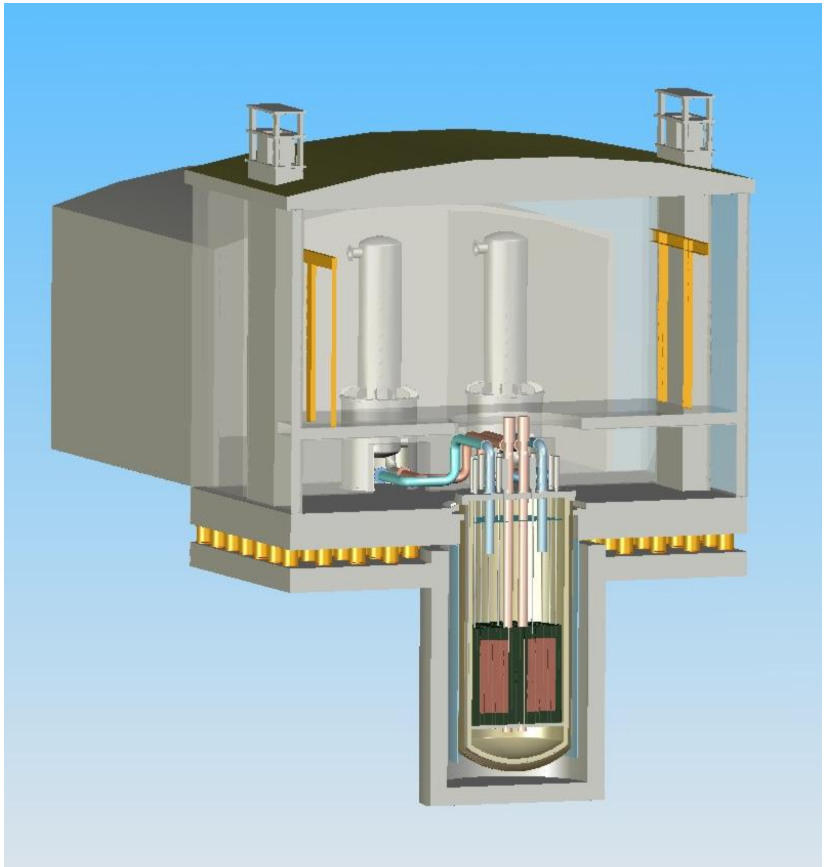
Core Physics Characteristics and Issues for the Advanced High-Temperature Reactor (AHTR)



D.T. Ingersoll, E. J. Parma,
C.W. Forsberg, J.P. Renier

ARWIF 2005
Advanced Reactors With Innovative Fuels (and Coolants)

February 16-18, 2005

OAK RIDGE
NATIONAL LABORATORY

Sandia National Laboratories

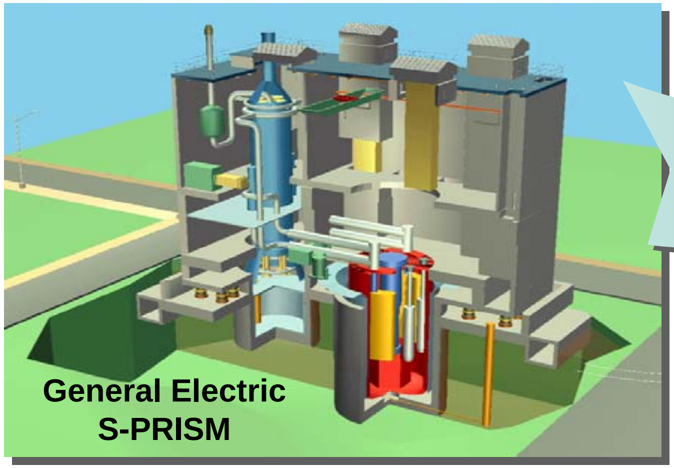
AHTR ≠ MSR

(Solid fuel; salt coolant)

(Fuel dissolved in salt)

The Advanced High-Temperature Reactor

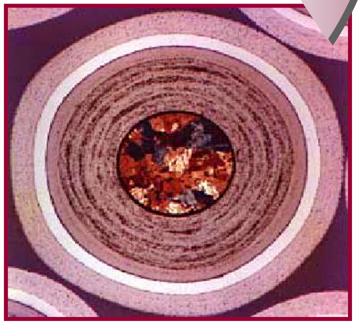
Combining Existing Technologies in a New Way


General Electric
S-PRISM

Passively Safe Pool-Type Reactor Designs


GE Power Systems MS7001FB

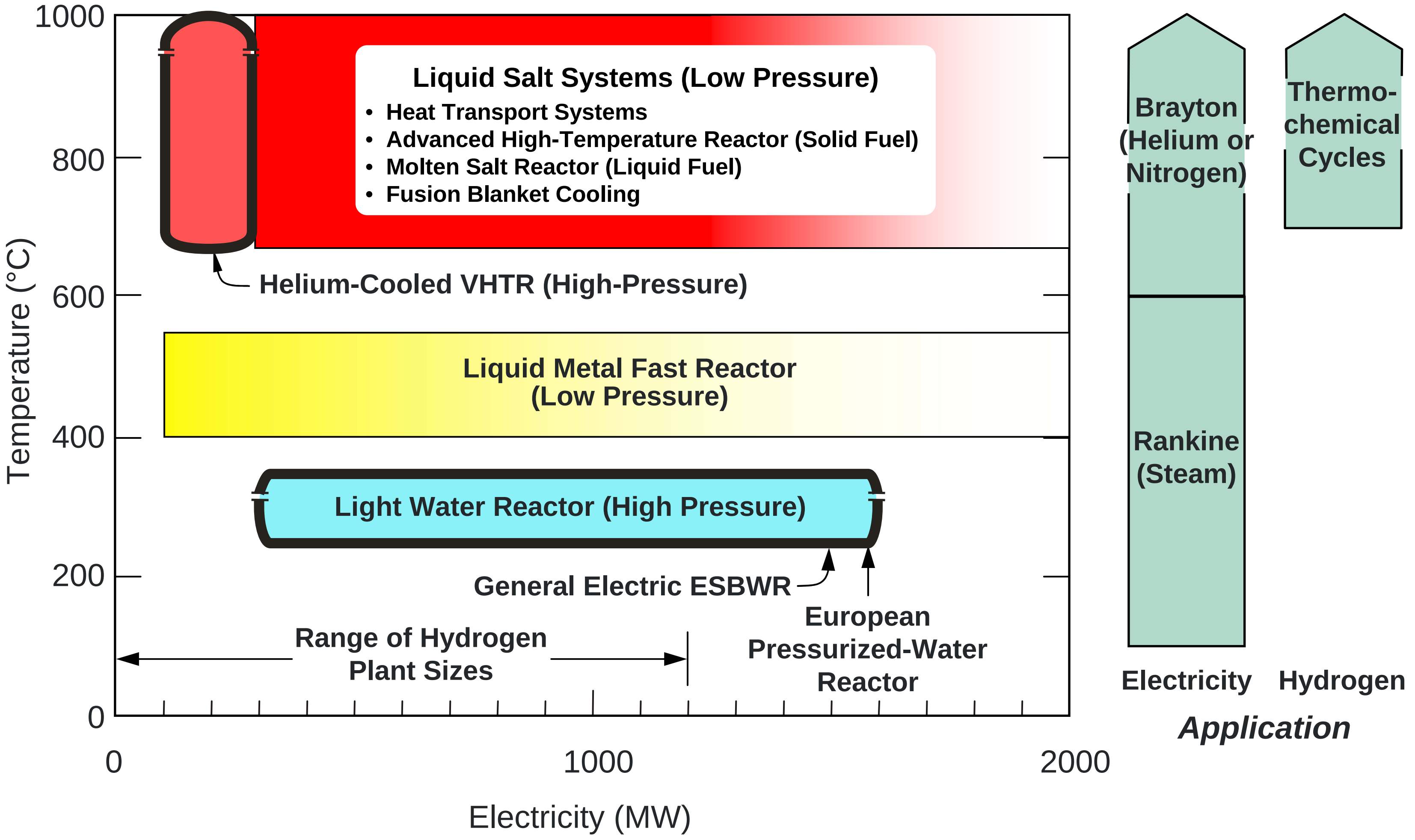
Brayton Power Cycles



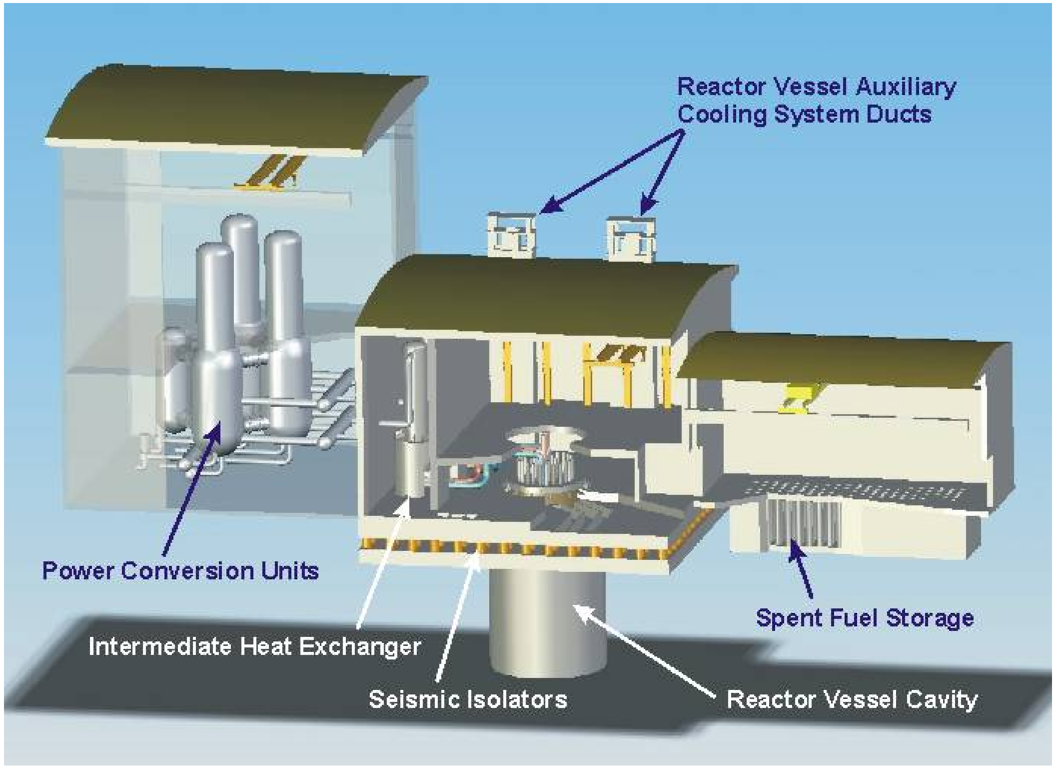
High-Temperature Coated-Particle Fuel

High-Temperature, Low-Pressure Molten-Salt Coolant

AHTR Fills the High-Temperature, High-Power Need

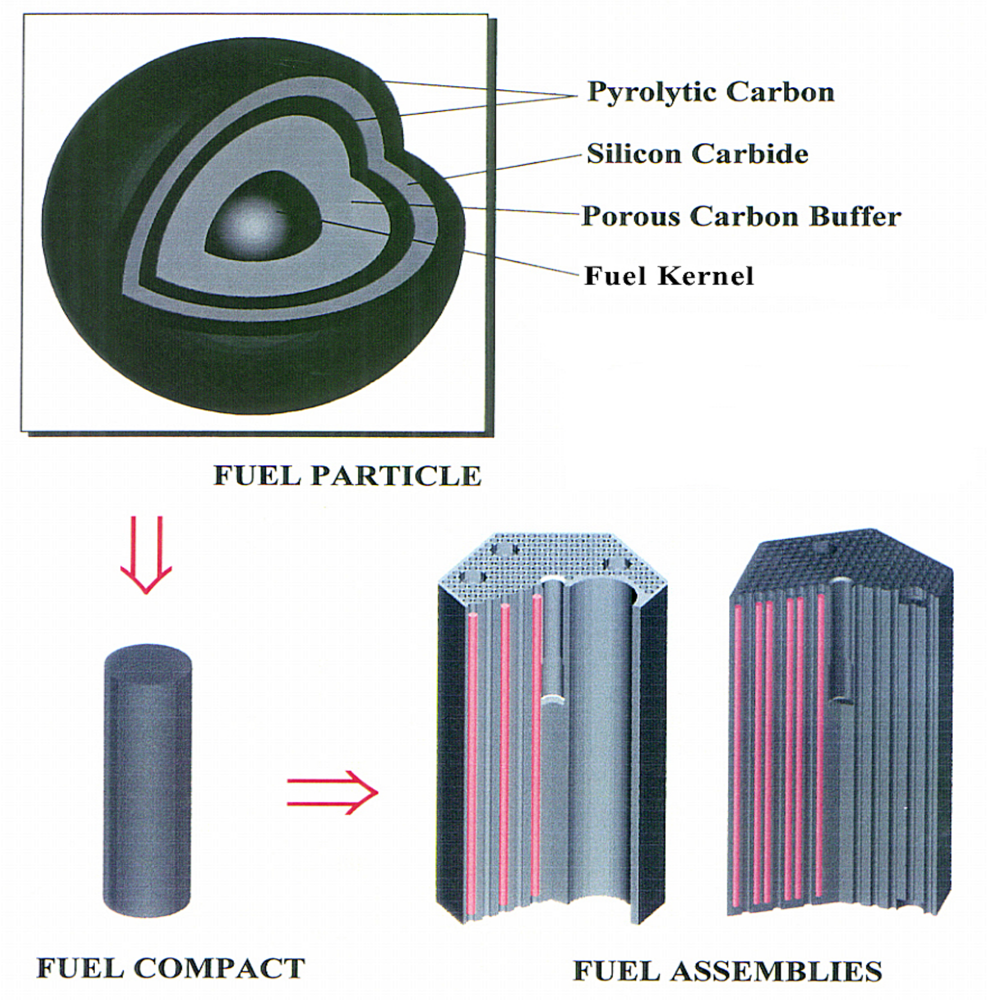


2400 MW(t) AHTR Nuclear Island Has Similar Size To 1000 MW(t) GE S-PRISM



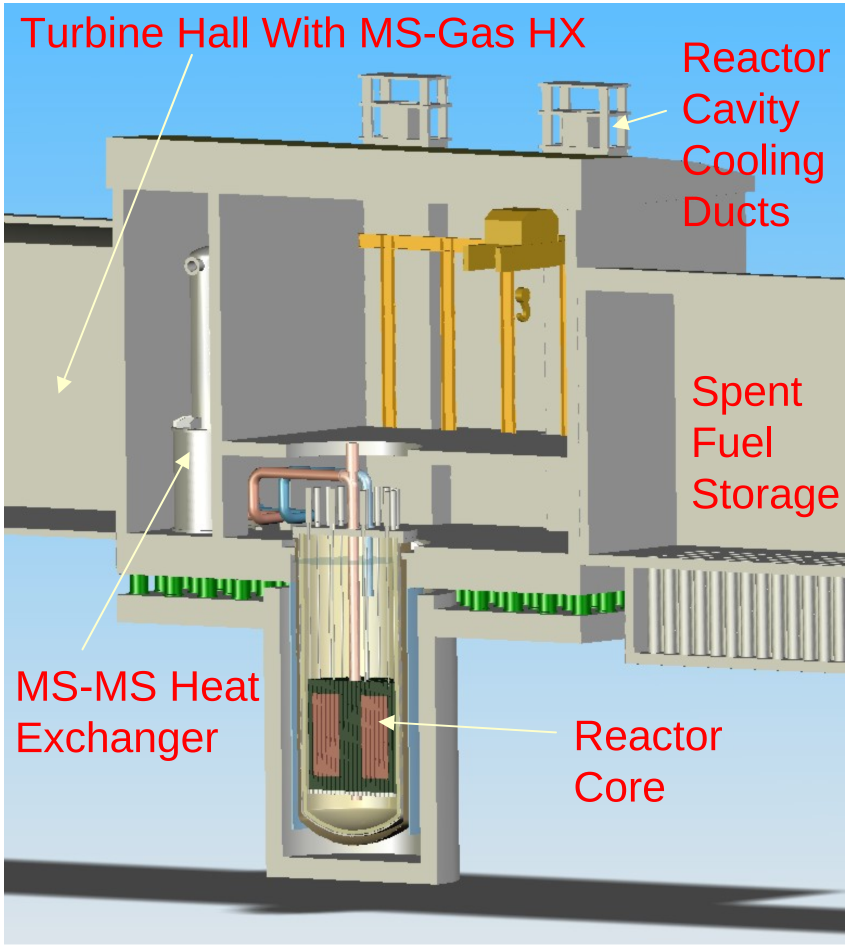
- **Similar vessel size (9 m dia)**
  - **Space for 2400 MW(t) AHTR core with low power density**
- **Similar equipment size due to larger volumetric heat capacity of liquid salt**
- **Higher capacity decay heat removal system due to higher vessel temperature**
- **Higher electrical output**
  - **S-PRISM: 380 MW(e)**
  - **AHTR: 1200 MW(e)**

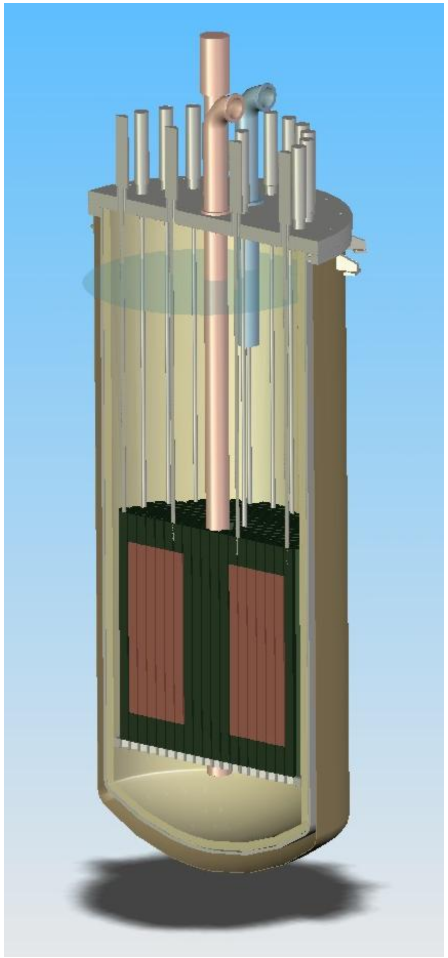
The AHTR Uses Coated-Particle Graphite-Matrix Fuel Elements



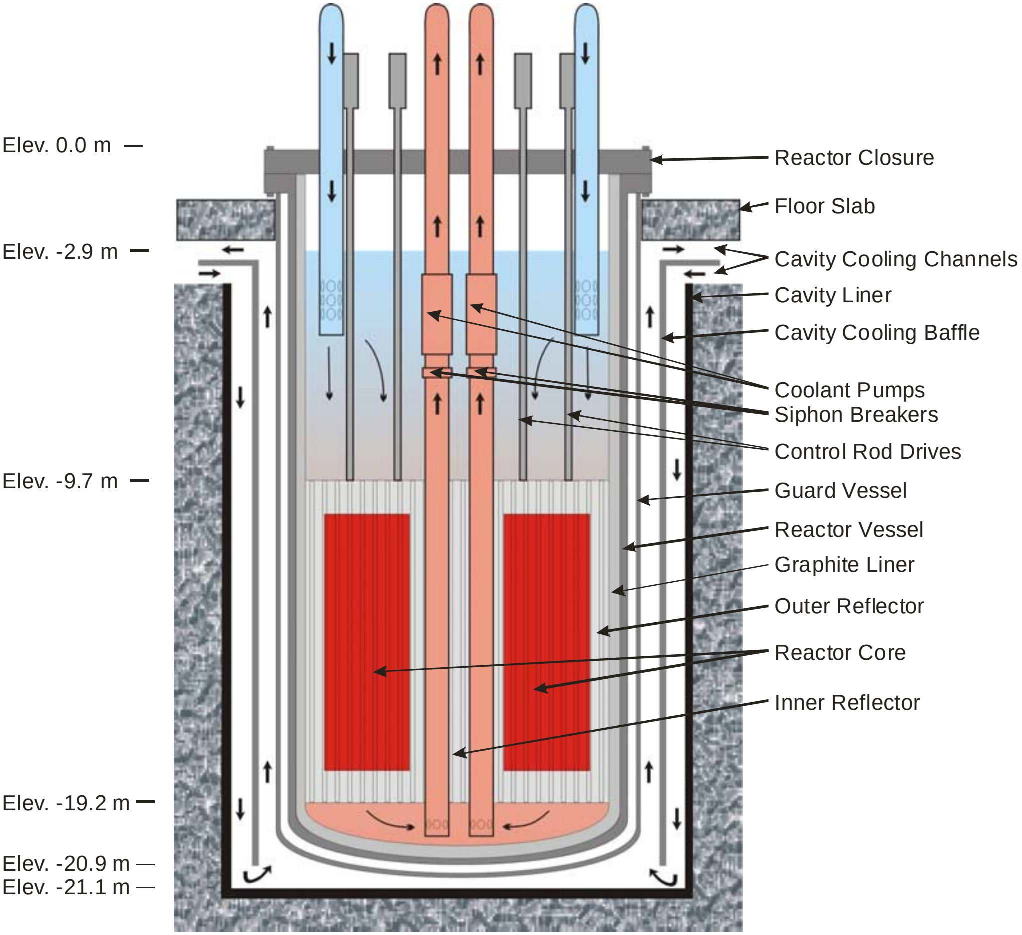
- Same fuel as used in gas-cooled high-temperature reactors
- Peak operating limit: 1250ºC
- Failure temperature: 1600ºC
- Graphite blocks provide neutron moderation and heat transfer to coolant

Models of Conceptual AHTR Design





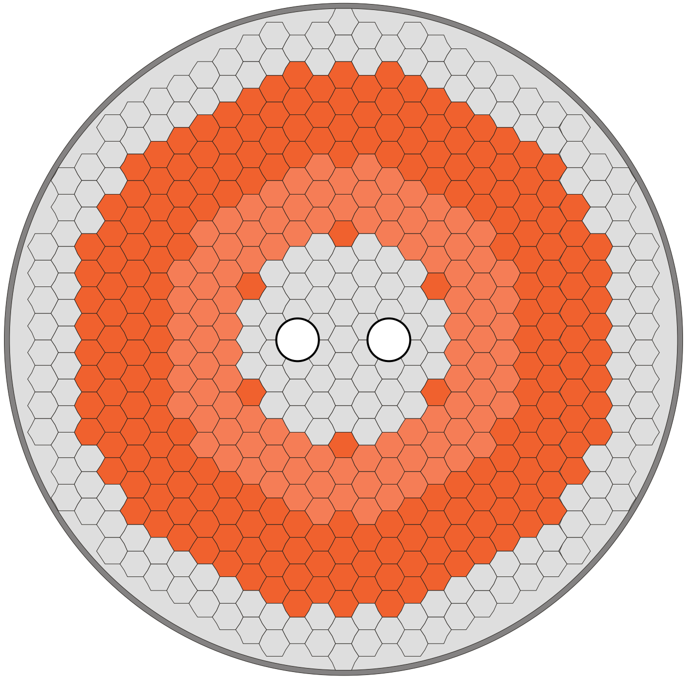
AHTR 9.0m Vessel Allows 2400 MW(t) Core



Elev. 0.0 m
Elev. -2.9 m
Elev. -9.7 m
Elev. -19.2 m
Elev. -20.9 m
Elev. -21.1 m

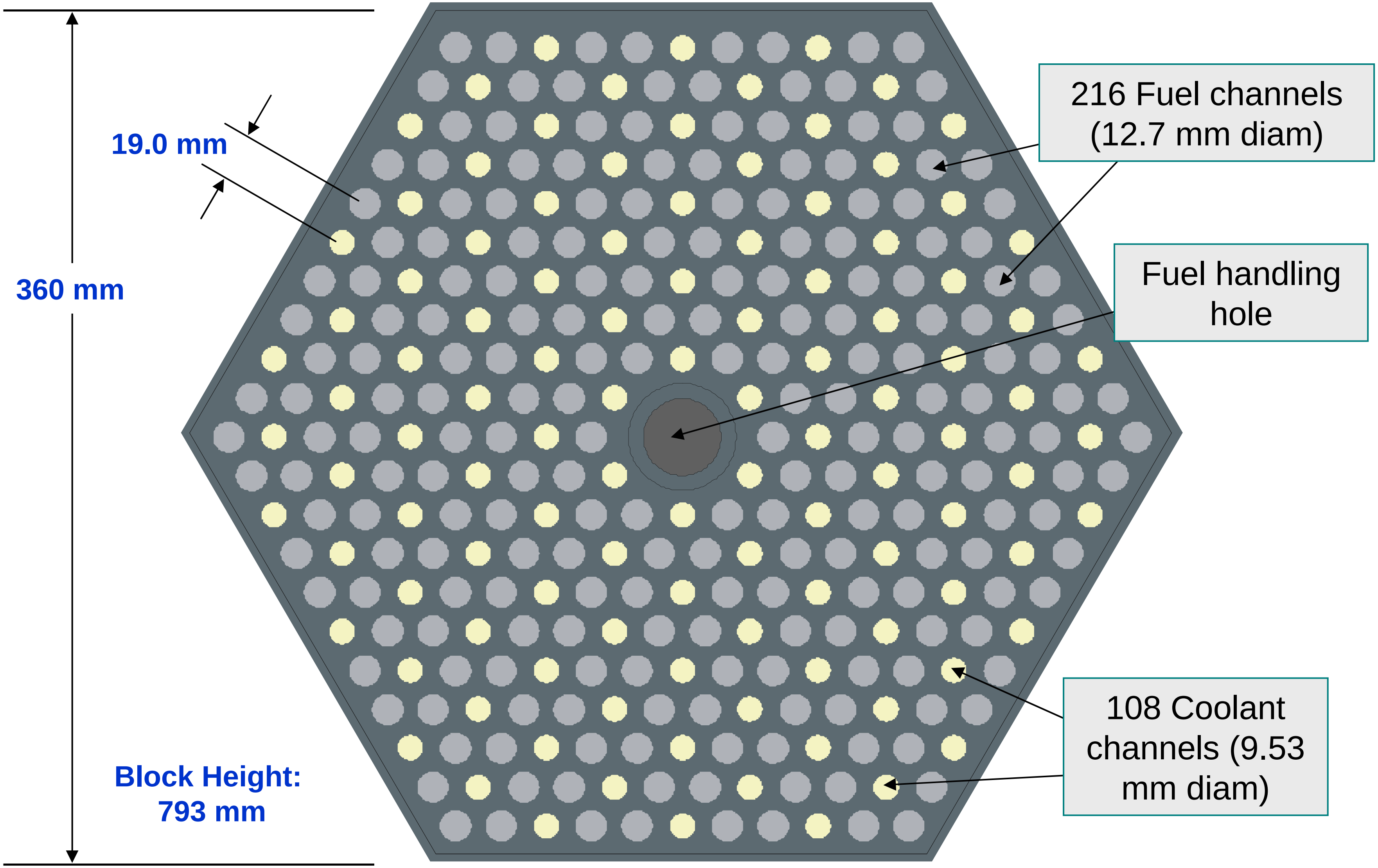
Reactor Closure
Floor Slab
Cavity Cooling Channels
Cavity Liner
Cavity Cooling Baffle
Coolant Pumps
Siphon Breakers
Control Rod Drives
Guard Vessel
Reactor Vessel
Graphite Liner
Outer Reflector
Reactor Core
Inner Reflector

102 GT-MHR fuel columns
222 Additional fuel columns
324 Total fuel columns



Power density = 8.3 MW/m^3

AHTR Fuel Block (standard GT-MHR block)



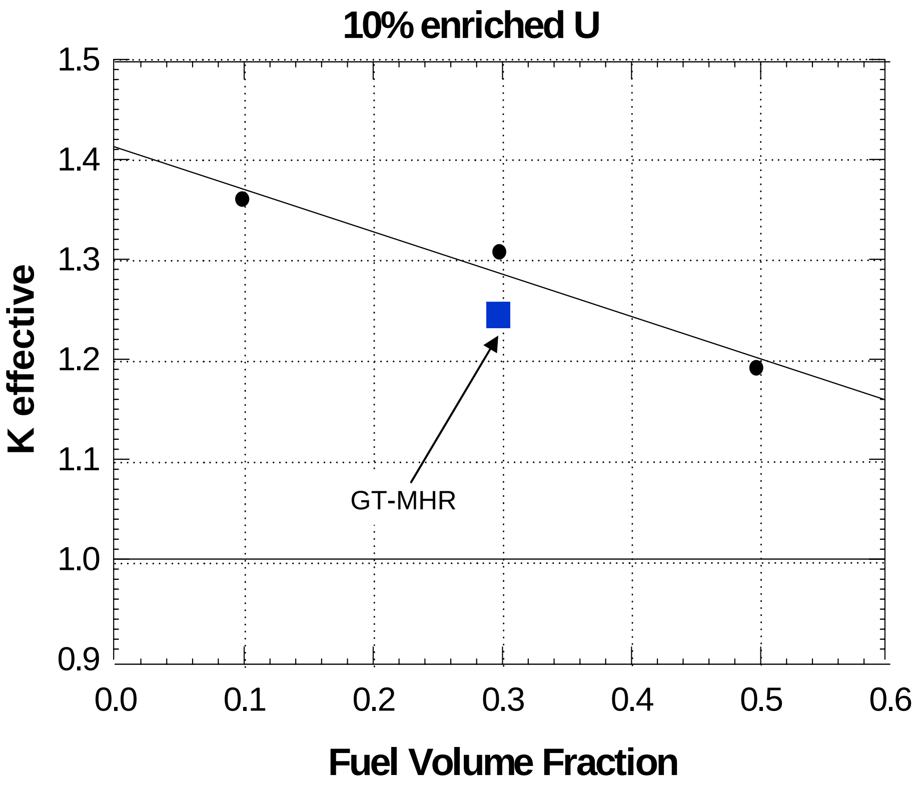
Block Height:
793 mm

216 Fuel channels (12.7 mm diam)

Fuel handling hole

108 Coolant channels (9.53 mm diam)

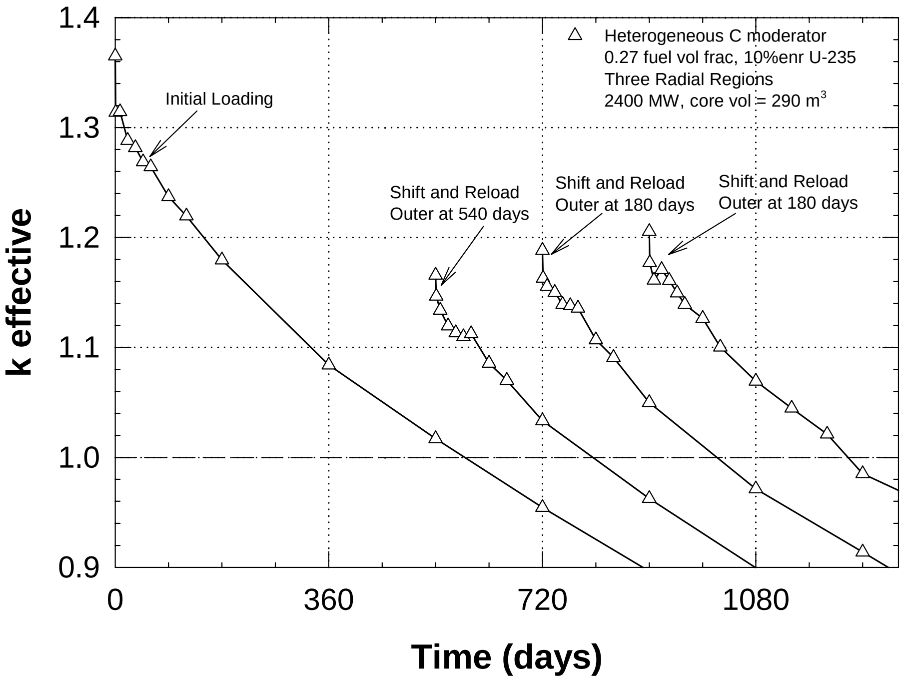
AHTR And GT-MHR Have Similar Neutronics



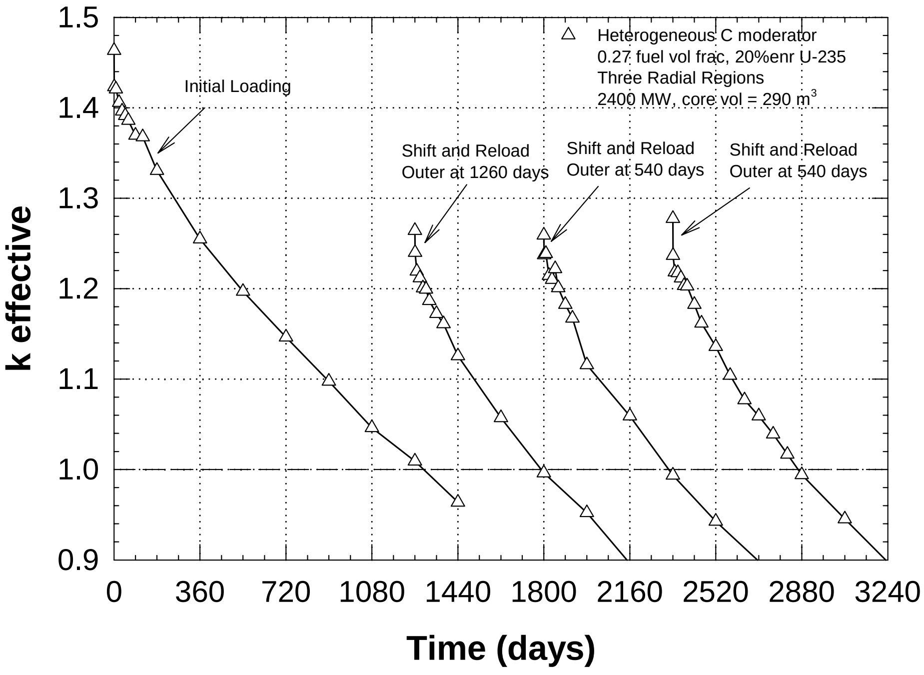
- Excess reactivity similar for given core loading
- Neutron lifetime ~1ms
- k_{eff} increases with higher moderator to fuel ratio (undermoderated in design region)
- Large negative temperature feedback due to Doppler effects (~ -$0.01/K)
- Similar fuel burnup/ fuel cycle behavior

AHTR Burnup Predictions for Different Fuel Enrichments (3 Zone Core)

10% Enrichment (shuffle time ~240 d)

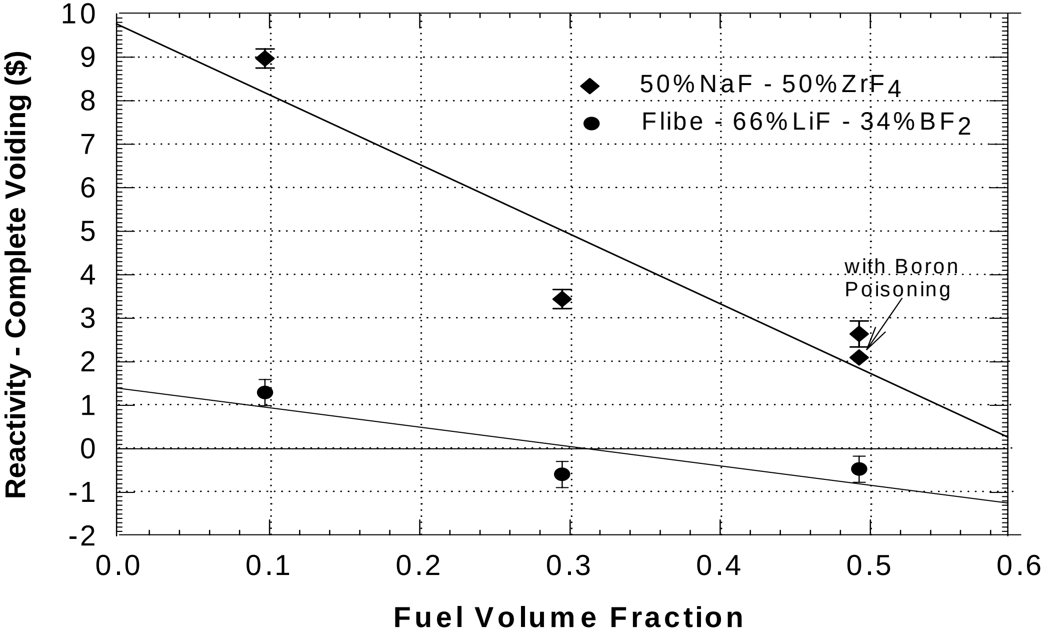


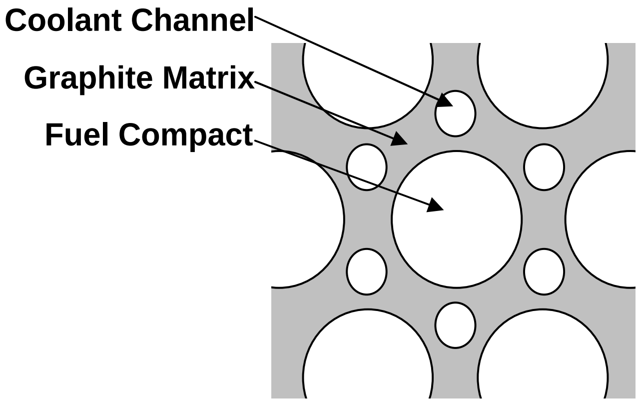
20% Enrichment (shuffle time ~540 d)



Key Difference: AHTR Void Coefficient

Depends on Salt Composition and Core Configuration


10% enriched U



Coolant Fraction = 10%
Fuel Fraction = 50%

Coolant Channel Radius = 0.4 cm
Fuel Radius = 1.265 cm
Pitch = 3.407 cm

Fuel Particle Packing Fraction = 0.3

Void Coefficient vs. Salt Choice

SNL Model With No Burnable Poisons; Pure ^{7}Li in Salt

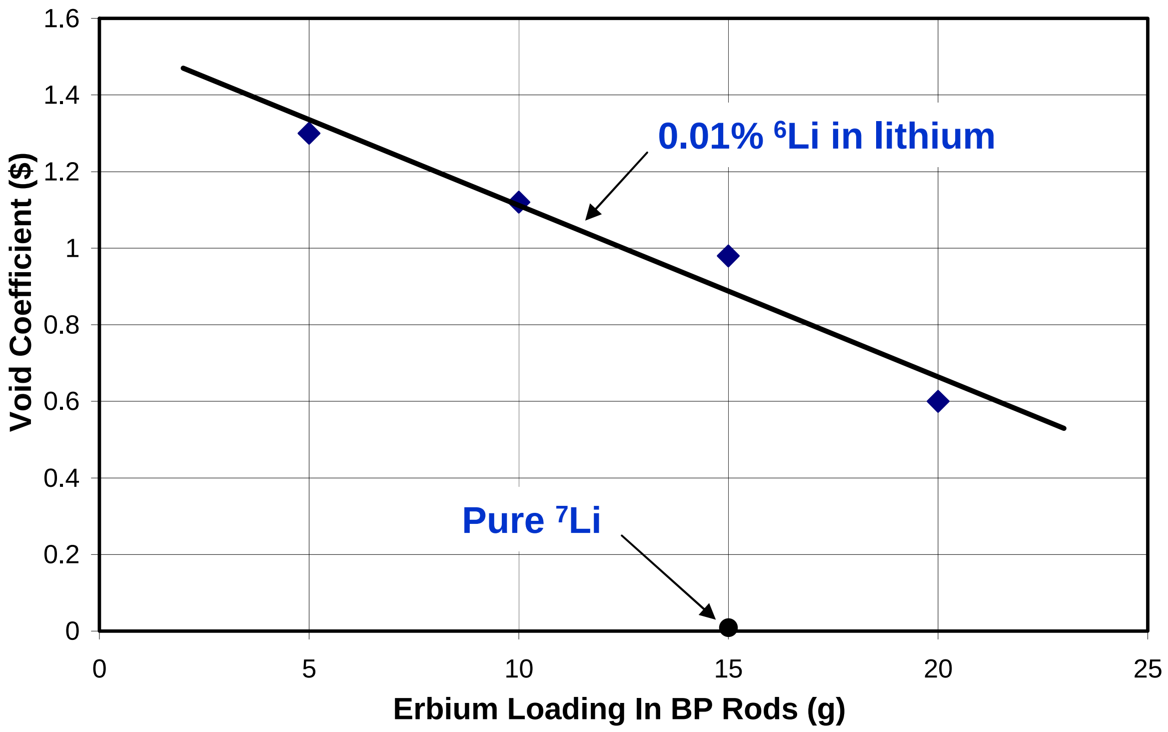
Salt	Total Void Reactivity Effect ($)
BeF_2	-1.46
LiF/BeF_2 (66/34)	-0.47
MgF_2/BeF_2 (50/50)	-0.49
-------------------------	-------------------------
LiF (Li-7)	+0.16
ZrF_4/BeF_2 (50/50)	+0.43
ZrF_4/LiF (52/48)	+1.25
-------------------------	-------------------------
NaF/BeF_2 (57/43)	+1.82
ZrF_4	+1.41
NaF/ZrF_4 (25/75)	+1.88
NaF/ZrF_4 (50/50)	+2.64
NaF/ZrF_4 (75/25)	+3.82
NaF	+7.05

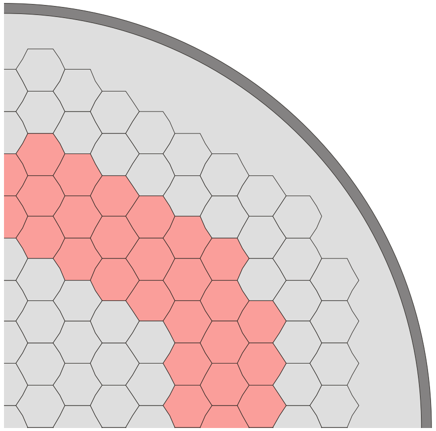
- Example for 10% coolant fraction, 50% fuel fraction and complete core voiding
- Moderation benefit dominates for lower-Z elements in salt
- Absorption dominates for higher-Z elements in salt

Ranking (best to worst)

Be, Li-7, Mg, Zr, Na

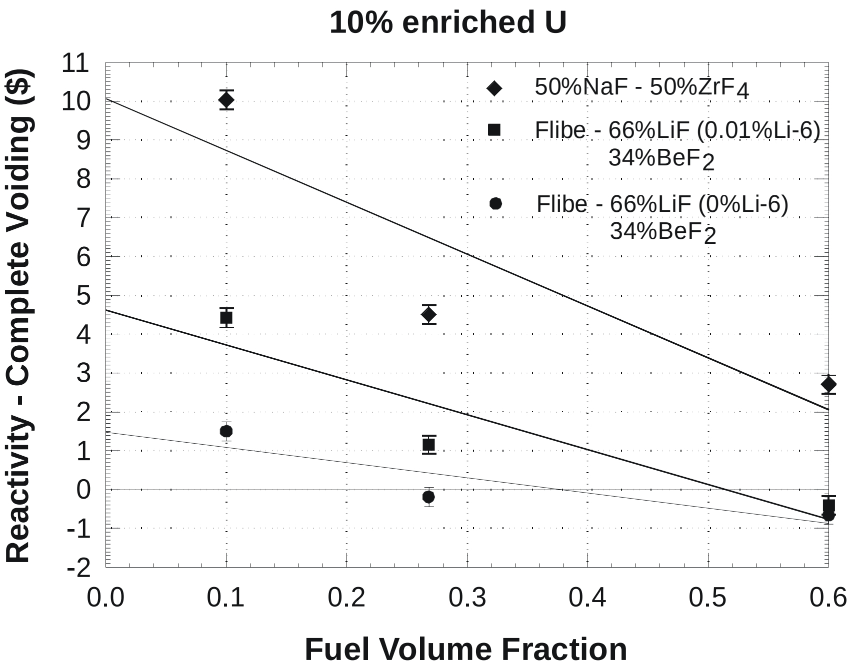
Impact of Burnable Poisons and ^{7}Li Purity on Void Coefficient – ORNL Model

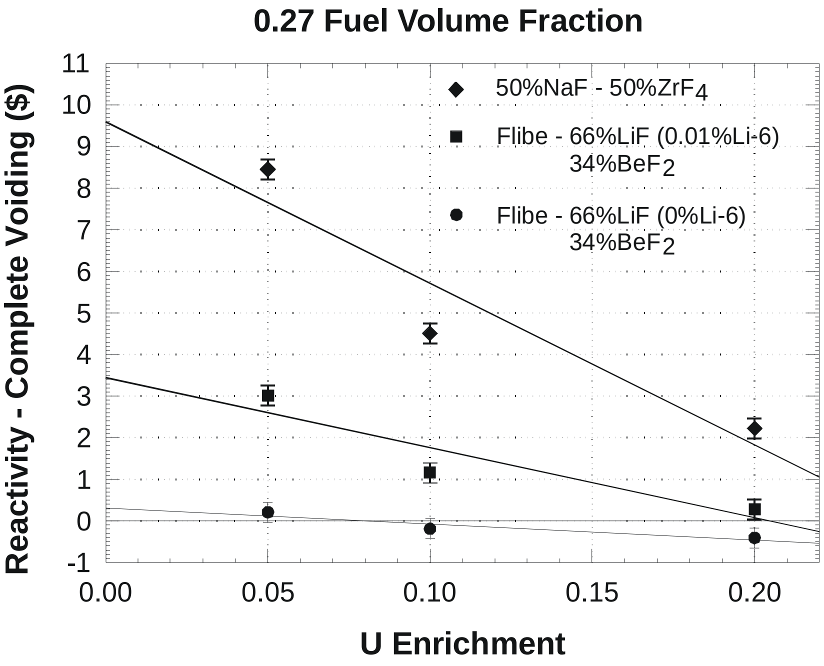




- $2LiF\text{-}BeF_2$ Salt
- 1 mol% VF_3 Buffer
- 102-column core (600MW)
- 14 BR rods per assembly
- 14 wt% ^{235}U enrichment

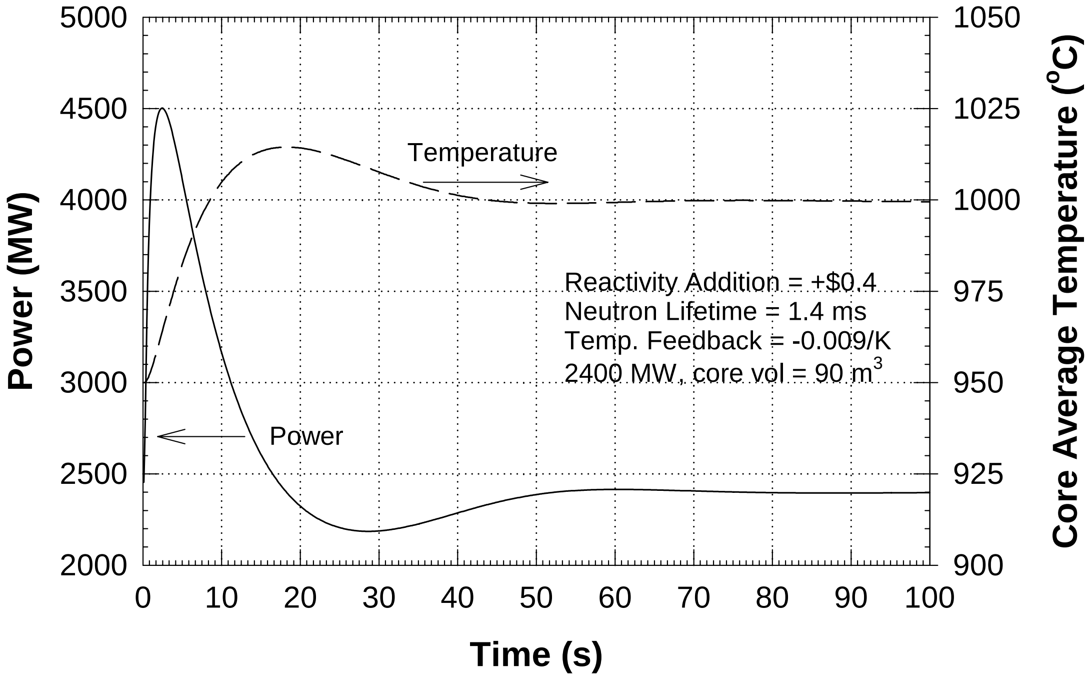
Variation of Void Coefficient With Fuel Fraction and Enrichment





AHTR Transient Behavior With Competing Feedback Effects

Example: Na-Zr Salt (worst salt) with 20% Flow Blockage: +$0.40 Instantaneous Reactivity Insertion



- **Core power increases but is mitigated by increase in fuel temp of ~60°C**
- **Slow transient (10's of seconds)**
- **Core reaches lower equilibrium power**
- **Concern is heat-up of blocked fuel columns (~9 °C/s)**

Conclusions on Void Coefficient

- **Decreases with increasing uranium loading and increasing burnable poison loading**
- **Depends on the neutron spectrum – decreases with increasing U/C ratio**
- **Is very sensitive to ^{7}Li isotopic purity in 2LiF-BeF$_2$ salt**
- **Increases with increasing coolant hole diameter**
- **Relatively insensitive to fuel burnup**
- **Options for reducing:**
  - **higher fuel loading (volume fraction or enrichment)**
  - **higher burnable absorber loading**
  - **poisoning the graphite blocks**
  - **Different fuel/coolant geometry**
- **Need substantial neutronics analysis to evaluate options**

Lithium Purity Considerations

- Large inventory of 99.99% ^{7}Li is available

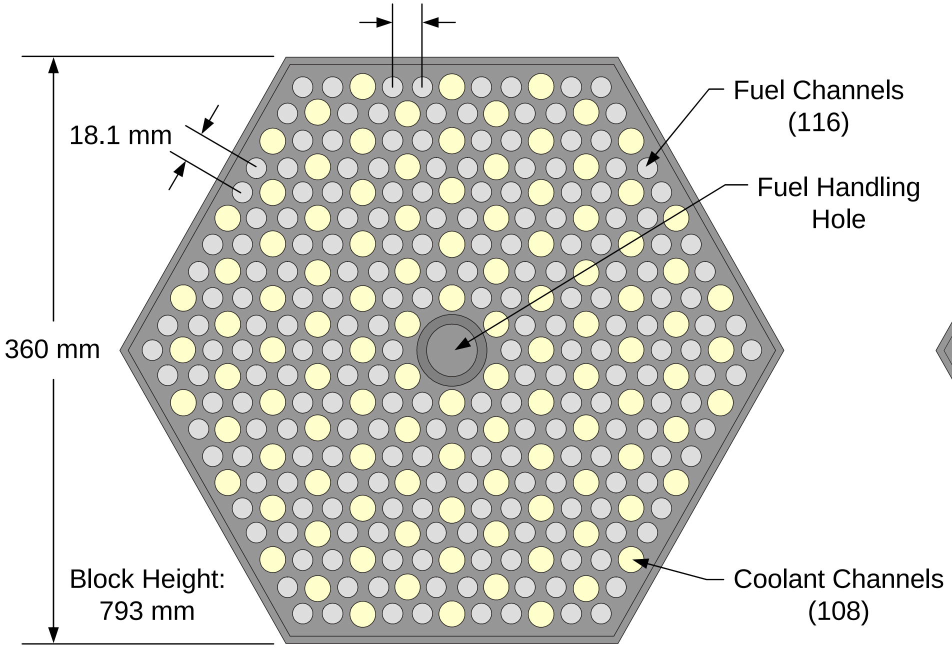
- Enriching to 99.999% ^{7}Li (0.001% ^{6}Li) will be very expensive

- ^{6}Li level will eventually reach equilibrium at 0.001%
  - Burnout of initial ^{6}Li “contamination”
  - Production of ^{6}Li primarily from Be(n,α) reaction
  - Will take a few years to reach equilibrium

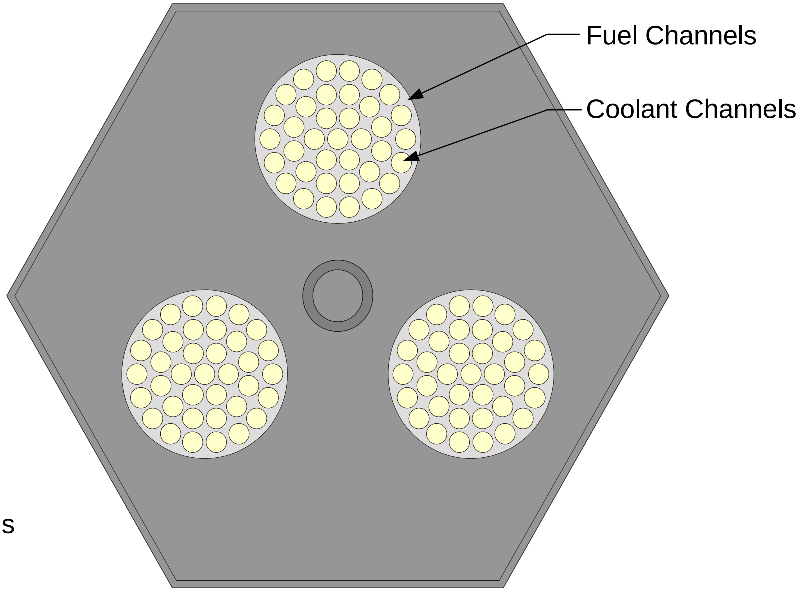
- Need to develop acceptable design with 4-9s ^{7}Li (maybe 0.99995)

Heterogeneous Fuel Designs May Help Ensure A Negative Void Coefficients

Homogeneous Fuel



Heterogeneous Fuel



Future Physics Investigations

- Control rods (number and location)
- Reserve shutdown mechanism
- Power density
- Power peaking
- Decay heat
- Modeling the fuel double heterogeneity
- Validation of methods

▶ Now in progress