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The quest for advanced reactor concepts

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NUCLEAR ENGINEERING
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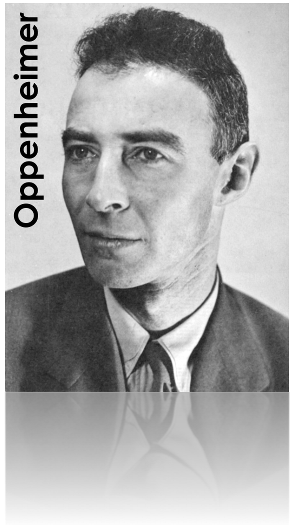
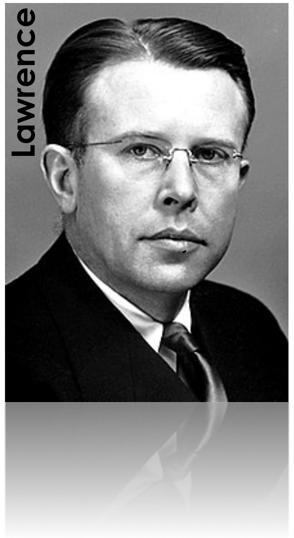
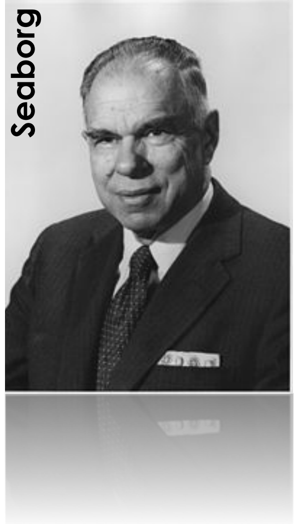
University of California, Berkeley

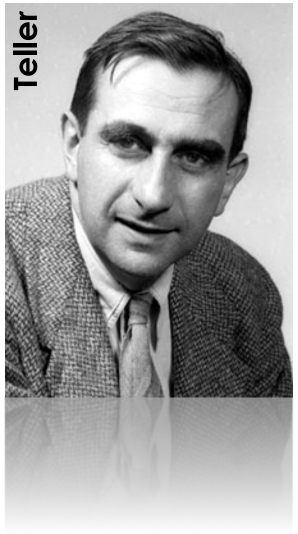
Berkeley has historic ties to nuclear science and technology

- UC Berkeley was founded on March 23rd 1868
- 1928 - J. Oppenheimer becomes professor at UCB
- 1928 - Ernest O. Lawrence starts at UCB then found Lawrence Berkeley and Lawrence Livermore National Laboratories
- 1930 - Ernest O. Lawrence builds the first cyclotron in Berkeley
- Elements discovered by laboratory physicists: Neptunium, Plutonium, Cerium, Berkelium, Californium, Einsteinium, Fermium, Mendelvium, Nobelium, Lawrencium, Dubnium, and Seaborgium


Oppenheimer


Lawrence


Seaborg


Teller

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Reactor design


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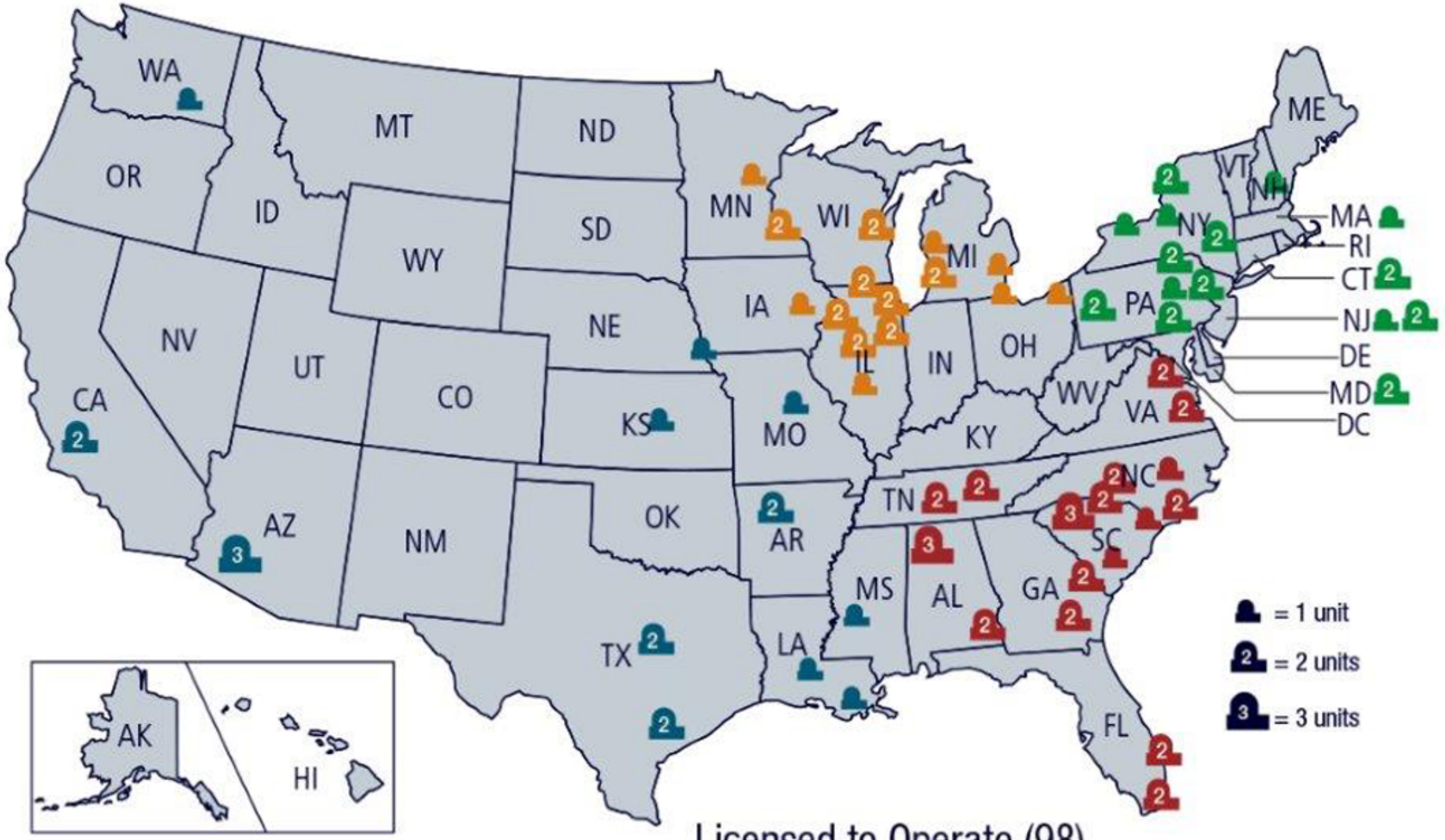
Nuclear waste

Faculty
8.5 FTE
2 Adjunct
3 Prof. of the graduate school

Students
70 Bachelor
89 PhD
11 Master of Engineering

U.S. Operating Commercial Nuclear Power Reactors

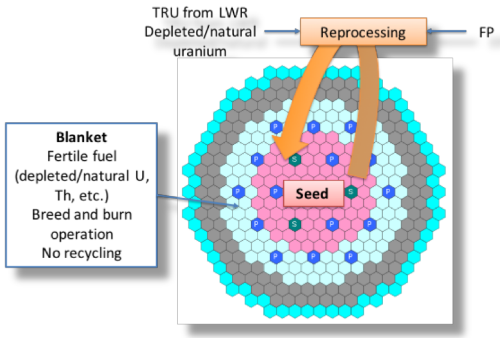


Licensed to Operate (98)

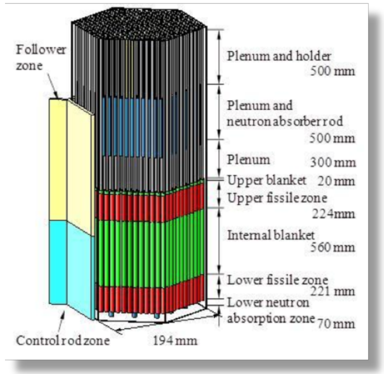
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

As of Sept. 2018

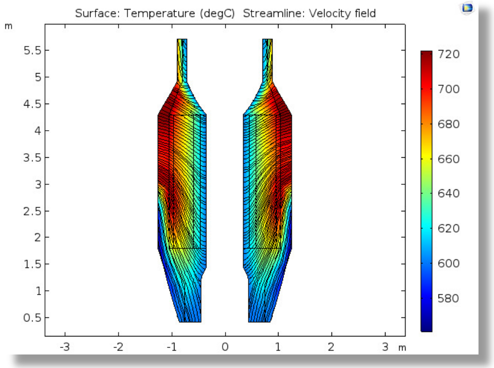
Seed and blanket sodium cooled fast reactor



Reduced-moderation boiling water reactor (RBWR)



Fluoride-cooled high-temperature reactor (FHR)



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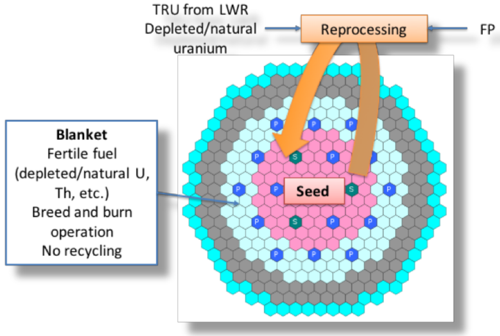


TRU from LWR
Depleted/natural uranium

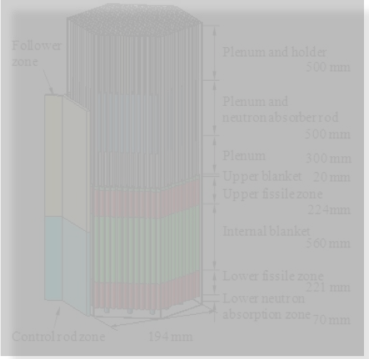
Reprocessing

FP

Blanket
Fertile fuel
(depleted/natural U, Th, etc.)
Breed and burn operation
No recycling

Seed

Reduced-moderation boiling water reactor (RBWR)



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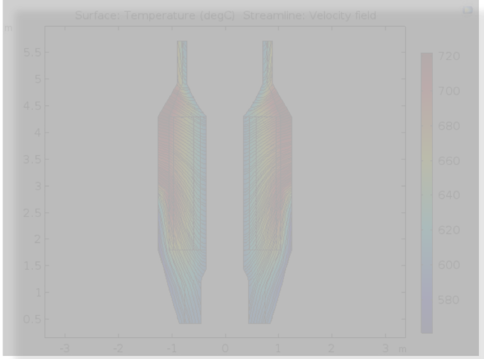
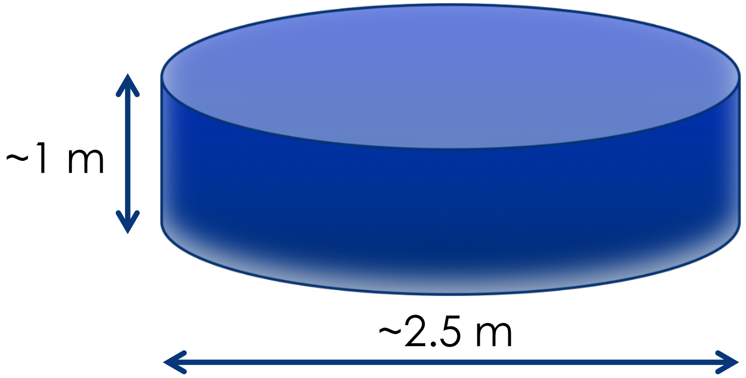


Sodium-cooled fast reactor (SFR) burner cores are designed to be of a pancake shape

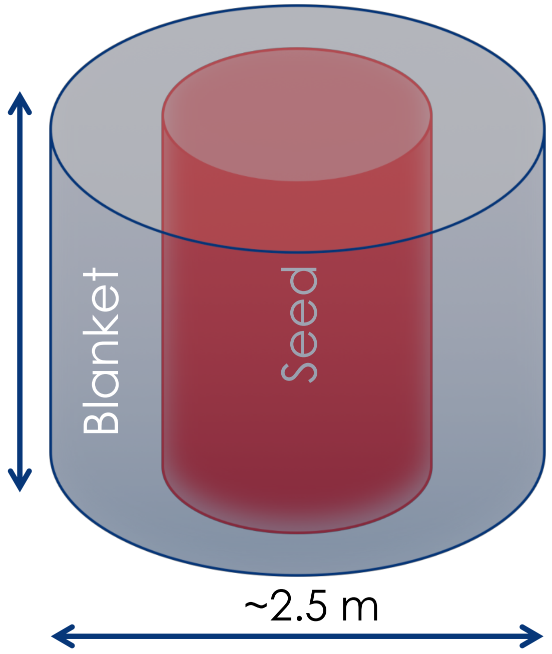
20% to 30% neutron leakage probability

Enhanced radial leakage is necessary to achieve passive safety



There is no constructive use for leaking neutrons

Using a cigar-shape core it is possible to make efficient use of leaking neutrons



Provide early commercialization path for SFR

Reduce fuel cycle cost

Works within the radiation damage limits of existing materials

Reduce reprocessing needs

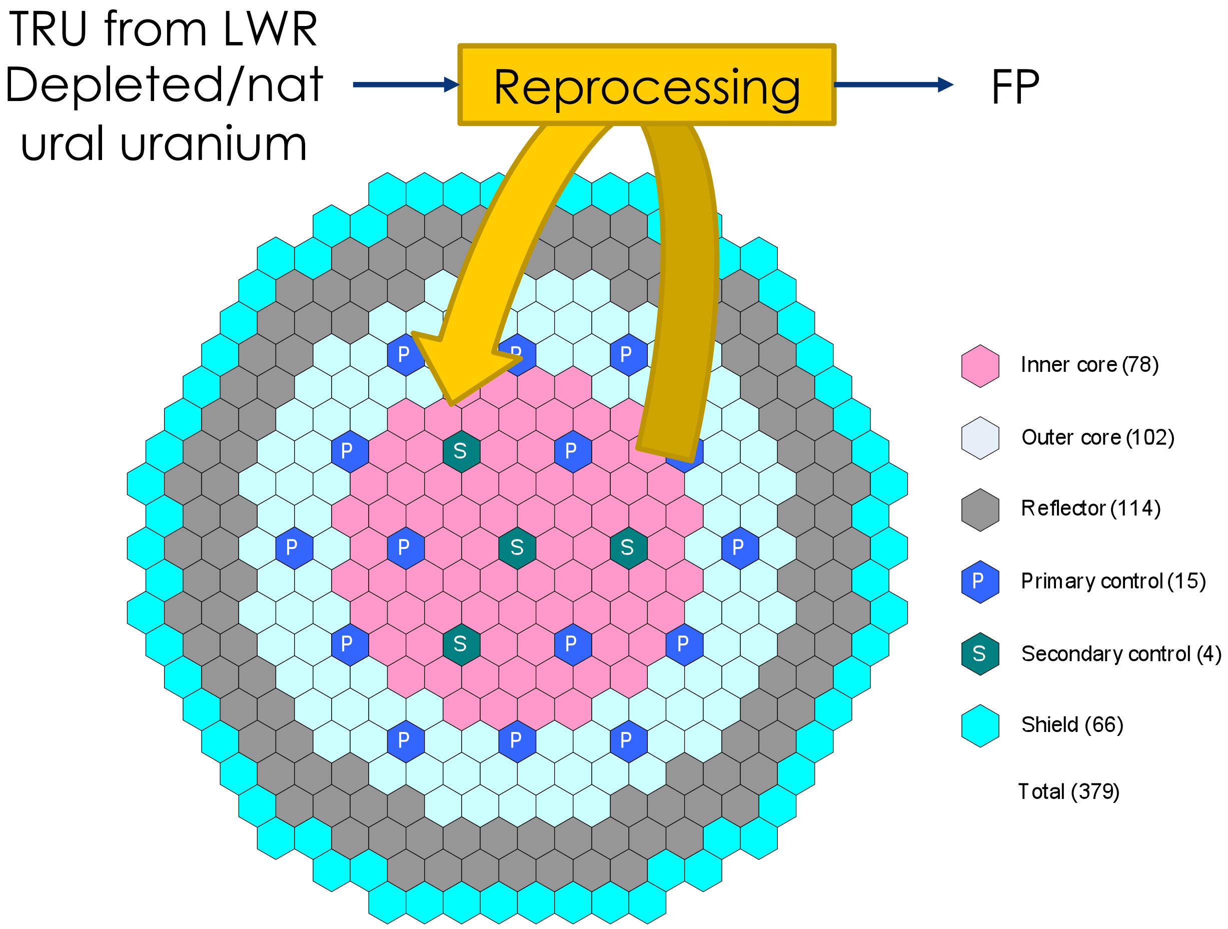
Enable thorium fuel cycle

Transmute TRU from LWR used nuclear fuel

TRU burner SFRs operate on a closed fuel cycle

Advanced Burner Reactor (ABR) designed by ANL

- Continuous recycling
- Multi-batch fuel
- External feed of natural/depleted uranium
- Two-enrichment zones (TRU-to-HM ratio)
- Conversion ratio <1 (>0.6)

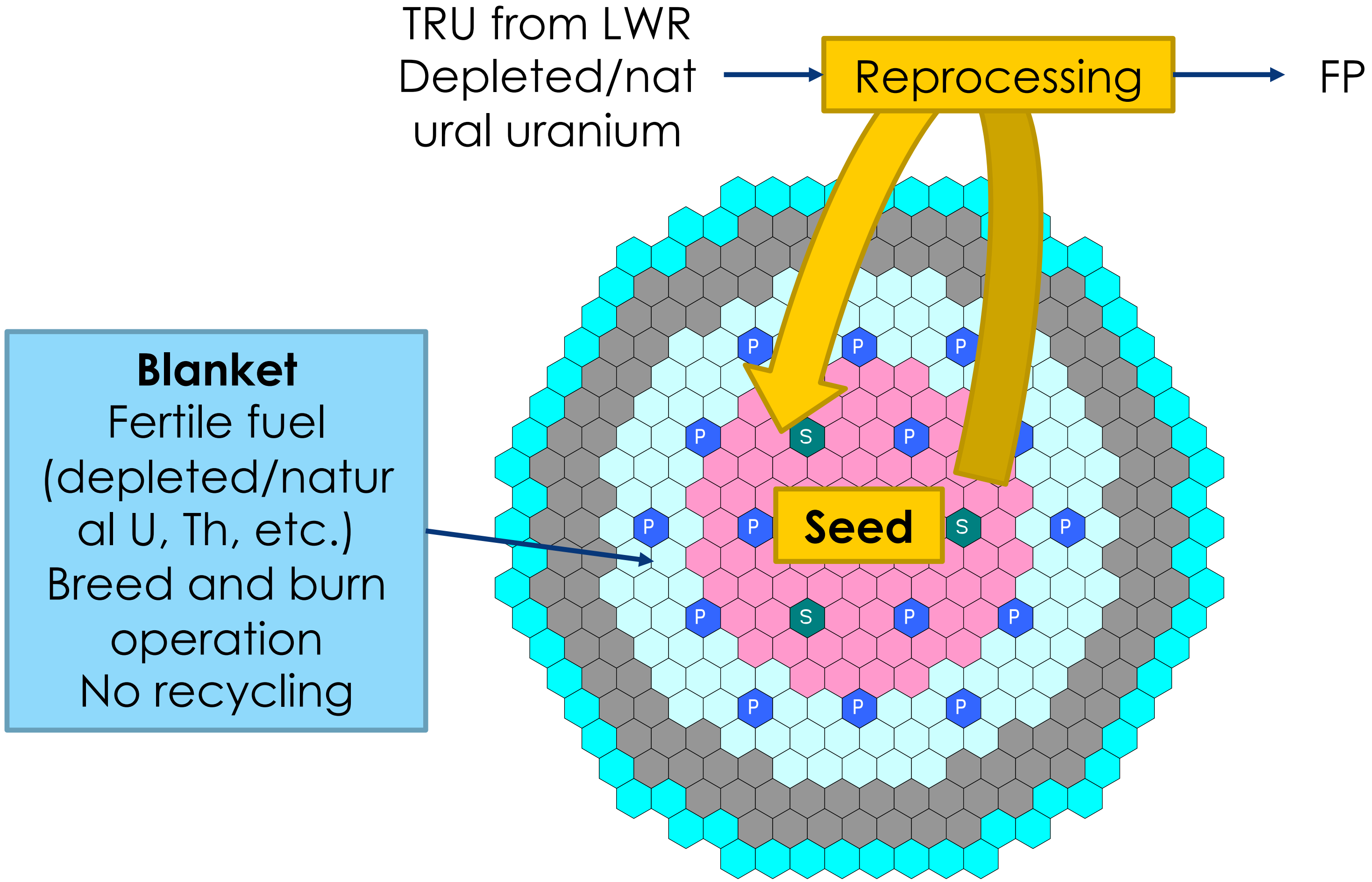


TRU from LWR
Depleted/natural uranium

Reprocessing

FP

Seed & blanket cores combine a TRU burner seed with a breed & burn blanket



TRU from LWR
Depleted/natural uranium

Reprocessing

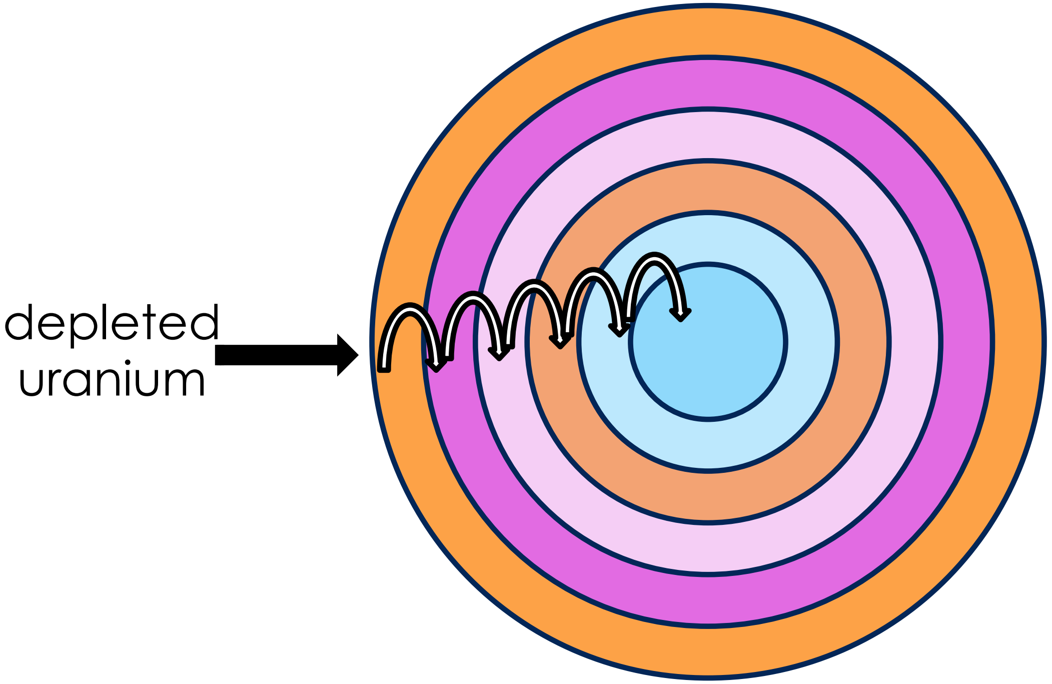
FP

Seed

Blanket
Fertile fuel
(depleted/natural U, Th, etc.)
Breed and burn operation
No recycling

Breed & Burn are fast reactors that operate on a once-through fuel cycle

- Fresh fuel is depleted uranium only—**no enrichment**
- Bred Pu and MA are burned (fissioned) in situ—**no reprocessing**
- Examples: Feynberg (1958), Toshinsky (1997), Sekimoto (2000), TerraPower (2008)



Radiation damage and safety are main challenges for B&B reactors

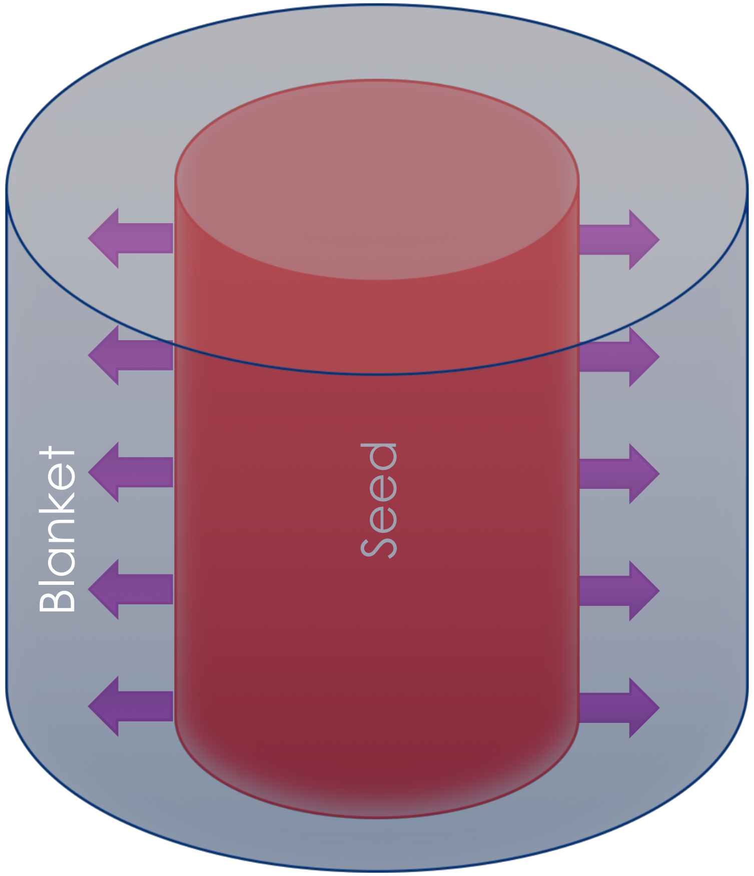
- Average discharge burnup expected from the TerraPower TWR (a B&B reactor) is ~20% FIMA

Characteristic	Minimum required	Proven
Peak burnup, FIMA	35%	15%
HT-9 clad dpa	480-550	200

- Sodium void reactivity worth of large low-leakage B&B cores is large positive and core expansion negative reactivity feedback is small → safety concern

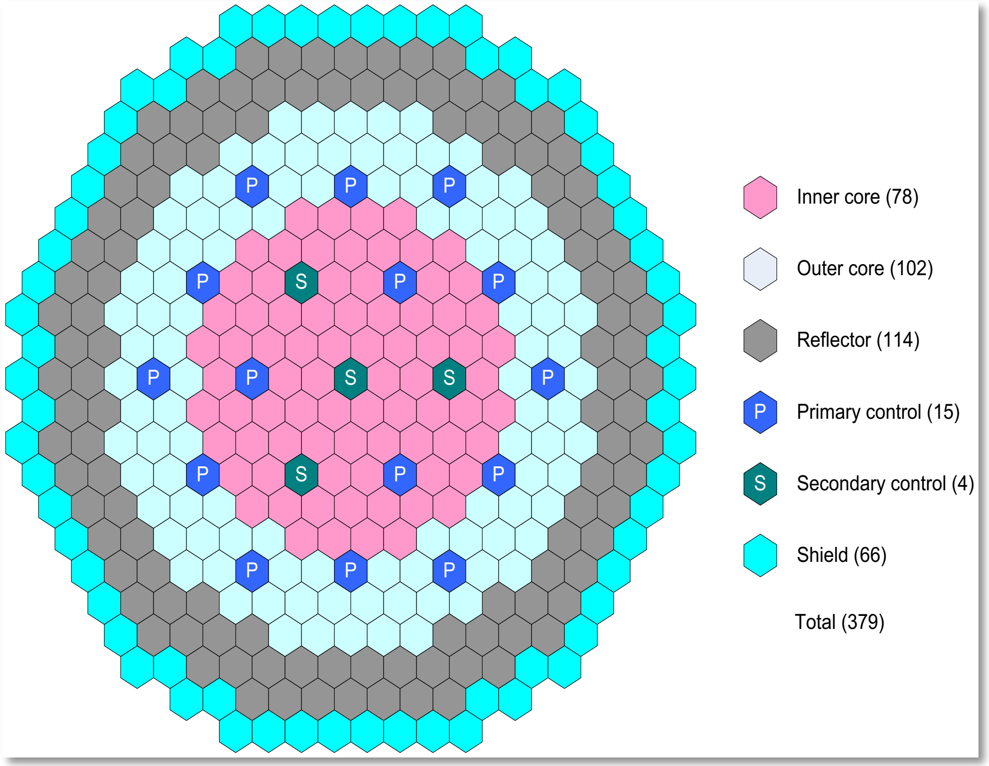
In the S&B cores leakage neutrons drive the subcritical blanket

- The seed functions similarly to an external neutron source
- No minimum burnup requirement (neutrons are always available from the seed)
- B&B possible with any blanket fuel (thorium, oxide fuel, LWR used fuel, etc.)



S&B SFRs feature similar power and diameter as S-PRISM, but higher Δp

- Reference design: GE Hitachi’s S-PRISM 1,000 MWt
- Cladding: HT-9
- Seed fuel: U-TRU-10Zr
- Seed fuel can be either self-sustaining or TRU burner
- Makeup feed: TRU recovered from Light Water Reactor (LWR) UNF with 50 MWd/kg and 10-year cooling
- Active core height: 250 cm
- Pressure drop: ~0.9 MPa

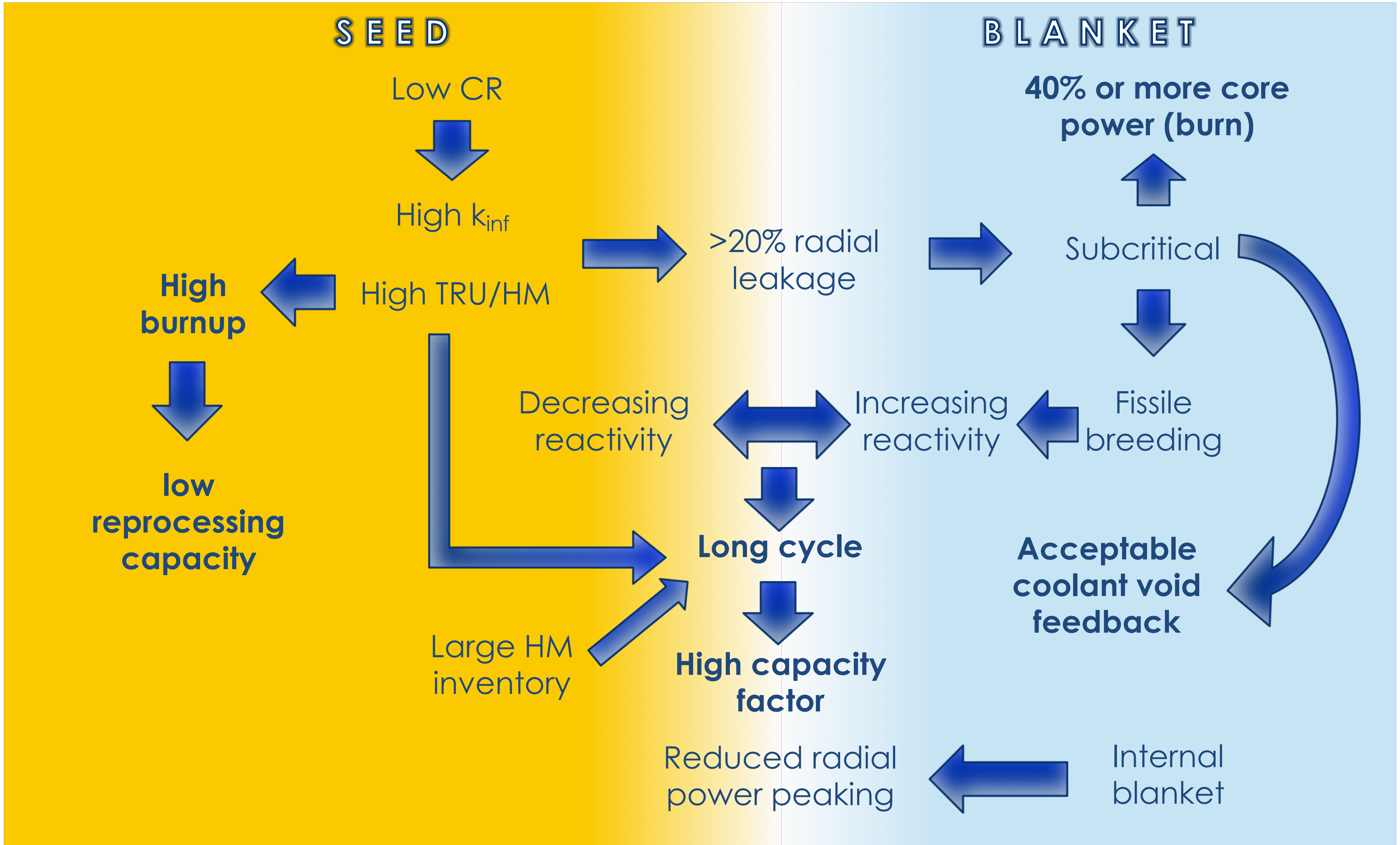


Advanced Burner Reactor (ABR) core layout based on S-PRISM

The high transmutation S&B SFR features conversion ratio ~0 seed and a thorium blanket

Property	High transmutation S&B SFR	ABR
Fuel form	U-TRU-10Zr/Th	U-TRU-10Zr
Seed CR at BOEC	0.0	0.5
Number of seed assemblies	30	144
Number of blanket assemblies	96/145	n/a
Fuel residence time, # cycle (S/B)	2/5	6/6/7
Fuel cycle length, EFPD	1550	221
Burnup reactivity swing, %Δk/k	-3.60	-2.90
Average blanket power fraction, %	57.7	n/a
Average discharge burnup, MWd/kg	312.2/70.2	131.9
Peak radiation damage, dpa	185/207	200
TRU feed rate, kg/EFPY	158.1/none	173.8
Reprocessing capacity, kg/GWt-yr	494.5	2508.1
Sodium void worth, $	6.56 ± 0.07	9.17
Doppler coefficient, ¢/°C	-0.07 ± 0.02	-0.08

A symbiosis exists between low CR seed and subcritical blanket



SEED

Low CR

High k_{inf}

High TRU/HM

High burnup

low reprocessing capacity

Large HM inventory

Decreasing reactivity

>20% radial leakage

Long cycle

High capacity factor

Reduced radial power peaking

BLANKET

40% or more core power (burn)

Subcritical

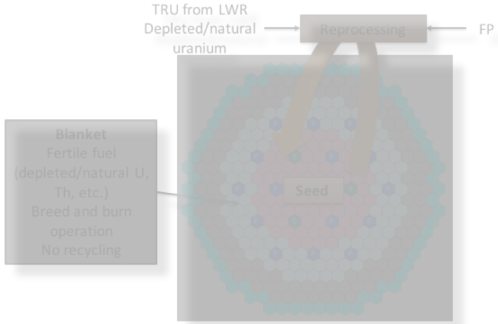
Increasing reactivity

Fissile breeding

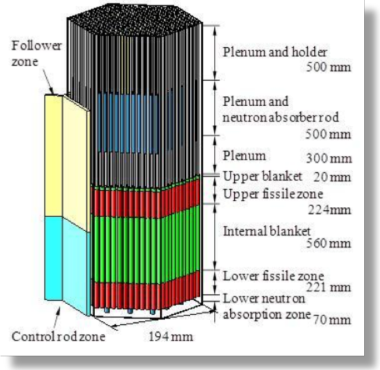
Acceptable coolant void feedback

Internal blanket

Seed and blanket sodium cooled fast reactor



Reduced-moderation boiling water reactor (RBWR)



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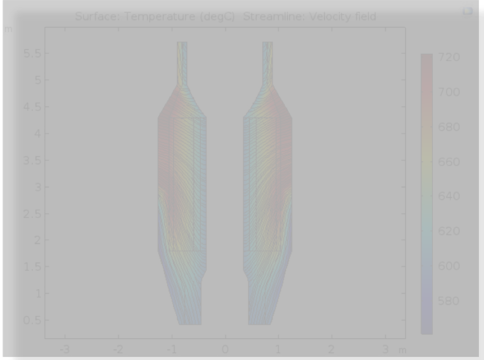
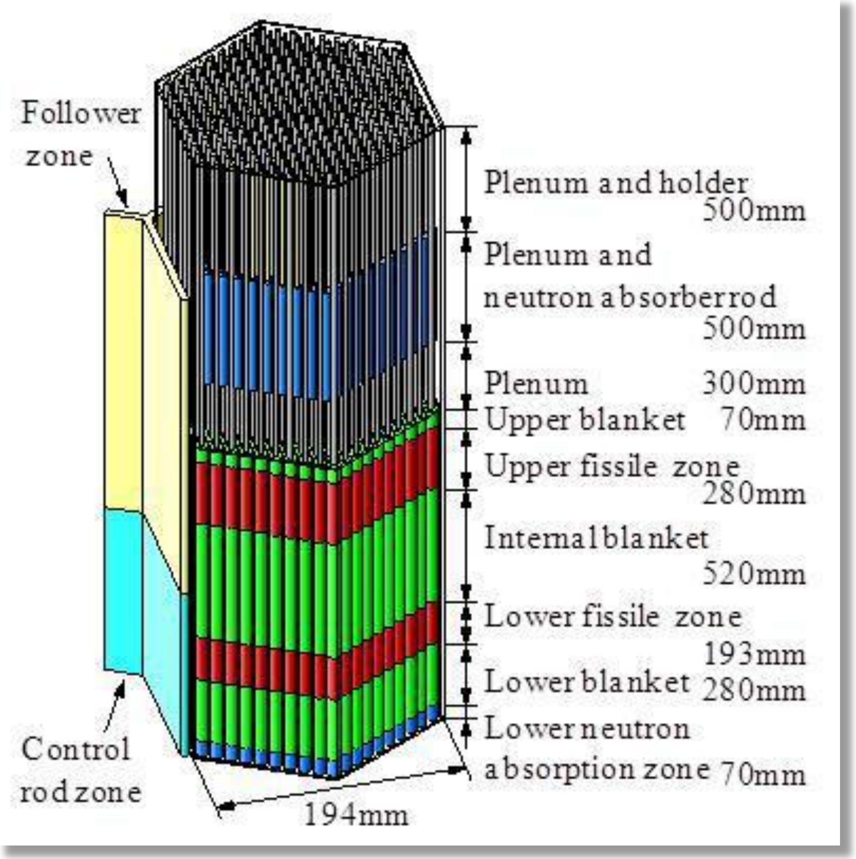


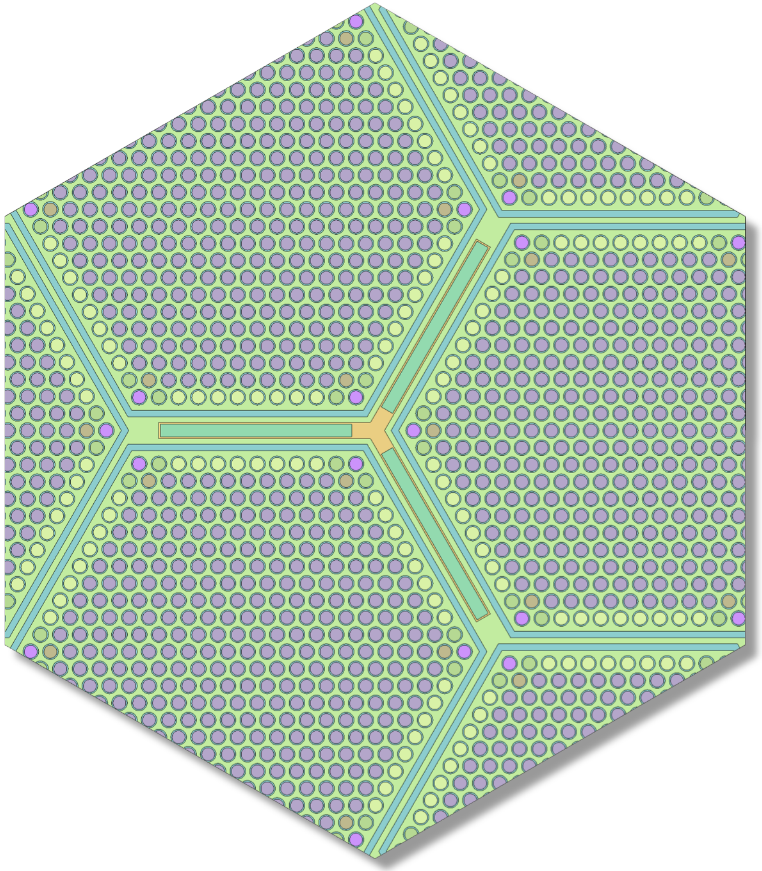
RBWR is expected to improve resource utilization and reduce waste using current LWR technology

- Use an epithermal neutron spectrum to establish multirecycling fuel cycles normally reserved for fast reactors
  - LWRs use ~0.6% of natural heavy metal resources; multirecycling would approach 100% utilization
  - Reduces high-level waste volume significantly per energy generated
- Compatible with the Advanced BWR (ABWR) pressure vessel and balance of plant
  - Should be easier to license, possibly reduce capital cost
- Design option for fuel sustainability (RBWR-AC) or LWR waste reduction (RBWR-TB2)

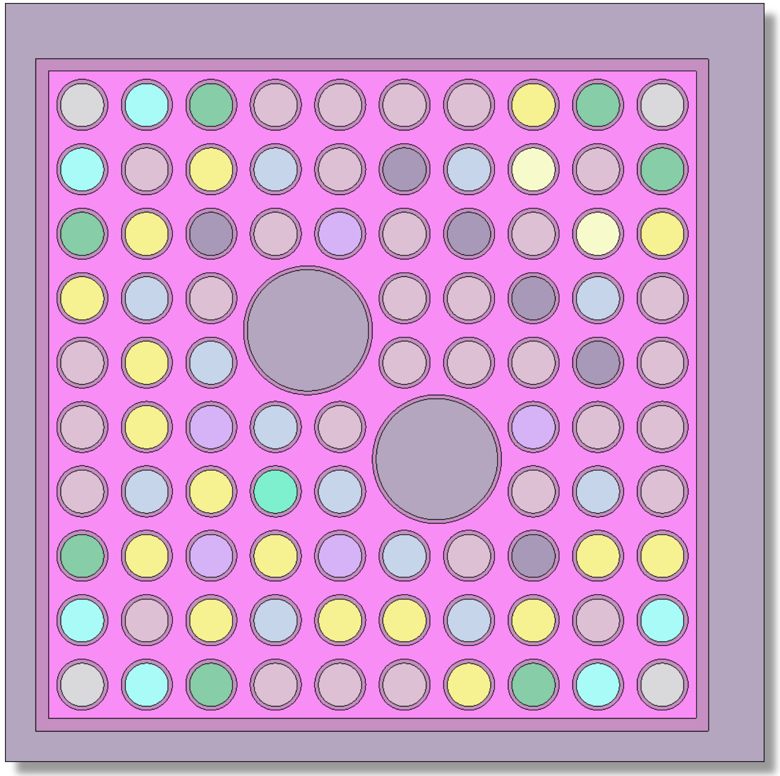


RBWR bundle

RBWR cores feature a tight hexagonal lattice

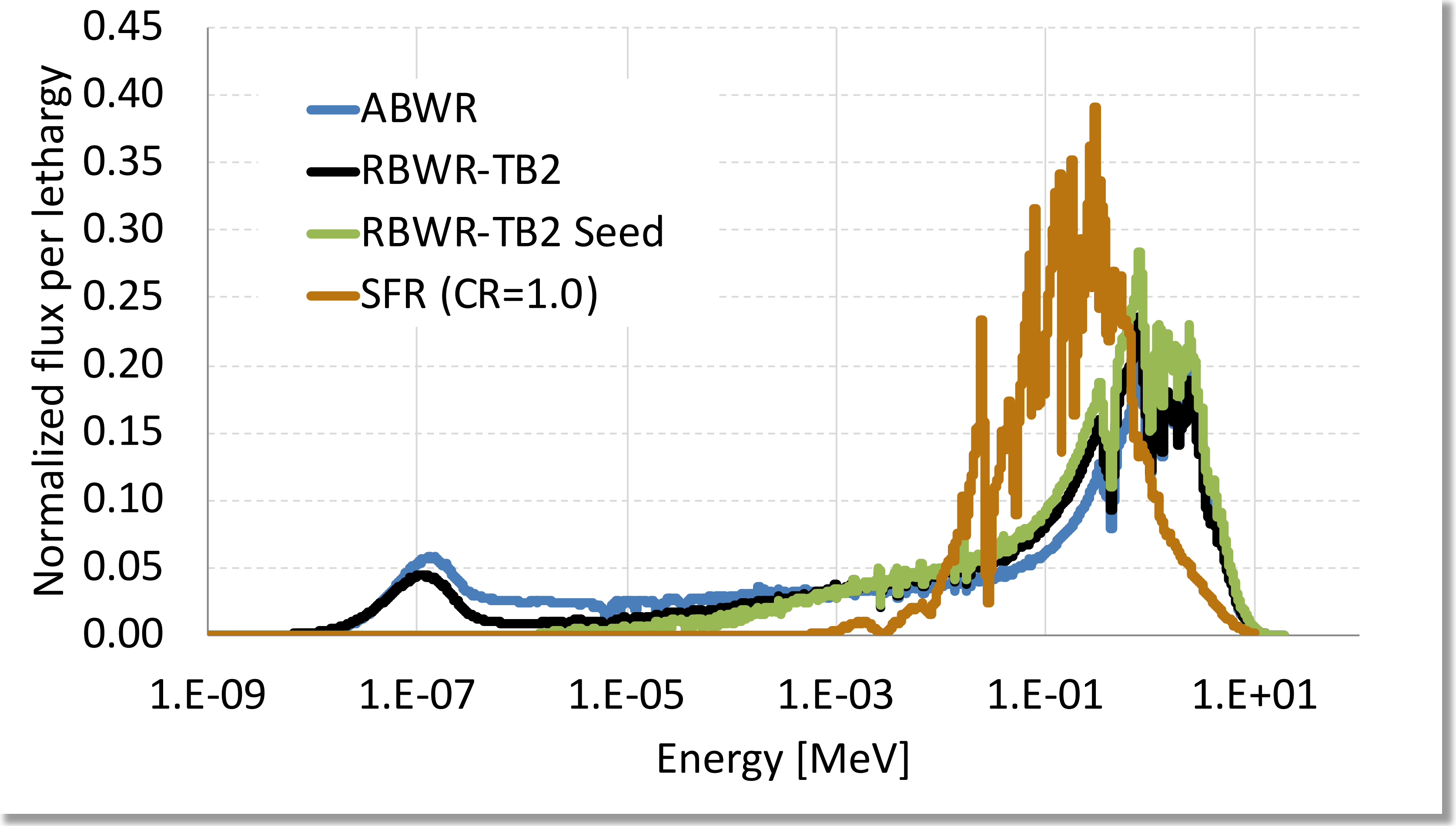


RBWR bundle with Y-shape control blades



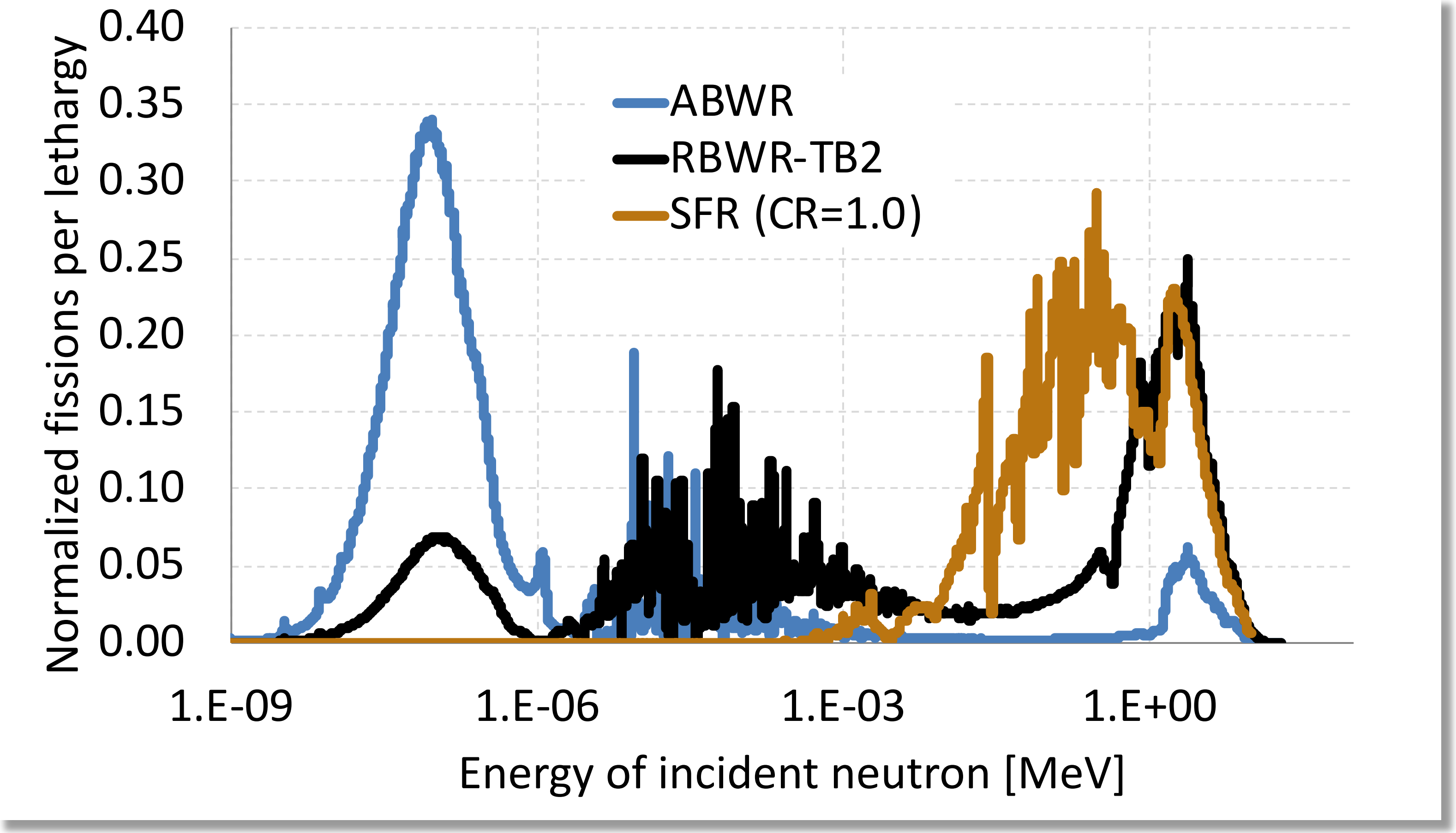
ABWR bundle with cruciform control blades

The RBWR features an epithermal spectrum



Neutron spectrum of the RBWR-TB2 compared against other reactors

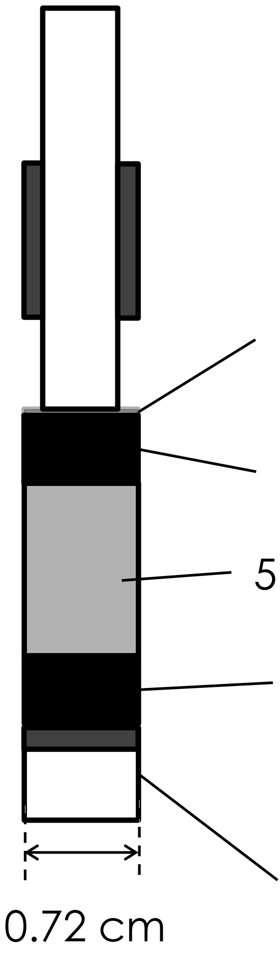
The RBWR features an epithermal spectrum



Spectrum of neutrons inducing fission

Fraction of fissions induced in each energy range for the RBWR-TB2	
< 1 eV	16.4%
1 eV - 1 MeV	37.6%
> 0.1 MeV	46.0%

RBWRs use short fuel pins with a layered seed/blanket structure



130 cm upper reflector with 50 cm B_4C absorbers

2 cm upper blanket (DU)

22.4 cm upper seed (70.7% TRU enrichment)

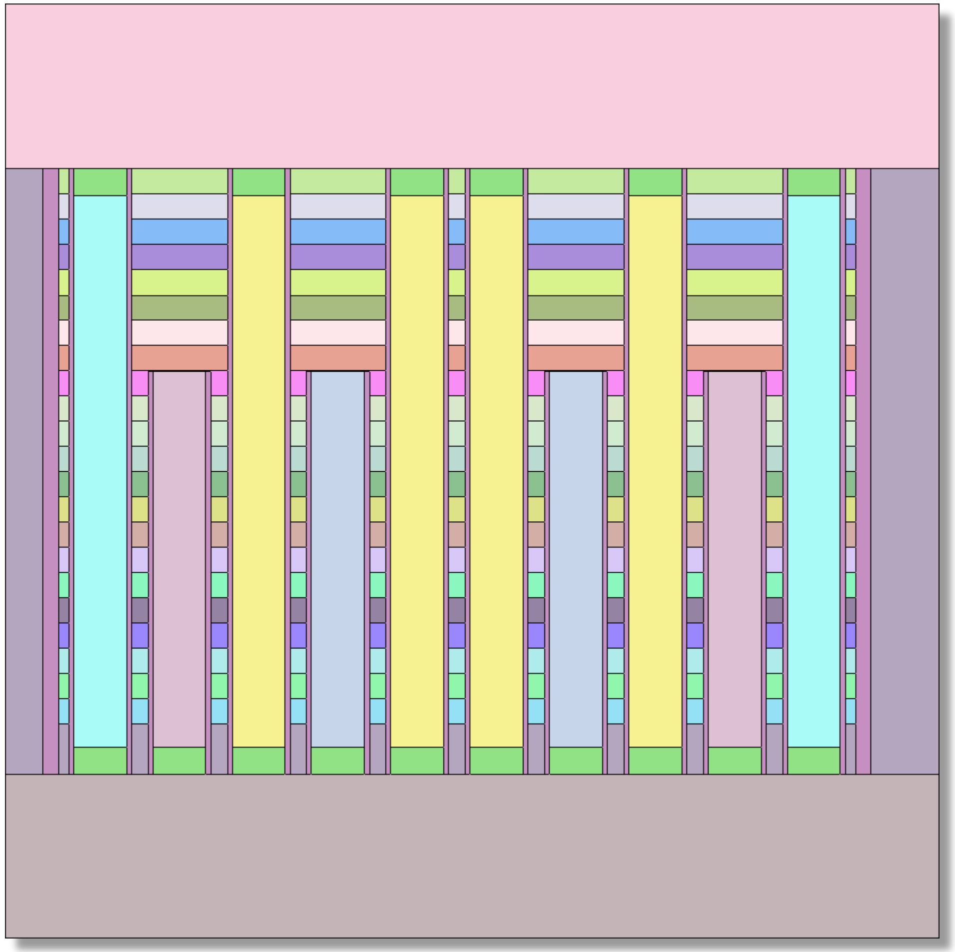
56 cm internal blanket (DU)

22.1 cm lower seed (80.5% TRU enrichment)

30 cm lower reflector with 7 cm B_4C absorbers

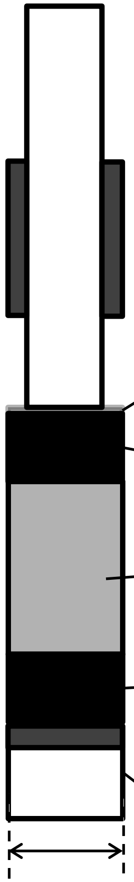
0.72 cm

RBWR vertical configuration



ABWR vertical configuration

Coolant void coefficient is a trade-off between leakage and spectrum hardening



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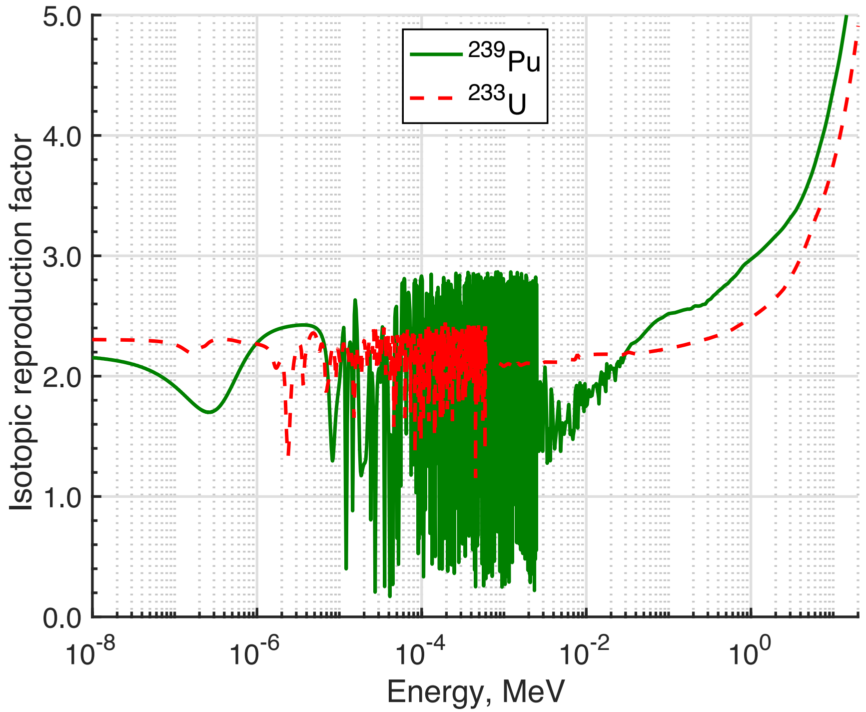
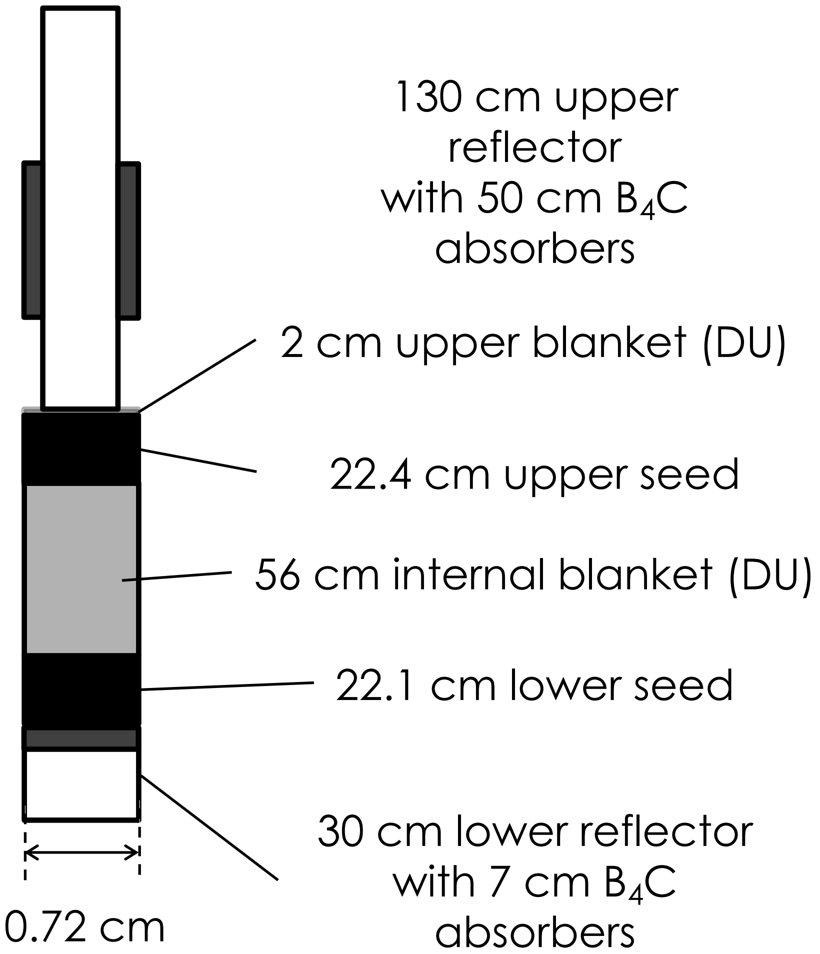


Reproduction factor as a function of energy

Thorium blankets greatly simplify the core structure



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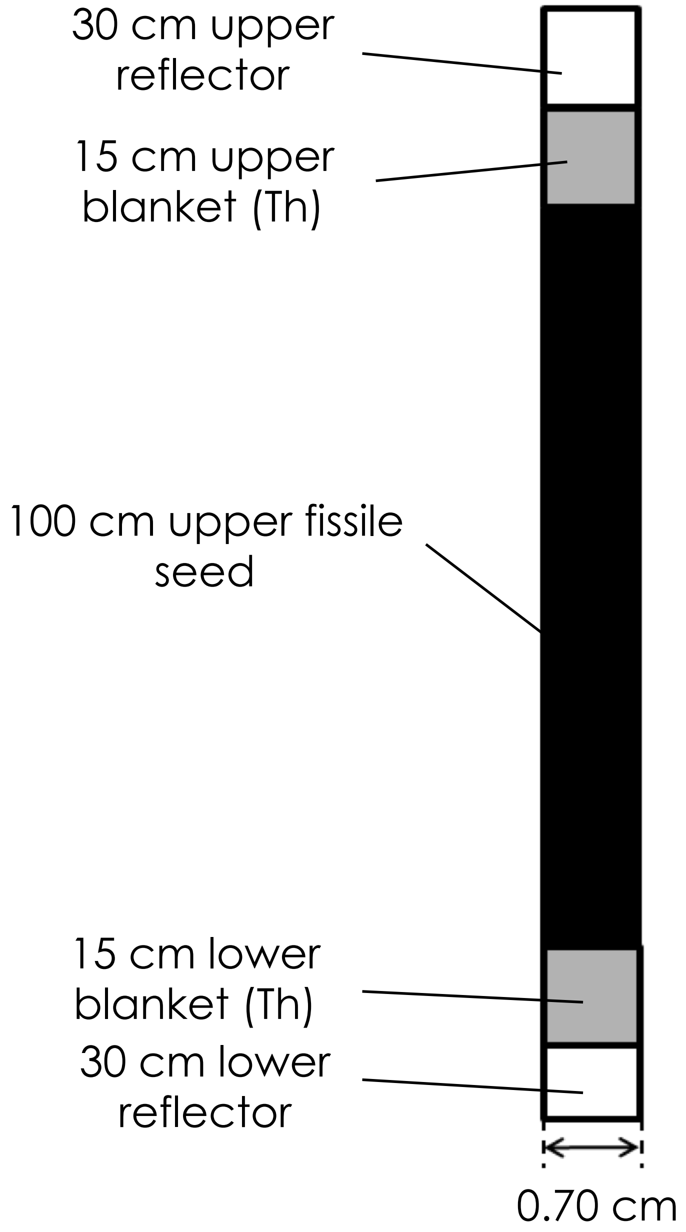
22.1 cm lower seed

30 cm lower reflector with 7 cm B_4C absorbers

0.72 cm

RBWR vertical configuration with DU seed



30 cm upper reflector

15 cm upper blanket (Th)

100 cm upper fissile seed

15 cm lower blanket (Th)

30 cm lower reflector

0.70 cm

RBWR vertical configuration with Th seed

RBWR designs need to conform to several constraints, mostly related to safety

- All trans-fertile material must be **recycled** (1.2% of the heavy metals is lost in recycling and fabrication processes).
- The core should fit within an **ABWR pressure vessel**.
- Provide the full **ABWR power** in order to make use of most of the ABWR technology and engineering and to keep the design economical.
- Maintain **criticality** in the equilibrium cycle (approach to equilibrium has not been assessed).
- Possess **negative coefficients of reactivity** for fuel temperature, coolant void, and power.
- Have **sufficient shutdown margin** to shut down the core at any point in the cycle at cold, zero-power state.
- Remain compatible with the **ABWR pumps** (core pressure drop to ≤ 0.3 MPa, and core flow rate ≤ 120% of the ABWR flow rate).
- **Avoid coolant dryout**.
- Operate with a two-phase density wave oscillation **decay ratio ≤ 0.7** to assure flow stability.

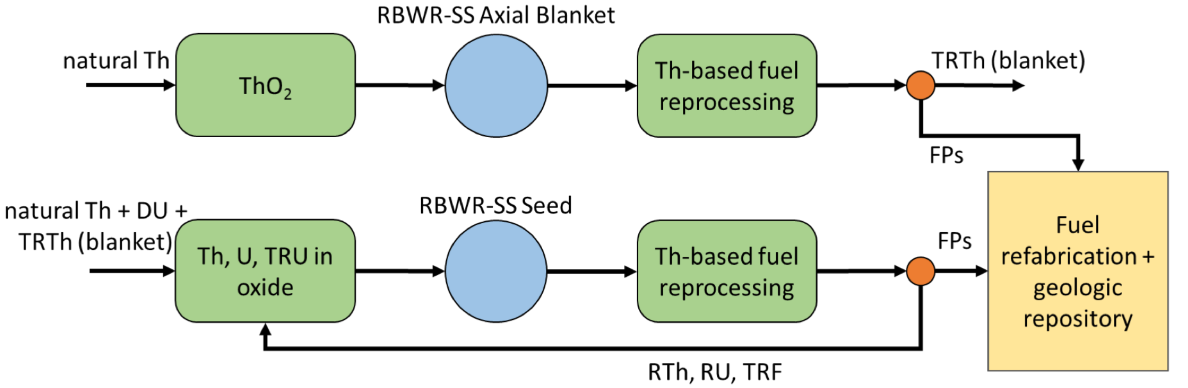
Optimal designs are the result of a complex trade-off

Variable	MCPR (↑)	Critical average burnup (↑)	Void reactivity coefficient (↓)	Shutdown margin (↑)	Δp (↓)
Coolant flow rate	↑	↓	↓		↑
Depletion time			↑	↓	
Seed length	↑	↓	↑	↑	↑
Outer blanket lengths		↑	↑		↑
Internal blanket length		↓	↓		
Makeup DU fraction			↑	↑	
Axial enrichment variation	*	*		↑	↑
Pitch to diameter ratio (P/D)	↑	↓	↓	↑	↓
Number of pins per assembly	↑		↓	↑	↑
Power	↓	↓			↑

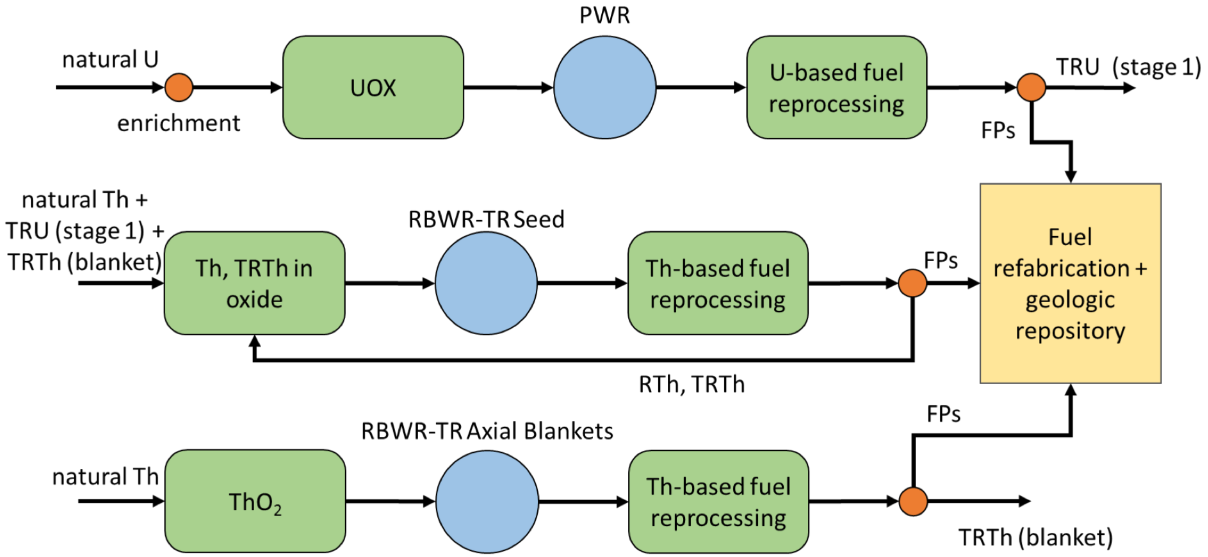
* Any variation from uniform causes a decrease

Two RBWR variants were analyzed: (1) fuel self-sustained, and (2) transmuter

Fuel self-sustained



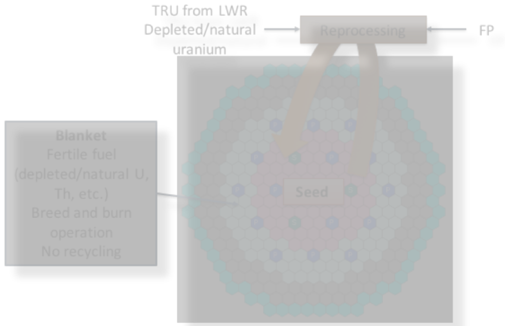
Transmuter



Th-blanket RBWR designs are unable to meet shutdown margin constraints

- It was found that even using the most conservative thermal-hydraulic correlations, it is not possible to design a self-sustaining fuel cycle without significant power down rate. In particular, it is not possible to design the core to have sufficient shutdown margin while also having negative void feedback.
- It was found that it is not possible to design a transmuter RBWR such that both the shutdown margin and the negative void feedback constraints are met.
- Shutdown margin and reactivity coefficient constraints maybe met using multiple seed layers.
- No significant differences were found in regards to back end of the fuel cycle properties when comparing uranium and thorium fed RBWRs.

Seed and blanket sodium cooled fast reactor



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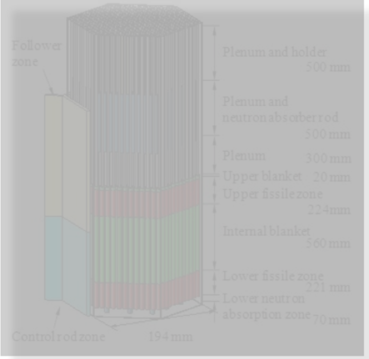
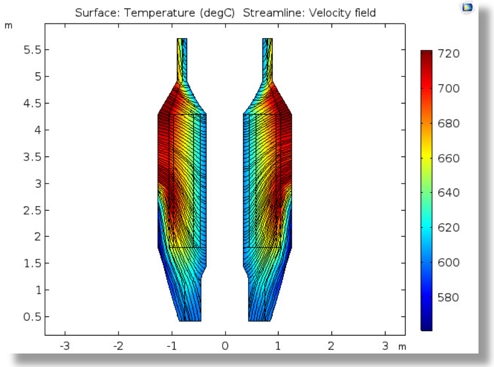
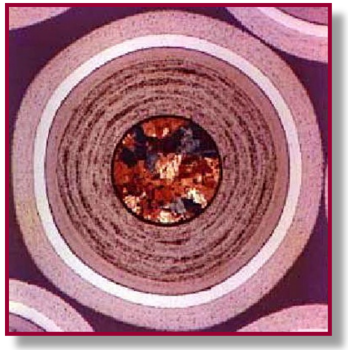


Fluoride-cooled high-temperature reactor (FHR)



Fluoride-cooled high-temperature reactors combine existing technologies



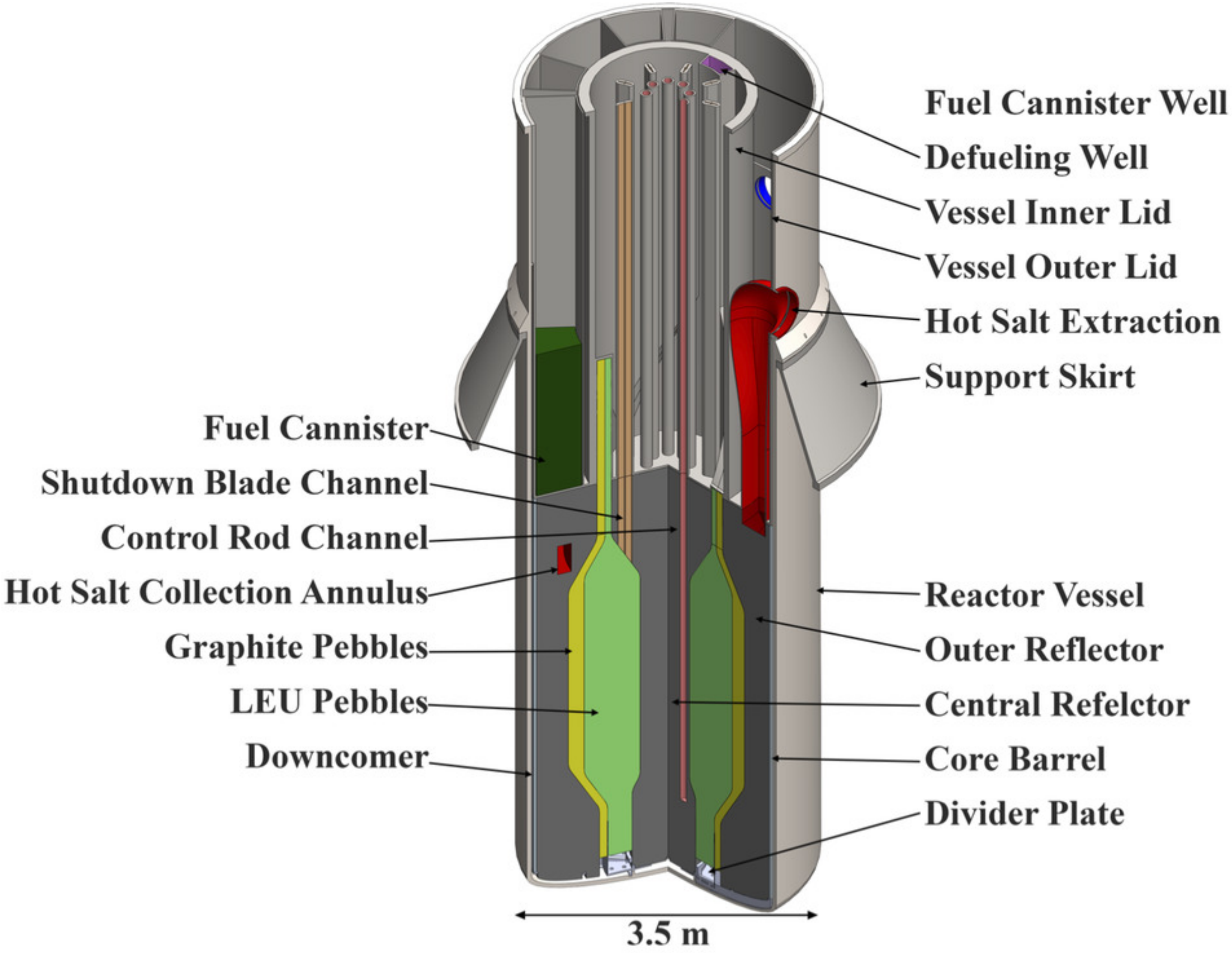
- **Fuel**: high-temperature coated-particle fuel developed for high-temperature gas-cooled reactors (HTGRs) with failure temperatures >1650°C

- **Coolant**: high-temperature, low-pressure liquid-salt coolant ($^7Li_2BeF_4$) with freezing point of 460°C and boiling point >1400°C (transparent)

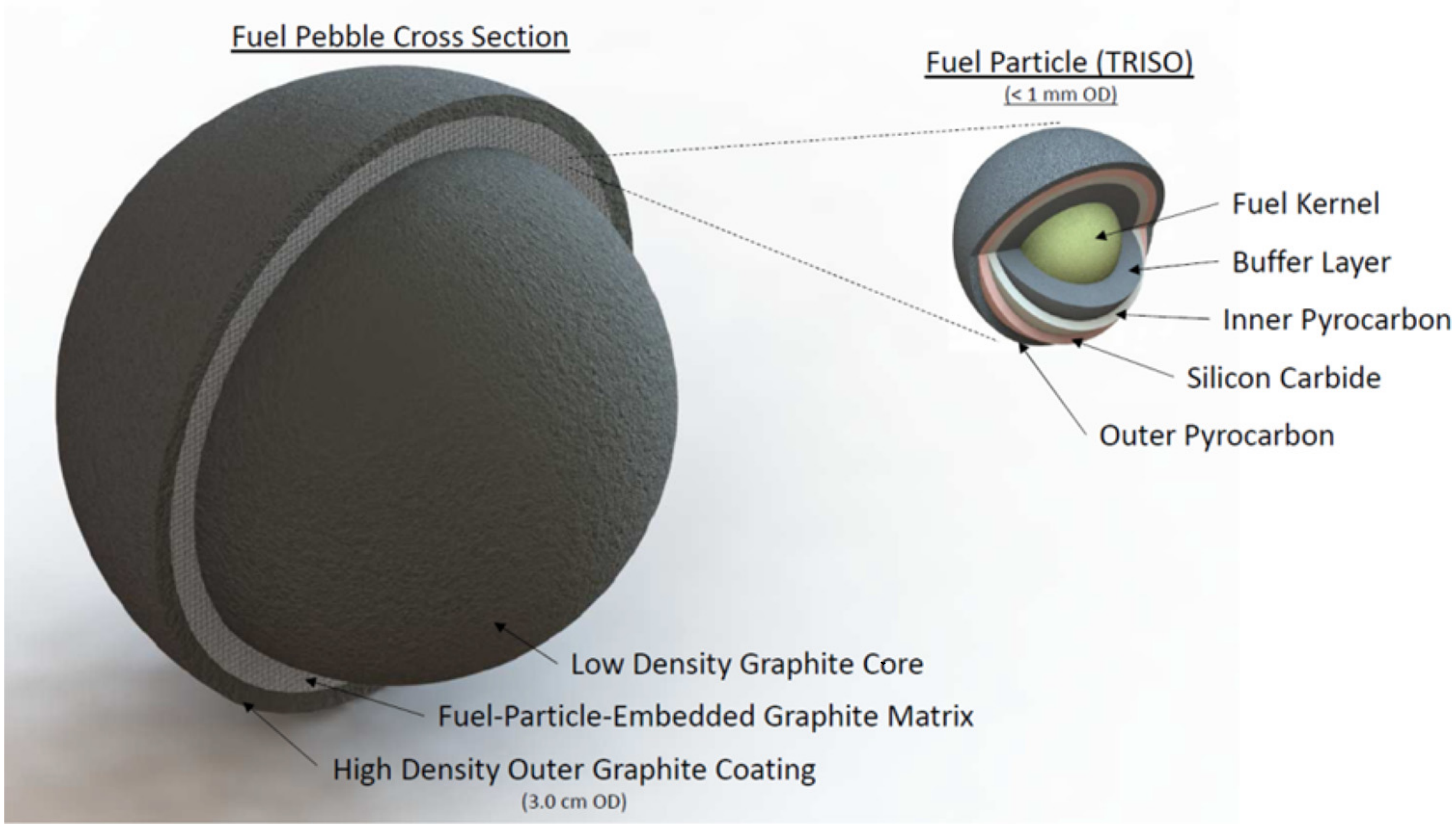
- **Power Cycle**: modified air Brayton power cycle with General Electric 7FB compressor

The reference design
Mk1 PB-FHR is a pebble bed

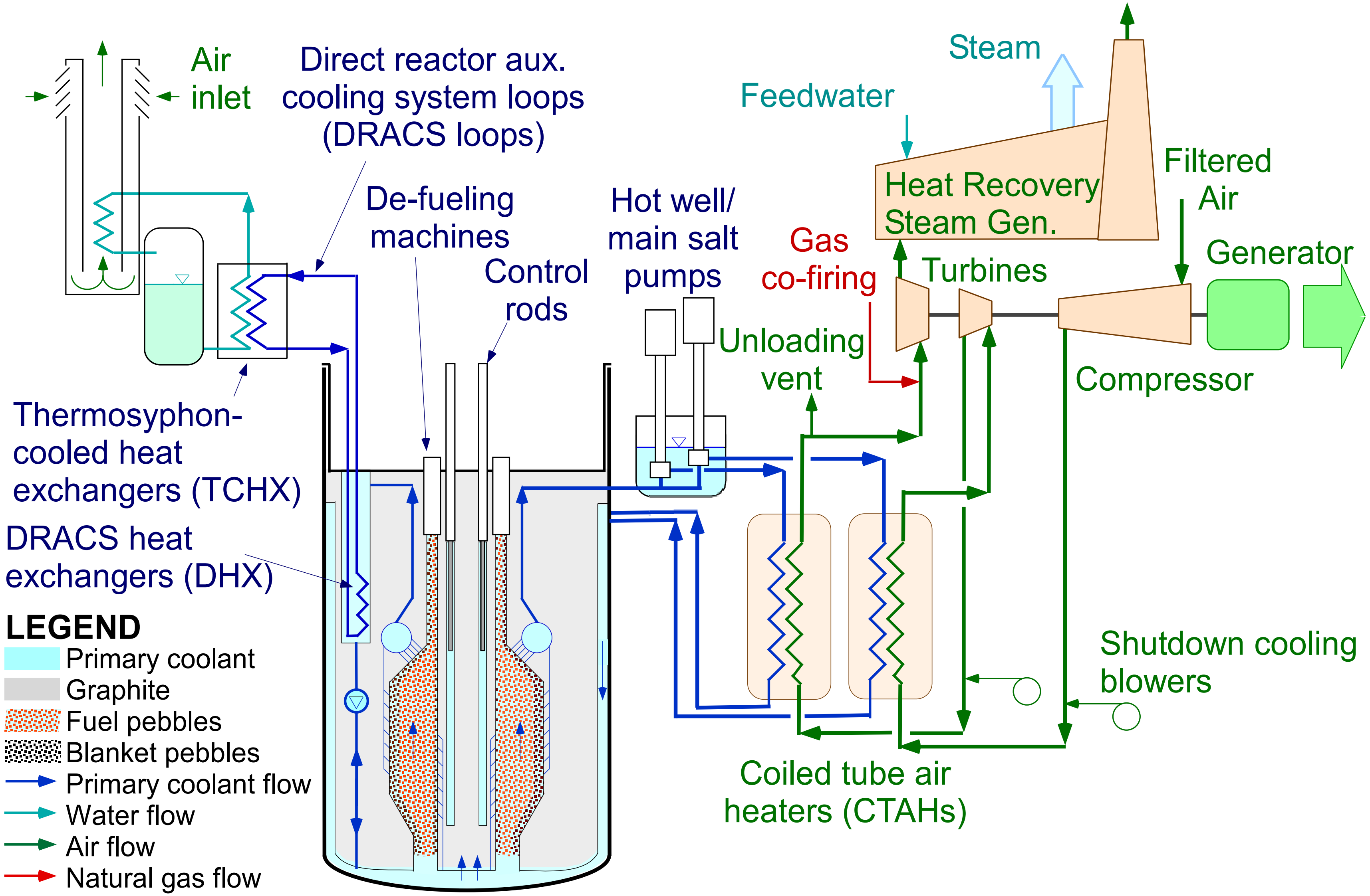
- Annular pebble bed core with center graphite reflector
- Flibe coolant
- Core inlet/outlet temperatures 600°C/700°C
- Control elements in center reflector
- Reactor vessel 3.5 m outer diameter, 12.0 m high
- Power level: 236 MWth, 100 MWe (base load), 242 MWe (peak with natural gas)



Pebble design aims to address average density and peak fuel temperature constraints



Mk1 PB-FHR is the conceptual design developed at UC Berkeley



Air inlet

Direct reactor aux. cooling system loops (DRACS loops)

De-fueling machines

Control rods

Hot well/ main salt pumps

Gas co-firing

Unloading vent

Feedwater

Steam

Heat Recovery Steam Gen.

Filtered Air

Turbines

Generator

Compressor

Thermosyphon-cooled heat exchangers (TCHX)

DRACS heat exchangers (DHX)

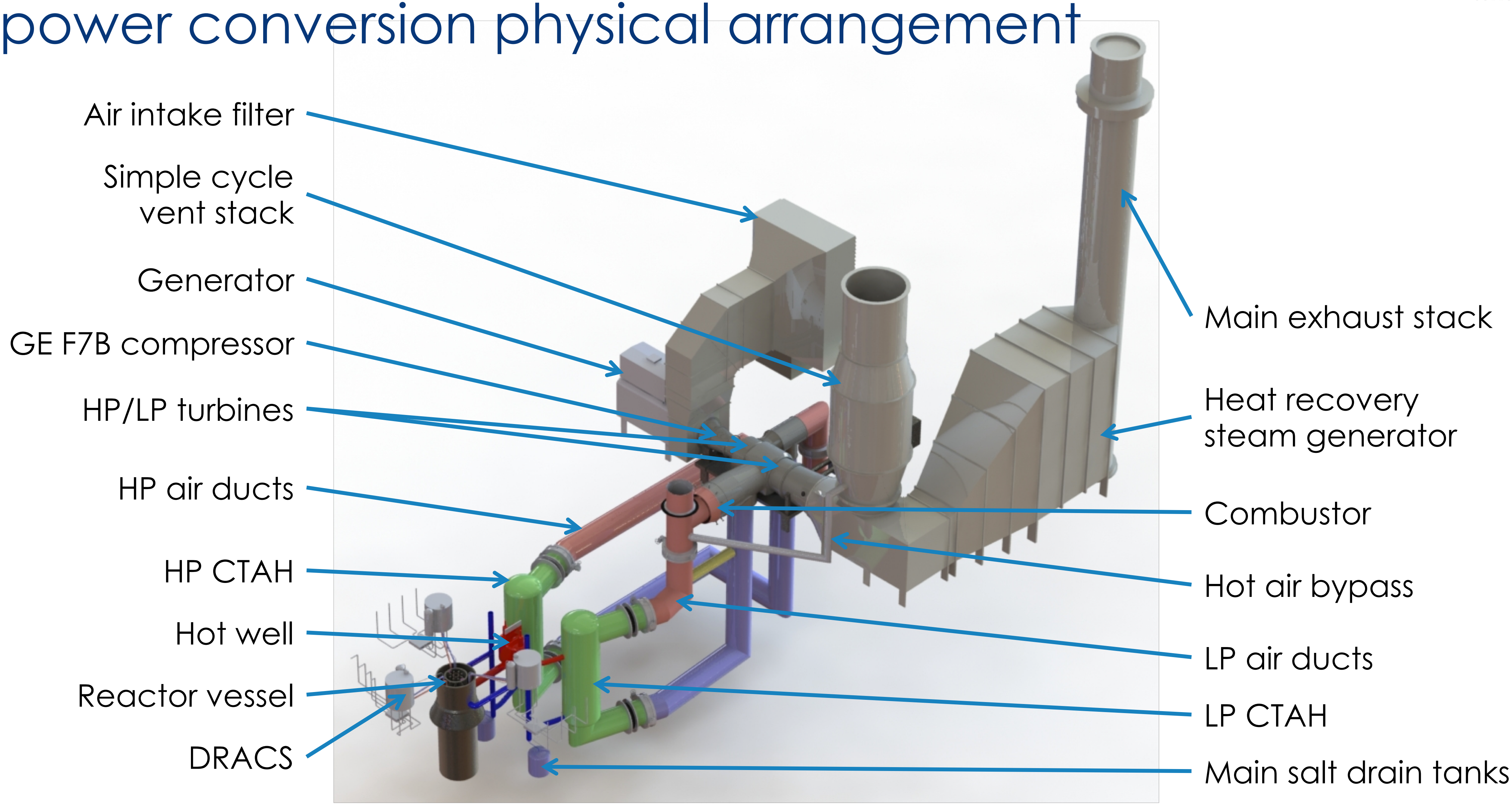
Shutdown cooling blowers

Coiled tube air heaters (CTAHs)

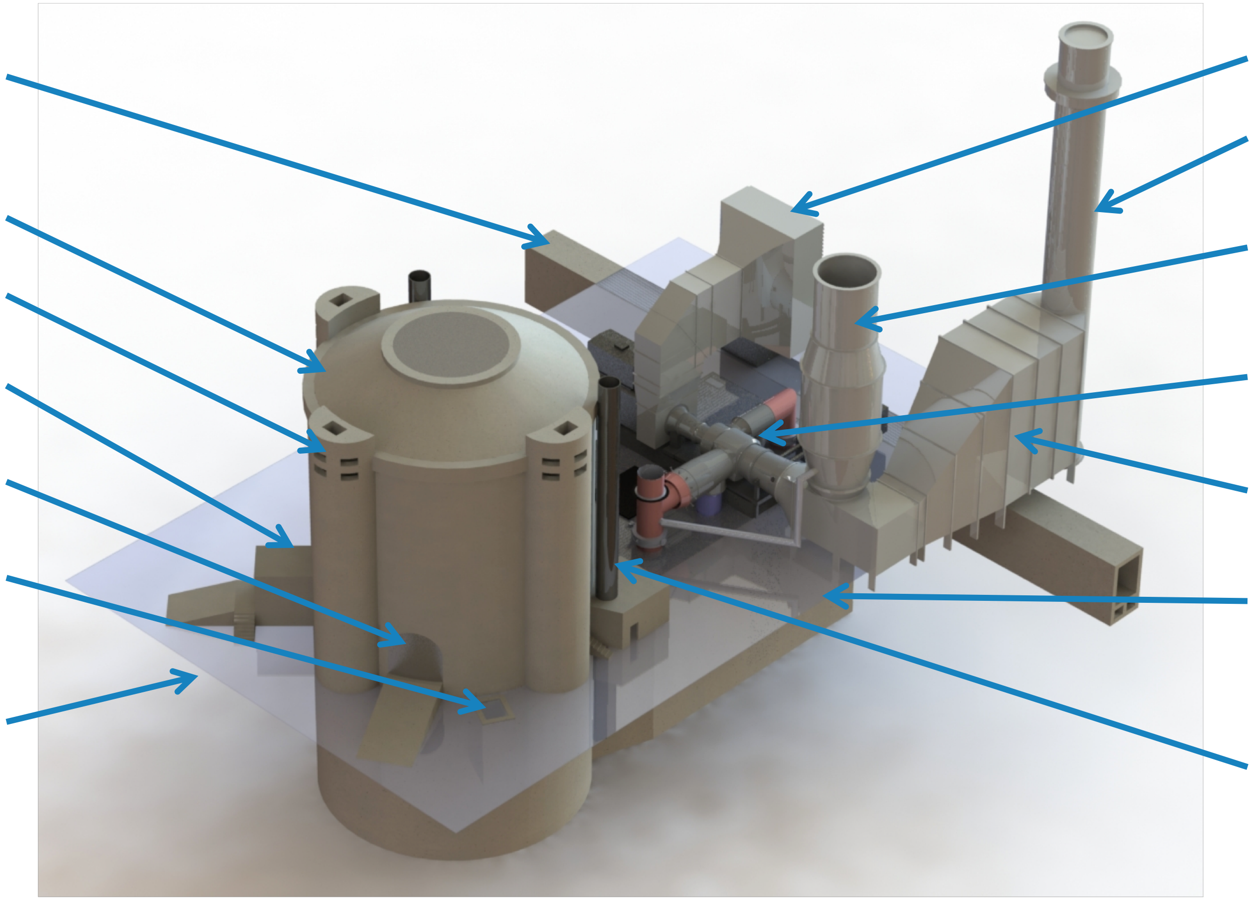
LEGEND

- 🟦 Primary coolant
- ⬜ Graphite
- ▨ Fuel pebbles
- ▩ Blanket pebbles
- → Primary coolant flow
- → Water flow
- → Air flow
- → Natural gas flow

Nuclear Air-Brayton Combined Cycle (NACC) power conversion physical arrangement



The Mk1 structures are designed for modular construction



Underground common utilities tunnel

Shield building

DRACS chimney

Personnel airlock

Equipment hatch

Fuel canister well

Grade level

Intake filter

Main stack

Simple cycle bypass stack

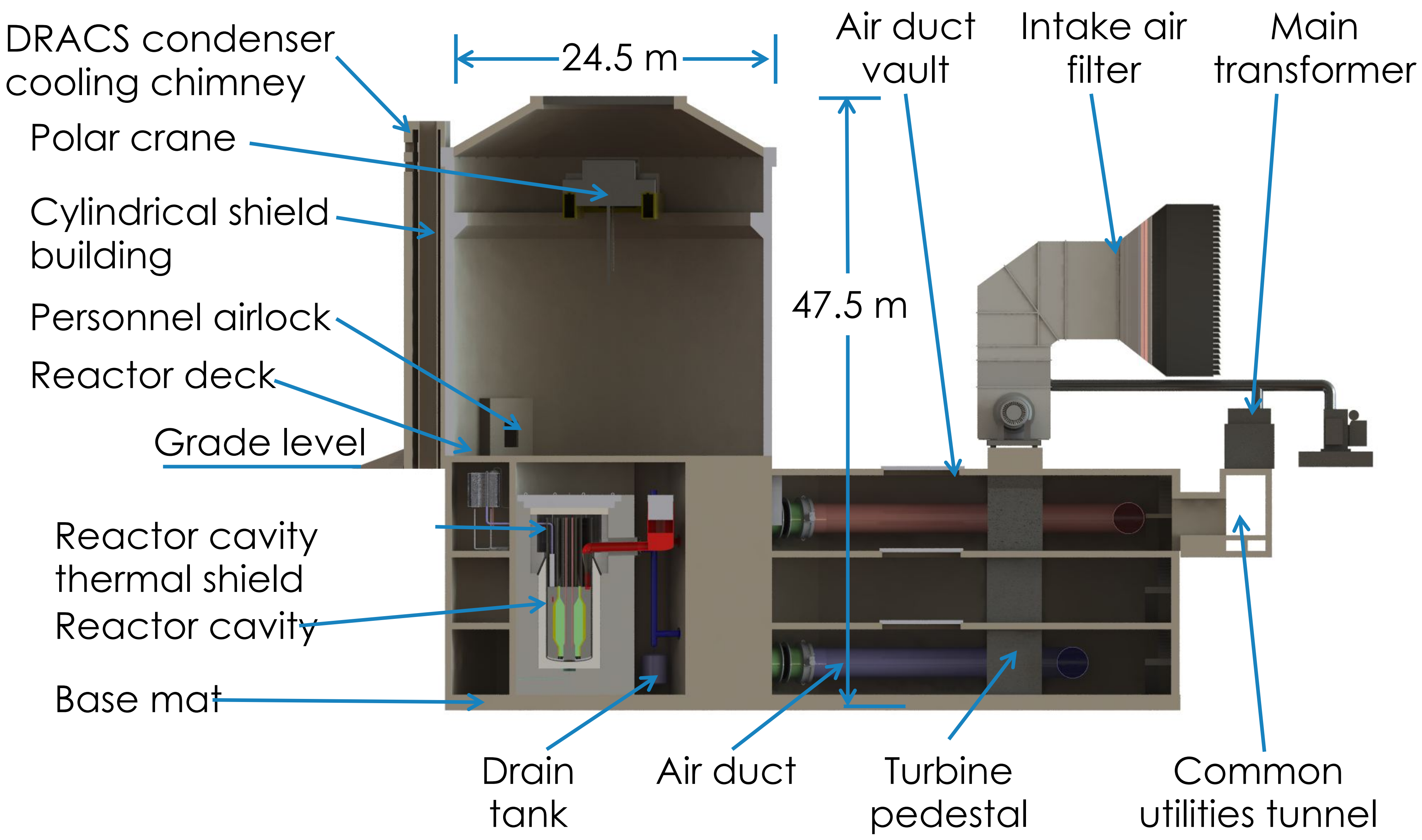
Modified GE 7FB gas turbine

HRSG

Below-grade air duct vault

Ventilation exhaust system

Mk1 reactor building elevation view



Transient scenarios for the PB-FHR are modeled using two approaches

Serpent/OpenFOAM

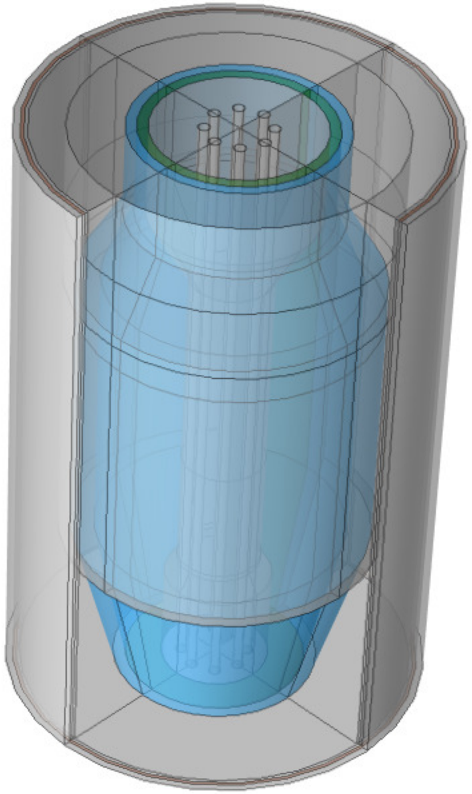
- Monte Carlo neutronics
- OpenFOAM C++ toolkit for thermal-hydraulics
- Finite-volume solver
- Flexible (any material and geometry)
- Open source (almost)
- Computationally expensive

COMSOL Multiphysics®

- Commercial tool
- Finite-element solver
- Fully coupled
- Flexible interface
- Computationally cheap

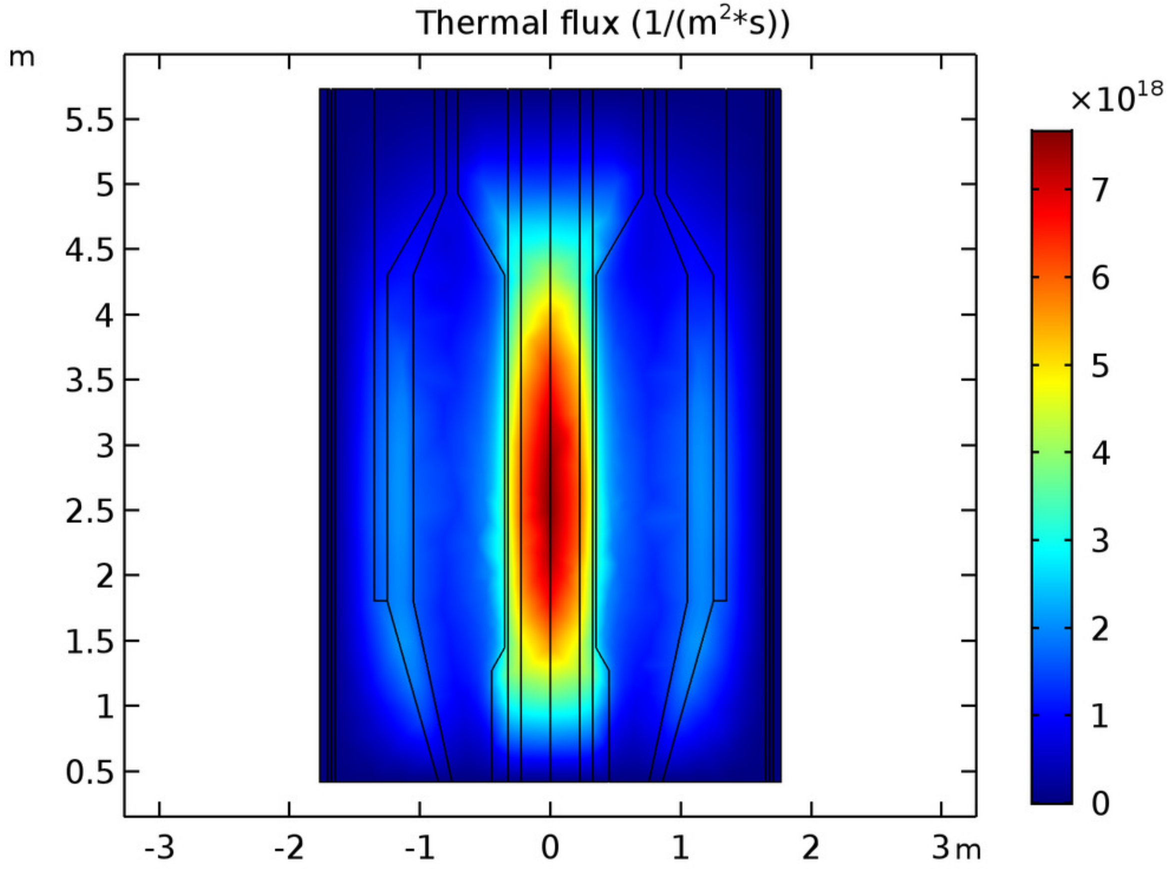
COMSOL® Multi-group diffusion/SP$_3$ model

- 3-D geometry
- Multi-group neutron diffusion model (SP$_3$ extension)
- Cross-sections from Serpent full core model
- Porous media thermal-hydraulics model
- Convective heat transfer coefficient from Wakao correlation

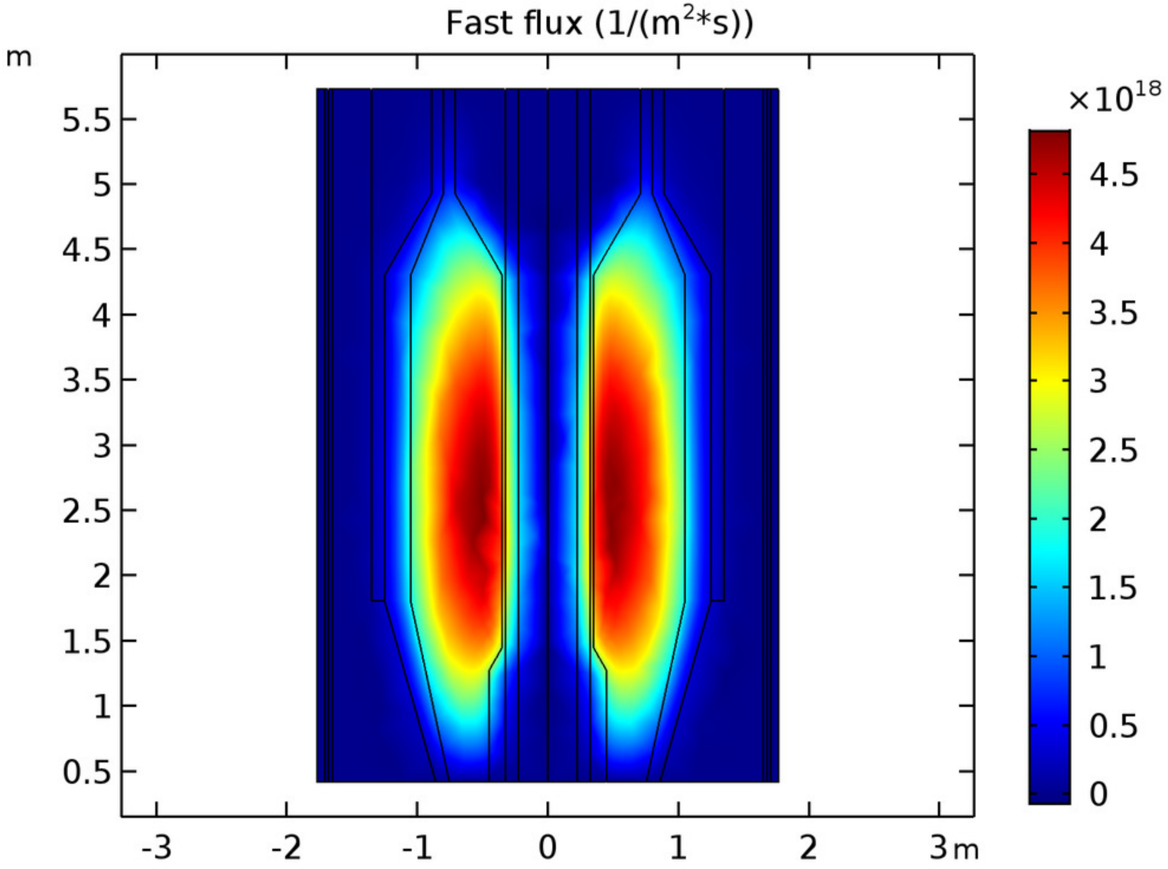


Mk1 PB-FHR model
in COMSOL

COMSOL® solver provides thermal-hydraulics and neutronics data

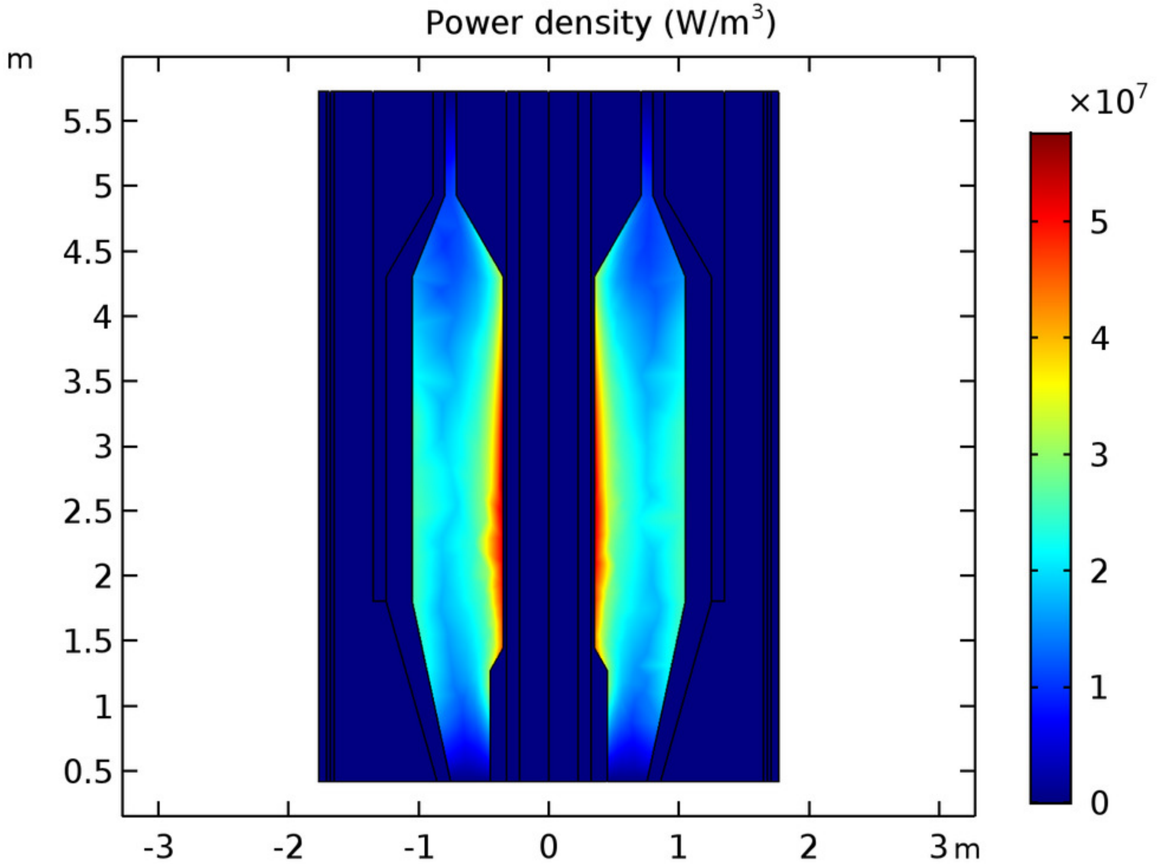


Thermal neutron flux

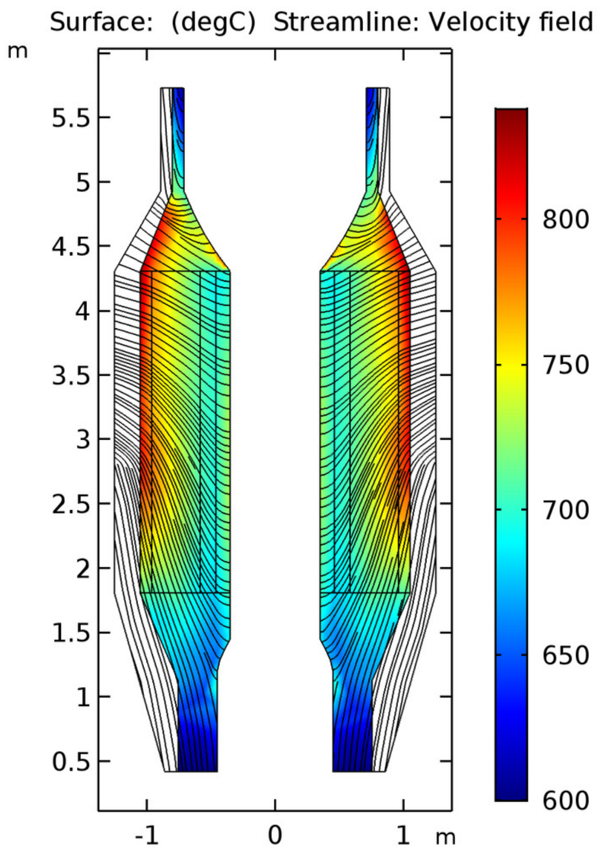


Fast neutron flux

COMSOL® solver provides thermal-hydraulics and neutronics data

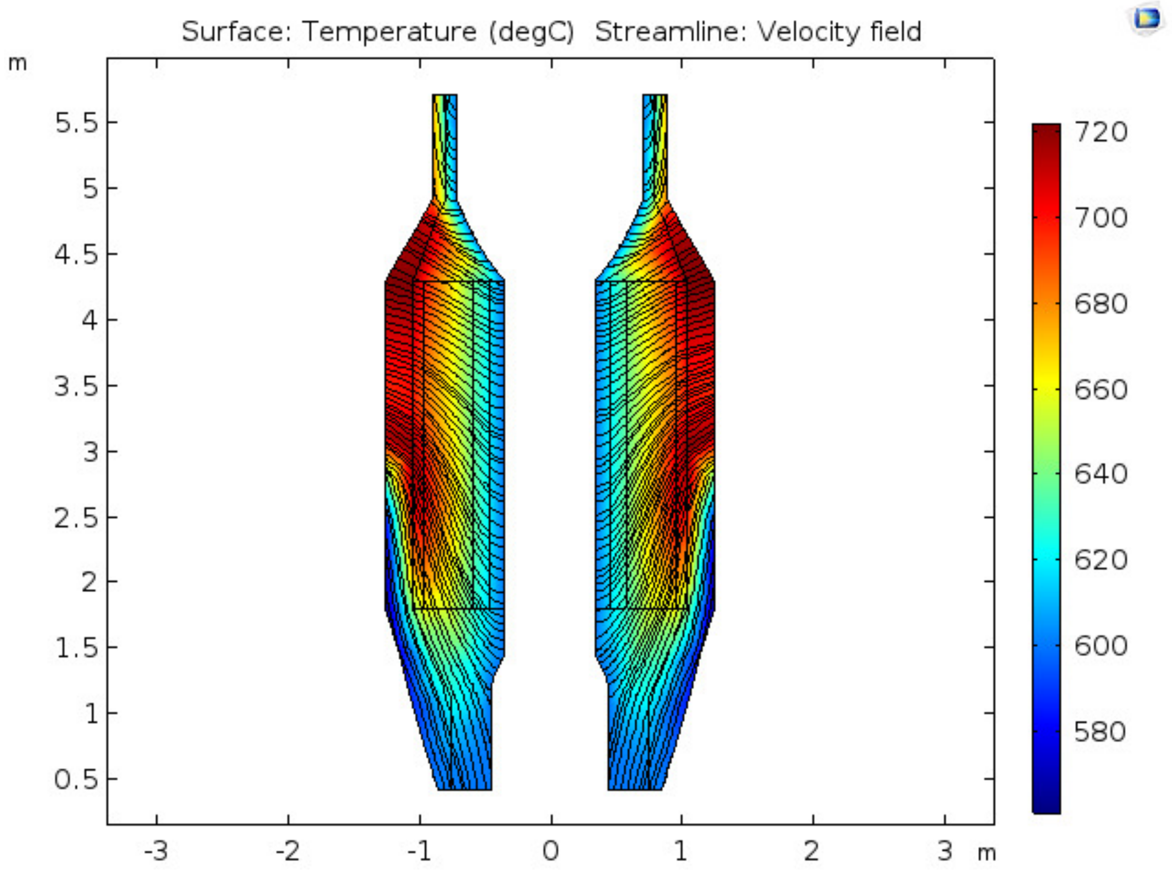


Power density distribution

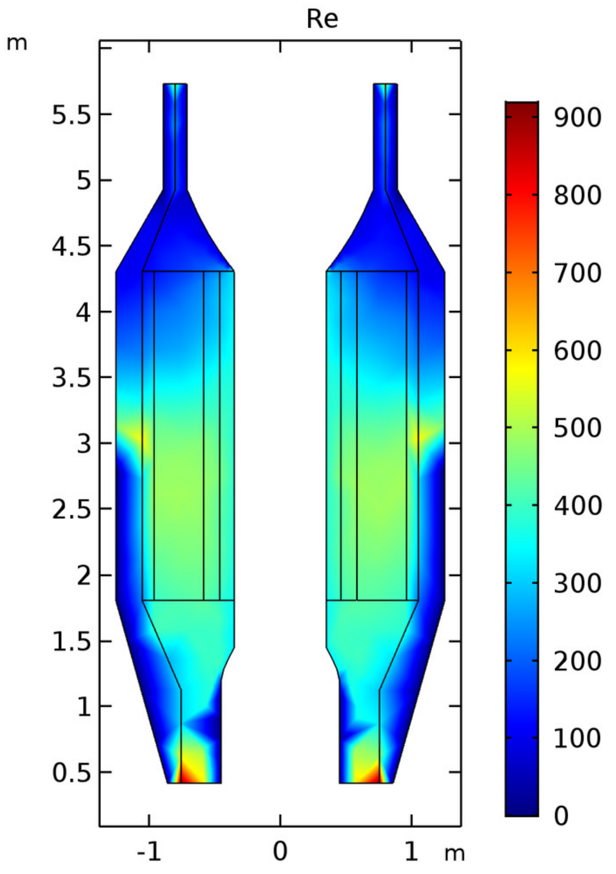


Fuel temperature

COMSOL® solver provides thermal-hydraulics and neutronics data



Flibe temperature



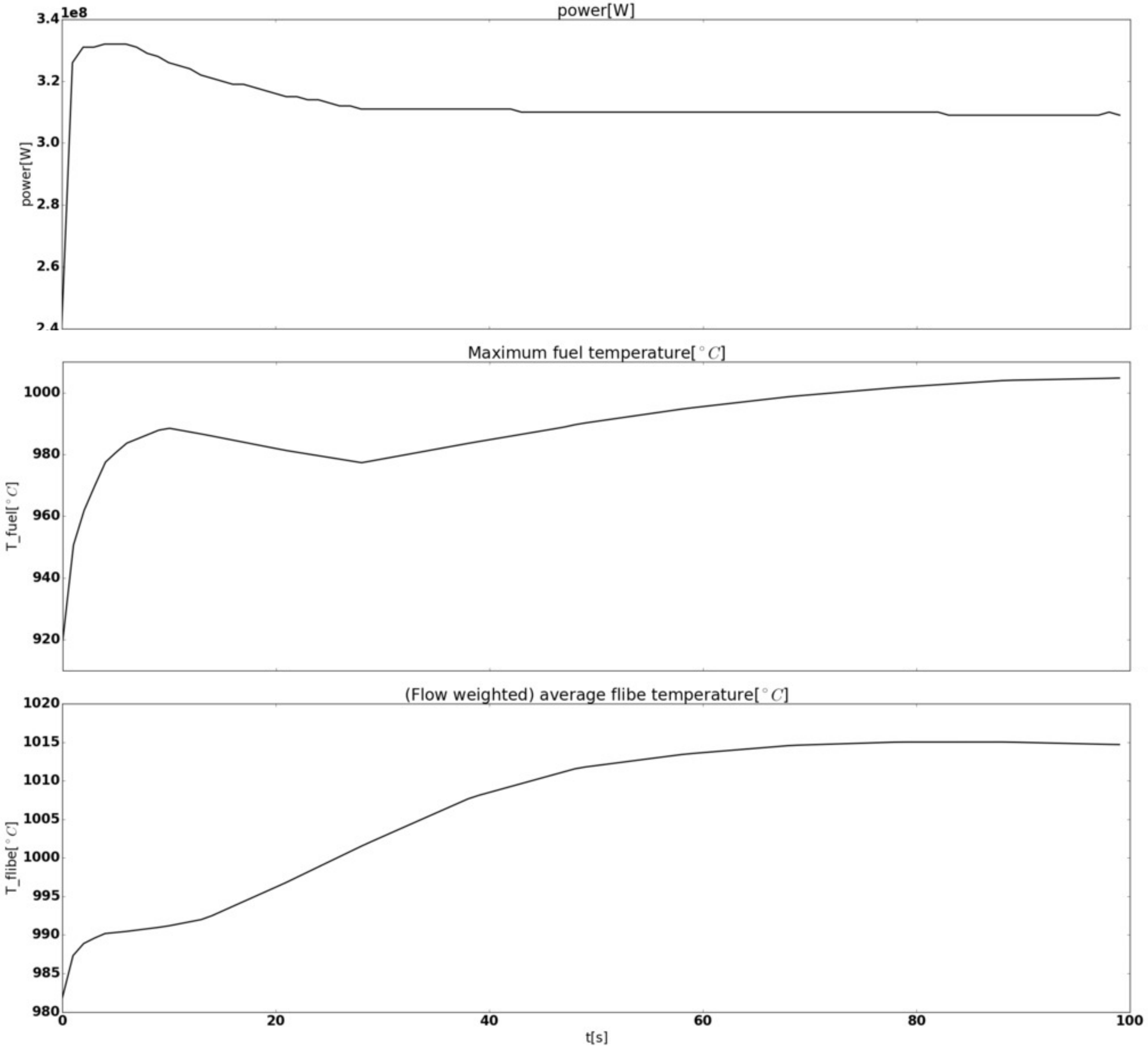
Reynolds number

The Mk1 PB-FHR features large margins to accommodate a reactivity insertion accident

Total core power

Maximum fuel temperature

Flibe outlet temperature



Conclusions

- Seed&Blanke SFR
  - Improve resource utilization
  - Might improve economics (n-th of a kind)
  - Require a well-established reprocessing infrastructure
- RBWR
  - Greatly increase resource utilization
  - Although it is based on BWR technology it greatly challenges its safety margins
- PB-FHR
  - Can use combined natural-gas/nuclear cycle to improve economics
  - Large safety margins
  - Requires 20% enriched uranium

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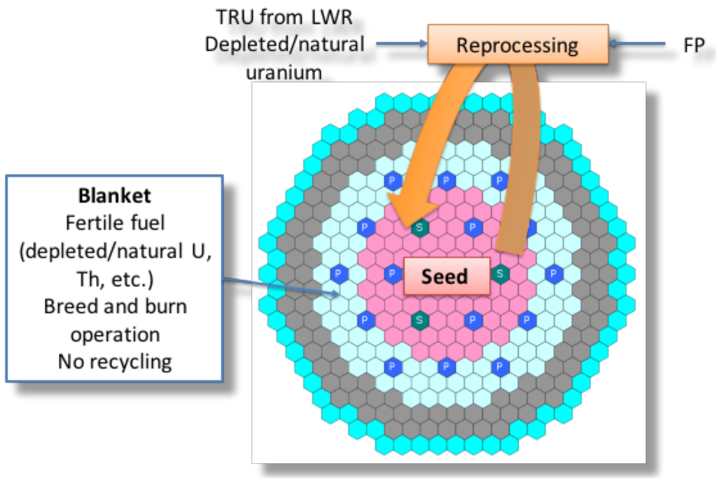
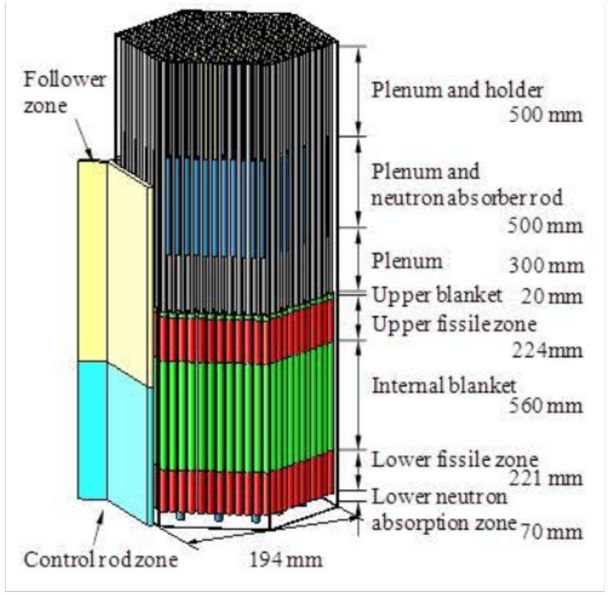
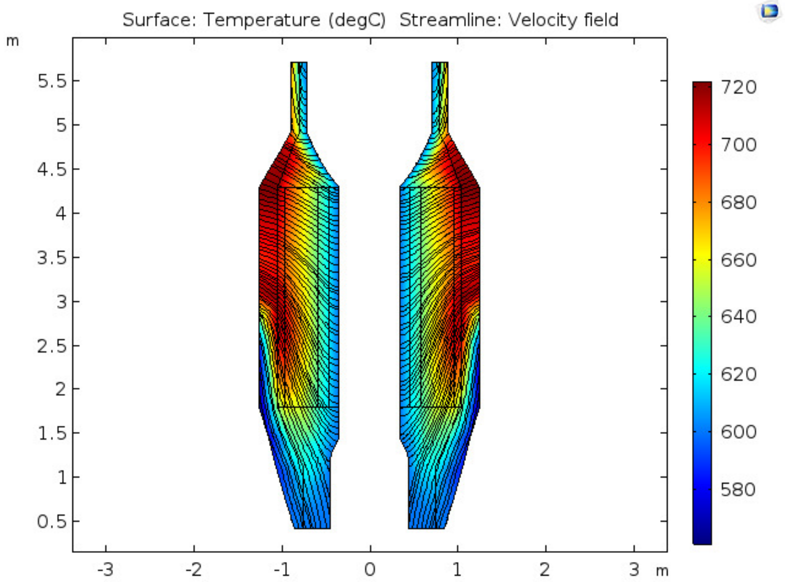

TRU from LWR
Depleted/natural uranium
Reprocessing
FP

Blanket
Fertile fuel (depleted/natural U, Th, etc.)
Breed and burn operation
No recycling

Seed





Thank you! Questions?