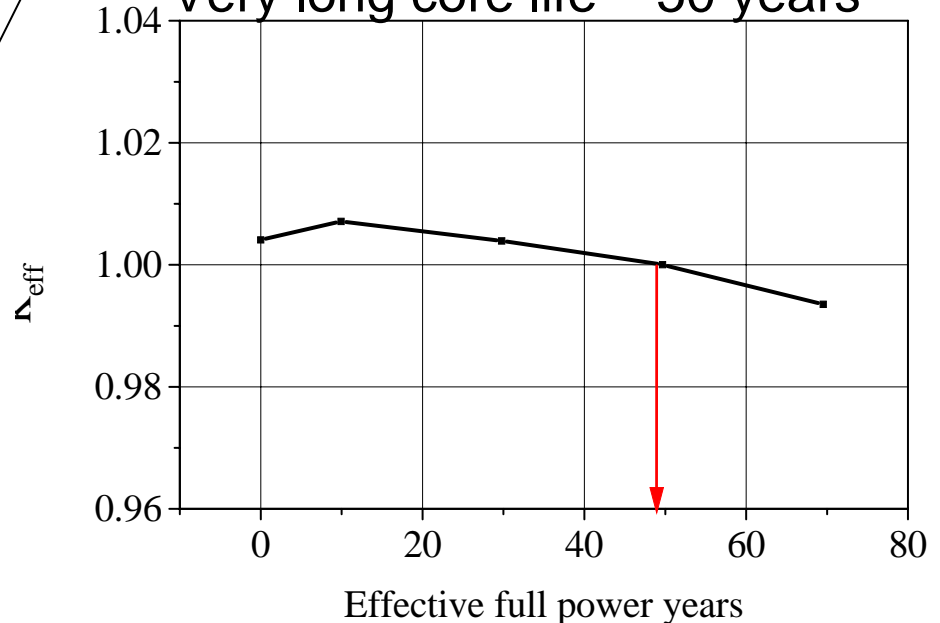- Heavier density fuels achieve higher BOL reactivity
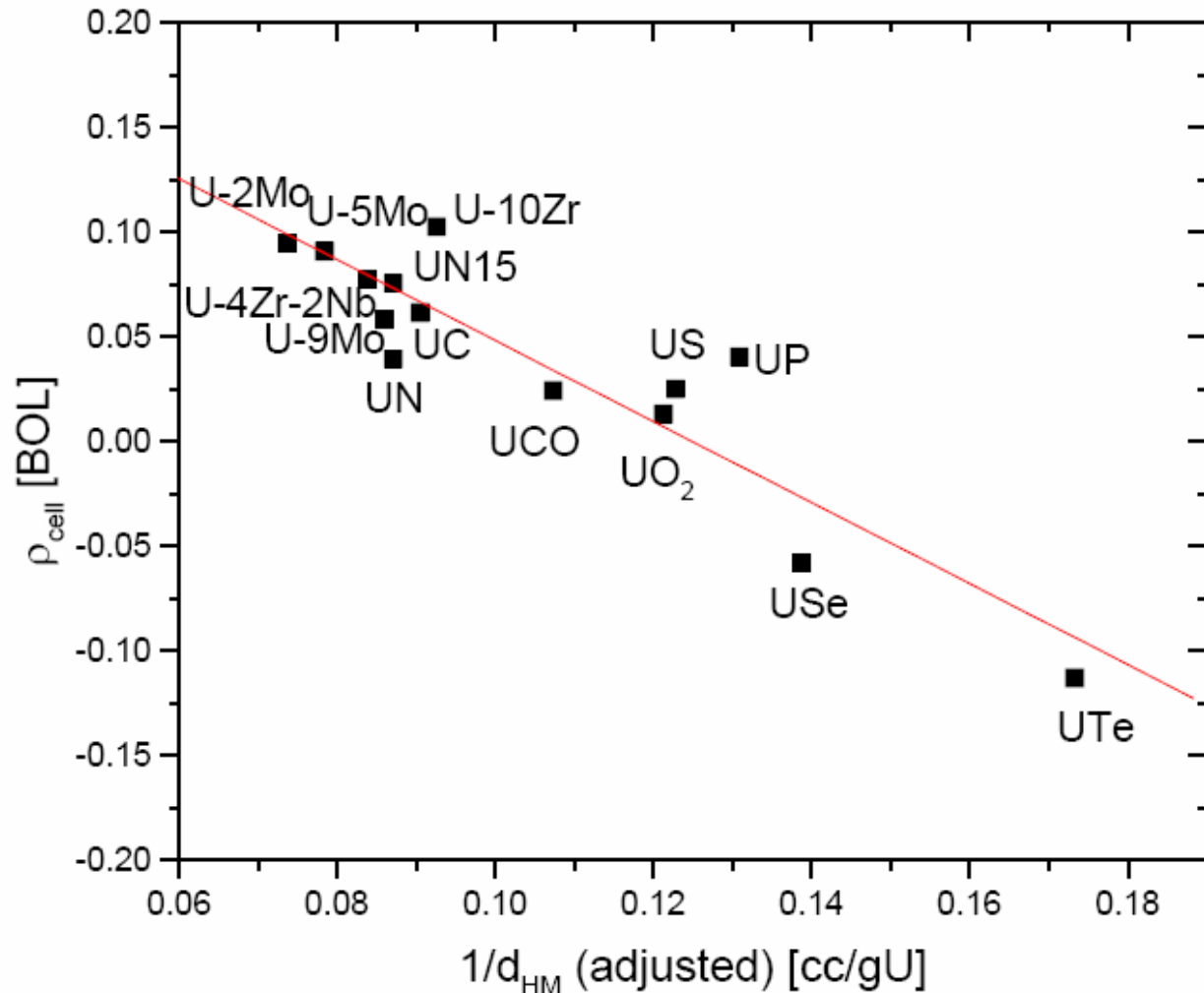
Gen IV Goals 3: Economy

- Indirect link
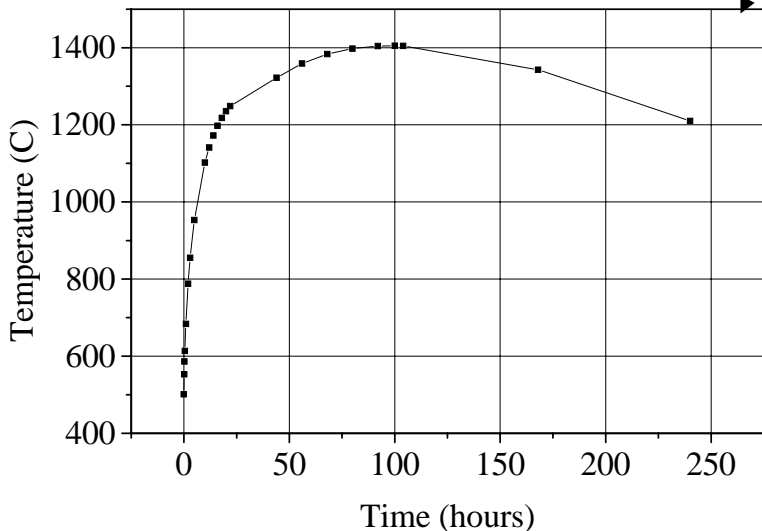 - Capital cost via safety - examples
    - Reduced peaking allows higher power density for given structural material temperature limits, hence more energy from the same vessel and lower cost
    - Low reactivity swing reduces number of control rods (CRDs expensive)
- Direct link
  - Fuel cycle cost
    - Strive for low enrichment (TRU weight fraction)
    - Strive for high specific power

Example of long life, low power density design

Inner reflector

reflector

Shield

Active core
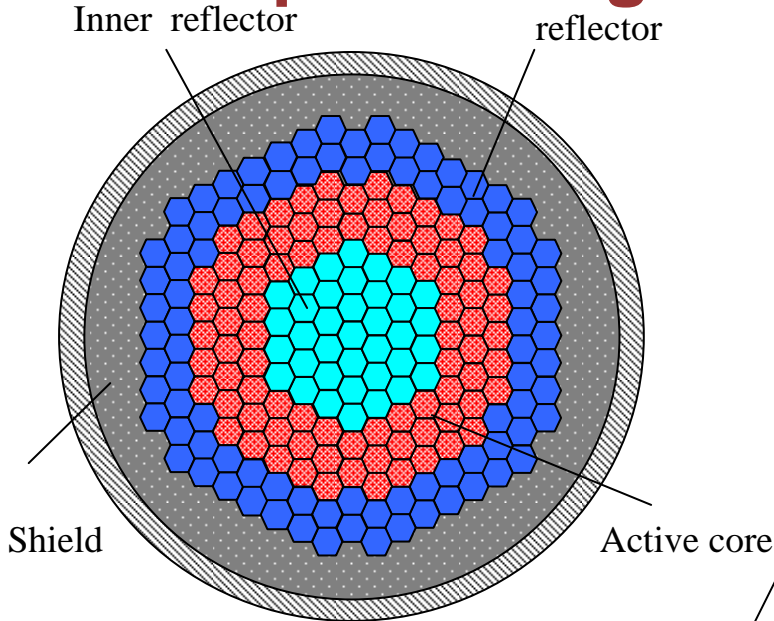
- Synergistic twin to thermal GT-MHR
- Same low power density – 8kW/l
- Passive decay heat removal by conduction and radiation
- Excellent safety
- Neutronically feasible
- Very long core life – 50 years

Temperature (C) vs Time (hours)

k_{eff} vs Effective full power years

35

But very high fuel cycle cost!!!

$$FCC = \frac{C}{8.766\, pL\eta T}\, \frac{xT}{1-e^{-xT}}$$

Chart legend: FCC-PWR (4%), FCC-GCFR (13%), T-PWR, T-GCFR

Bd=50MWd/kg
Bd=180MWd/kg

Y-axis (left): Fuel Cycle cost (mills/kWhr)
Y-axis (right): Core residence time for fixed burnup
X-axis: Specific power (kW/kgHM)
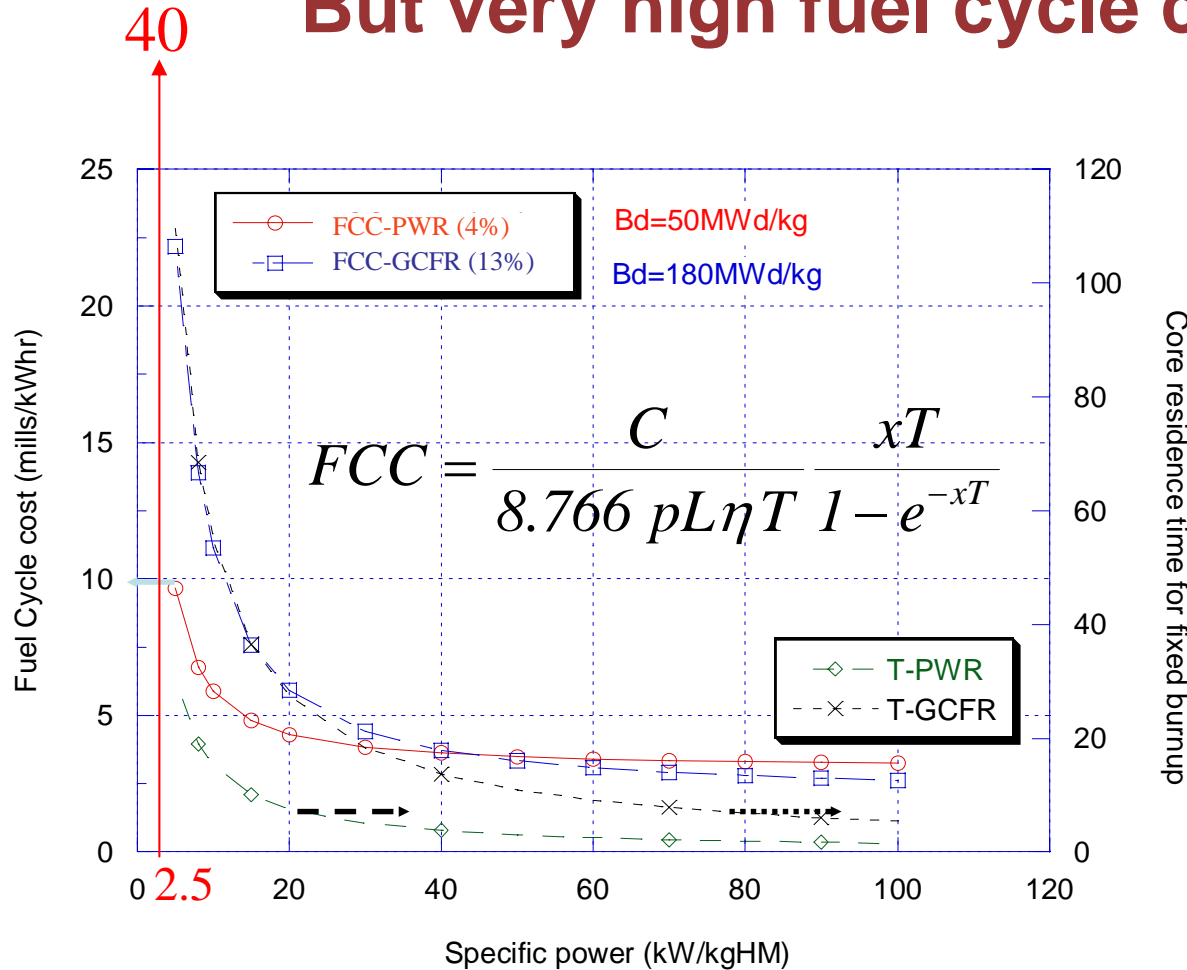
GFR

- For U235 enriched fuel
- η=45%, L=0.90
- Bd=180MWd/kgHM
- discount rate x=10%/yr
- C=3936 $/kg for e=13%

PWR

- η=33%, L=0.90
- Bd=50MWd/kgHM
- discount rate x=10%/yr
- C=1200 $/kg for e=4.5%
- Fabrication 200$/kg
- SP=38kW/kgHM

- Twin to MHR-GT not economically feasible
- Specific power should not be much below 20kW/kg, Shoot for 25kW/kgHM (BWR)
- **SUPERSAFE reactor of no use without a buyer**
- **What works for thermal reactor may not work for fast reactor**
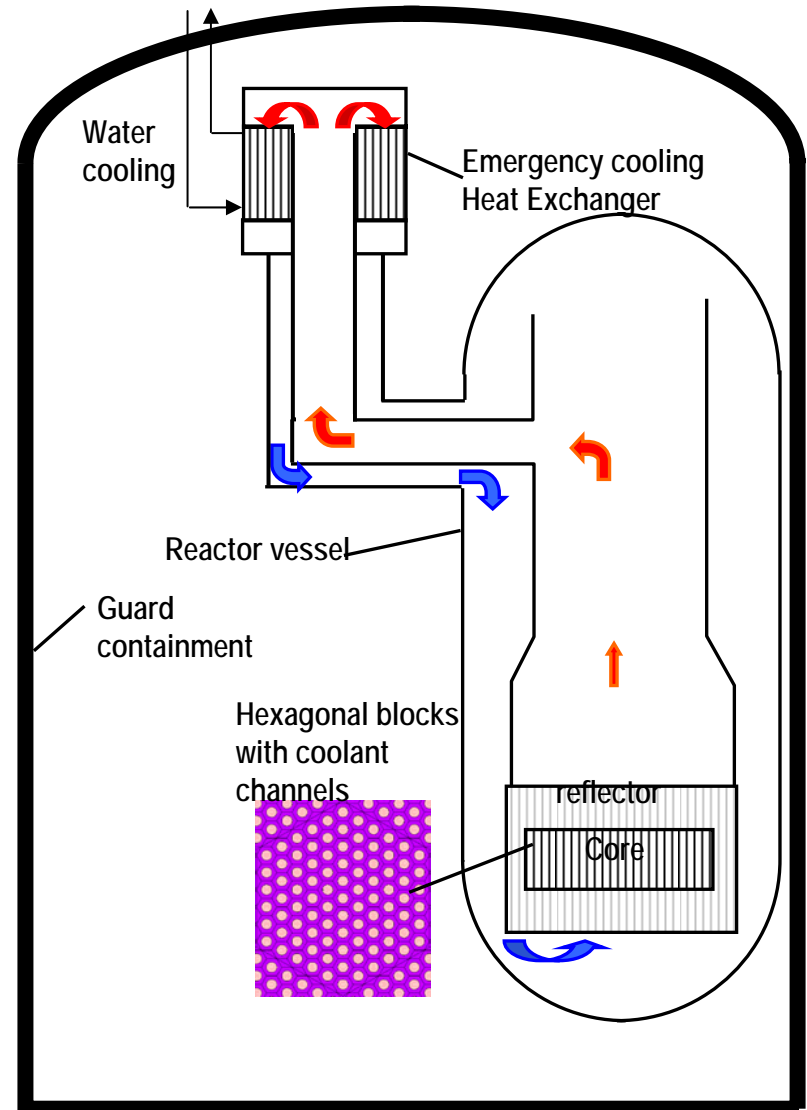
Gen IV Goals 4: Safety

- Reactivity increase from coolant depressurization
- Primary issue is post LOCA decay heat removal
  - Gen IV emphasis is on enhanced safety
  - Current trend – rely on passive means

GFR with natural circulation decay heat removal at elevated pressure

•4x50% cooling loops

•after depressurization of primary system, containment pressure increases and provides elevated pressure needed for natural circulation

Requires

Low pressure drop core, hence large coolant volume fraction – but neutronics favors small coolant volume fractions

Water cooling

Emergency cooling Heat Exchanger

Reactor vessel

Guard containment

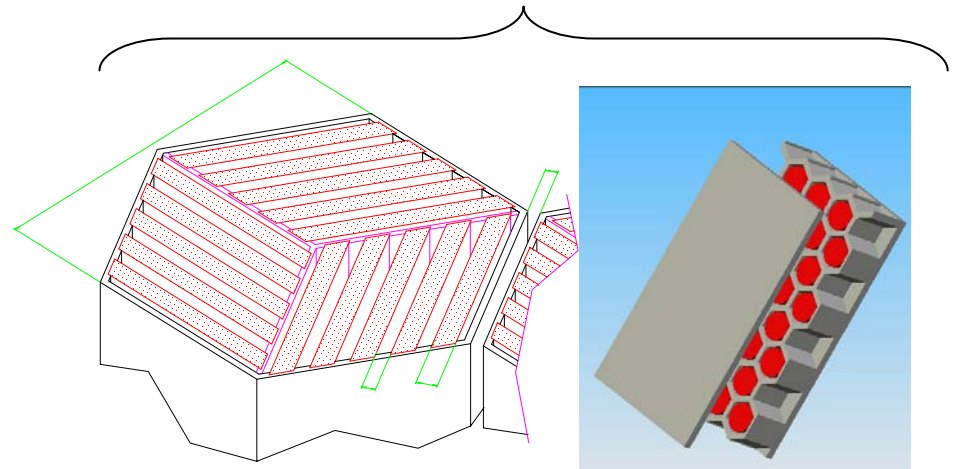Hexagonal blocks with coolant channels

reflector

Core

Approaches to reconcile neutronics thermal hydraulic requirements

- Problem
  - Neutronics needs high fuel volume fraction
  - Post-LOCA thermal hydraulics favors low pressure drop
- Use inverted fuel assembly or plate fuel assembly
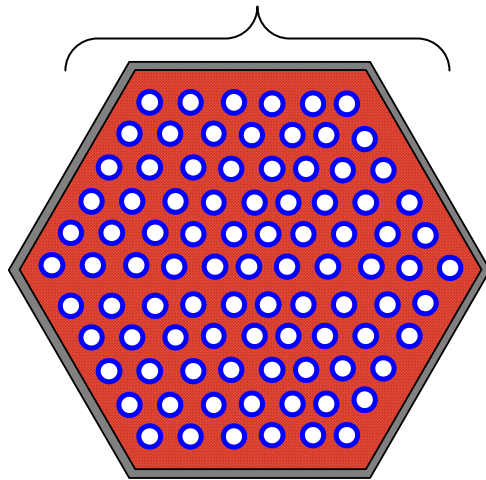
MIT approach

CEA approach

Courtesy of CEA Cadarache. Used with permission.

Neutronic Design for Safety

- Most GFRs have slightly positive CVW
- Is this acceptable?
- How to assure safety with slightly positive CVW?
  - Rely on other reactivity coefficients, which are negative
    - Doppler feedback
    - Fuel thermal expansion coefficient
    - Core radial expansion coefficient
    - CRD driveline expansions coefficient
  - Strive for a design with such a combination of reactivity coefficients that can achieve reactor shutdown without exceeding structural materials and fuel temperature limits

Possible Safety Approach

- Follow IFR approach of reactor self-controllability
- Goal: reactor should have sufficiently strong passive regulation of power to compensate for operator errors or equipment failures even if the scram fails.
- Core designed such that it inherently achieves safe shutdown state without exceeding temperature limits that would lead to core or vessel damage
- This must be achieved under the most restricting anticipated transients without scram (ATWS)
  - Unprotected (without scram) loss of flow (ULOF)
  - Unprotected loss of heat sink (ULOHS)
  - Unprotected overpower (UTOP) –
    - largest worth CRD withdrawal

Possible Safety Approach (cont')

- Note that this is much stronger requirement than for LWRs

- Loss of coolant is not credible in IFR since coolant under no pressure and if vessel fails, the coolant remains in guard vessel (but it is an issue in GFR, hence it needs to be accommodated)

- Inherent shutdown is determined by:

  ➢ Reactivity feedbacks

  ➢ Material and coolant-related limits (e.g., clad, boiling, freezing T for IFR)

- Need to find such combination of reactivity feedbacks and limits that makes it possible to achieve self-controllability

Safety Approach (cont')

- Quasi-static balance for reactivity encompassing all paths that affect reactivity is

  $+\Delta\rho cvw$ for GFR

$$0 = \Delta\rho_{power} + \Delta\rho_{flow} + \Delta\rho_{temp} + \Delta\rho_{external}$$

- Since time constants of heat flow changes and temperature induced geometry changes and of delayed neutrons are in the range of half second to several minutes, and transients are slower, most feedbacks are linear permitting above equation to be represented as

  $+\Delta\rho cvw$ for GFR

$$0 = \Delta\rho = (P-1)A + (P/F-1)B + \delta T_{inlet} C + \Delta\rho_{external}$$

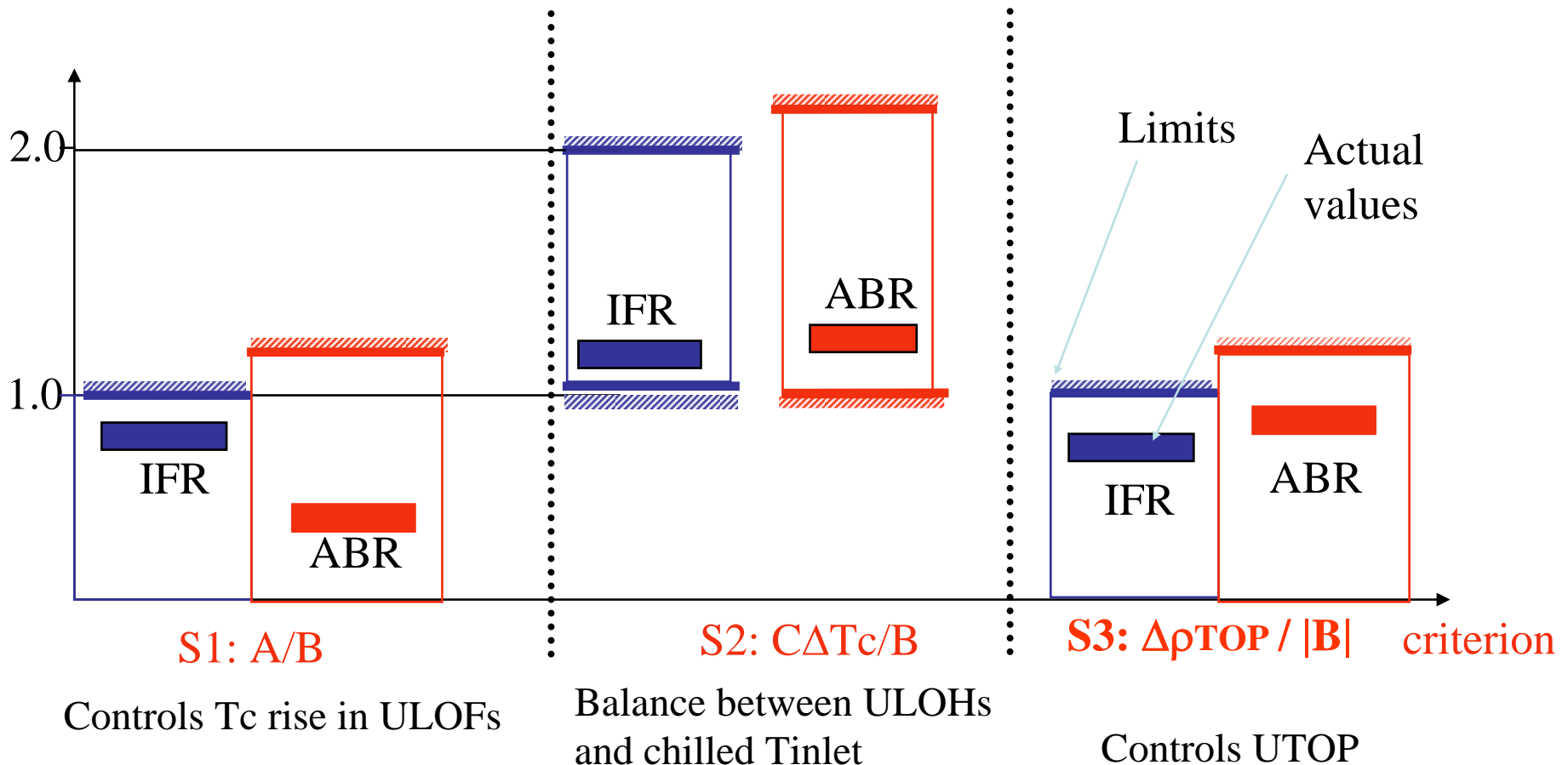P,F –   power and coolant flow normalized to full power and flow

δTin –   change from normal coolant temperature

A,B,C – integral reactivity parameters that arise from temperature and
          structural changes - discussed next

Three criteria for A,B,C can be derived to achieve self-controllability

Wade and Chang, "The IFR Concept Physics of Operation and Safety, Nucl. Sci. Eng., Vol. 100, p. 507, 1988

Self-controllability criteria for LMRs

- ABR – fertile free, lead cooled actinide burner
- LMRs can be designed to satisfy these criteria in spite of positive CVW
- Transient calculations still needed to confirm the performance

S1: A/B

Controls Tc rise in ULOFs

S2: CΔTc/B

Balance between ULOHs and chilled Tinlet

S3: $\Delta\rho$TOP / |B| criterion

Controls UTOP

GFR self controllability

- Designing a GFR with self controllability is a challenge
- Differences
  - Additional term in reactivity balance to account for CVW
  - Direct cycle – separate ULOHS and ULOF may not be possible – loss of heat sink (precooler) may lead to loss of flow to prevent compressor surge or stall, hence ULOF and ULOHS will be always combined
  - Self-controllability criteria need to be updated
  - Decay heat removal may not be fully passive
- Issues
  - MIT design with UO2 fuel has too large Doppler feedback (low conductivity, softer spectrum)
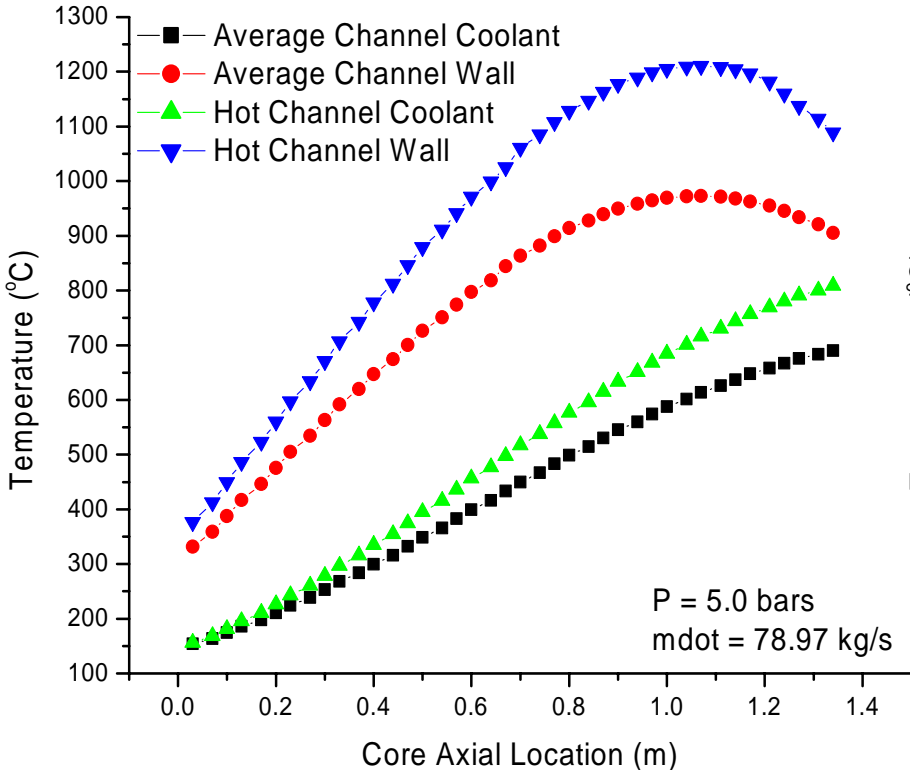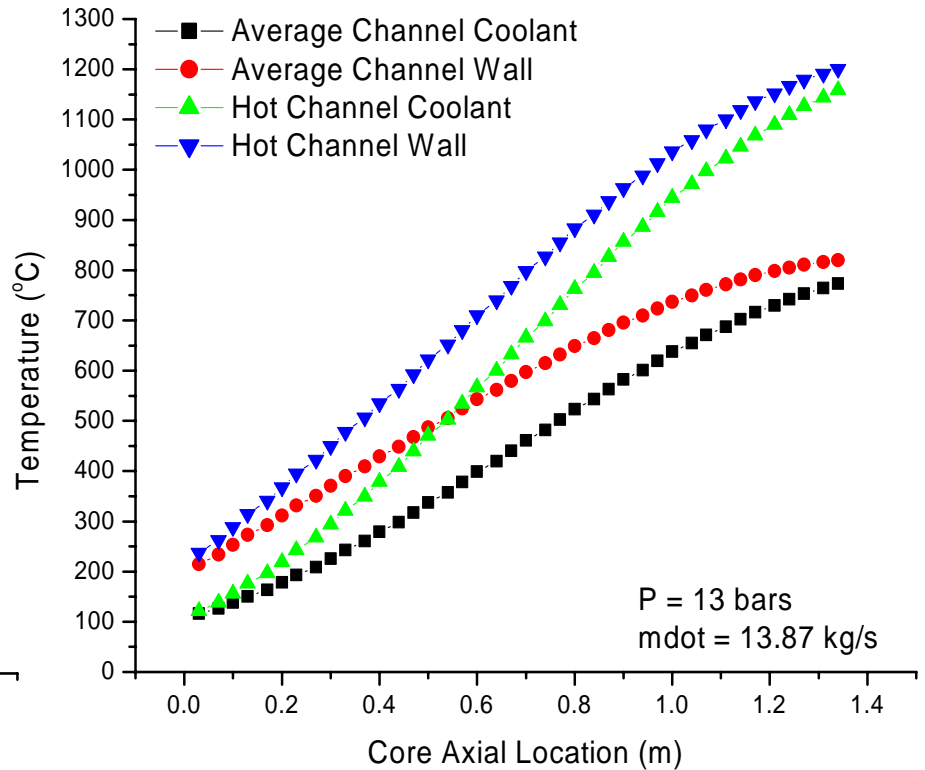
Questions

Extra Slides

Natural circulation performance - CO_2 and He

Post LOCA core temperature profiles

CO_2

Helium

- Limits – peak cladding temperature=1200°C, maximum core-average outlet T=850°C
- 2% decay heat can be removed by natural circulation
- CO2 much better than He – requires backup pressure of 5bars versus 13 bars for He
- Helium – issue of excursion type instabilities

IFR criteria for passive self-regulation

S1-criterion   A/B < 1.0; A,B negative

- A-net power reactivity coefficient (Doppler, fuel thermal expansion)

  $A = (\alpha_d + \alpha_{th}) \Delta T_f \ [\cent]$

- B-power/flow coefficient of reactivity - controls asymptotic temperature rise in ULOF (coolant density, CRD-driveline, core radial expansion coefficients

  $B = [\alpha_d + \alpha_{th} + \alpha_{den} + 2(\alpha_{crd} + 2/3\alpha_{rad})] \Delta T_c/2 \ [\cent]$

- Key strategies:
  - ➢ Small negative A - metallic fuel, hard spectrum
  - ➢ Large negative B - minimize coolant density coefficient

- Large B also favors large temperature rise across the core
- But penalties on efficiency, hence compromise needed

IFR criteria for passive self-regulation

S2-criterion   1.0<(C ΔTc/B) < 2.0; C negative

- C –inlet temperature coef. of reactivity $= -\left[\partial\Delta\rho \,/\, \partial T_{in}\right]$

- provides balance between the ULOHS and the chilled inlet temperature inherent response (Doppler, fuel thermal exp., coolant density core, radial exp.)

  C= (α_d+ α_{th}+ α_{den} + α_{rad}) [¢/K]

- range comes from cladding limit and coolant temperature rise

- Main efforts:

  ➢ Minimize coolant density coefficient

 ➢ Increase core radial expansion coefficient, if needed

IFR criteria for passive self-regulation

S3-criterion $\Delta\rho_{TOP} / |B| < 1.0$

- Controls asymptotic temperature rise in UTOP
- The rod worth of the most reactive control rod must be limited
- Strategies:
  - Minimize reactivity swing
    - Use fertile, maximize η, CR=1 is a good candidate
    - Increase Vf - limited by cladding stress constraint
    - Low-leakage core favored, but hurts coolant void worth
  - Large B - minimize coolant density coefficient
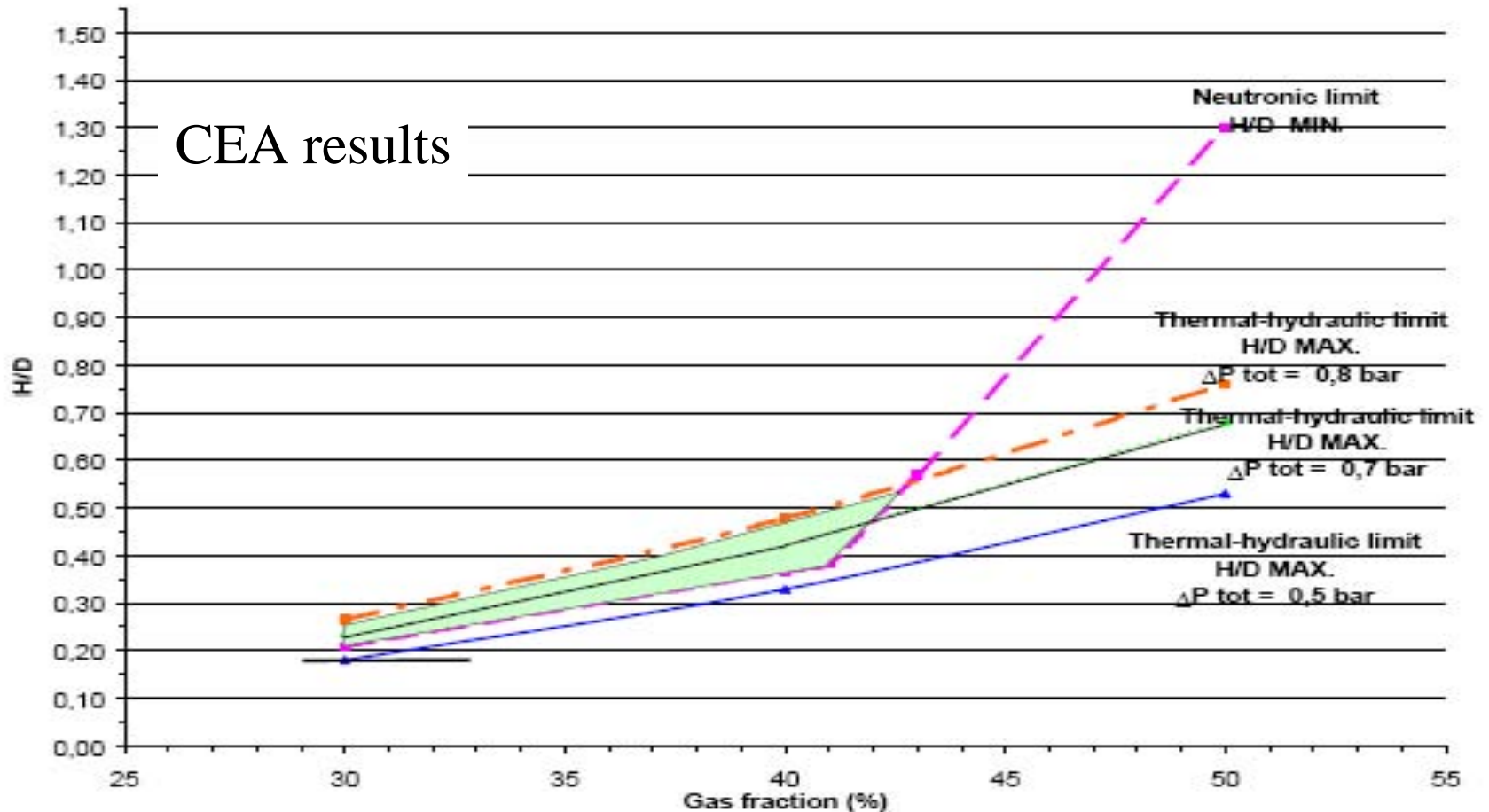 - Increase number of CRDs

Feasibility domain for plate core at 50kW/l

- Feasibility domain for carbide CERCER (50/50) 2400MWth core q'''= 50W/cc

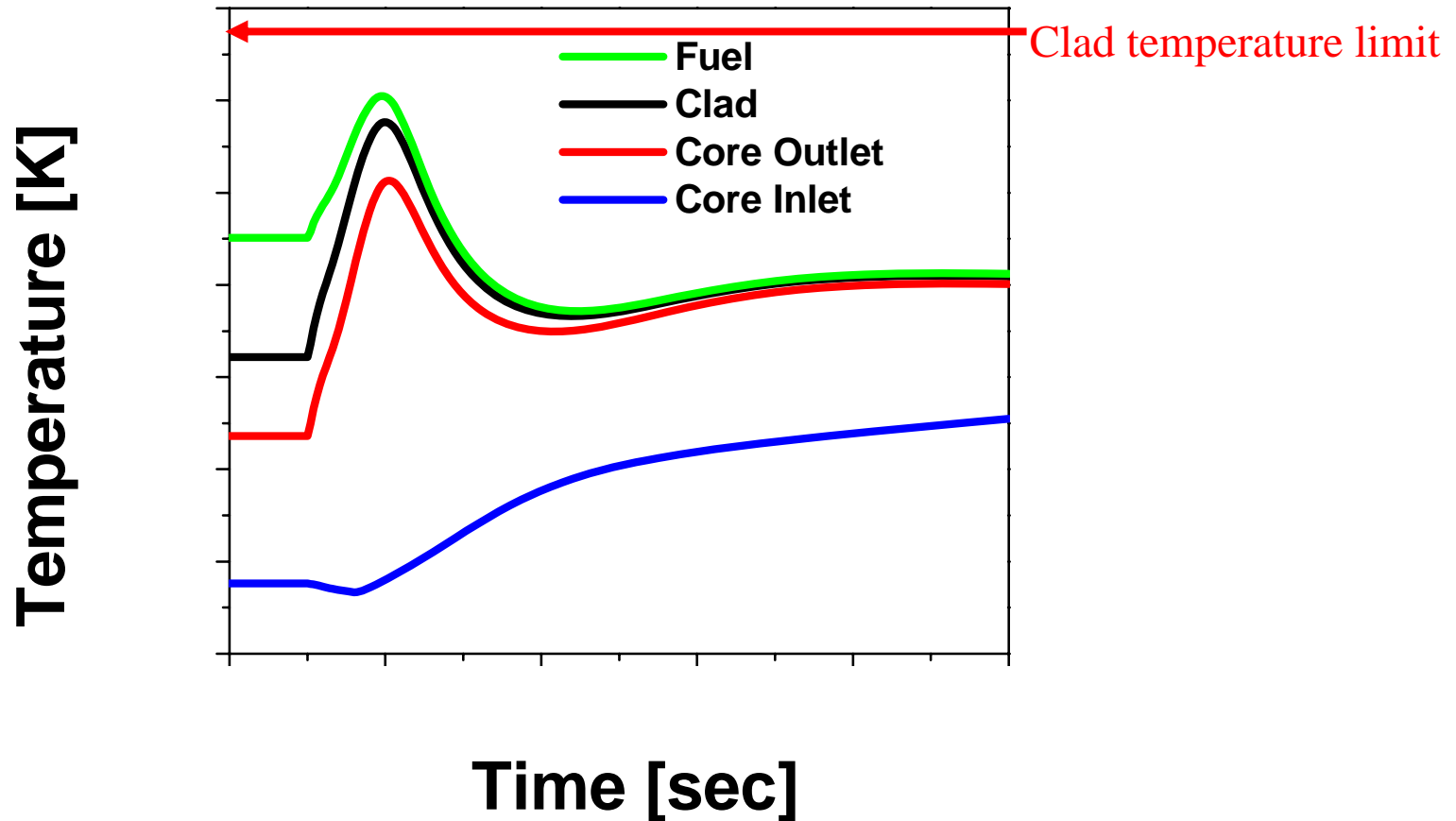Courtesy of CEA Cadarache. Used with permission.
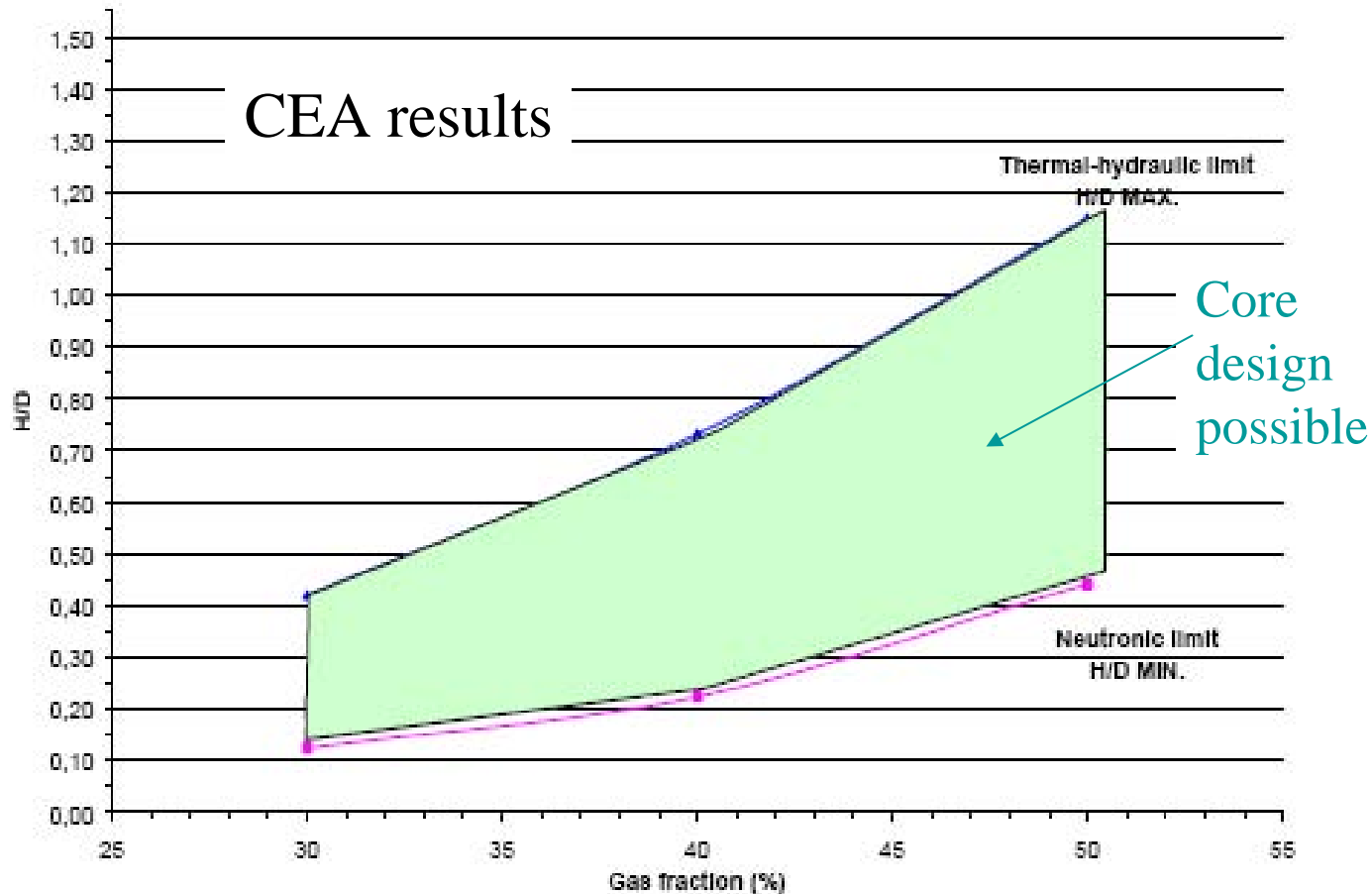
Feasibility domain for plate core at 100kW/l

- Feasibility domain for carbide CERCER (50/50) 2400MWth core q'''= 100W/cc

CEA results
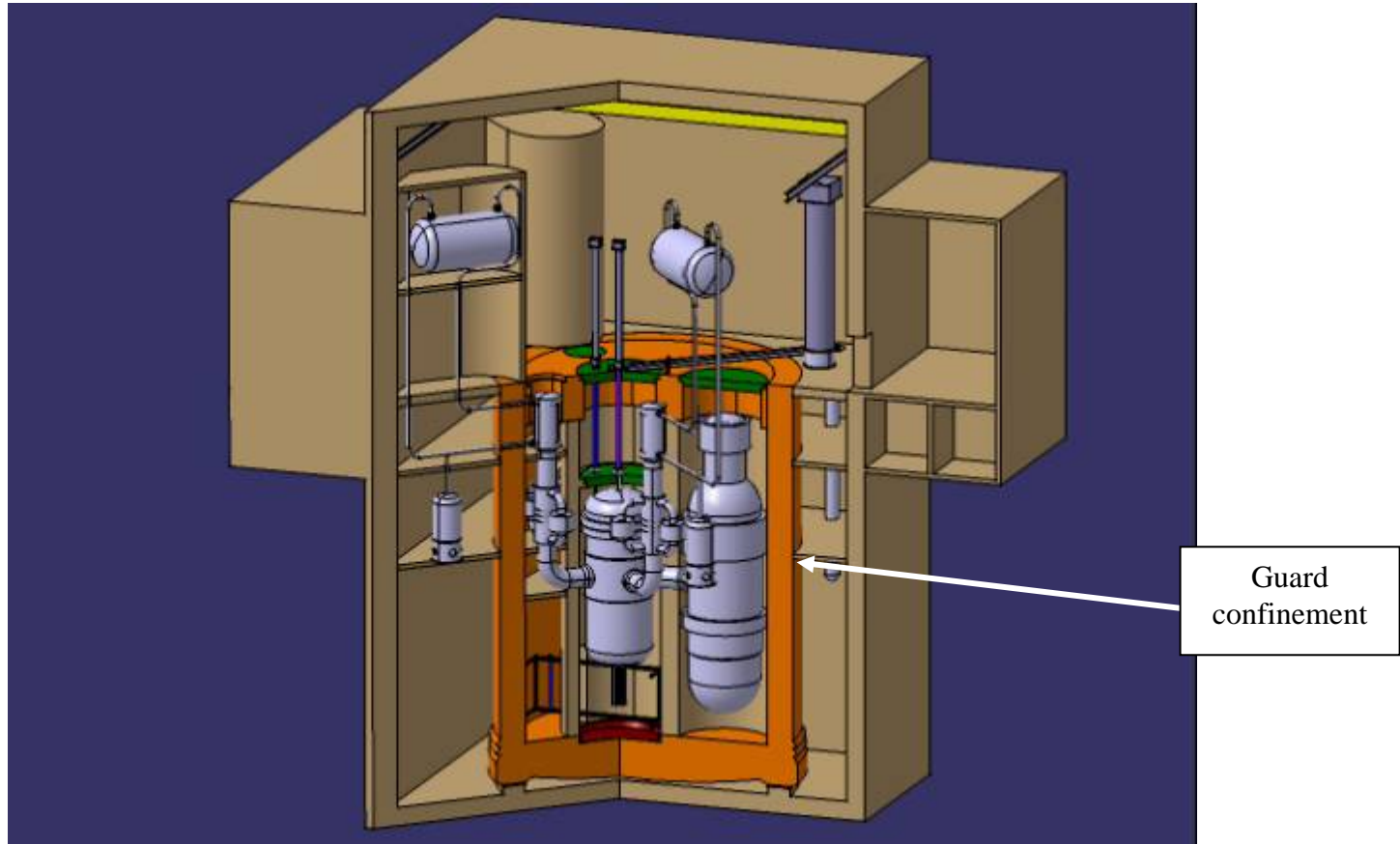
Courtesy of CEA Cadarache. Used with permission.

Typical reactor response to ULOF

- Cladding must remain below temperature limit

Example of GFR design for passive decay heat removal

Guard confinement

Courtesy of CEA Cadarache. Used with permission.

CEA and Framatome helium cooled design

Example – neutronic data for CEA design

Table 2.3: Neutronics characteristics – 2400 MWt Plate Core

	First cycle	Equilibrium cycle
Power density (MW/m^3)	100	
TRU enrichment (%)	15.2	18.5
U+Pu+MA inventory (tons) Pu / MA inventory (tons/GWe)	59.3 7.7 / 0	59.3 9.5 / 0.6
Core management EFPD	$3 \times 831 = 2493$	
Average, Max burn up (at%) Max damages (dpa SiC)	10.1 / 14.7 163	10.1 / 14.7 152
Average flux level – BOL (n.cm^2.s^{-1}) Max fast flux >0.1MeV (n.cm^2.s^{-1})	16.7×10^{14} 11.7×10^{14}	$15,9 \times 10^{14}$ 11.0×10^{14}
Breeding Gain - BOL / EOL	-0.07 / -0.04	0.05 / -0.05
Doppler Constant - BOL / EOL (10^{-5})	-1872 / -1175	-1405 / -968
He depressurization - BOL / EOL (10^{-5})	212 / 253	253 / 257
Delayed neutron fraction - BOL / EOL (10^{-5})	388 / 344	347 / 332

Example – key design data for CEA design

Table 2.2: Design data and Thermal-hydraulics– 2400 MWt Plate Core

Power density (MW.m^{-3})	100
Active core volume (m^3)	24
Core diameter/height (m)	4.44 1,55
H/D	0.35
(U,Pu)C (% vol.)	22.4
SiC structures (%vol.)	26.4
Gas (% vol.)	51.2
He coolant / He gaps	40.1 / 11.1
Plate thickness (mm)	7 (including 2 × 1 mm for plate closure)
Plates per S/A (in a plan)	27
Number of fuel S/A	387
Core pressure drop (bar)	0.6
Tmax** cladding BOL (°C)	1075
Tmax** fuel BOL (°C)	1210

**taking into account a correction for plate macro-structure heterogeneity