Design Rationale for Metal-Fuel Fast Reactors Toward Advanced Fuel Cycles

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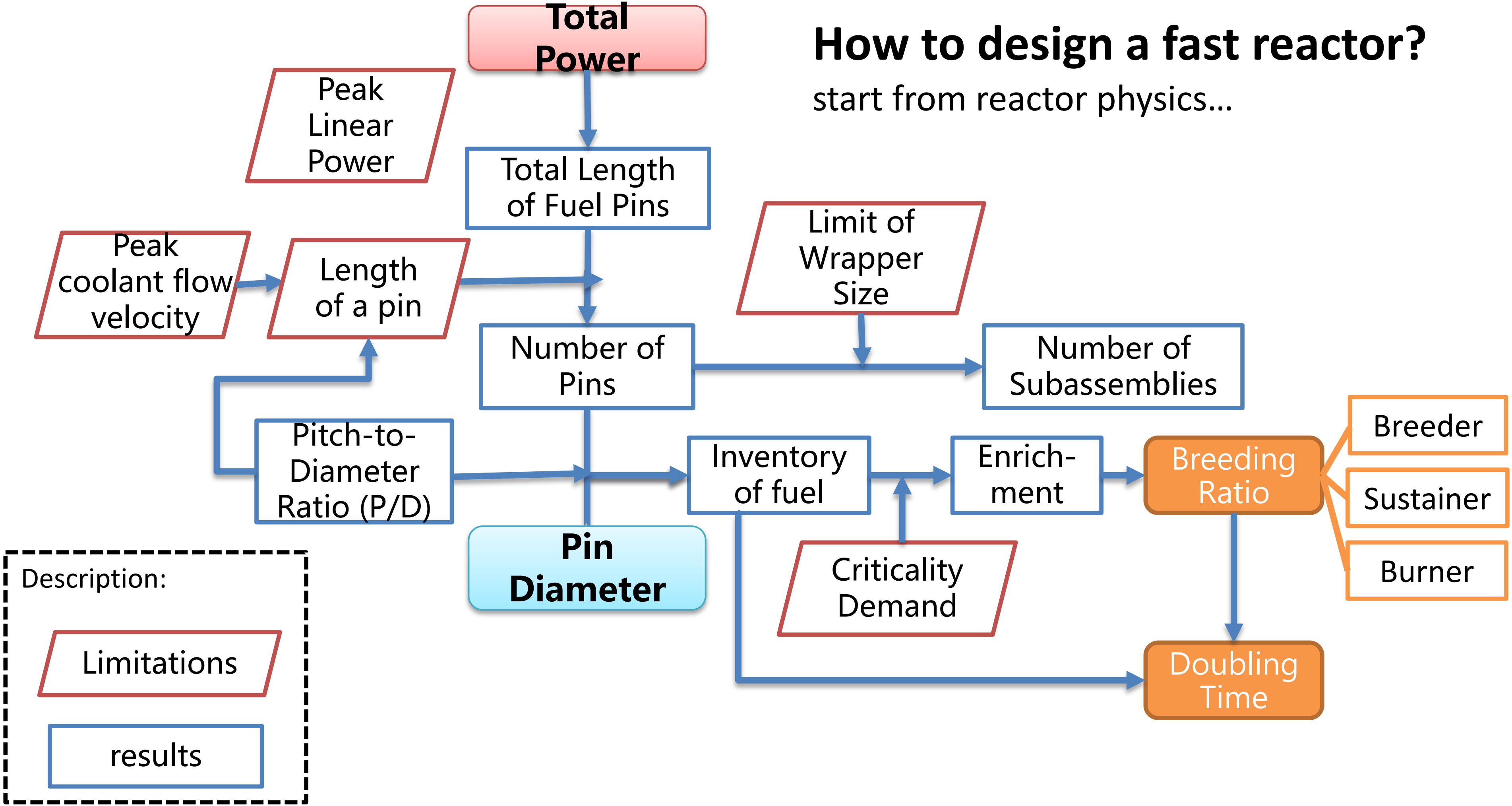
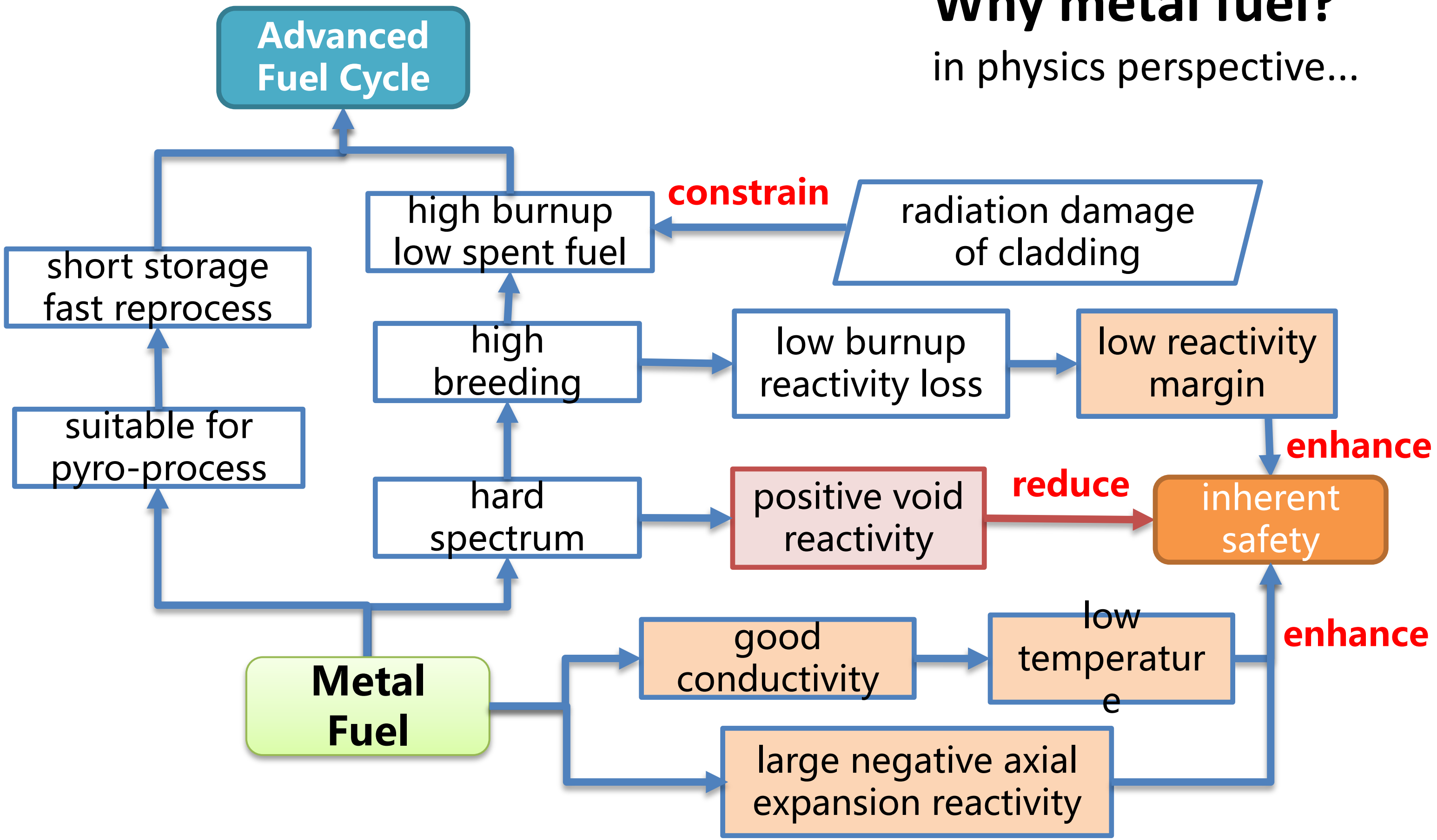
How to design a fast reactor?

start from reactor physics…



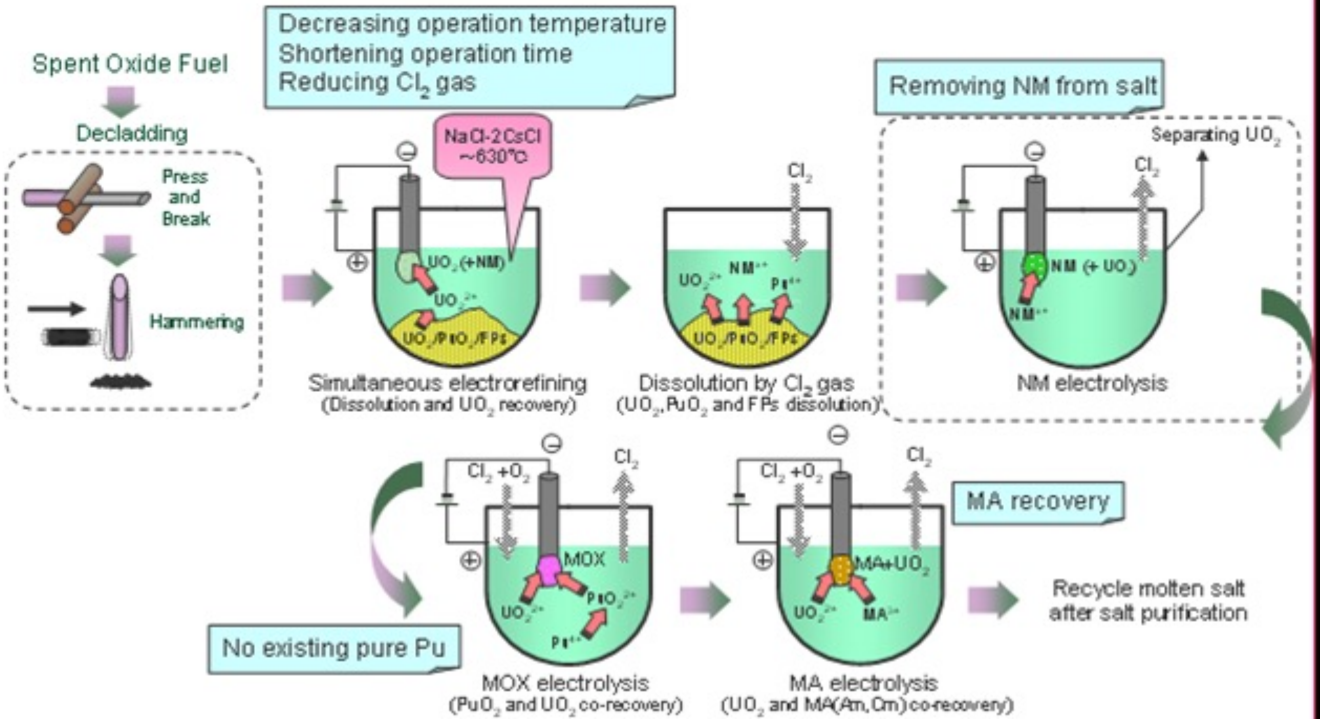
Why metal fuel?

in physics perspective...



Metal Fuel Naturaly Fits Pyro-processing

- To achieve a high-efficiency nuclear fuel cycle and fully utilize uranium resources, metallic fuel coupled with pyroprocessing and related fuel fabrication technologies offers an ideal solution for safe and efficient nuclear energy utilization.



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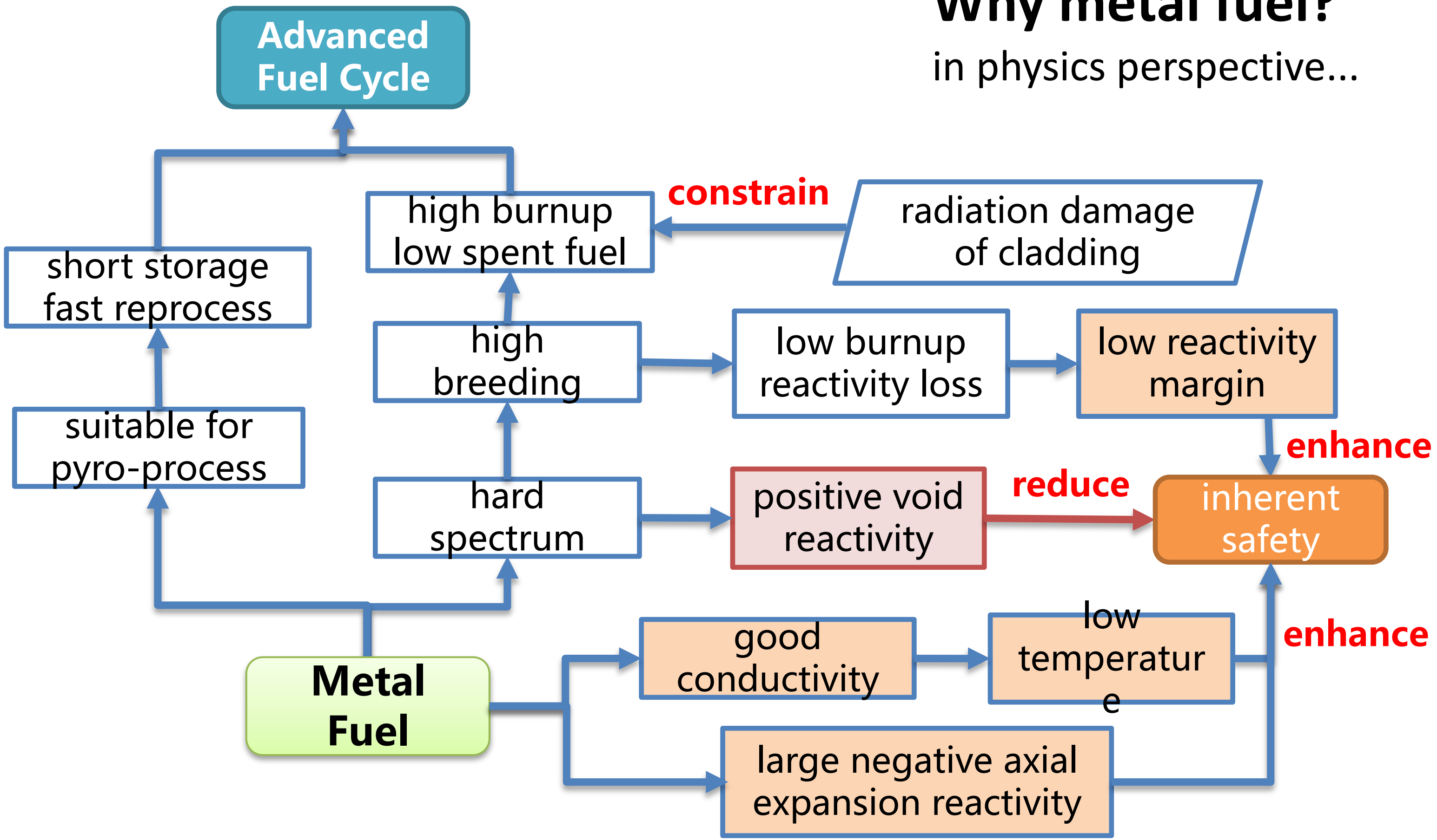


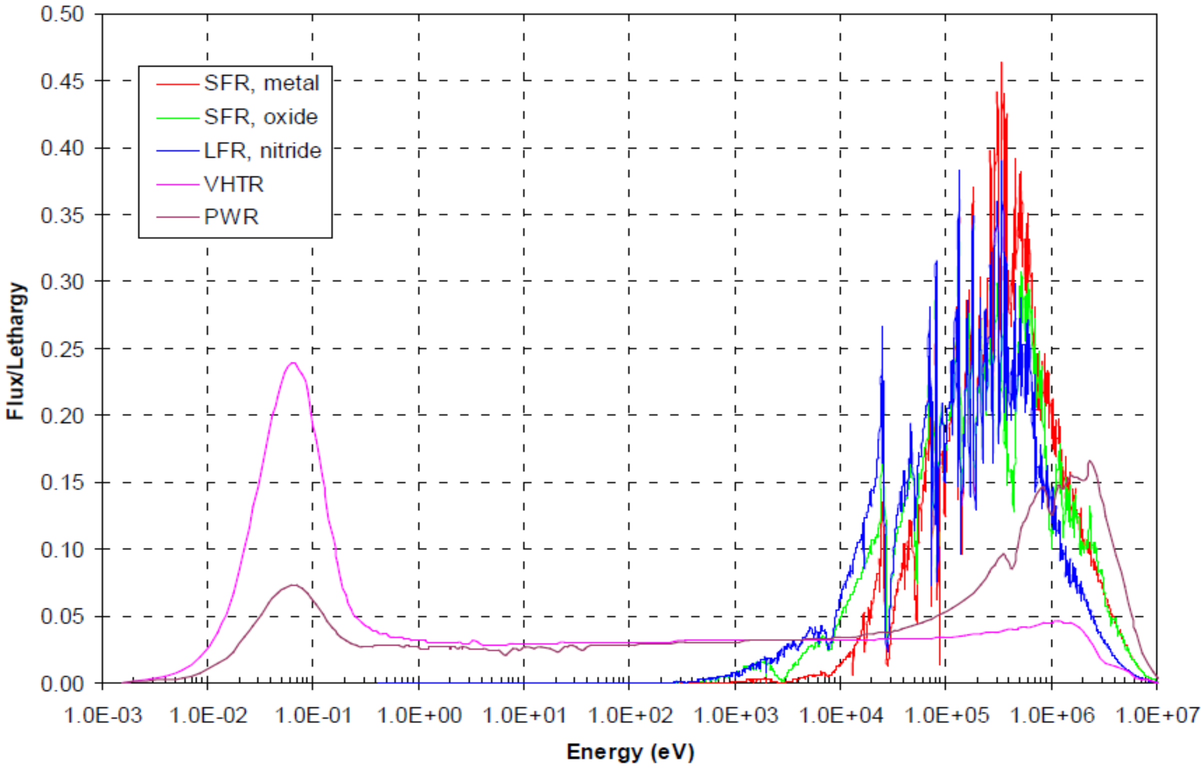
Harder Neutron Spectrum of Metallic Fuel

- Compared with oxide fuel, metallic fuel contains no low-atomic-number oxygen atoms and features higher density, yielding a harder neutron spectrum.

Comparison of Spectra

Neutron Energy/MeV	Neutron Flux Ratio	
	UO_2 Fuel	Metal Fuel
<0.1	39.0	34.5
>0.1	61.0	65.5

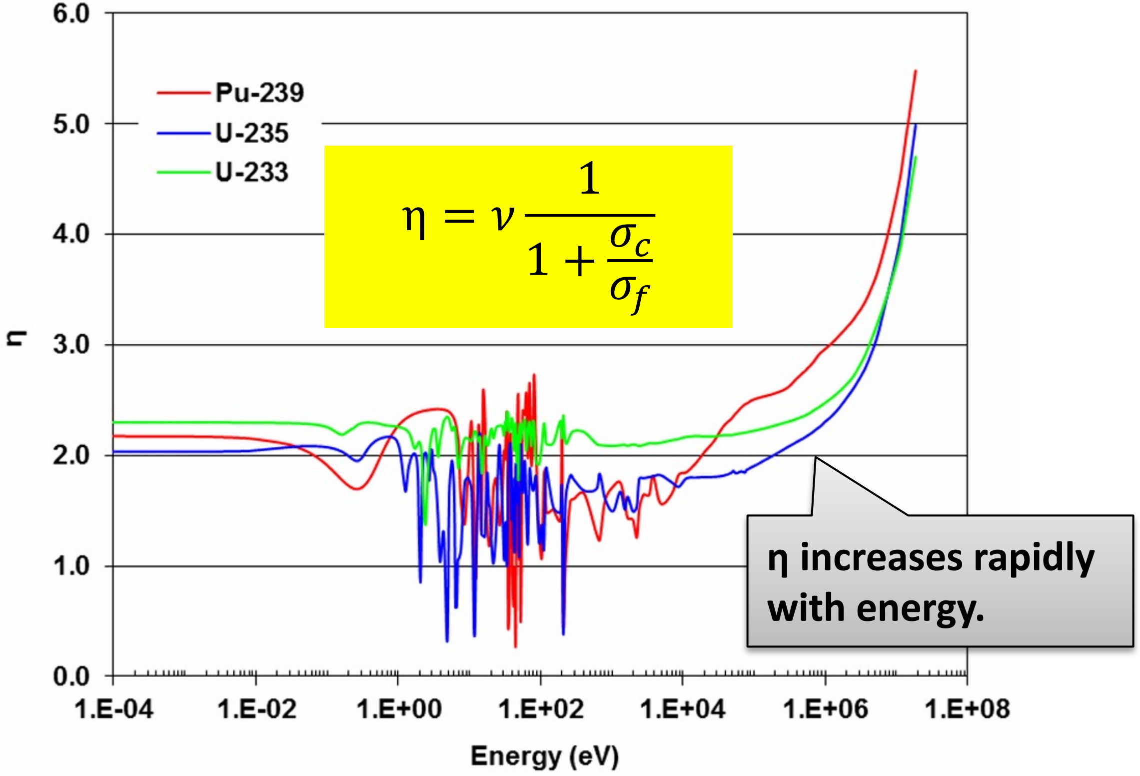
Neutron Spectra of Main Reactor Types



Hard Spectra Enable High Breeding Ratios

- Harder neutron spectra increase the effective fission neutron yield of heavy nuclei, generating surplus neutrons to support breeding.
- Metallic fuel cores therefore generate abundant surplus neutrons to sustain chain fission while capturing neutrons in U-238 to produce plutonium.

Neutron yield per capture



$$\eta = \nu \frac{1}{1+\frac{\sigma_c}{\sigma_f}}$$

- $\eta = \nu \frac{\sigma_f}{\sigma_a} = \nu \frac{\sigma_f}{\sigma_{f+}\sigma_c} = \nu \frac{1}{1+\sigma_c/\sigma_f}$

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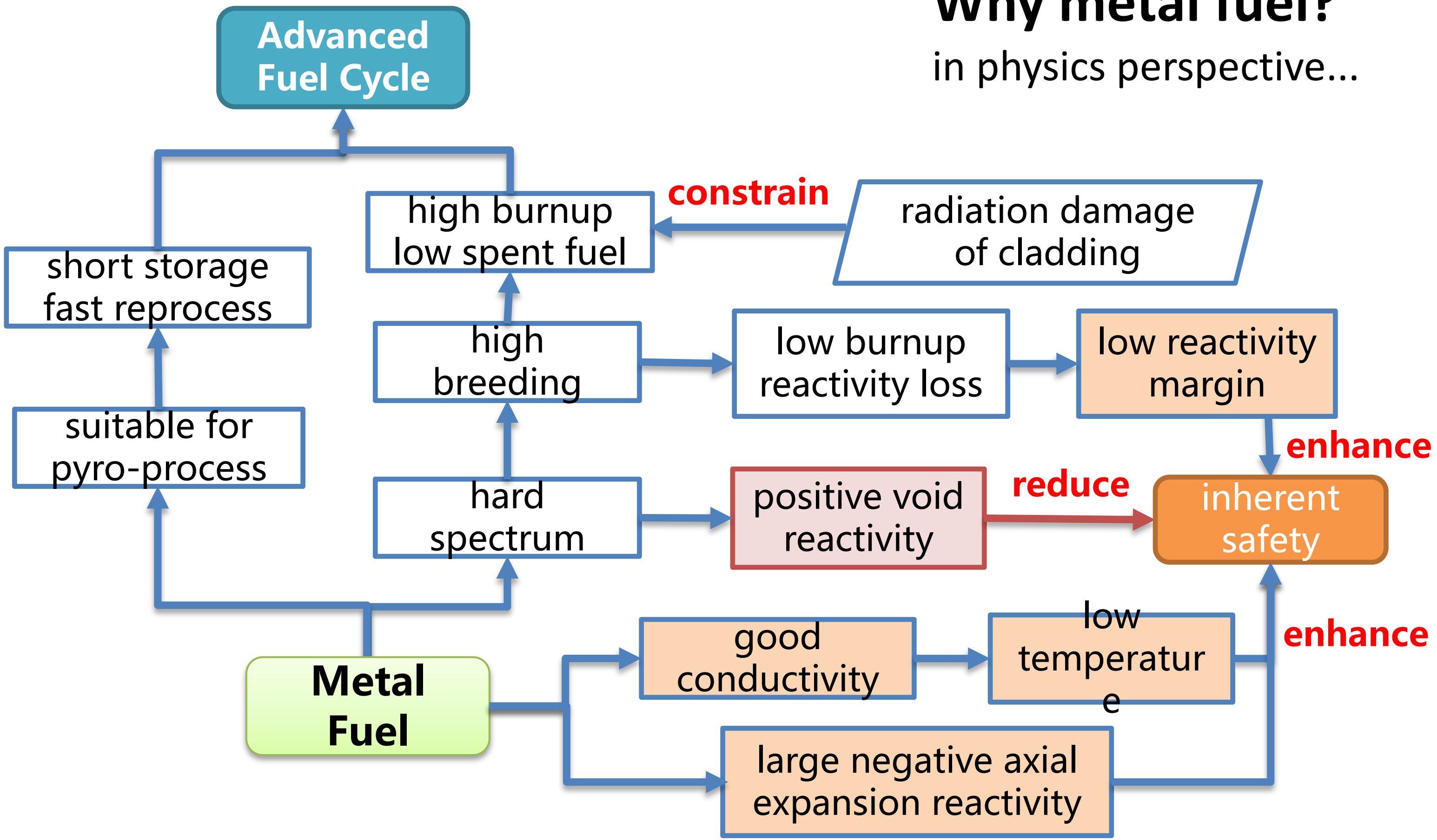
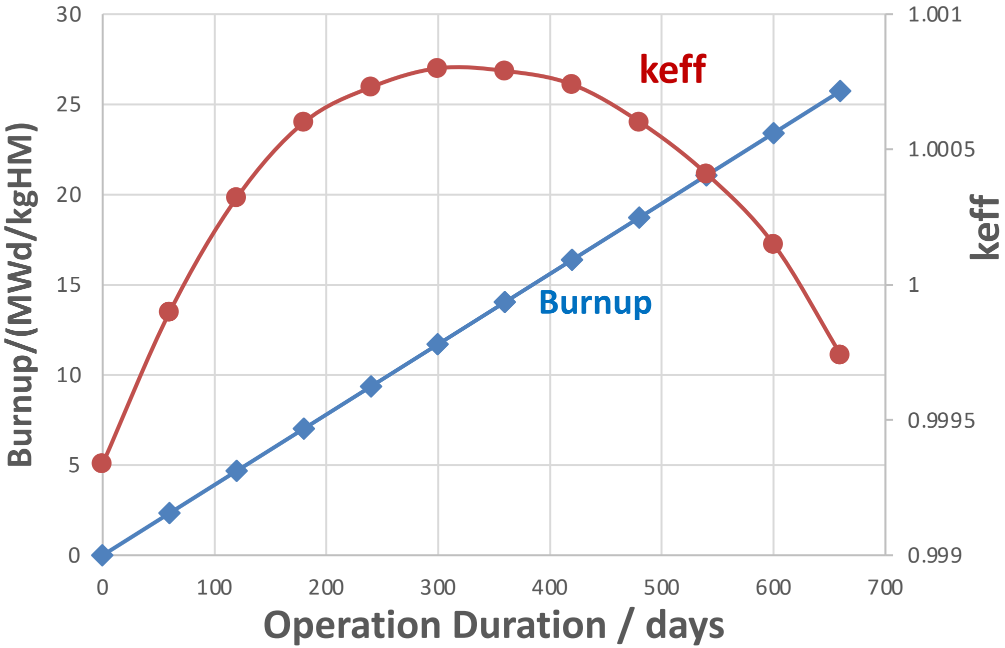


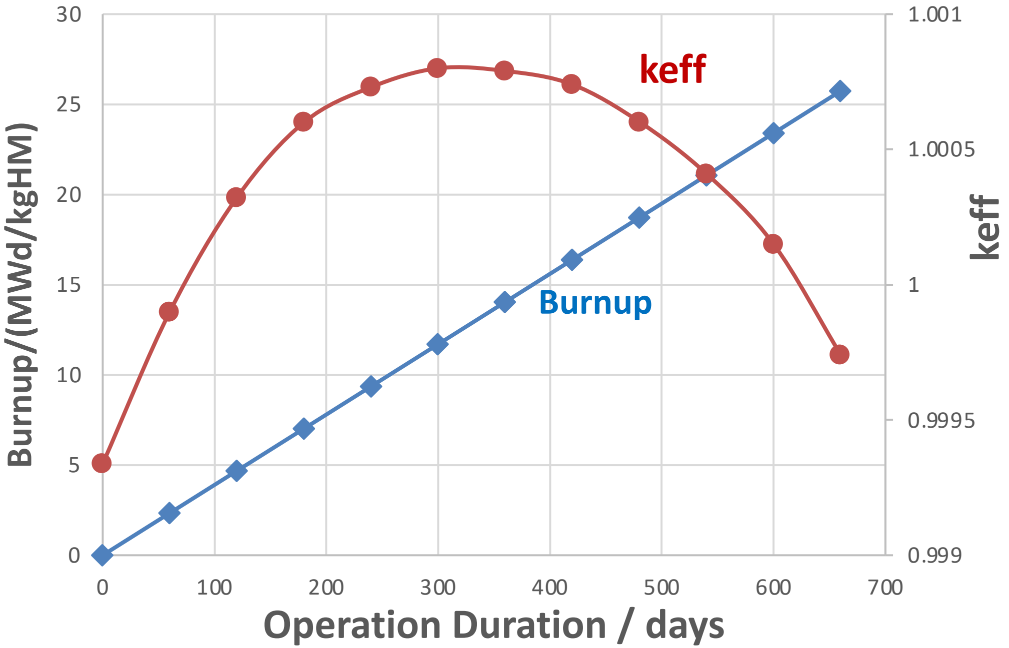
High Breeding Enables Long Cycle Period



from a 3,000 MWth U-TRU-Zr metallic fuel core at fixed control rod positions

- For a 3,000 MWth U-TRU-Zr metallic fuel core design, single-cycle burnup reactivity ranges from −500 pcm to +500 pcm.
- In comparison, large UO_2/MOX fast reactors exhibit burnup reactivity between −4,000 pcm and −2,000 pcm.
- Metallic fuel cores therefore require minimal initial excess reactivity at beginning-of-cycle, delivering significant inherent criticality safety advantages.
- Low excess reactivity also relaxes control rod worth requirements (fast reactors rely entirely on control rods for reactivity management).

High Breeding Enables Long Cycle Period



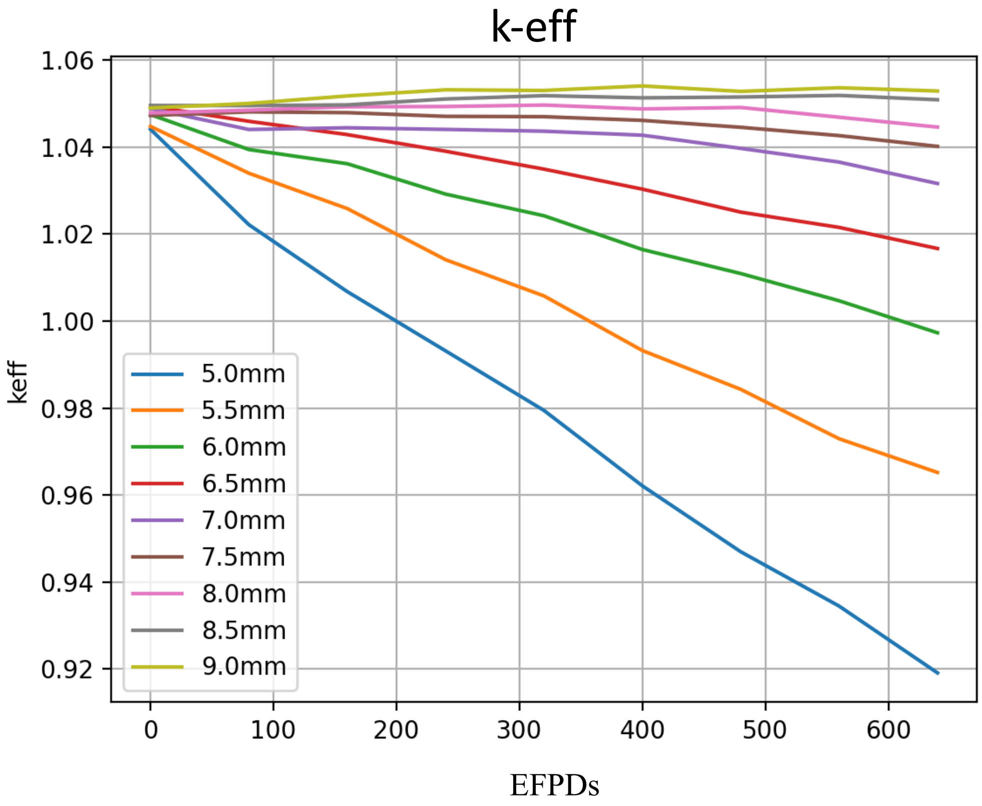
from a 3,000 MWth U-TRU-Zr metallic fuel core at fixed control rod positions

Comparison of Control Rod Numbers Between MOX-fueled and Metal-fueled Cores

Control Rod	Total Number	
	MOX core	Metal Core
Shim rods + Regulating rods	19	9
Safety Rods	10	7

- Metallic fuel fast reactors exhibit substantially superior breeding performance.
- Enrichment below 15% yields near-zero or even positive burnup reactivity.
- High breeding eliminating the need for excessive excess reactivity and drastically cutting the number of control rods, thereby improving both safety and economic performance.

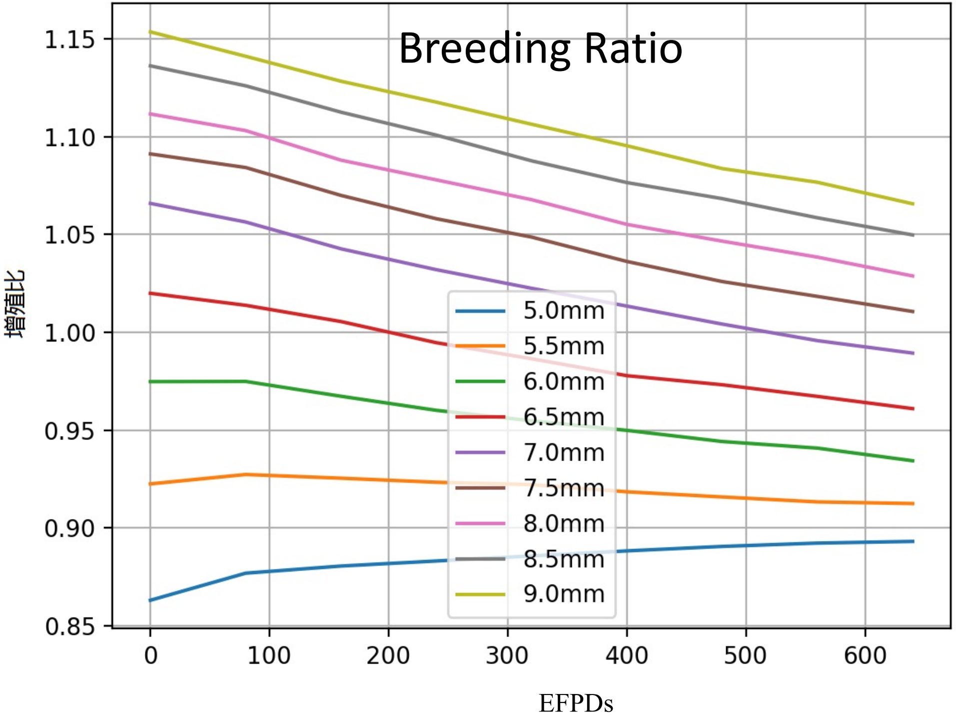
Breeding Optimization: Rod Diameter



Change of k_{eff} with burnup under different rod diameters

- Increasing rod diameter significantly mitigates burnup reactivity loss, and burnup reactivity remains nearly balanced when the rod diameter reaches approximately 7.0 mm.
- The physical mechanism can be explained as follows: larger rod diameter expands core volume, lowers neutron leakage fraction and increases total fuel loading, which reduces required fissile enrichment and raises the ratio of fissile production rate to fissile consumption rate.

Breeding Optimization: Rod Diameter

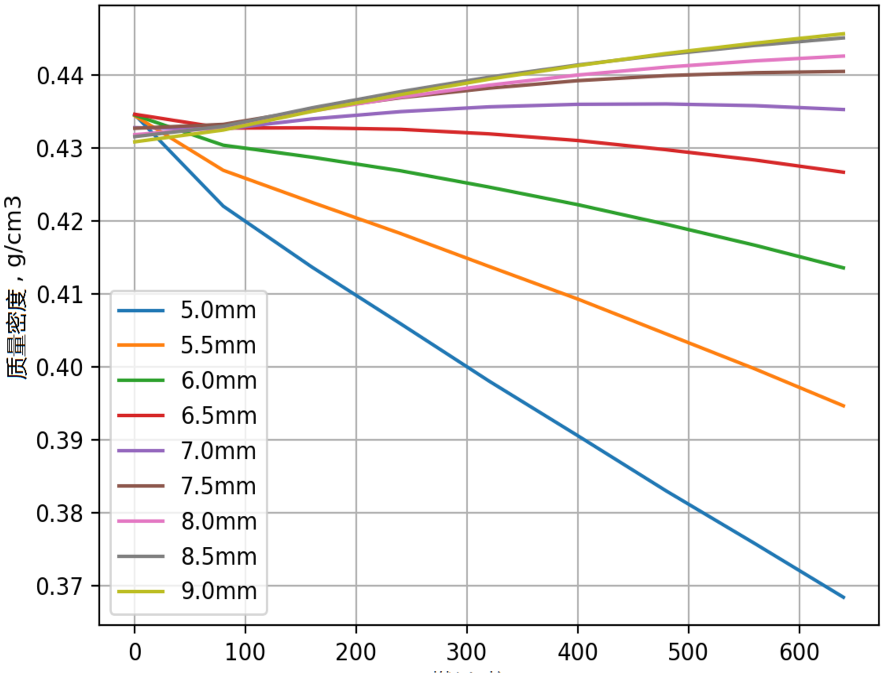


Change of breeding ratio with burnup under different rod diameters

- Larger rod diameters correspond to higher breeding ratio and regeneration ratio, both maintained above 1.0 throughout the full burnup cycle at a rod diameter of around 7.0 mm.

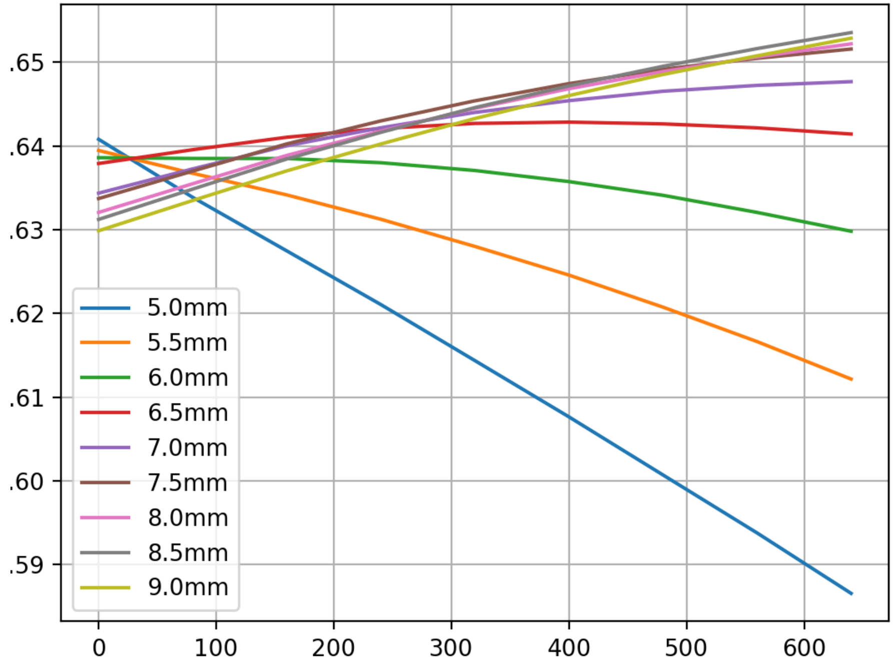
Breeding Optimization: Rod Diameter

Fissile Mass in Core



EFPDs

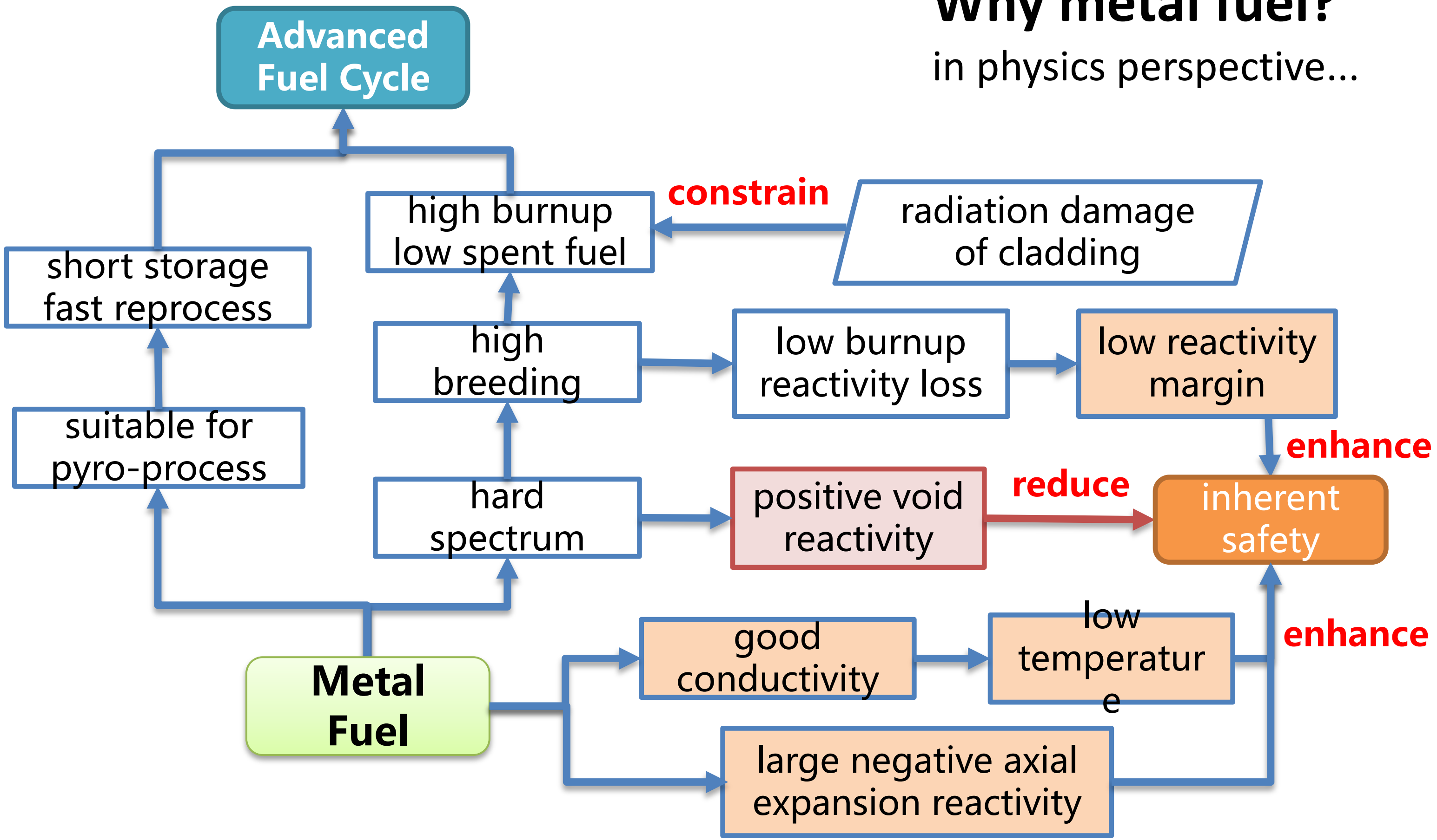
TRU Mass in Core



EFPDs

Why metal fuel?

in physics perspective...



Radiation Damage of Structure Material

A harder neutron spectrum corresponds to higher radiation damage cross-sections, so cladding radiation damage becomes the limiting factor for burnup depth in integral fast reactors.

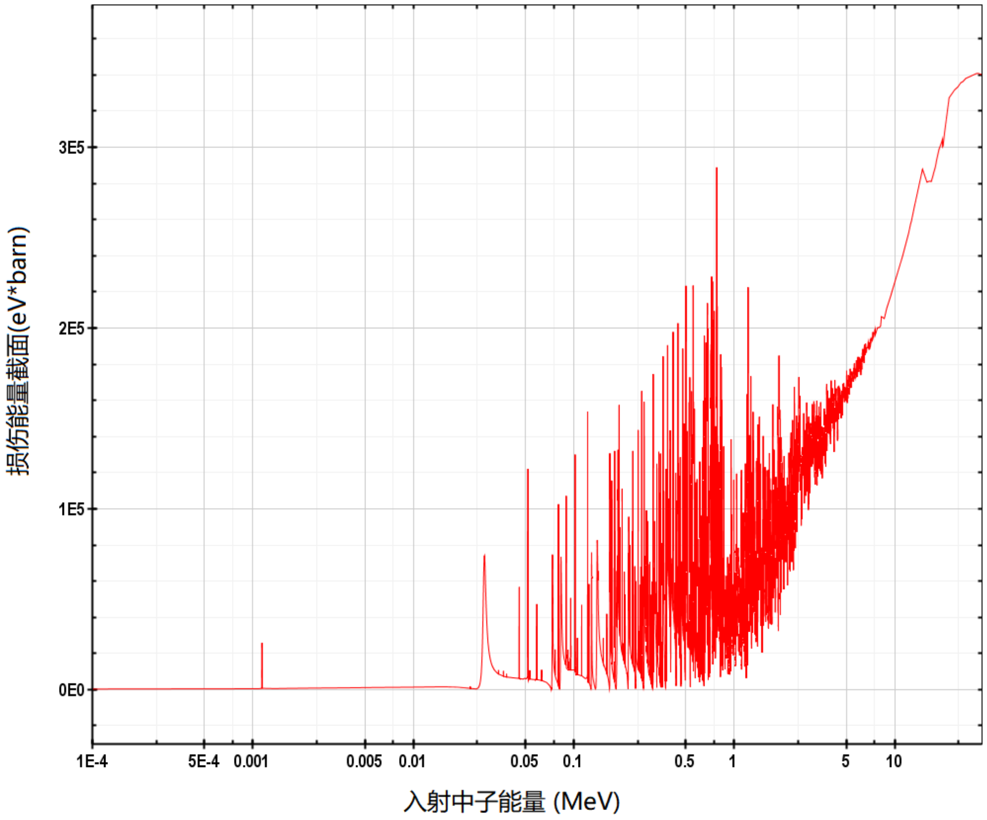
$$DPA = t\int \sigma_{dis}(E)\varphi(E)dE$$

$$\sigma_{dis}(E) = \frac{\beta}{2E_d}\sigma_{dmg}(E)$$

Threshold of Displacement Energy

Nuclides	E_d/eV
Cr	40
Mn	40
Fe	40
Ni	40
W	90
Al	27

DPA cross-section of Fe56



Incident Neutron Energy (MeV)

For metal-fuel fast reactor, the fuel endurance is limited by DPA, not burnup!

- Deeper burnup and spectral hardening exacerbate radiation damage to structural materials.
- The harder the spectrum, the lower the burnup per DPA.
- Based on the current state of fuel and structural material technology, cladding radiation damage constitutes the primary limiting factor for maximum burnup depth in integral fast reactors.
- Since the effective fission neutron yield of ^{239}Pu rises rapidly with spectral hardening, substantial positive reactivity is introduced.
- Metallic fuel fast reactors feature intrinsically harder neutron spectra than oxide-fueled fast reactors, leading to more severe positive sodium void reactivity effects.

Burnup per DPA

Type	Burnup per dpa/(GW·d/tHM)
PWR	4～5
Oxide-Fuel Fast Reactor	0.6～0.85
Metal-Fuel Fast Reactor	0.55～0.7

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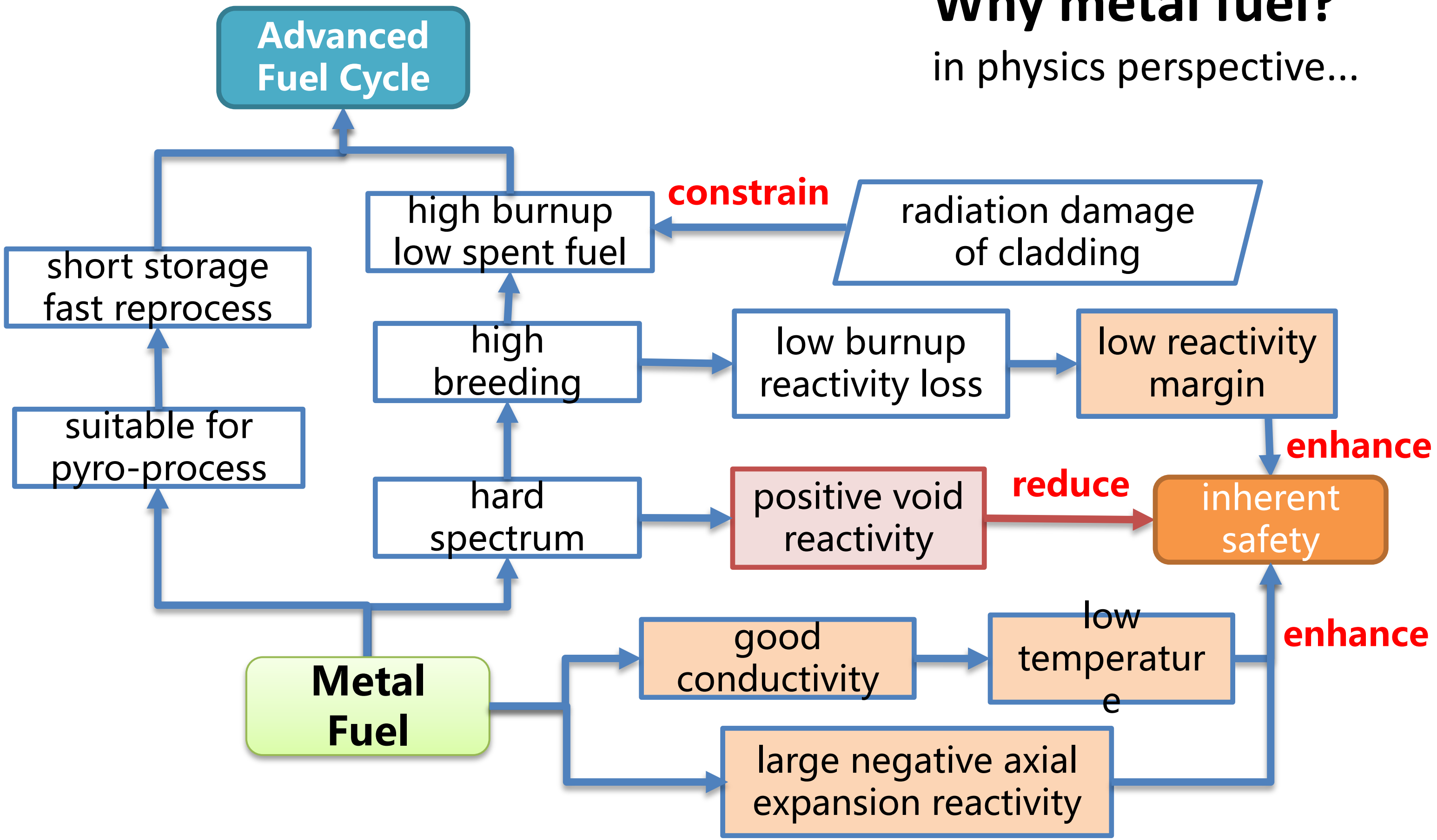
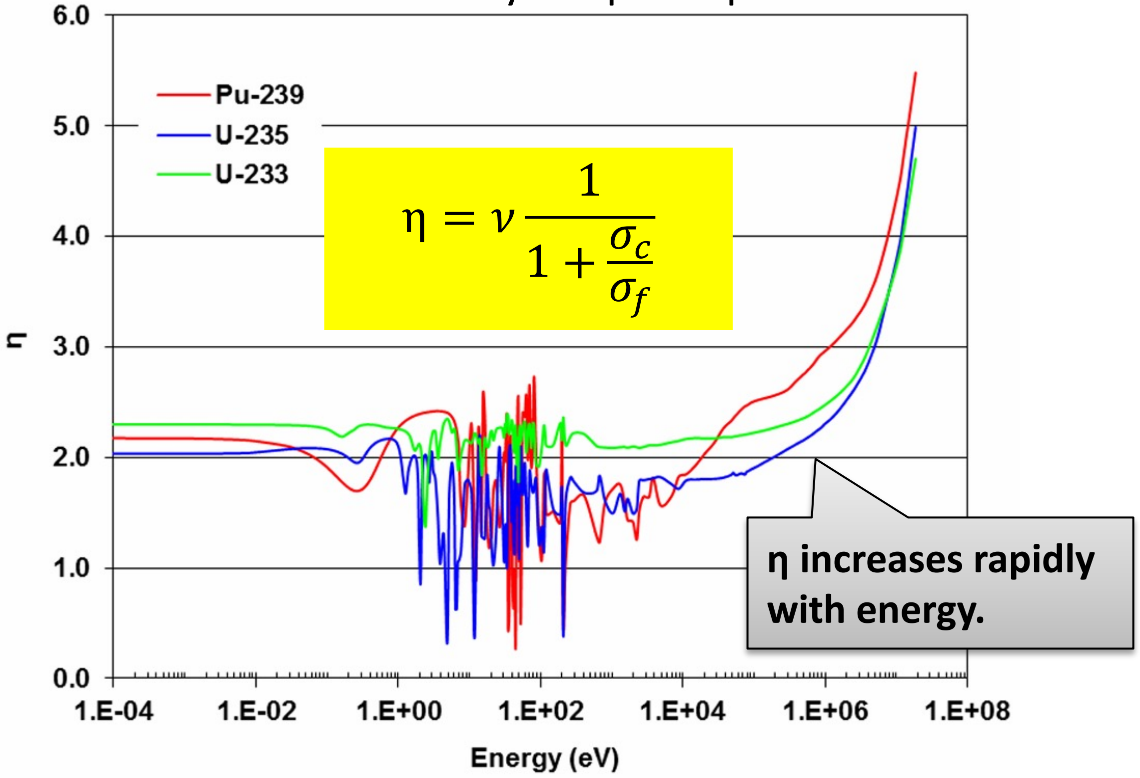


Harder Spectra Enable Larger Positive Reactivity

- Sodium void formation eliminates sodium neutron moderation and hardens the neutron spectrum.
- Since the effective fission neutron yield of ^{239}Pu rises rapidly with spectral hardening, substantial positive reactivity is introduced
- Metallic fuel fast reactors feature intrinsically harder neutron spectra than oxide-fueled fast reactors, leading to more severe positive sodium void reactivity effects

Neutron yield per capture



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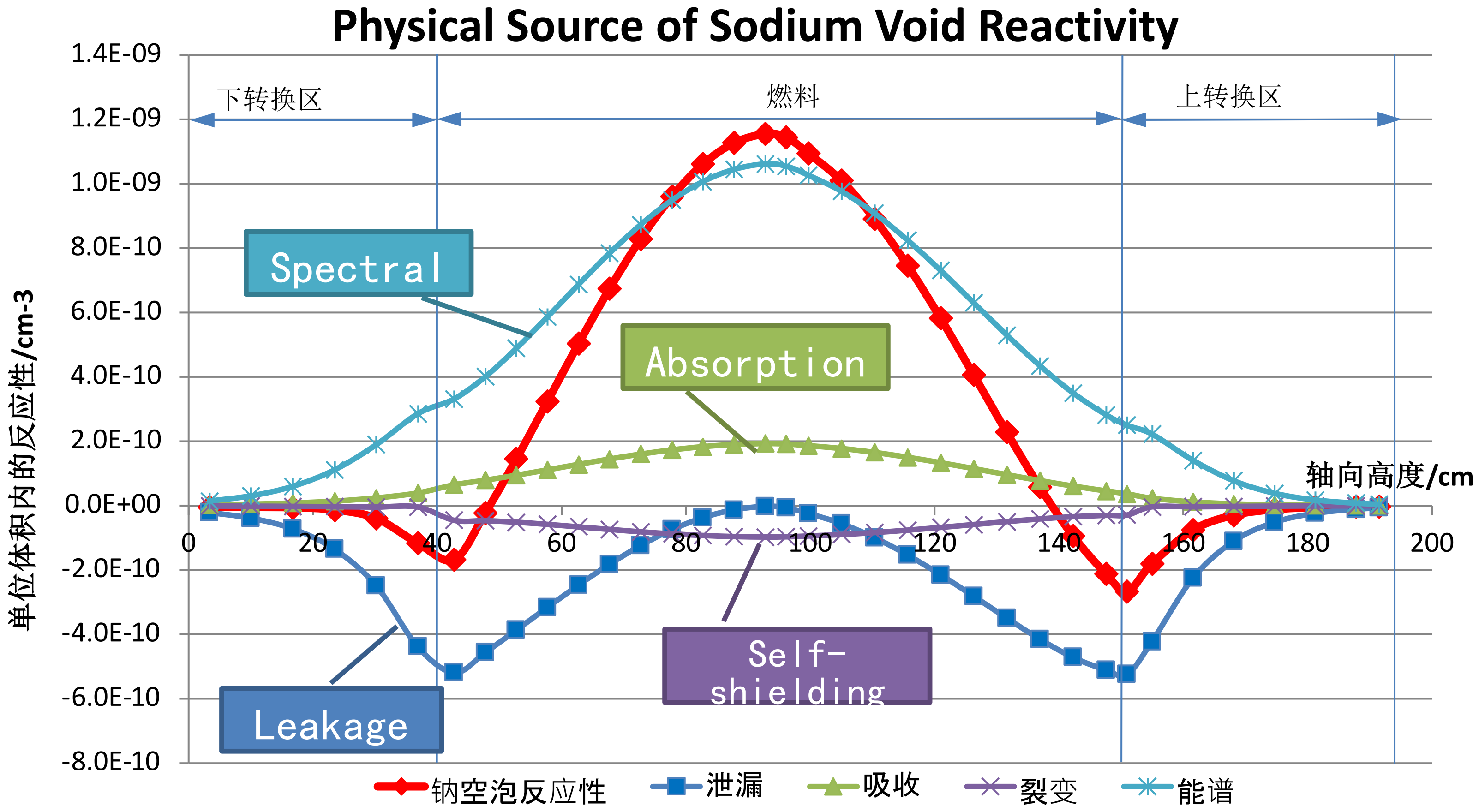
Reactivity Feedback



Metallic fuel with harder neutron spectra leads to more severe positive sodium void reactivity effects.

Technical Measures to Reduce Sodium Void Reactivity

- Conventional design schemes cannot fully eliminate sodium void reactivity; high-leakage core layouts are required to generate large negative leakage reactivity to offset the positive spectral hardening effect triggered by sodium voids.
- The upper blanket region is removed and replaced with a sodium plenum above the fuel zone. The plenum turns into a void cavity under sodium boiling conditions, increasing neutron leakage and introducing negative reactivity feedback.
- The mitigation magnitude and final reactivity value remain unsatisfactory.

Length of Sodium Vaccum/cm	Sodium Void Reactivity/pcm
0	2 117
20	1 705
30	1 648
40	1 566
50	1 561

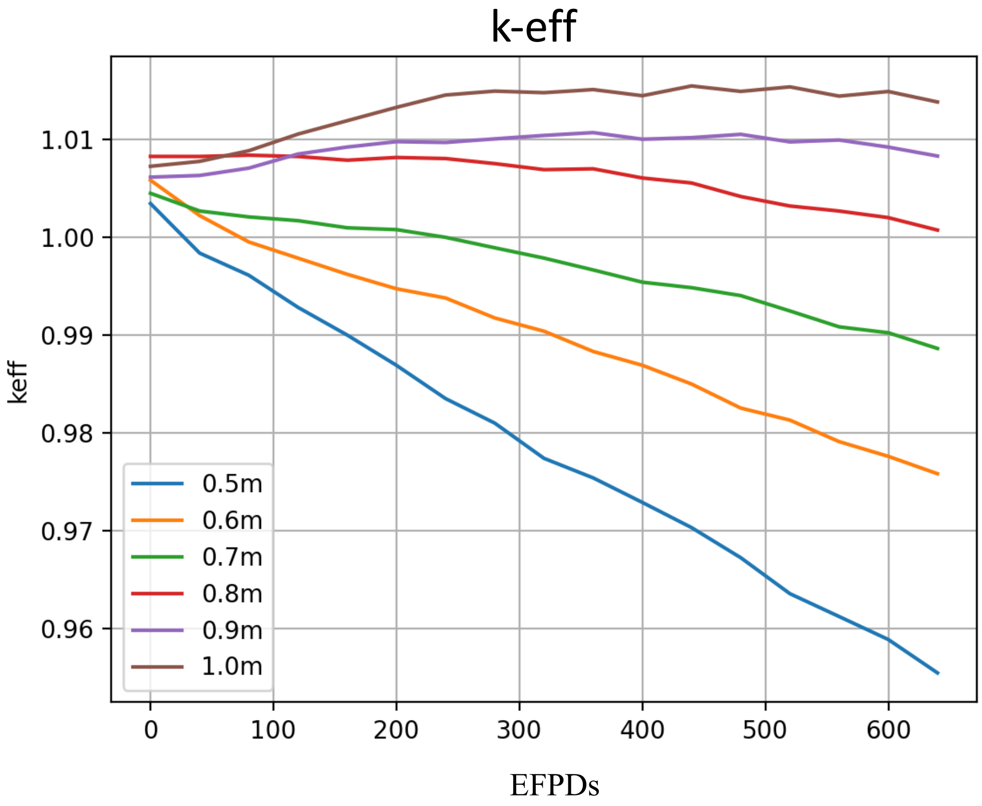
Technical Measures to Reduce Sodium Void Reactivity

- By reducing the core height-to-diameter ratio (H/D, the ratio between fuel active height and core equivalent diameter) to flatten the core geometry further amplifies axial neutron leakage and generates stronger negative reactivity during sodium void transients.
- Sodium void reactivity only turns negative when core fuel height drops to 0.5 m, corresponding to an extremely flat core with an H/D ratio as low as 0.126.
- The major drawback of this scheme is excessively high neutron leakage under normal operation and severely degraded internal breeding performance.

Impacts of Core Height-to-Diameter Ratio on Sodium Void Reactivity

Fuel active height / m	Core H/D ratio	Sodium void reactivity / pcm
1.0	0.357	1562
0.9	0.305	1421
0.8	0.256	1139
0.7	0.209	794
0.6	0.166	384
0.5	0.126	-403

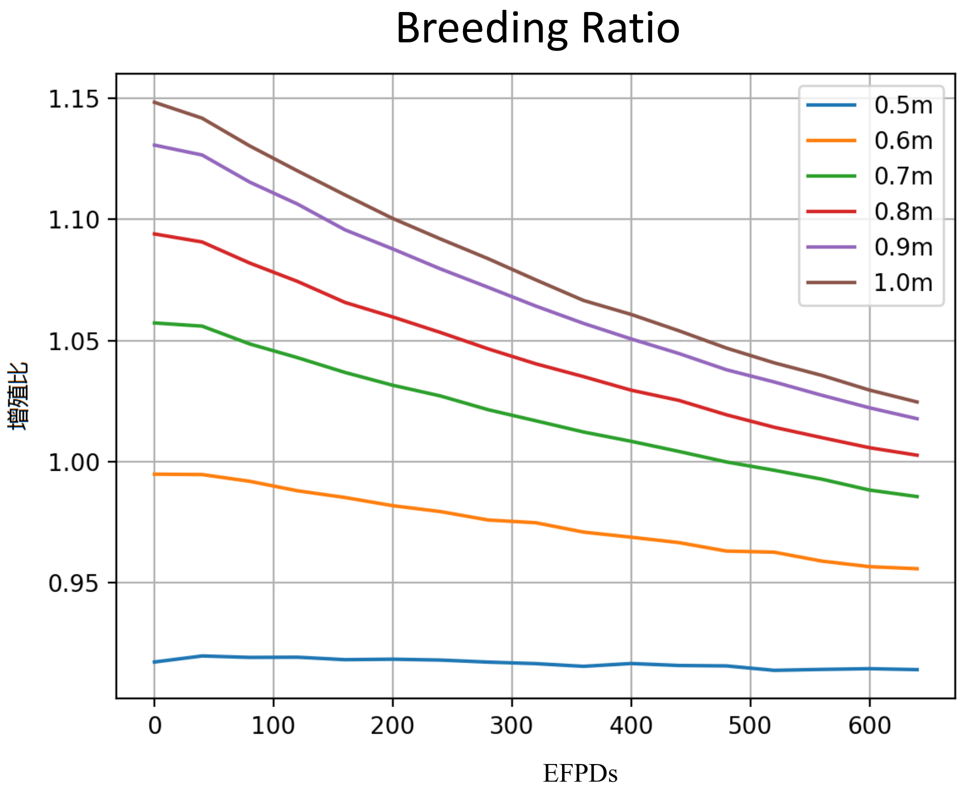
Adverse Effect from Reducing Core Height



Change of k_{eff} with burnup under different core height

- Flattened core geometry enlarges neutron leakage from upper and lower core surfaces, reducing surplus neutrons available for U-238 capture and breeding, which impairs internal breeding capacity and conflicts with the core design objectives of integral fast reactors.

Adverse Effect from Reducing Core Height



Change of breeding ratio with burnup under different core height

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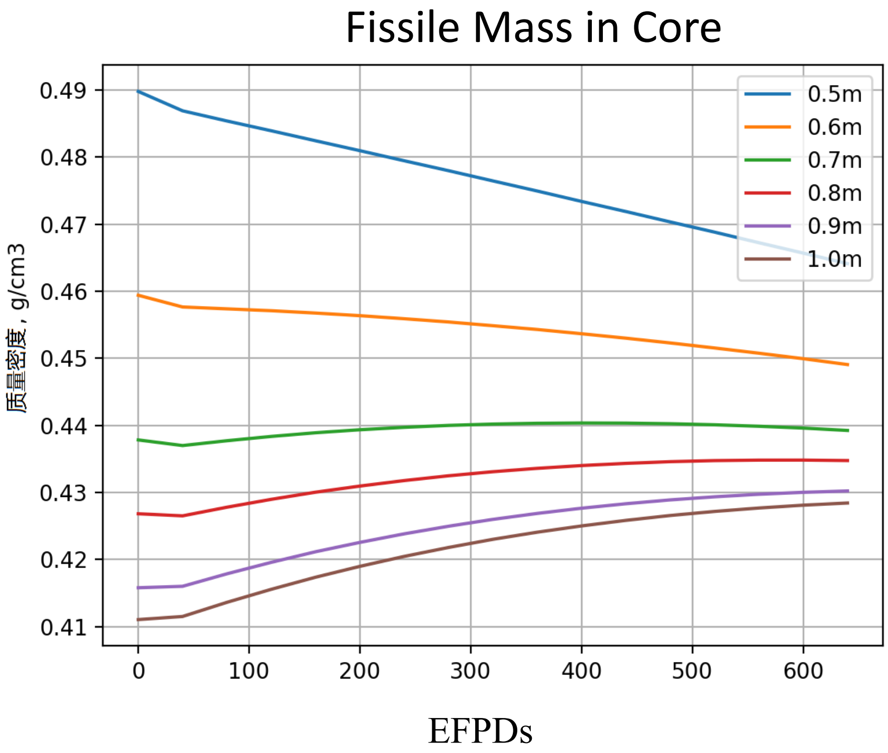

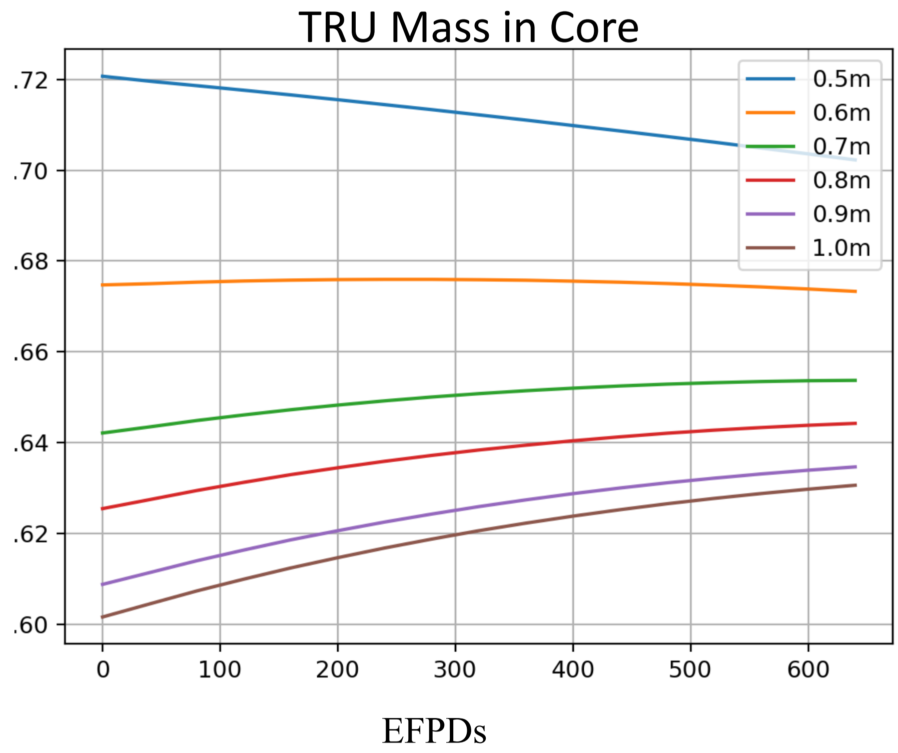

Flattened cores feature higher initial TRU and fissile loading, accompanied by faster depletion over burnup cycles.

Attitude Towards Sodium Void Reactivity

- Every sodium void mitigation measure discussed above introduces economic penalties:
  - enhanced neutron leakage enlarges core dimensions, raises required fissile loading or enrichment and amplifies power peaking factors;
  - spectral softening reduces breeding ratio and slows MA fission consumption.
- From a pure neutronic perspective, internal breeding performance and low sodium void reactivity are mutually exclusive.
- Sodium void reactivity shall be evaluated holistically against top-level reactor design objectives and overall safety margins.
- If reliable reactivity control systems and robust inherent safety features can mitigate accident progression under unprotected transients, sodium void reactivity shall be de-prioritized, and core design shall focus on maximizing internal breeding and realizing high-efficiency closed fuel cycles.

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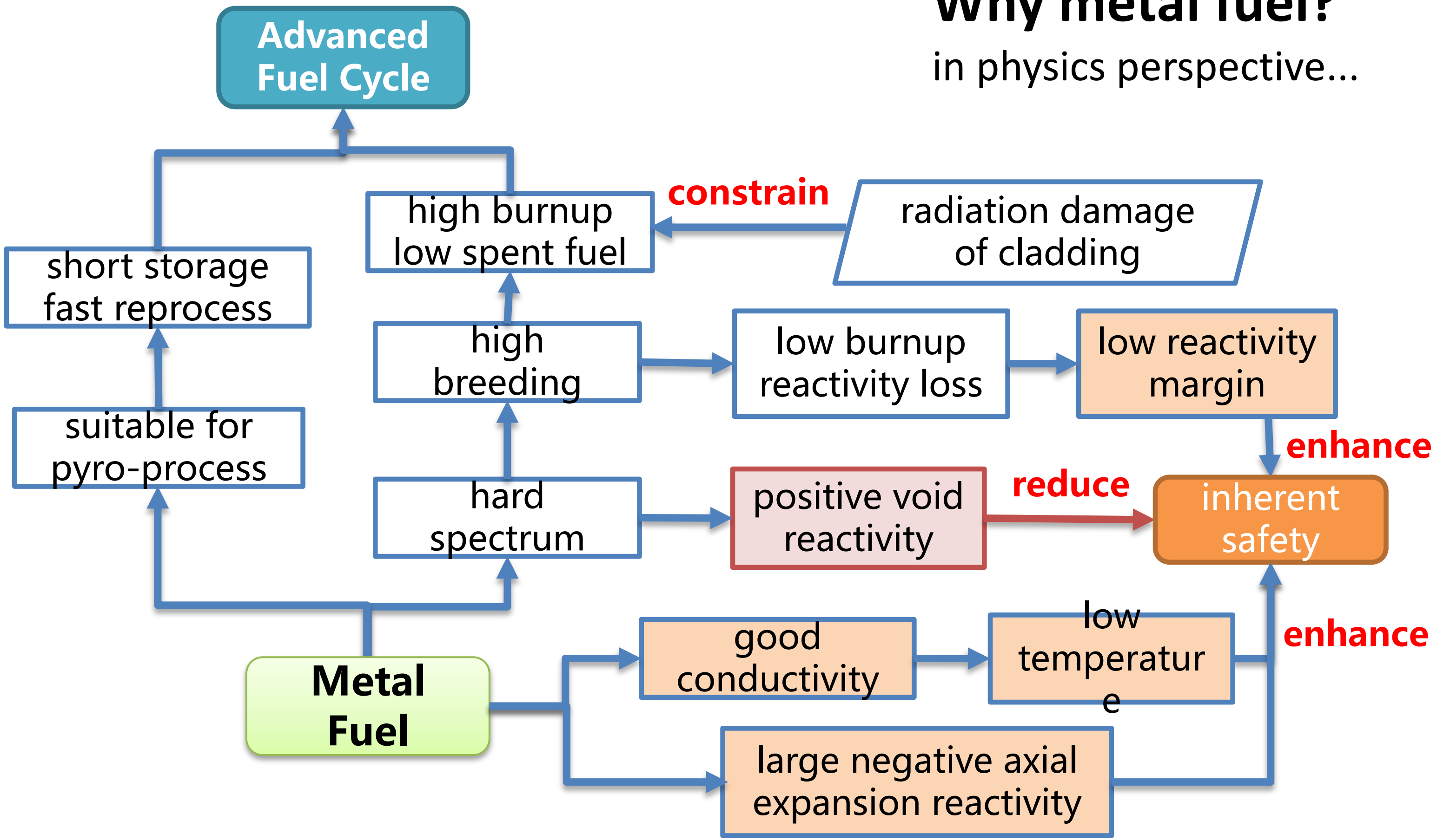

Temperature & Power Reactivity Feedback

- Metallic fuel delivers multiple safety advantages relative to oxide fuel.
- Its thermal conductivity far exceeds oxide fuel, and sodium bonding between fuel and cladding eliminates gaseous heat transfer gaps, drastically reducing thermal resistance and temperature gradients between fuel, cladding and coolant.
- Normal-operation average fuel temperatures remain below 600 ° C for metallic fuel, compared with approximately 1,200 ° C for oxide fuel.
- Low baseline fuel temperatures and high thermal conductivity provide substantial temperature margin during accident transients.

Temperature & Power Reactivity Feedback

Parameteer	Temperature Effect/pcm	Power Effect/pcm
Sodium density	118	305
Radial Expansion	−220	N/A
Axial Expansion	−220	−400
Doppler	−105	−180
Sum	−427	−275

- High linear thermal expansion coefficient of metallic fuel:
    - Oxide fuel exhibits a linear expansion coefficient of ~1.1×10^{-5} K^{-1}
    - Metallic fuel ranges from 1.6×10^{-5} K^{-1} to 1.8×10^{-5} K^{-1} under nominal operating temperatures.
- U-Pu-Zr alloys undergo a phase transition near 868 K, increasing linear expansion coefficients to $6.0–7.7 \times 10^{-5}$ K^{-1} and introducing strong negative reactivity feedback during accident temperature excursions.
- Core radial expansion originates from grid plate assembly expansion at elevated inlet sodium temperatures, increasing assembly lattice pitch and neutron leakage to introduce negative reactivity feedback.
- This effect only contributes to isothermal temperature feedback and is absent in power transients with fixed inlet temperature.
- Radial expansion of fuel pellets does not alter assembly lattice geometry and yields negligible core-wide reactivity variation.

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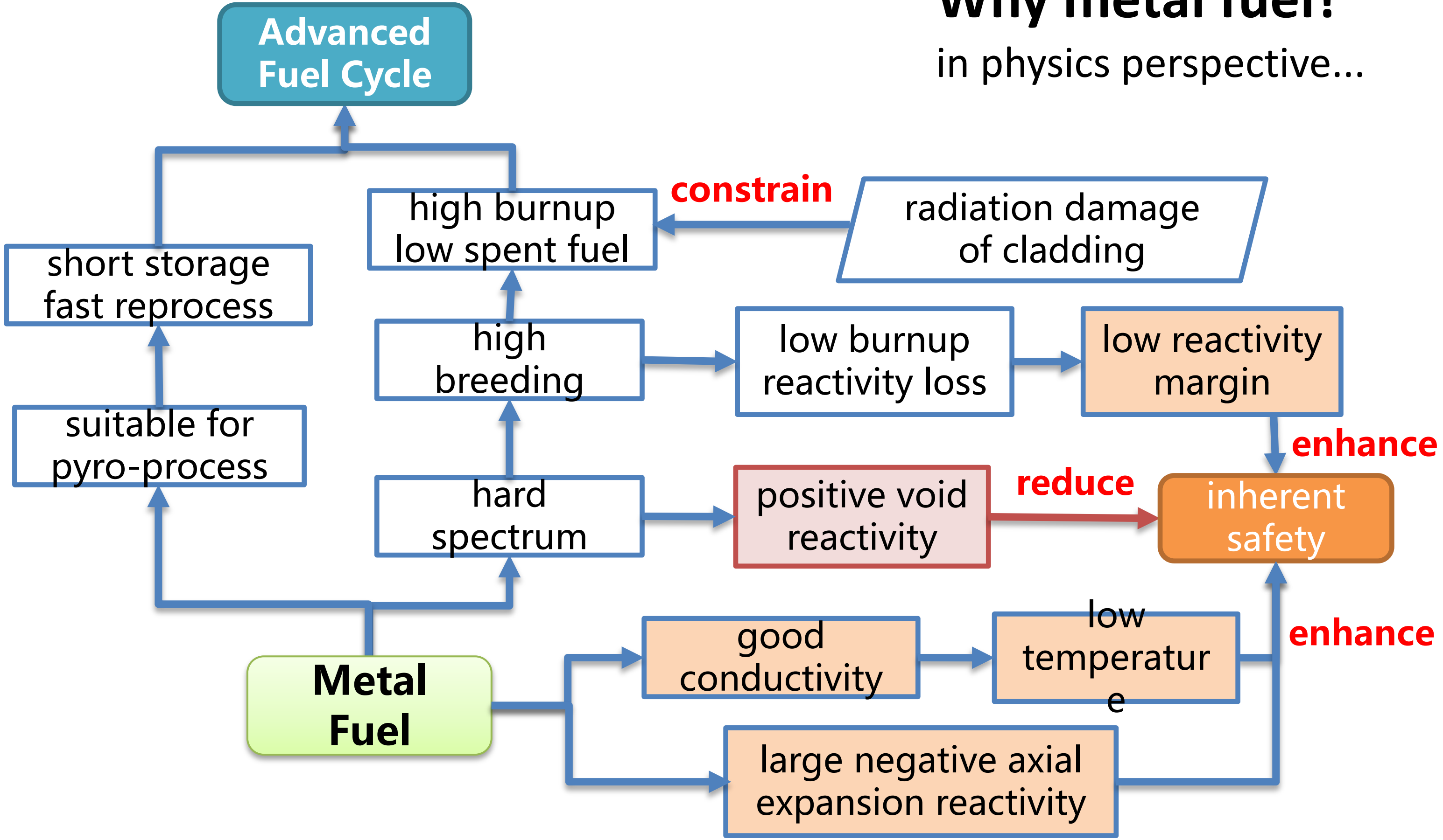
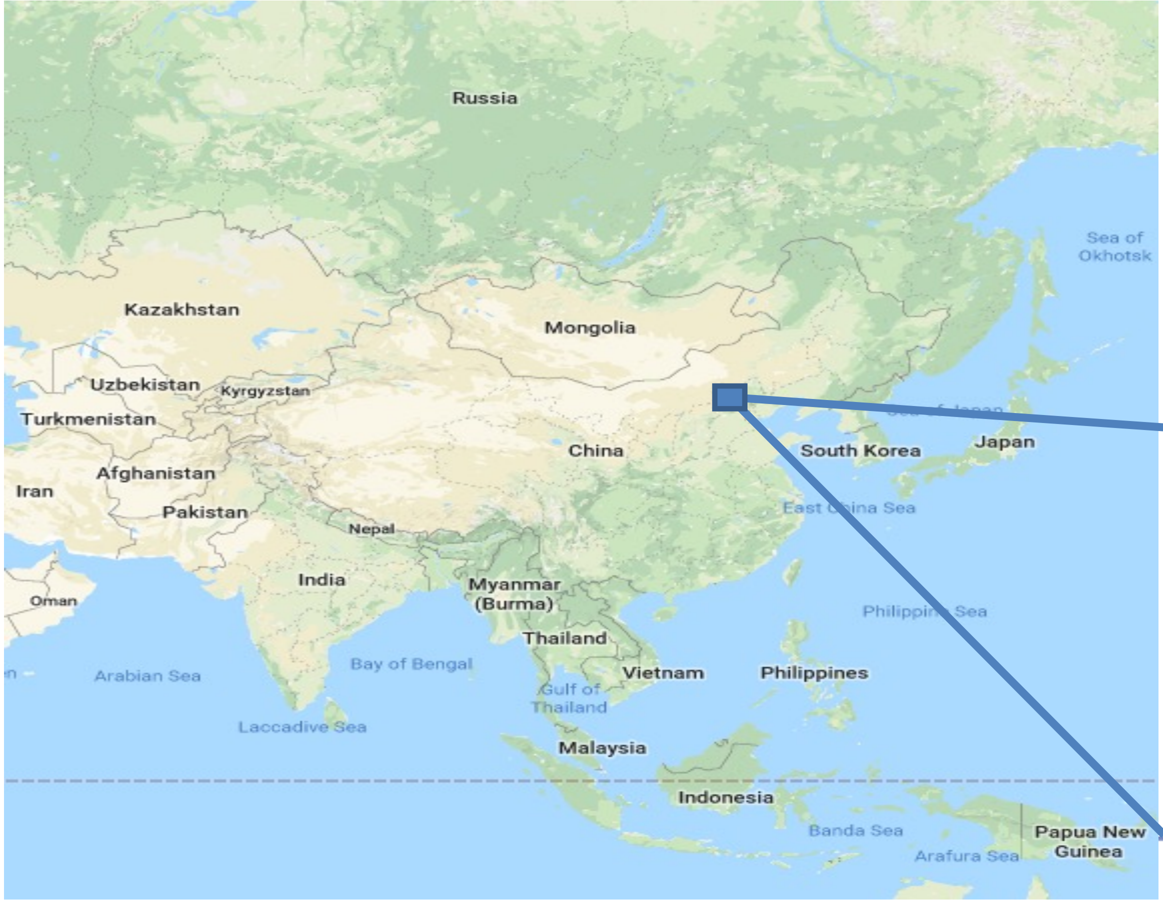


China Institute of Atomic Energy (CIAE)

- Founded in 1950
- Fundamental and comprehensive nuclear research base
- Origin of China nuclear industry
- Subordinated to China National Nuclear Corporation (CNNC)

China Institute of Atomic Energy (CIAE)



Where is China Institute of Atomic Energy (CIAE)?

反 应 堆 工 程 技 术 研 究 部

Department of Reactor Engineering Technology

China Institute of Atomic Energy

8 research fields completely cover the nuclear S&T.

Welcome for any form of international cooperation!

References

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