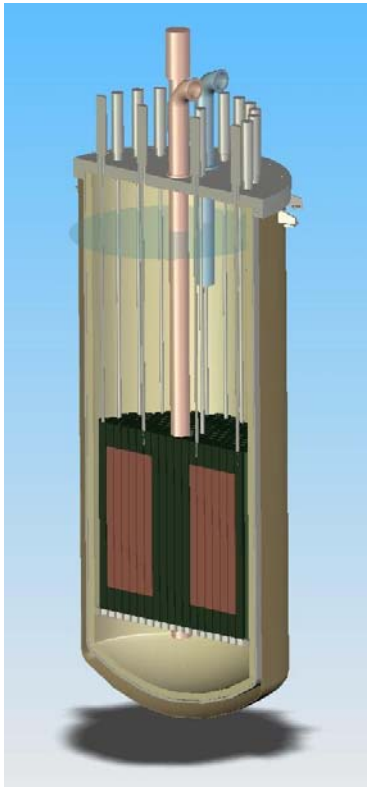
The Advanced High-Temperature Reactor

Dr. Charles Forsberg
Oak Ridge National Laboratory
P.O. Box 2008; Oak Ridge, TN 37831
E-mail: forsbergcw@ornl.gov
Tel: (865) 574-6783



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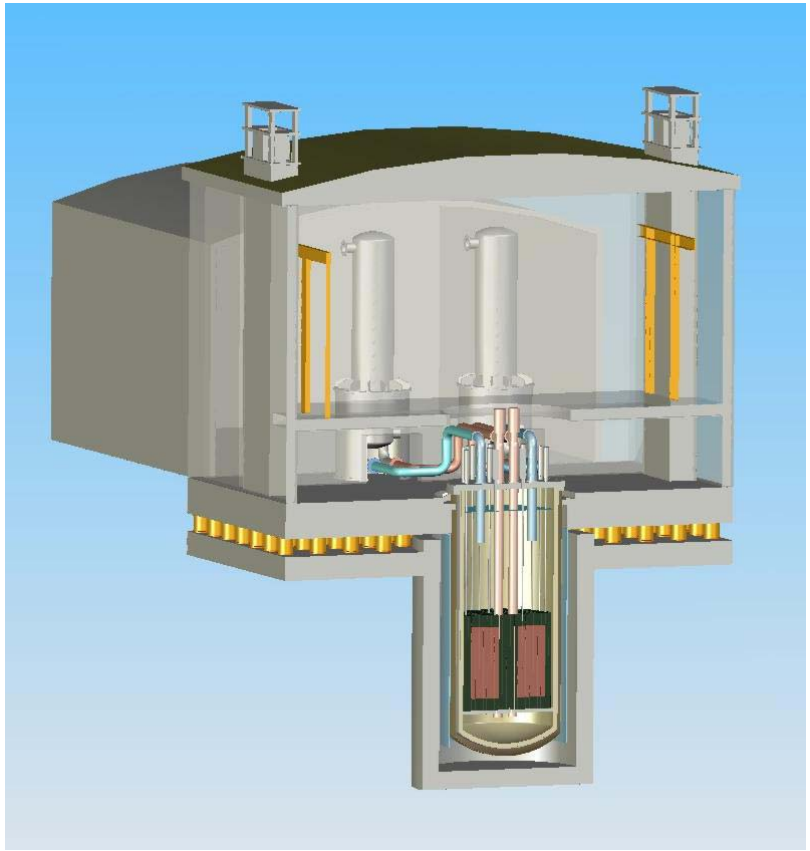


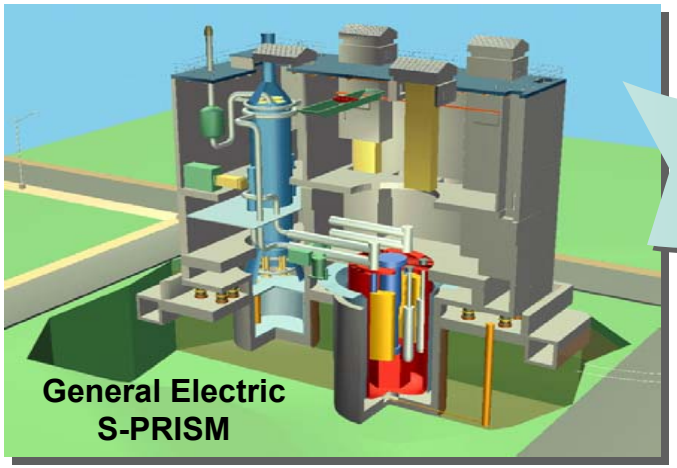
- Introduction
- Fuels
- Molten Fluoride Salt Coolants
- Materials
- Facility Design
- Reactor Core Design
- Energy Conversion
- Economics
- Research And Development

History, Characteristics, and Status: The Advanced High-Temperature Reactor

- New reactor concept that combines three characteristics in a single reactor
  - High temperature for electricity and H_2 production
  - Passive safety (same safety basis as modular gas-cooled reactors)
  - Large power output (improved economics)
- Joint effort
  - Oak Ridge National Laboratory
  - Sandia National Laboratories
  - University of California at Berkeley
- A series of studies and evaluations have been conducted, but a point design has not been fully developed

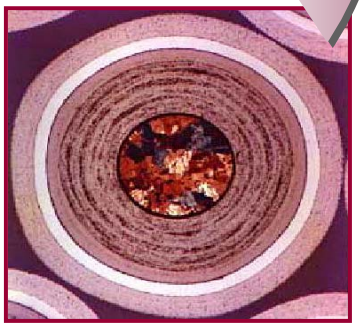
The Advanced High-Temperature Reactor

Combining Existing Technologies In A New Way



Passively Safe Pool-Type Reactor Designs

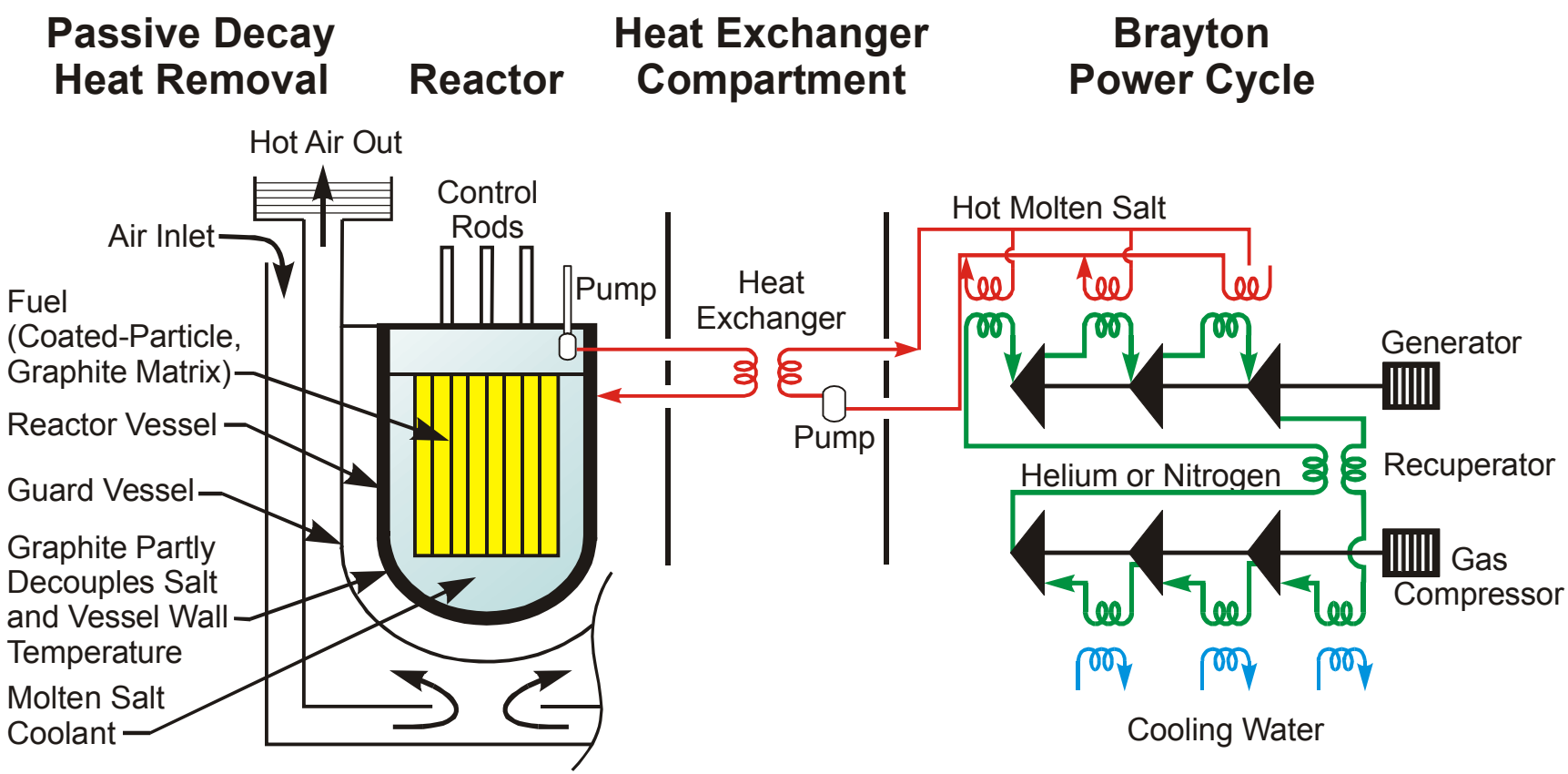
Brayton Power Cycles



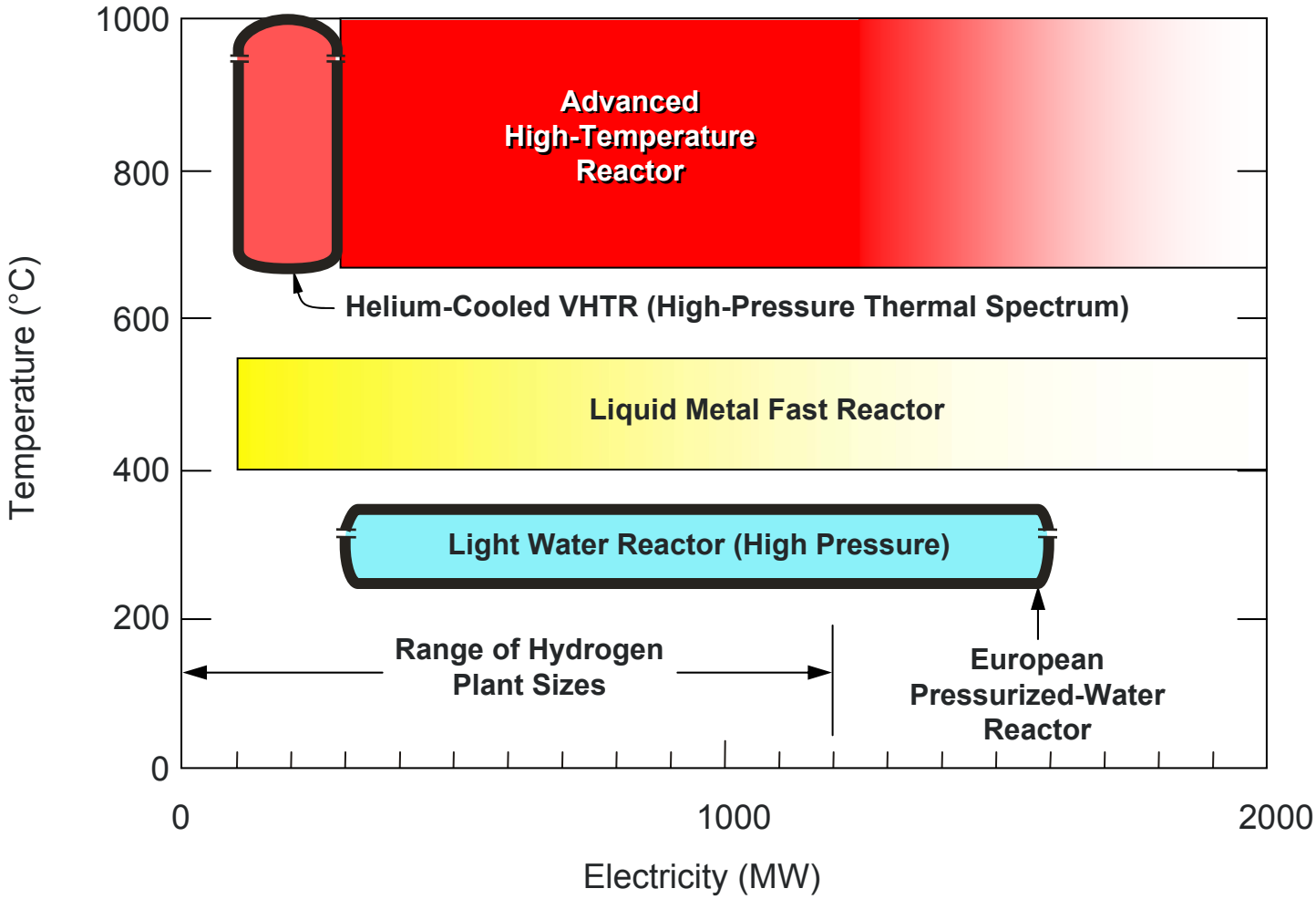
High-Temperature Coated-Particle Fuel

High-Temperature, Low-Pressure Transparent Molten-Salt Coolant

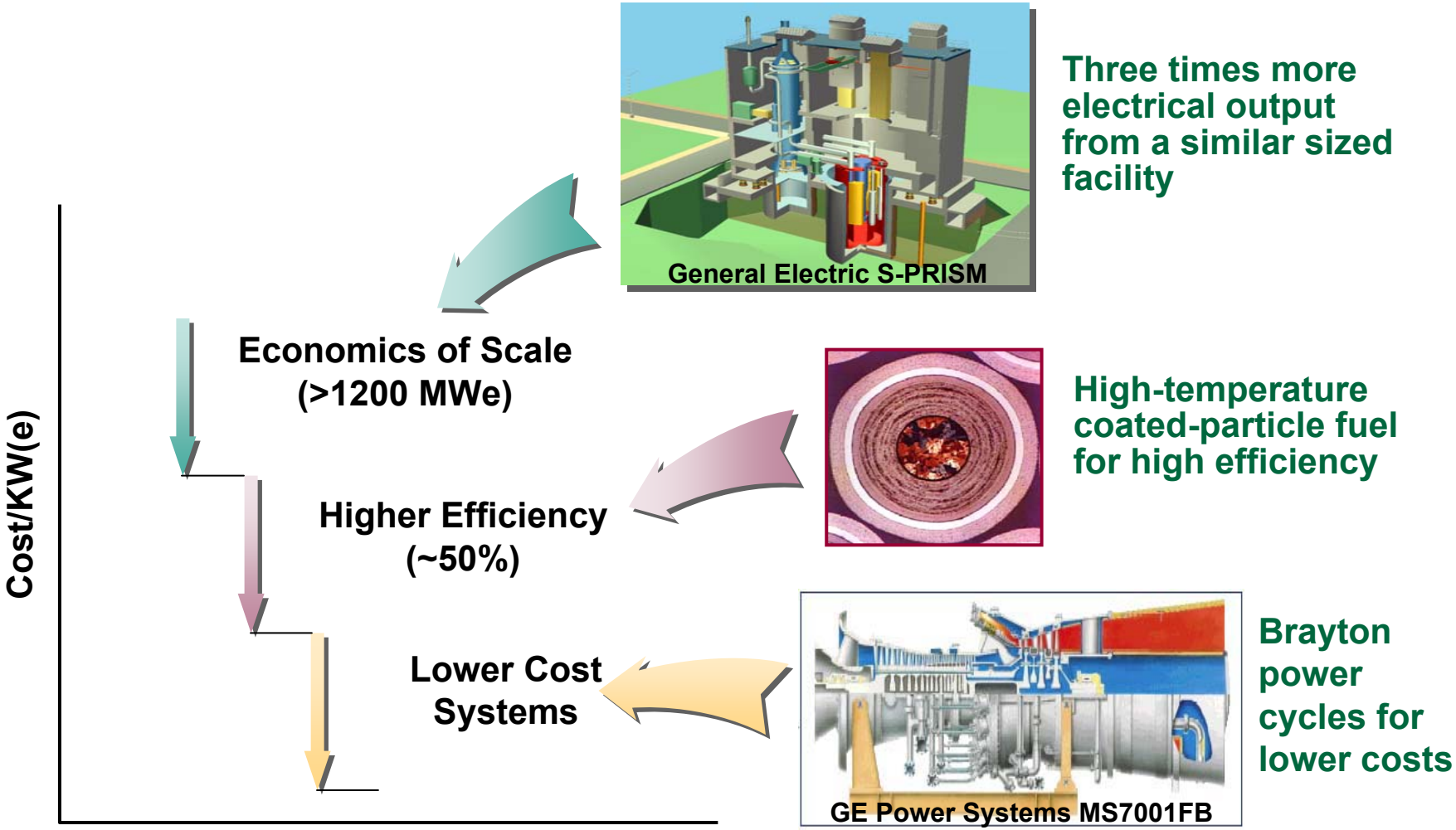
The Advanced High Temperature Reactor



The AHTR Extends High-Temperature Capabilities To Large Reactors



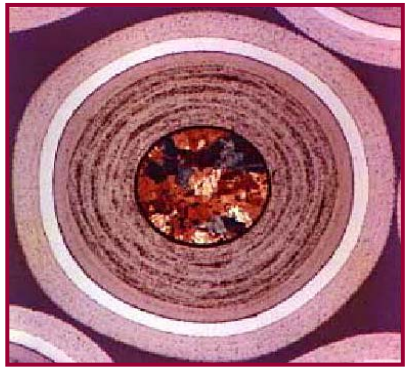
The Economic Goal Is To Drive Costs Significantly Below $1000/kW(e)



The Safety Goal Is To Match or Exceed Modular High Temperature Reactors

Passively Safe Pool-Type Reactor Design

High-Temperature Robust Fuel



Low-Pressure Low-Stored-Energy Molten-Salt Coolant

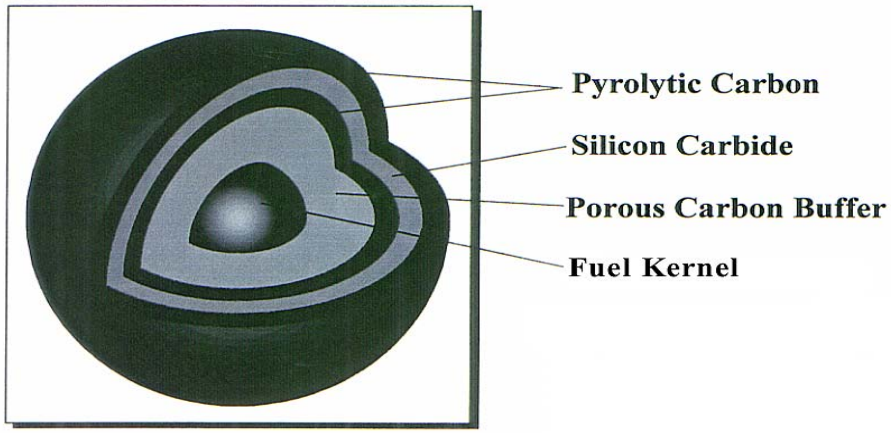
Superior Safety

Fuels

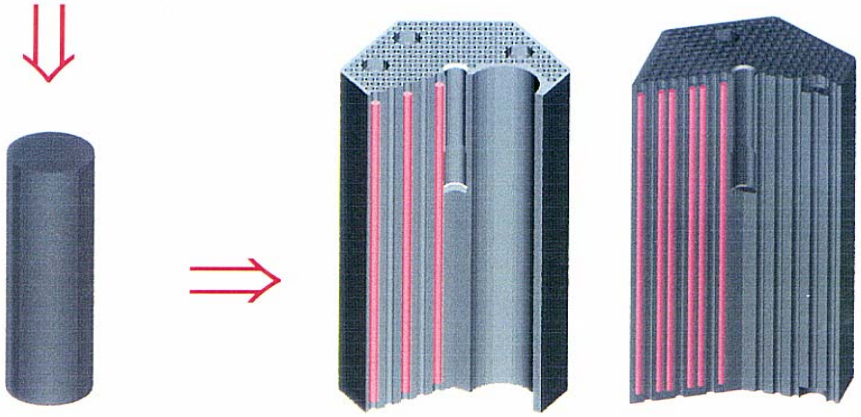
Only One Type of High-Temperature Nuclear Fuel Has Been Demonstrated on a Significant Scale

The AHTR Uses Coated-Particle Graphite Fuel Elements
(Peak Operating Temperature: 1250ºC; Failure Temperature >1600ºC)

Same Fuel as Used in Gas-Cooled Reactors



FUEL PARTICLE

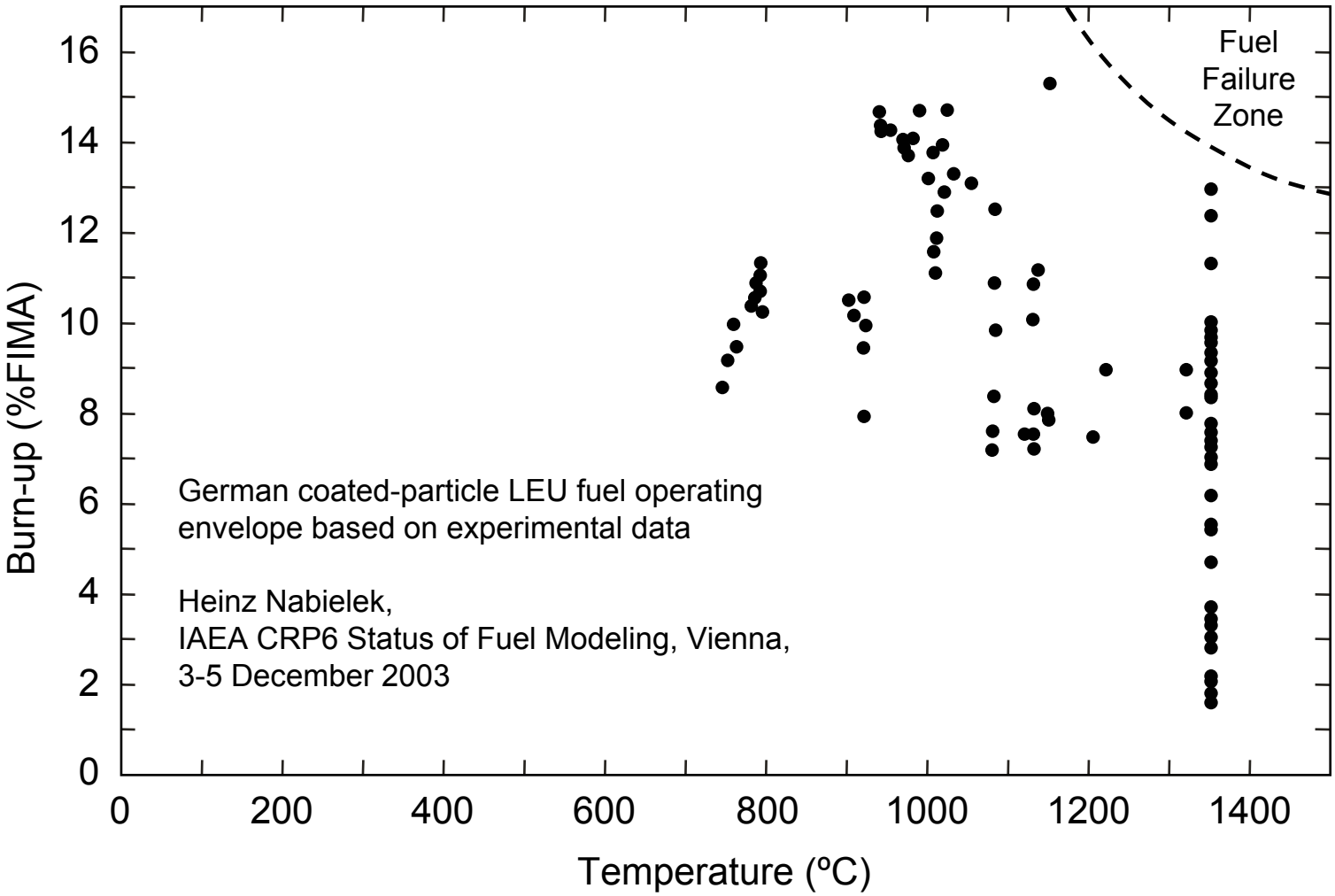


FUEL COMPACT

FUEL ASSEMBLIES

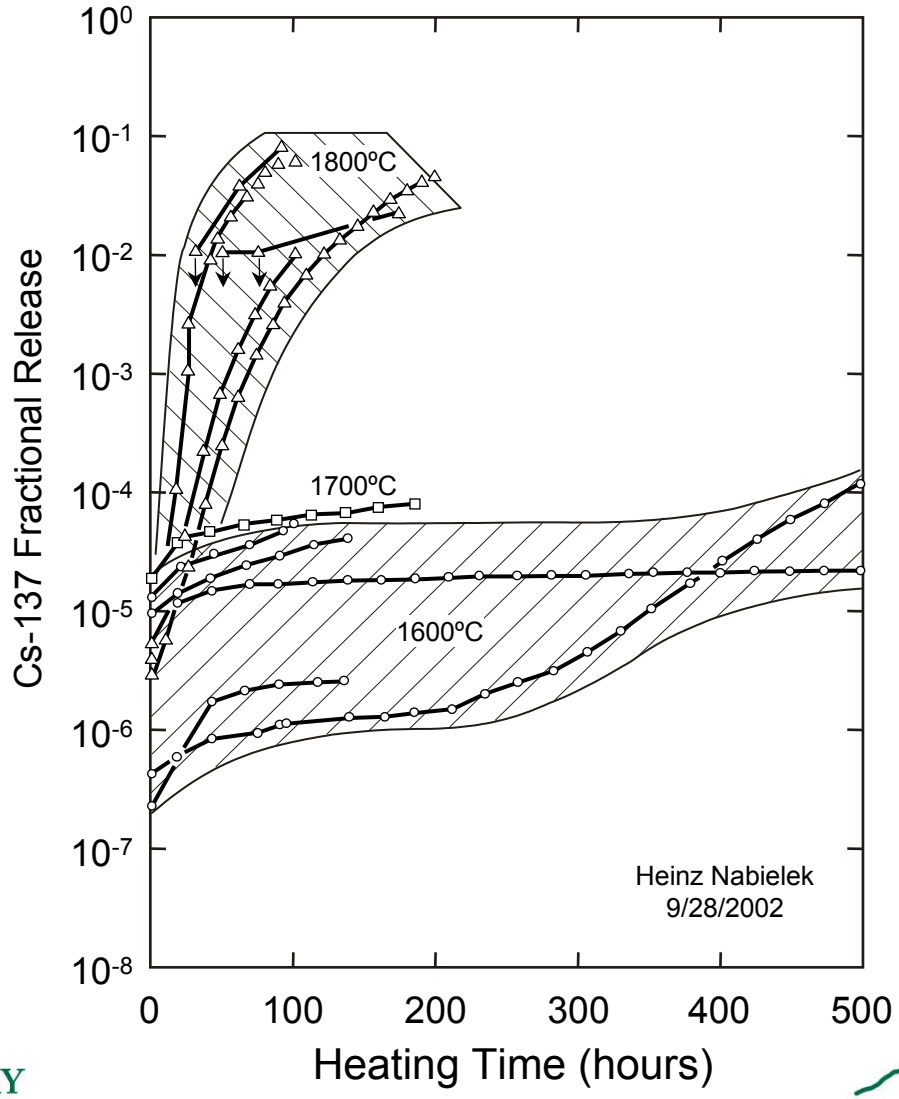
- Fuel particle with multiple coatings to retain fission products
- Fuel compact contains particles
- Compacts inserted into graphite blocks
  - Several options for graphite geometry (prismatic, rod, pebble bed, etc.)
  - Base design uses prismatic; other options viable
- Graphite blocks provide neutron moderation and heat transfer to coolant

Coated-Particle LEU Fuels Have High-Temperature Performance Capabilities



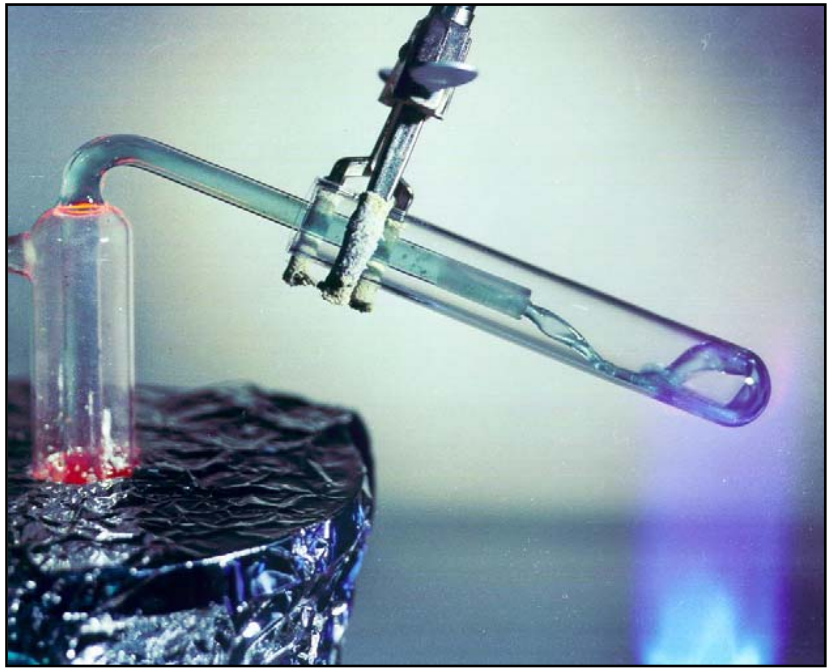
Coated Particle Fuels Have Low Radionuclide Releases Under Accident Conditions To ~1600ºC

Cesium Release Fraction From Heated Fuel Versus Time



Molten Fluoride Salt Coolants

Only Two Coolants Have Been Demonstrated As Compatible with High-Temperature Graphite Fuels



Helium

(High-Pressure/Transparent)

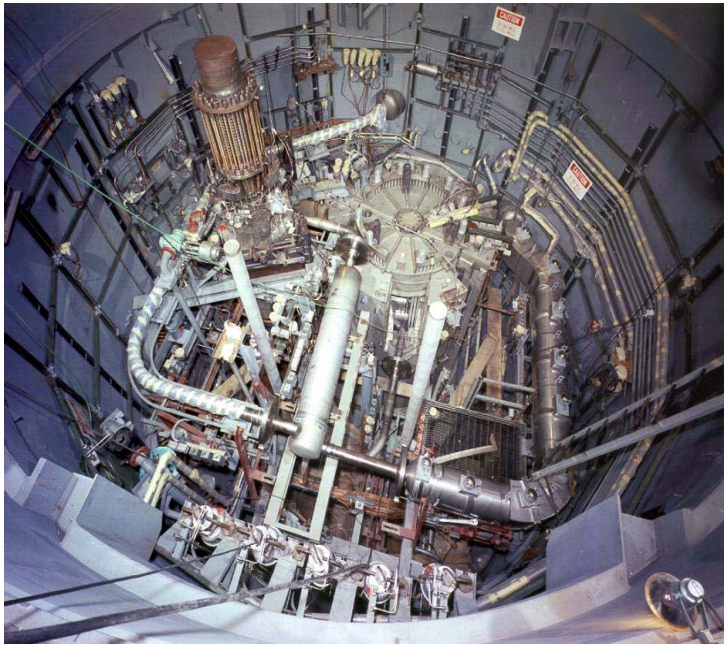
Molten Fluoride Salts

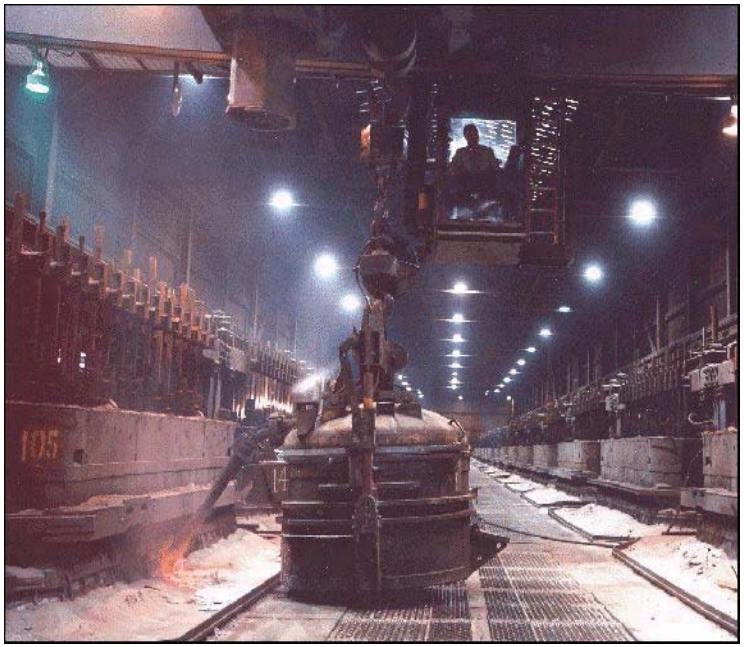
(Low Pressure/Transparent)

The AHTR Uses a *Molten Salt Coolant*

Good Heat Transfer, Low-Pressure Operation, And Transparent (In-Service Inspection)

Molten Fluoride Salts Were Used in Molten Salt Reactors With Fuel in Coolant (AHTR uses clean salt and solid fuel)





Molten Fluoride Salts Have Been Used for a Century to Make Aluminum in Graphite Baths at 1000°C

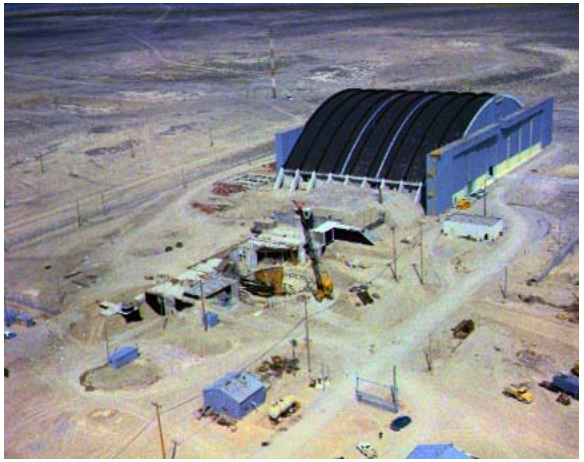
Molten Salt Technology Was Developed To Support Several Large (1950-1970) Programs

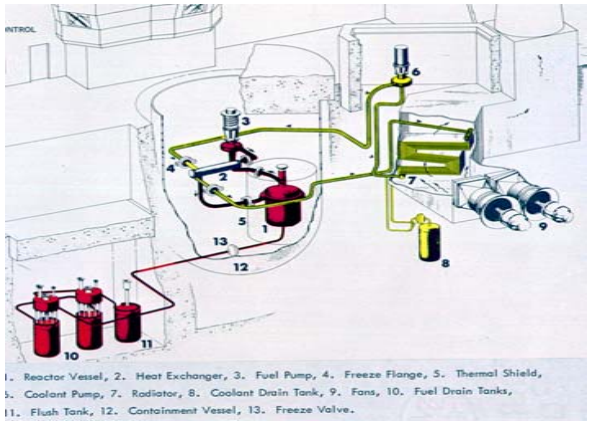
Molten Salt Reactors: Fuel Dissolved In Coolant

Aircraft Nuclear Propulsion Program

← ORNL Aircraft Reactor Experiment:
2.5 MW; 882ºC
Fuel Salt: Na/Zr/F

INEEL Shielded Aircraft Hanger→

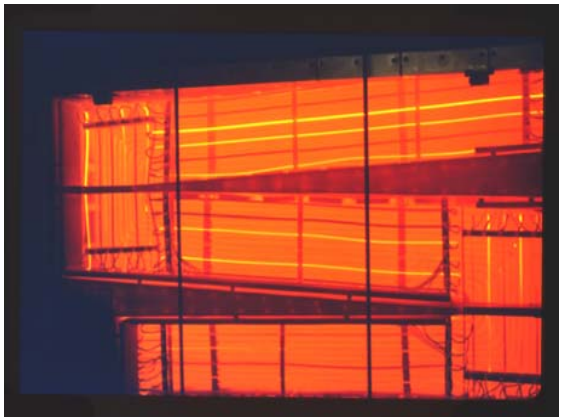




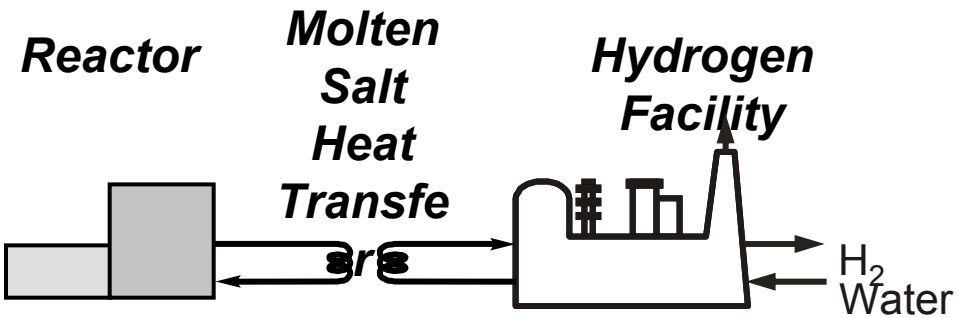
Molten Salt Breeder Reactor Program

← ORNL Molten Salt Reactor Experiment
Power level: 8 MW(t)
Fuel Salt: ^{7}Li/Be/F,
Clean Salt: Na/Be/F

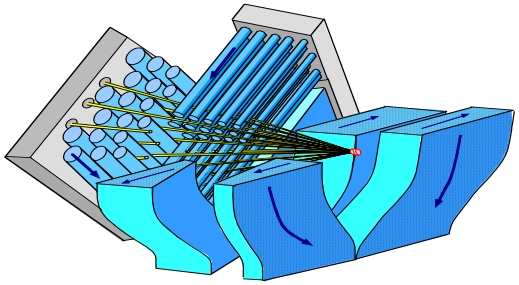
Air-Cooled Heat Exchangers →



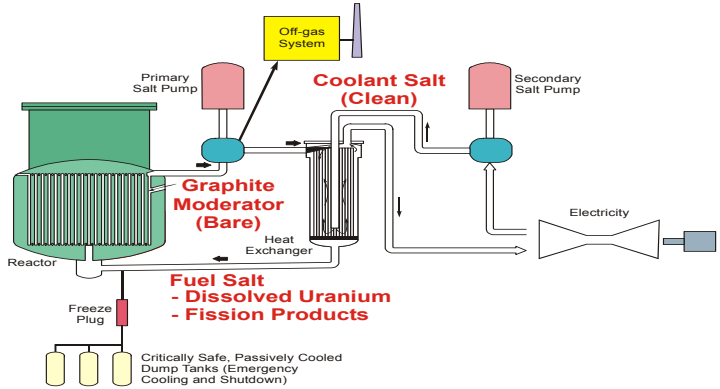
Molten-Salt Technology Is Being Developed for Multiple Future Applications



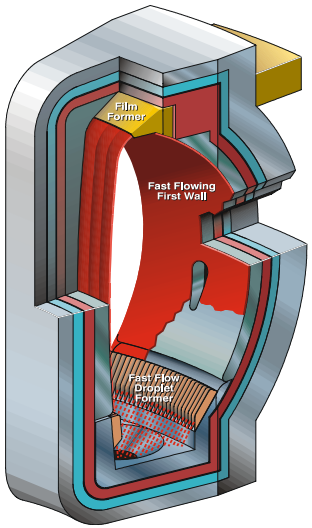
Reactor to Hydrogen Production Facility



Heavy-Ion Inertial Fusion



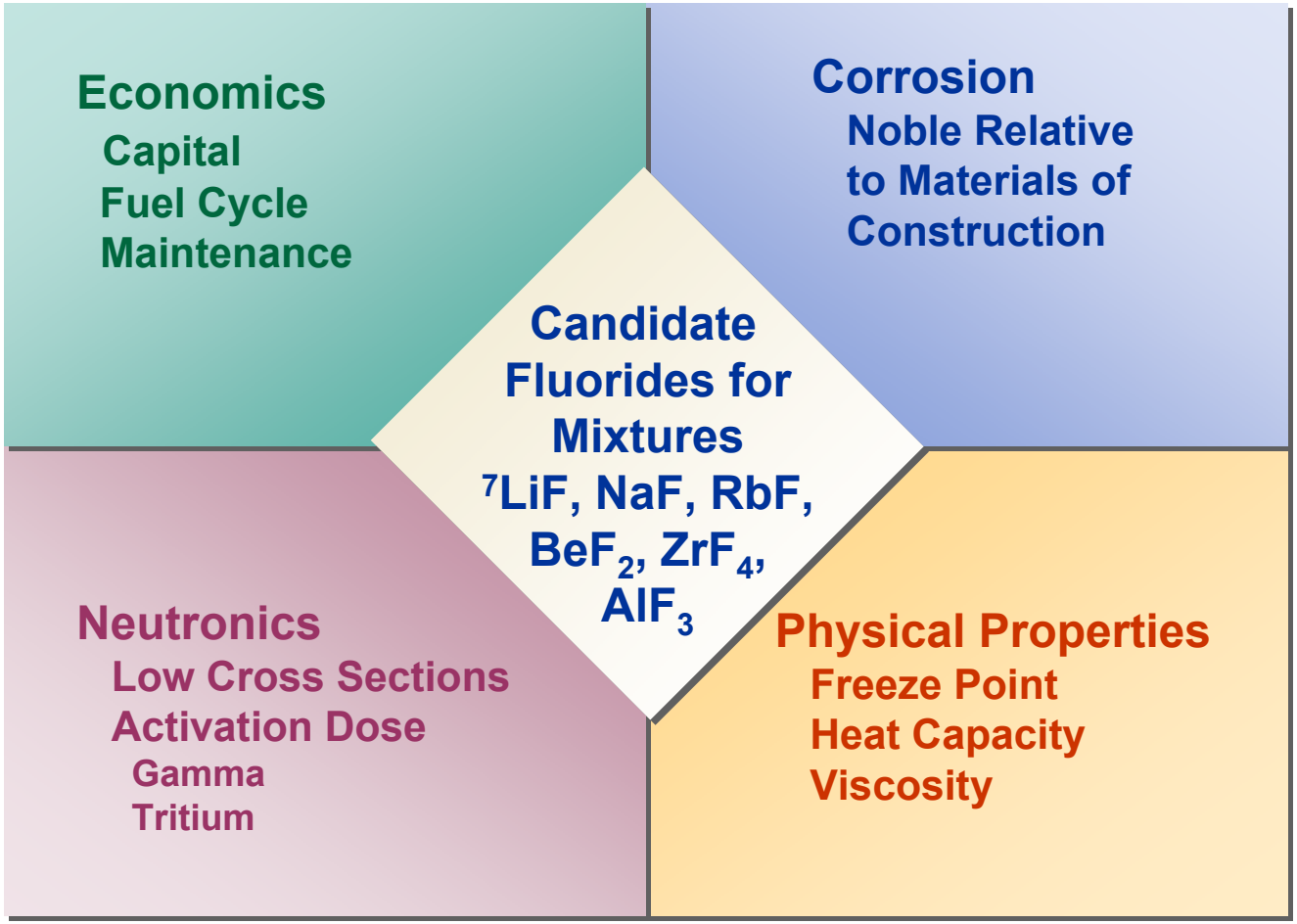
Molten Salt Reactor (EC and France)



Magnet Fusion Tokamak

Different Reactor Applications Require Different Mixtures of Molten Fluoride Salts

[Aircraft (Na:Zr), Breeder (Fuel: ^{7}Li:Be; Clean Secondary Salt: Na:B)]



Physical Properties of Demonstrated Coolants

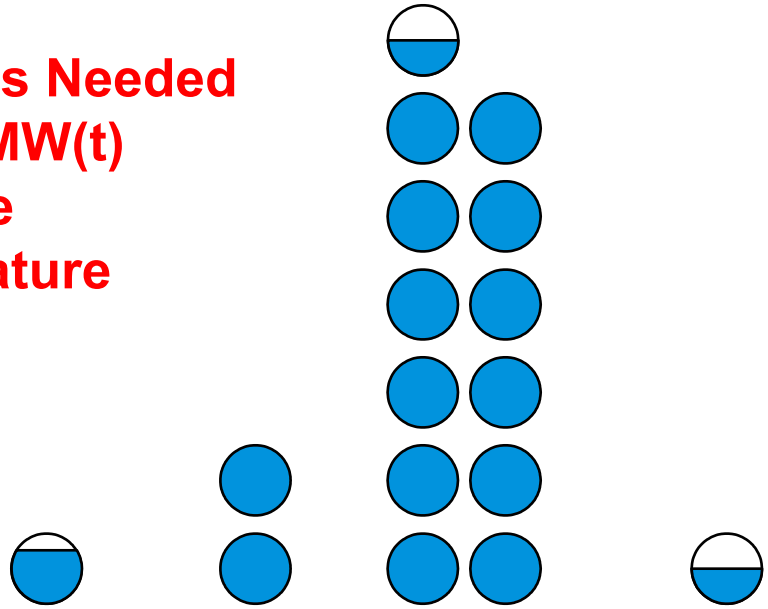
(Properties at ~700ºC Except for Pressurized Water at 290ºC)

Coolant	T_{melt} (ºC)	T_{boil} (ºC)	ρ (kg/m^3)	$\rho\ C_p$ (kJ/m^{3}ºC)	k (W/mºC)	$\nu \cdot 10^6$ (m^2/s)
$^7Li_2BeF_4$ (MSRE)	459*	1,430	1,940	4,540	1.0	2.8
0.58 NaF-0.42 ZrF_4 (ARE)	500*	1,290	3,140	3,670	~1	1.6
Sodium	97.8	883	790	1,000	62	0.25
Lead	328	1,750	10,540	1,700	16	0.13
Water	0	100	732	4,040	0.56	0.13

*Salts Used in Reactors. Examples of fluoride salts with lower melting points: Li-Na-Be (22-44-33): ~300ºC; Na-Rb-Zr (6-46-48): 380ºC

Molten Salts Have Superior Capabilities for Transport of Heat

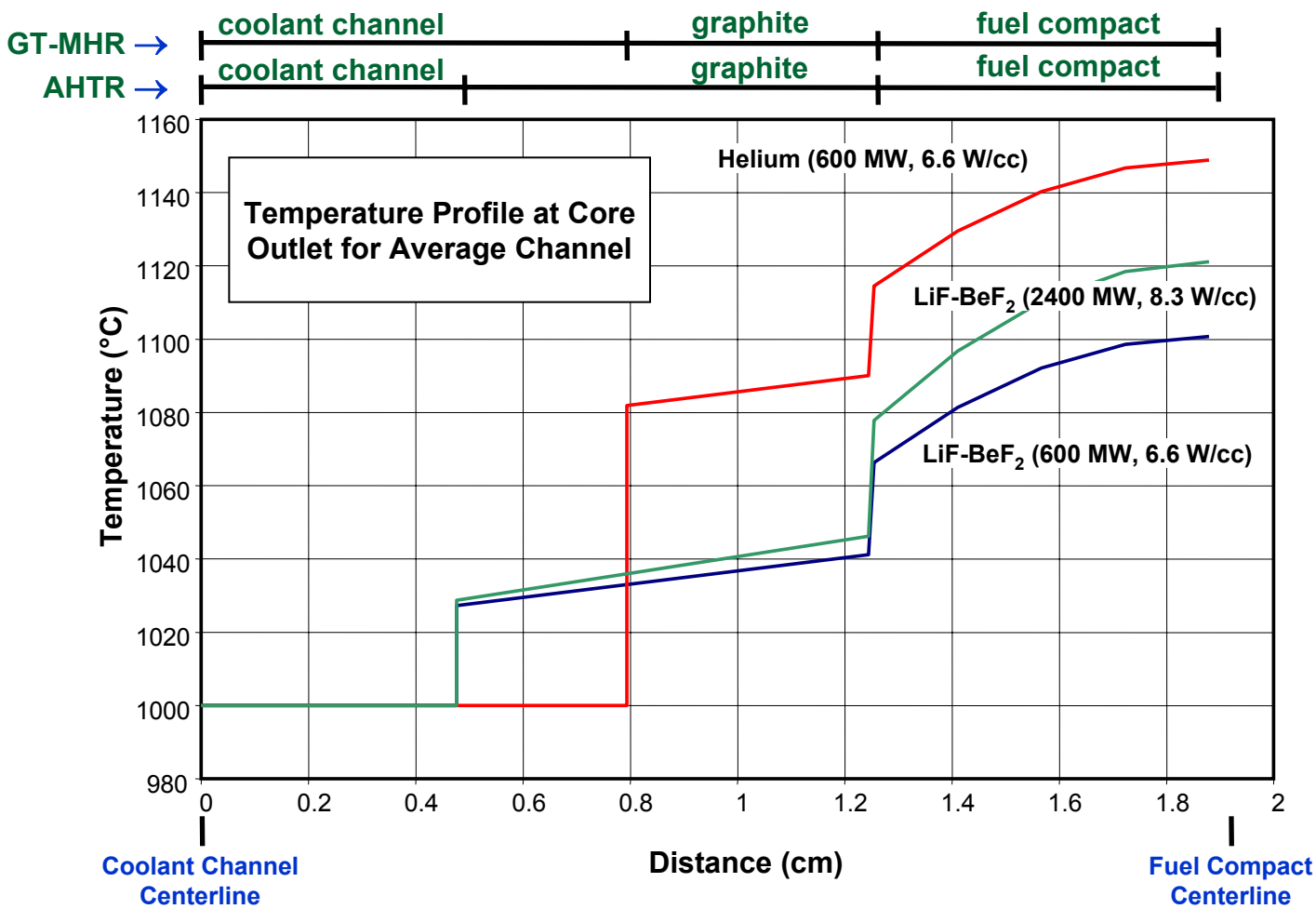
Number of 1-m-dia. Pipes Needed To Transport 1000 MW(t) With 100ºC Rise In Coolant Temperature



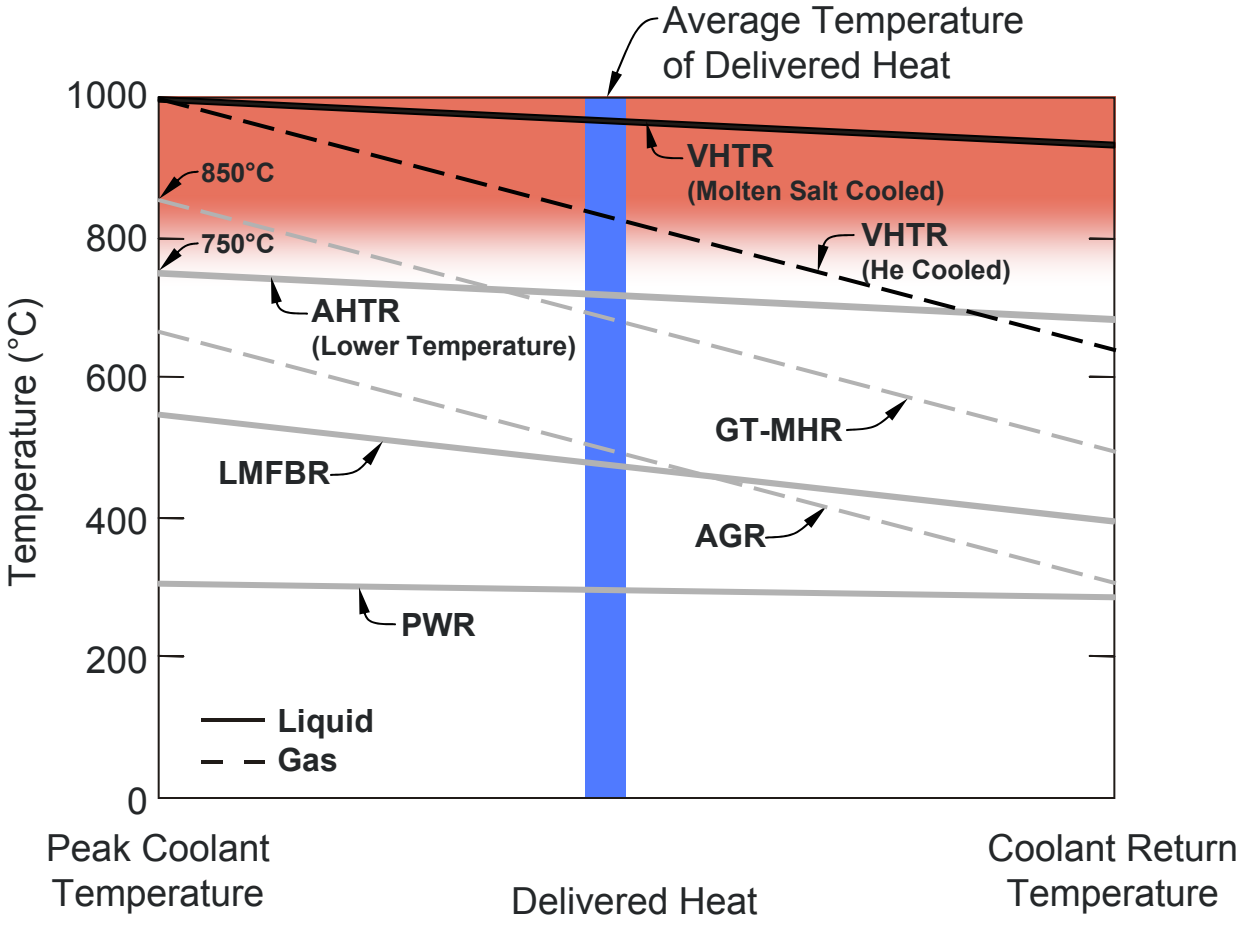
	Water (PWR)	Sodium (LMR)	Helium	Molten Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocities (m/s)	6	6	75	6

Liquids Remove Heat More Effectively Than Gas:

Cooler Fuel For the Same Coolant Exit Temperatures



For Any Coolant Exit Temperature, the Average Temperature of Delivered Heat (the Product) Is Higher with Liquid Coolants than with Gas Coolants



Materials

Graphite and Graphite Fuels

Compatibility with Molten Salt Tested to 1400ºC

Metals

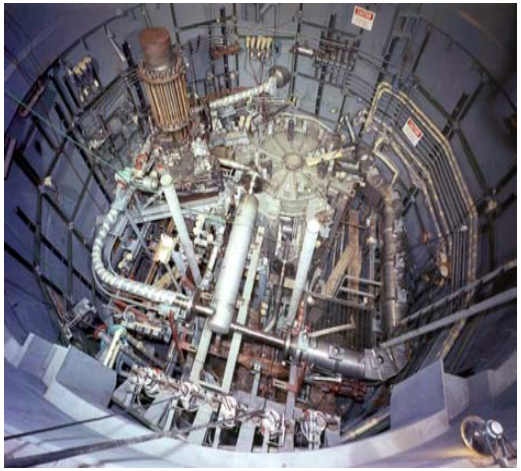
Existing Code Materials to 750ºC

Candidates For Higher Temperature Operation

Status: Similar to Helium-Cooled VHTR, Need to Qualify and Demonstrate Higher-Temperature Materials

Experience Shows that Fluoride Salts Are Compatible with Carbon-Based Materials

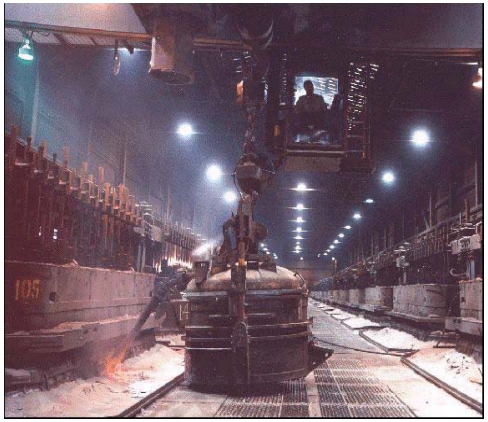
Same Graphite Radiation Damage Issues As With Gas-Cooled Reactors



Molten Salt Reactor Experiment (8 MW(t))

← Reactor Compartment

Graphite Core (Moderator) →



← Aluminum Plant: 1000ºC (NaF-ALF_3 Molten Salt in Graphite)

Molten Salt Reactor Experiment [8 MW(t)] Postirradiation Graphite →

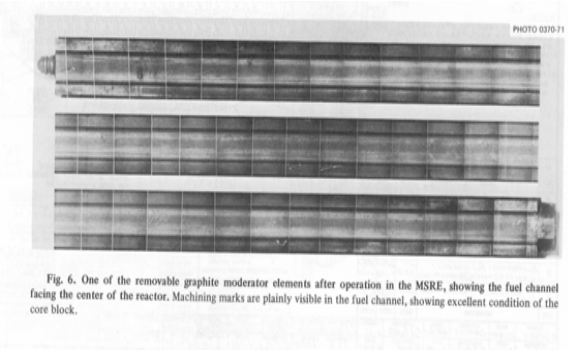


Fig. 6. One of the removable graphite moderator elements after operation in the MSRE, showing the fuel channel facing the center of the reactor. Machining marks are plainly visible in the fuel channel, showing excellent condition of the core block.

Hastelloy-N Qualified To 750ºC; Testing Required For Higher Temperature Materials

- High-temperature issues (salt or He systems)
  - Air oxidation
  - Creep
  - Material property changes at temperature
  - Corrosion
- Corrosion control strategy
  - Metals noble with respect to salt (Same corrosion strategy used in sodium systems)
  - Requires salt chemistry control
    - Pure molten salts
    - Maintain salt under highly-reducing conditions
- Test program required for high temperatures (>750ºC)
  - Flow loop corrosion testing
  - Some high-temperature corrosion mechanisms depend upon temperature differences

3000 hours at 815ºC with minimal corrosion by fluoride salt (Williams: Global 2003)

Facility Design

AHTR: A Low-Pressure, High-Temperature Liquid-Cooled Reactor

Not a Point Design

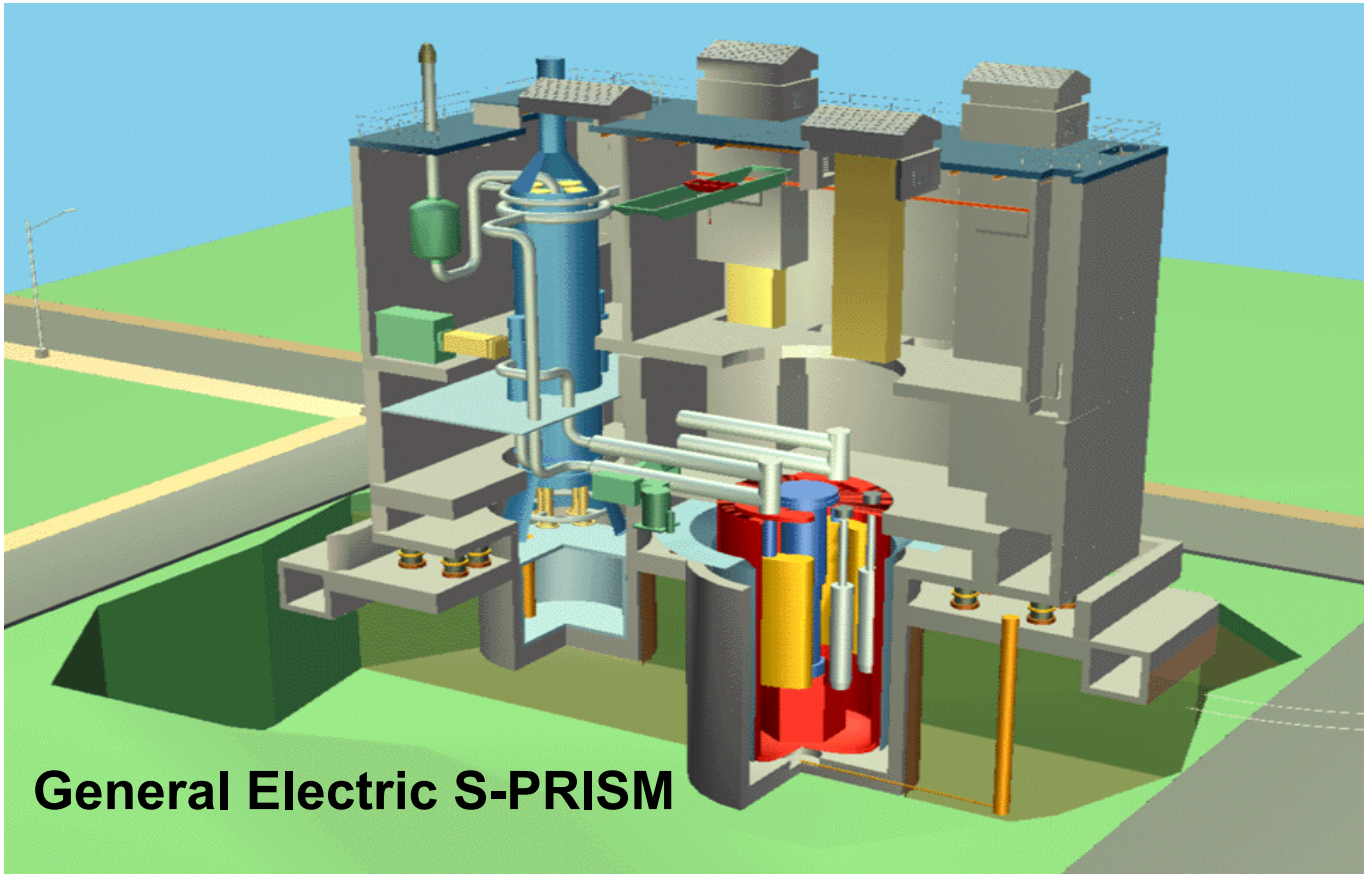
AHTR Parameters For 1000ºC Exit Temperature*

Power lever	2400 MW(t)		Core diameter	7.8 m
Core inlet/outlet temperature	900ºC/1000ºC		Core height	7.9 m
Core inlet/outlet pressures	0.230MPa/0.101 MPa		Fuel annulus	2.3 m
Core pressure drop	0.129 MPa (18.7 PSI)		Number of fuel columns	324
Coolant (several options)	$2LiF\text{-}BeF_2$		Number inner reflector columns	55
Coolant mass flow rate	12,070 kg/s (20% bypass)		Number outer reflector columns	138
Coolant volumetric flow rate	5.54 m^3/s		Fuel kernel	UCO
Coolant channel diameter	0.95 cm		Fuel enrichment	10.36 wt% ^{235}U
Coolant fraction (active core)	6.57%		Mean core power density	8.3 W/cm^3
Coolant velocity	2.32 m/s (7.6 ft/s)		Peak core power density	TBD W/cm^3
Core pumping power	716 kW		Reactivity, temperature	Negative Doppler
Vessel Pressure	~0.1 MPa		Reactivity, void (whole core)	TBD
Vessel external temperature			Mean fuel temperature	1050ºC
Vessel outside diameter	9.2 m		Peak fuel operating temperature	1168ºC
Vessel wall thickness	5-10 cm (material dependent)			
Net electric output	~1200 MW(e)			
Net plant efficiency	48-59%			

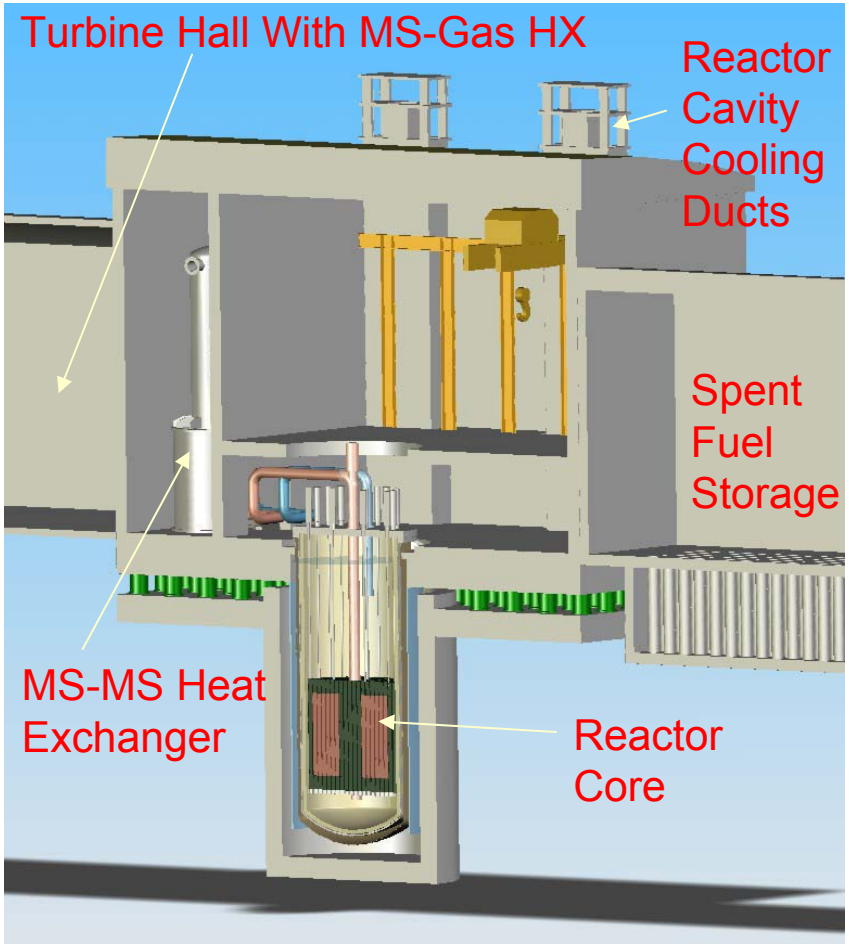
*Exit temperature dependent upon goals.
Range: 700 to 1100ºC

Proposed AHTR Facility Layouts Are Based on Sodium-Cooled Fast Reactors

Low-Pressure, High-Temperature, Liquid-Cooled

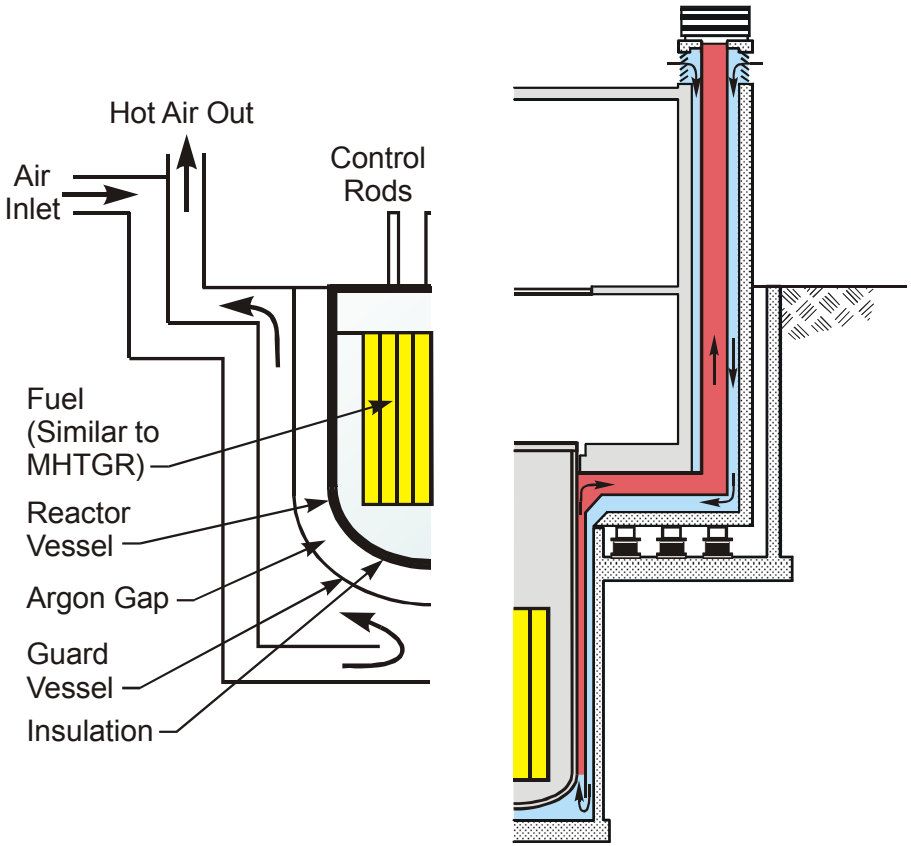


2400 MW(t) AHTR Nuclear Island Is Similar Size To 1000 MW(t) S-PRISM Plant



- **Differences from S-PRISM facility layout:**
  - **No SNF storage in vessel**
  - **No heat exchanger inside vessel**
  - **Molten salt-to-gas heat exchanger in turbine hall**
- **Same vessel size**
  - **Space for 2400 MW(t) AHTR core with low power density**
- **Similar Equipment Size**
  - **Molten salt volumetric heat capacity > sodium**
- **Higher capacity decay heat removal system**
  - **Higher vessel temperatures**
- **Higher electrical output**
  - **S-PRISM: 380 MW(e)**
  - **AHTR: >1200 MW(e)**

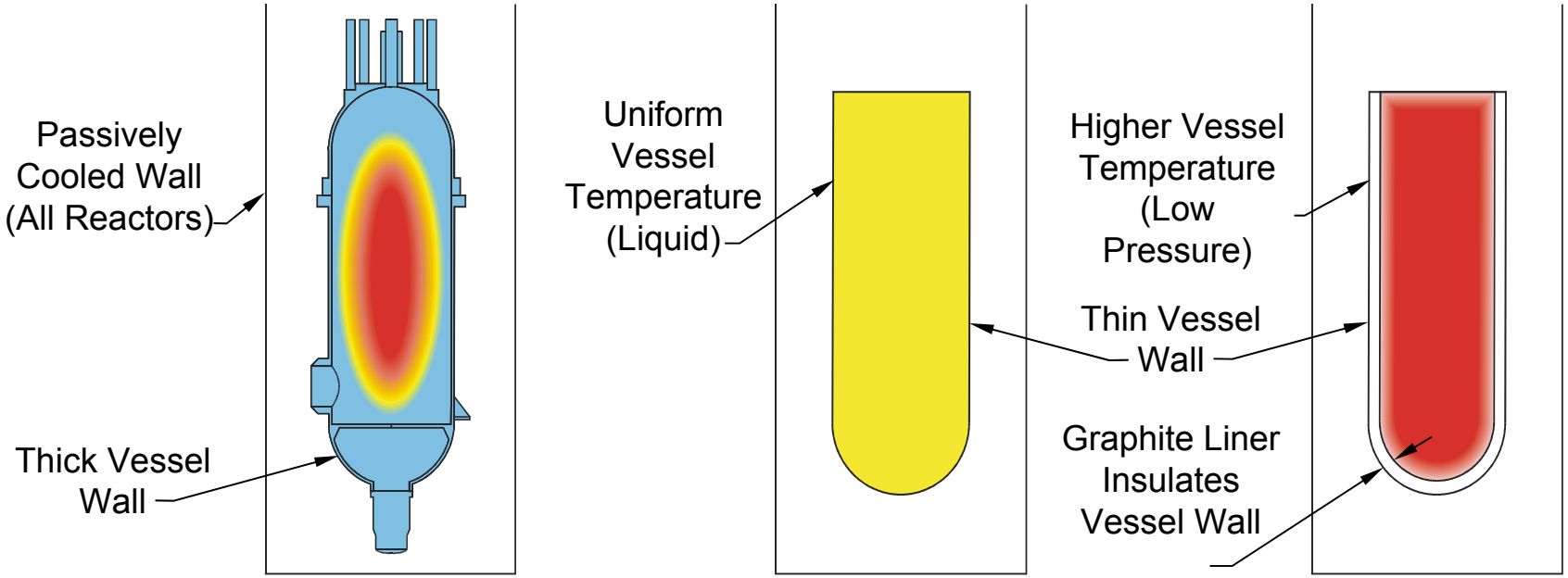
In an Emergency, Decay Heat Is Transferred to the Reactor Vessel and Then to the Environment



- Similar to GE S-PRISM (LMR)
- Argon Gap
  - Heat Transfer ~T^4
  - Thermal Switch Mechanism
- Heat Rejection: Temperature Dependent
  - LMR: 500-550ºC [~1000 MW(t)]
  - AHTR: 750-1000ºC [>2000 MW(t)]
- High Heat Capacity
  - Molten Salt and Graphite
  - High Temperature (limited by insulation of vessel from hot salt)

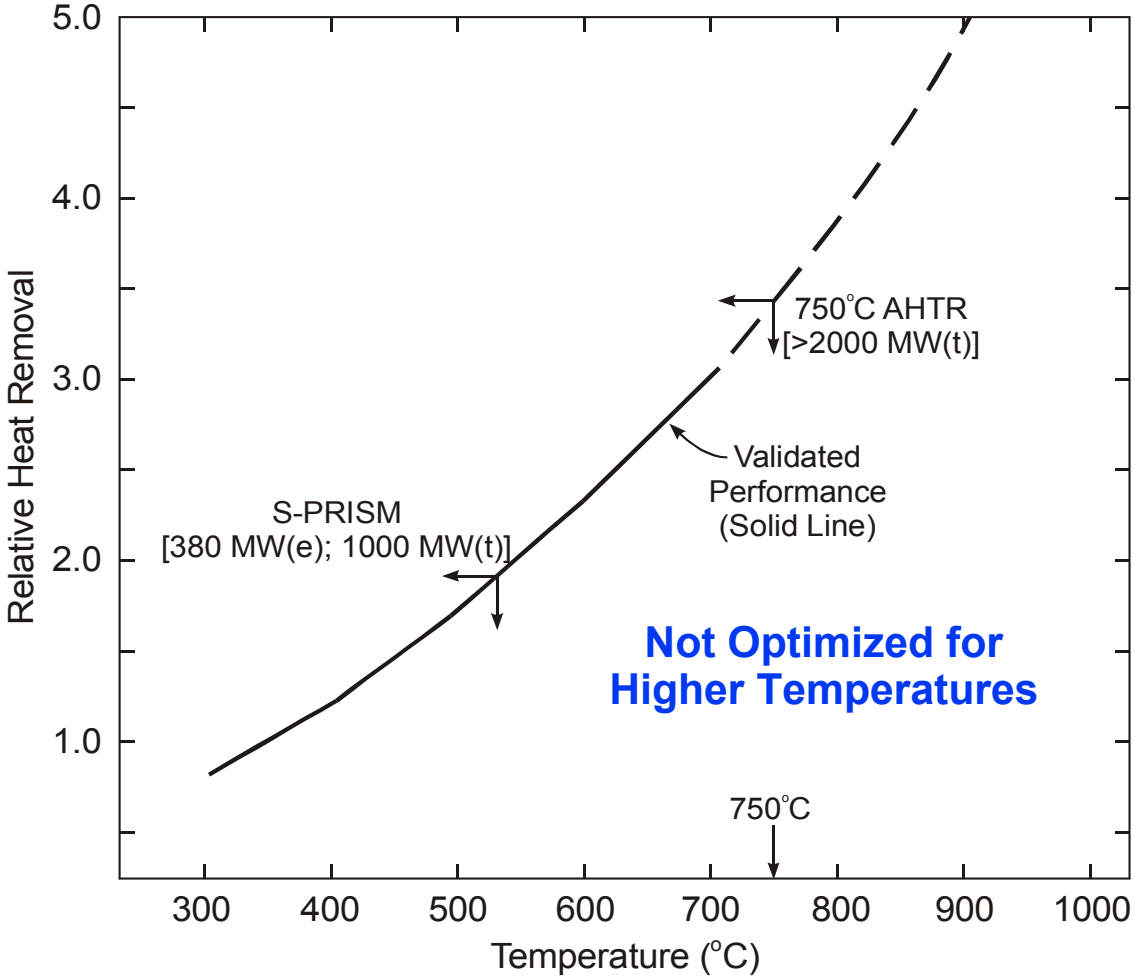
High-Temperature Low-Pressure Liquid Coolants Enable the Design of Large Reactors with Passive Safety

Reactor:	MHTGR	S-PRISM	AHTR
Coolant:	Helium	Sodium	Molten Salt
Power:	600 MW(t)	1000 MW(t)	>2000 MW(t)
Constraint:	Conduction	Sodium Boiling Point	Vessel

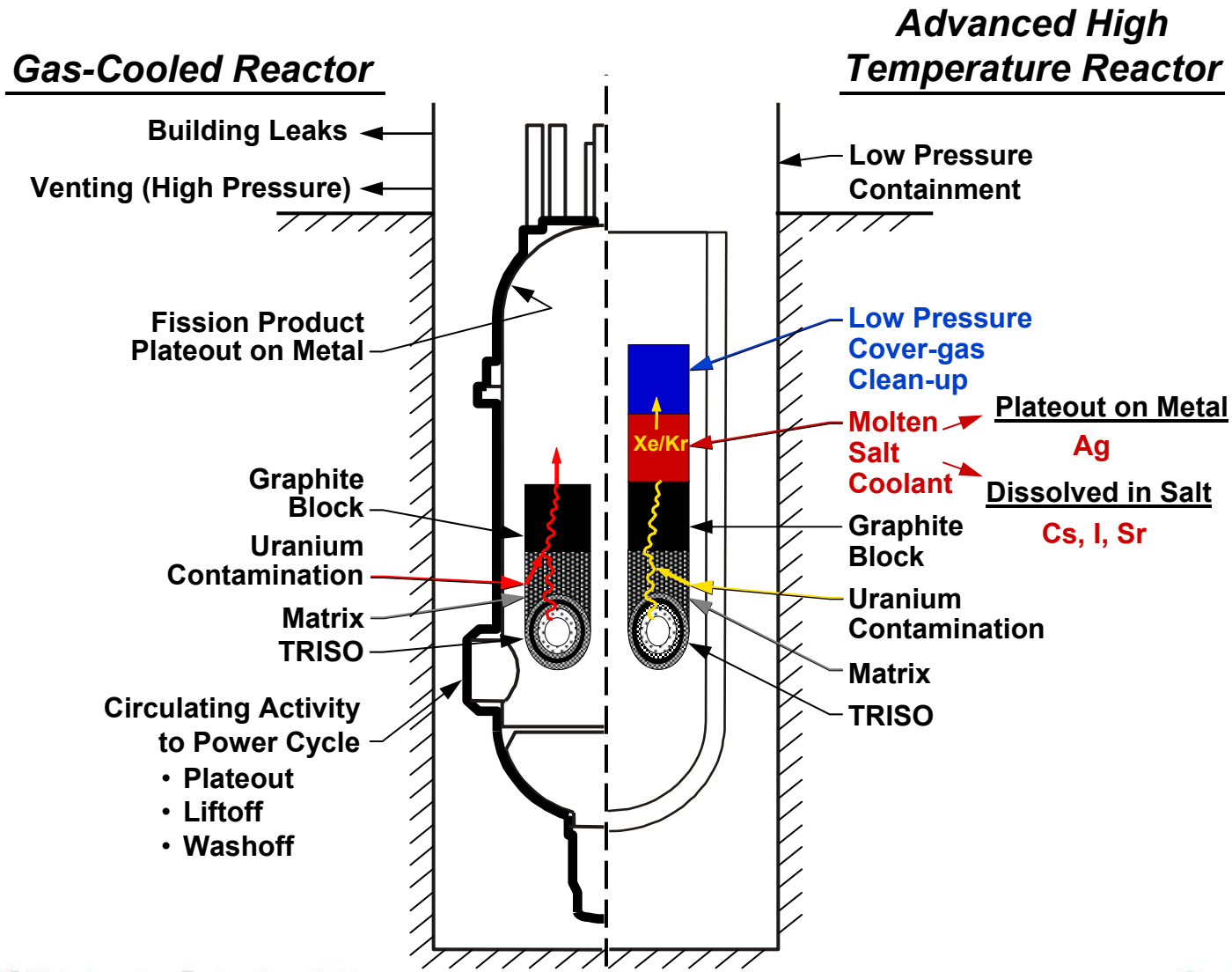


Decay Heat Removal Increases Rapidly With Temperature

S-PRISM Vessel with Air-Cooled System

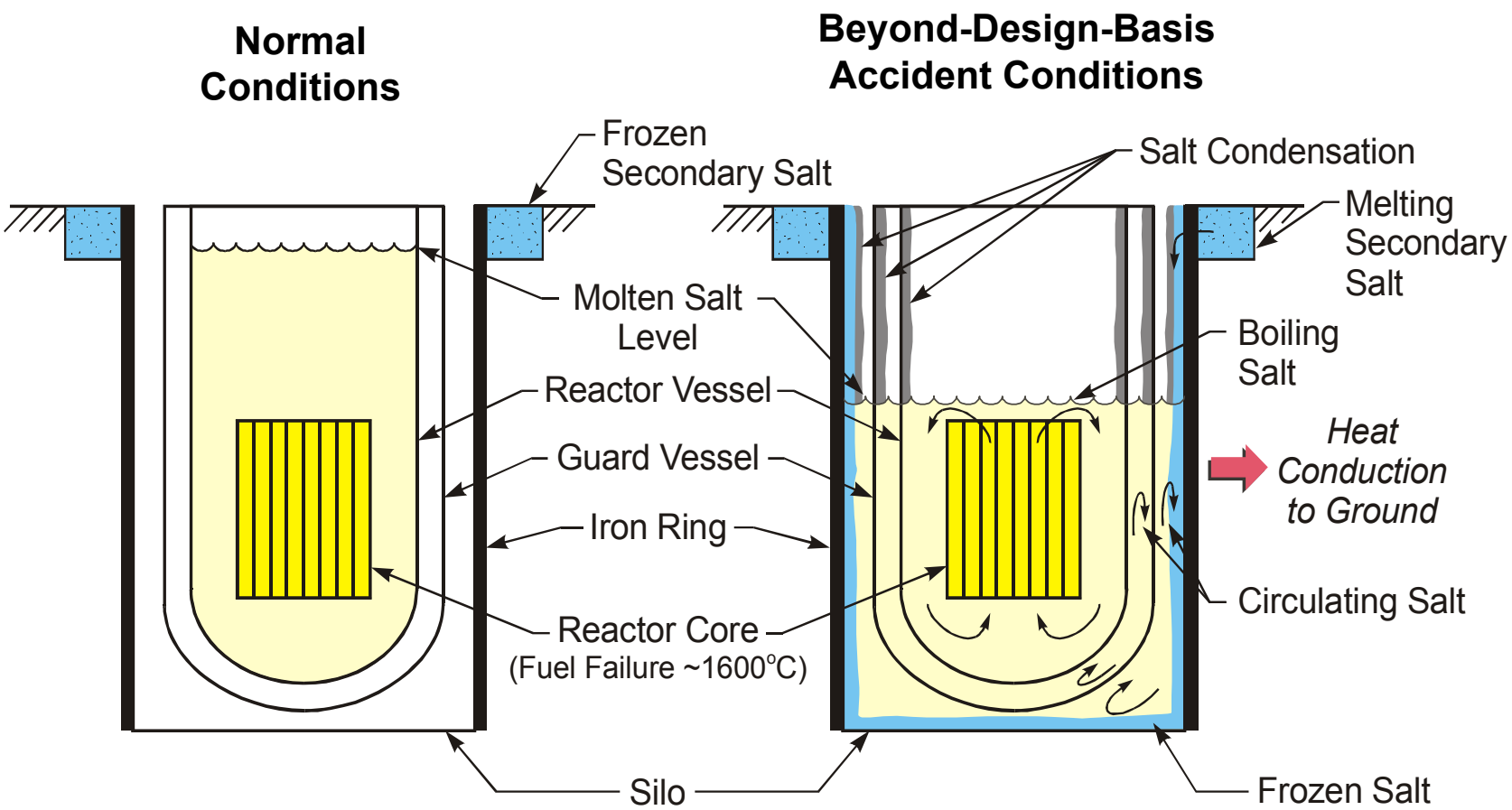


The AHTR Has Superior Fission Product Containment (More Barriers) Compared To Gas-Cooled Reactors



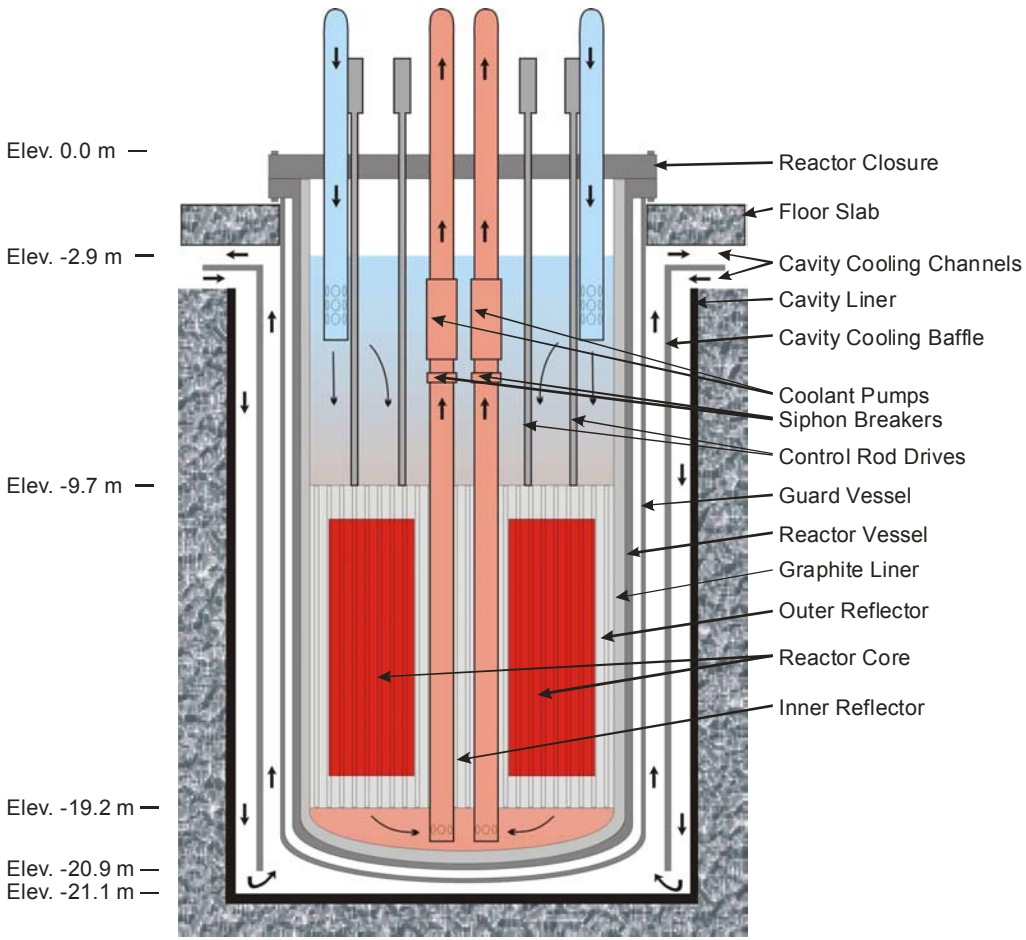
Beyond-Design-Basis Accident Avoids Radionuclide Release By Multiple Mechanisms

Molten Salts Trap Radionuclides (Including Cs and I) in the Salt, Isolate SNF from Air, Can Not pressurize Containment, and Transfer Heat to the Silo If Vessel Failure

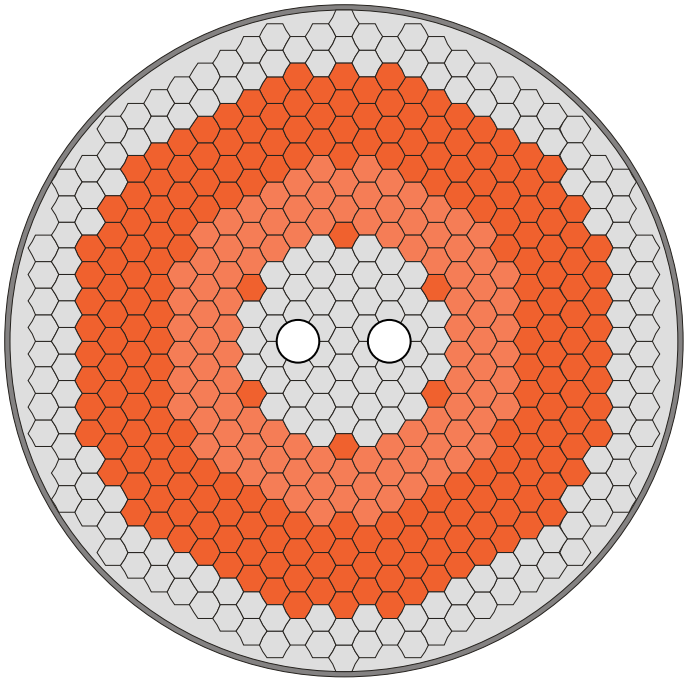


Reactor Core Design

AHTR 9.0m Vessel Allows 2400 MW(t) Core

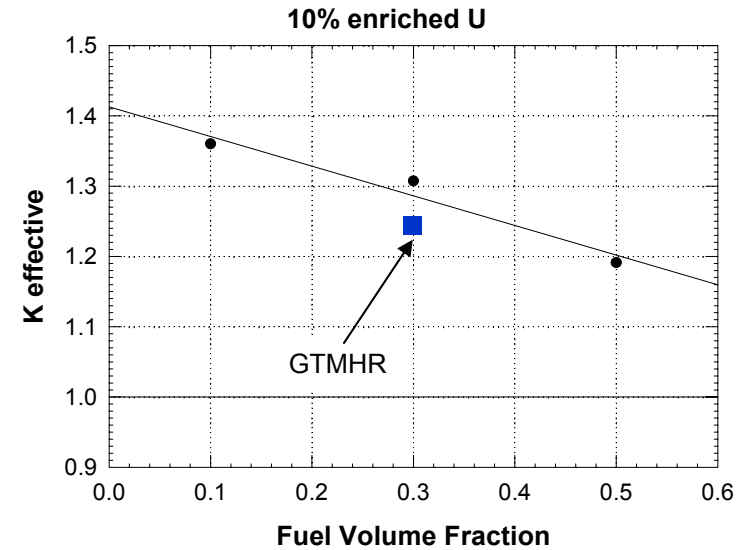


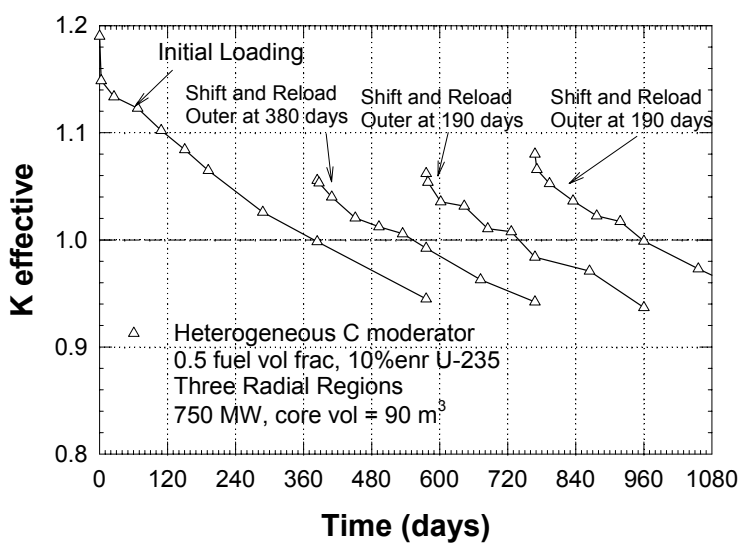
102 GT-MHR fuel columns
222 Additional fuel columns
324 Total fuel columns



Power density = 8.3 MW/m^3
(26% larger than 600 MW GT-MHR)

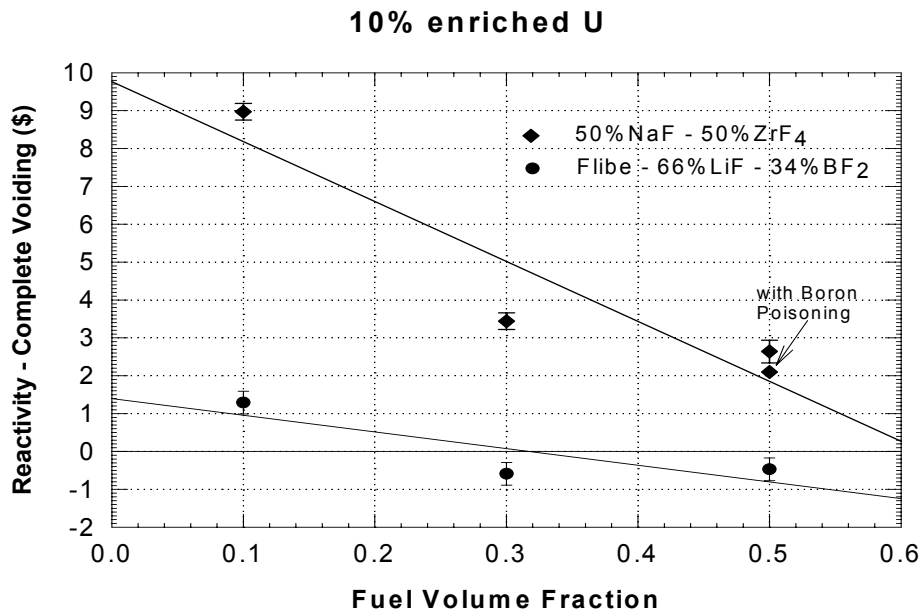
AHTR And Gas-Cooled Reactors Have Similar Neutronics

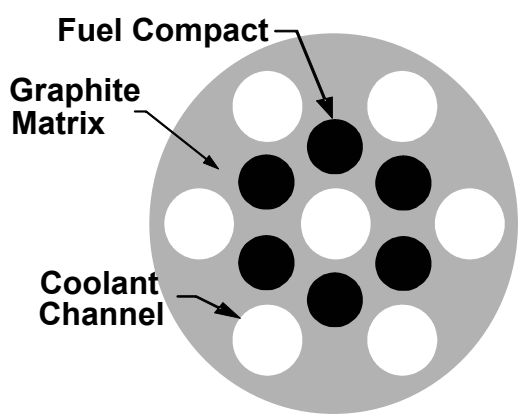




- Excess reactivity similar for given core loading
- Lower coolant volume fraction
- Neutron lifetime ~1ms
- k_{eff} increases with higher moderator to fuel ratio (undermoderated in design region)
- Large negative temperature feedback due to Doppler effects (~ -$0.01/K)
- Similar fuel burnup/ fuel cycle options
- At 8.3 W/cm^3, core life is ~ 580 days
  - 10% enrichment
  - 0.5 fuel volume fraction

Key Difference: AHTR Void Coefficient Depends on Salt Composition and Core Configuration



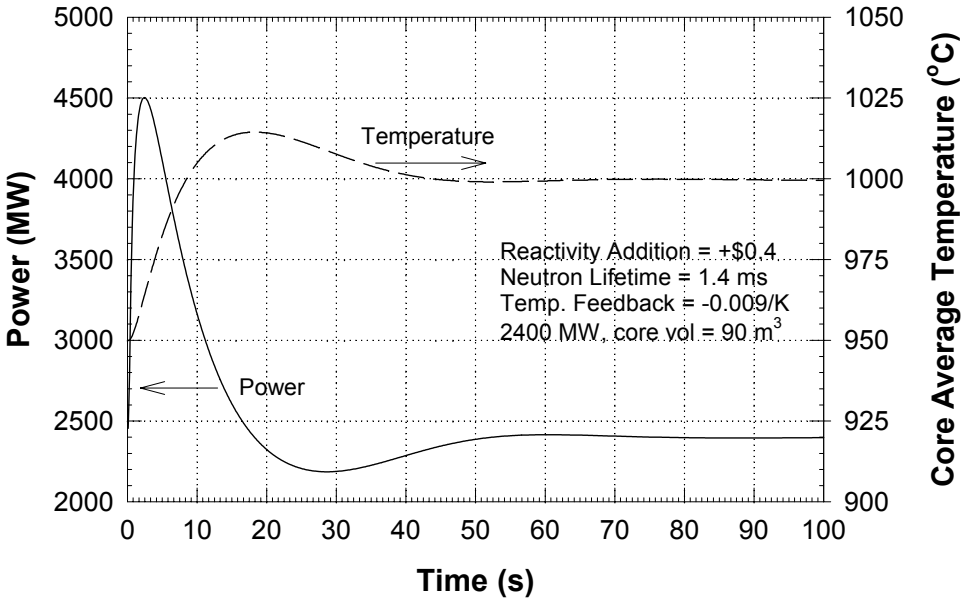


Traditional Gas-Cooled Fuel Model

- Void coefficient ranges from negative to positive, depending on coolant fraction and salt choice
- $^{7}LiFBeF_2$ salt yields negative VC for higher fuel fractions
- $NaZrF_4$ salt yields most positive VC of salt options
- 1st order effect is absorption, 2nd order effect is moderation
- Ranking: Be, ^{7}Li, Mg, Zr, Na
- Design options may allow use of several salts
  - Geometry
  - Coolant fraction
  - Heterogeneous core design
  - Burnable absorbers
  - Isotopic purity
  - Fuel loading/enrichment

AHTR Cores Have An Unusual Behavior If the Core Has a Positive Void Coefficient

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



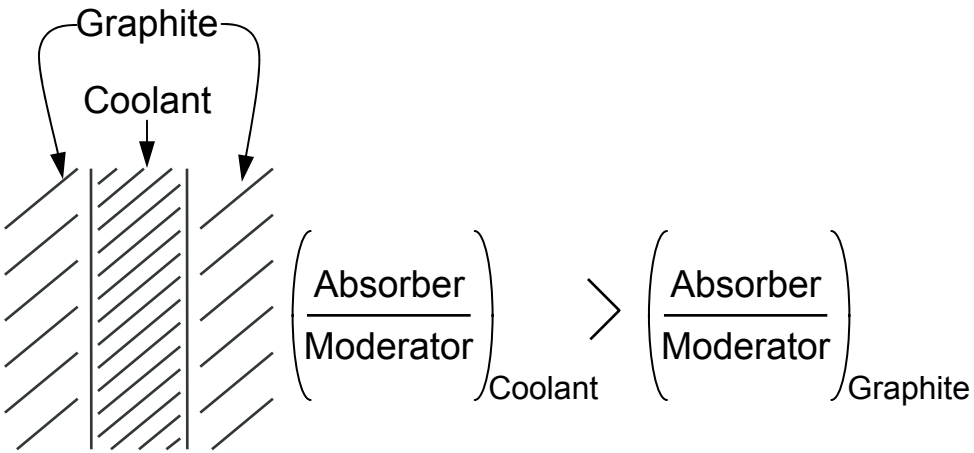
- Core power increases but is mitigated by increase in fuel temp of ~60°C.
- Slow transient (10's of sec).
- Core reaches lower equilibrium power – issue is heat-up of blocked fuel columns (~9 °C/sec)

- Void coefficient of reactivity impacts core design more for AHTR than for gas-cooled reactors
- Sign (+/-) and magnitude of void coefficient depend upon:
  - Salt composition
  - Core geometry
    - Coolant/fuel/graphite
    - Heterogeneous cores
  - Core fractions
    - Coolant
    - Fuel
  - Burnable absorber in:
    - Fuel
    - Graphite
  - Enrichment

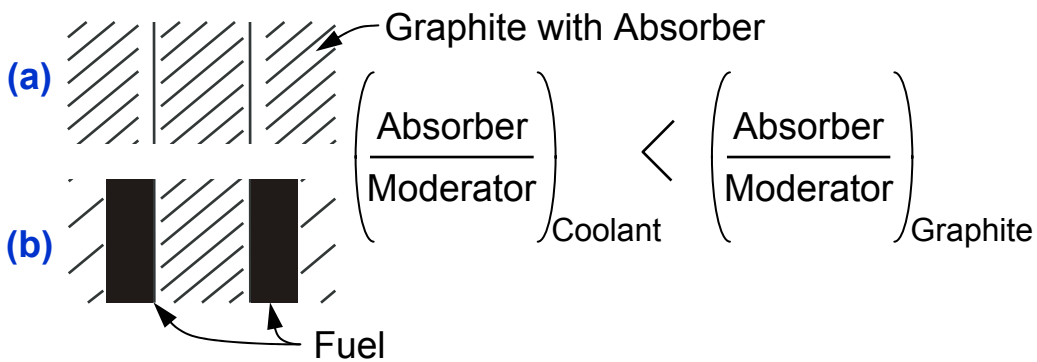
Void Coefficients Can Be Reduced or Made Negative By Several Methods

Examples: Neutron Absorbers in Graphite and Geometry

Potential for Positive Void Coefficient



Negative Void Coefficient Strategies

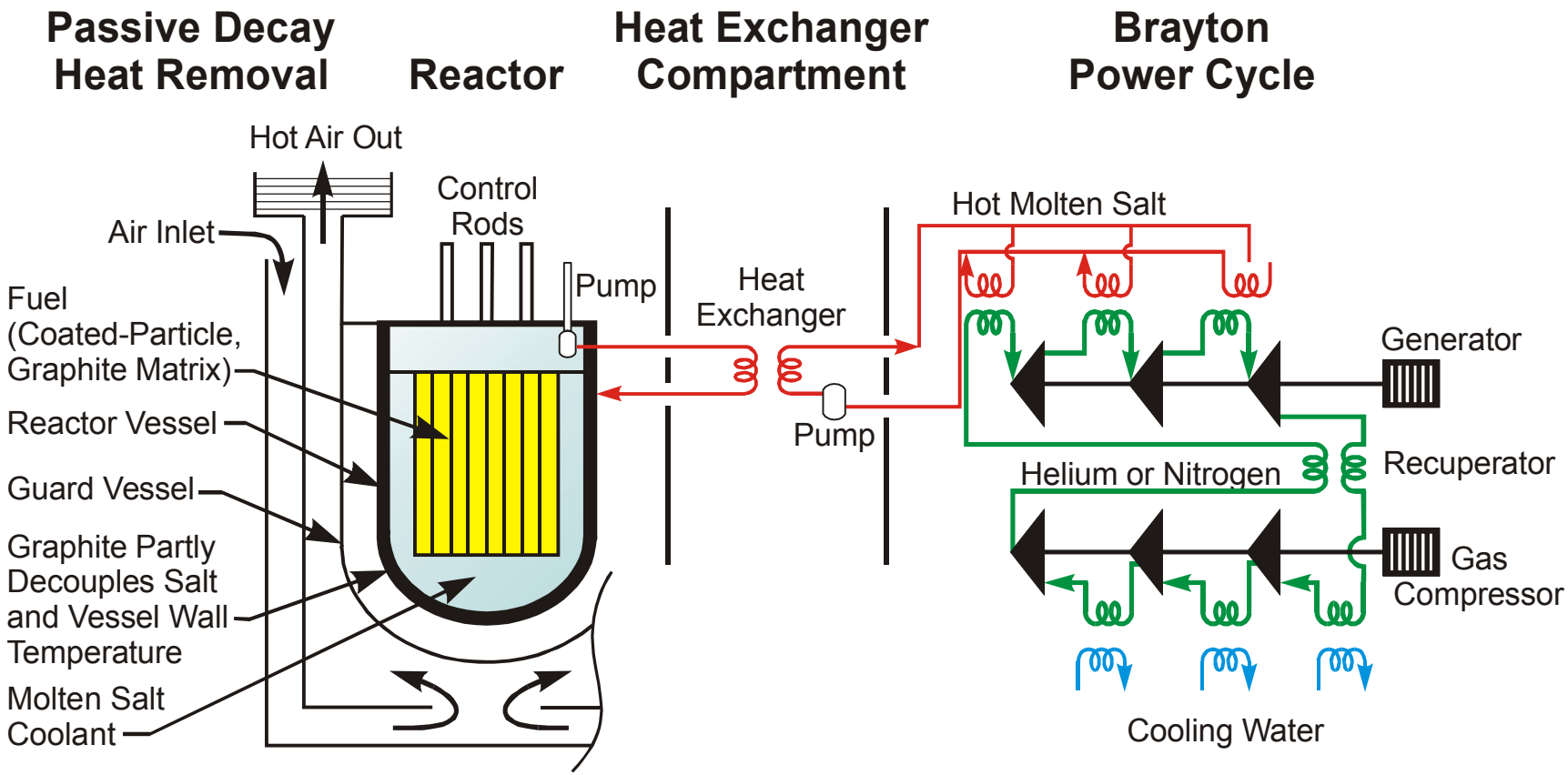


- Positive void coefficients can occur when the coolant neutron absorption-to-scattering ratio is greater than for the graphite
- Void coefficient can be reduced by:
  (a) Absorber: Addition of a neutron absorber to the graphite
  (b) Geometry: Placing fuel between the coolant and the graphite - example: N-Reactor
  - Large reactor: 4000 MW(t)
  - Water-cooled graphite reactor
  - Negative void coefficient

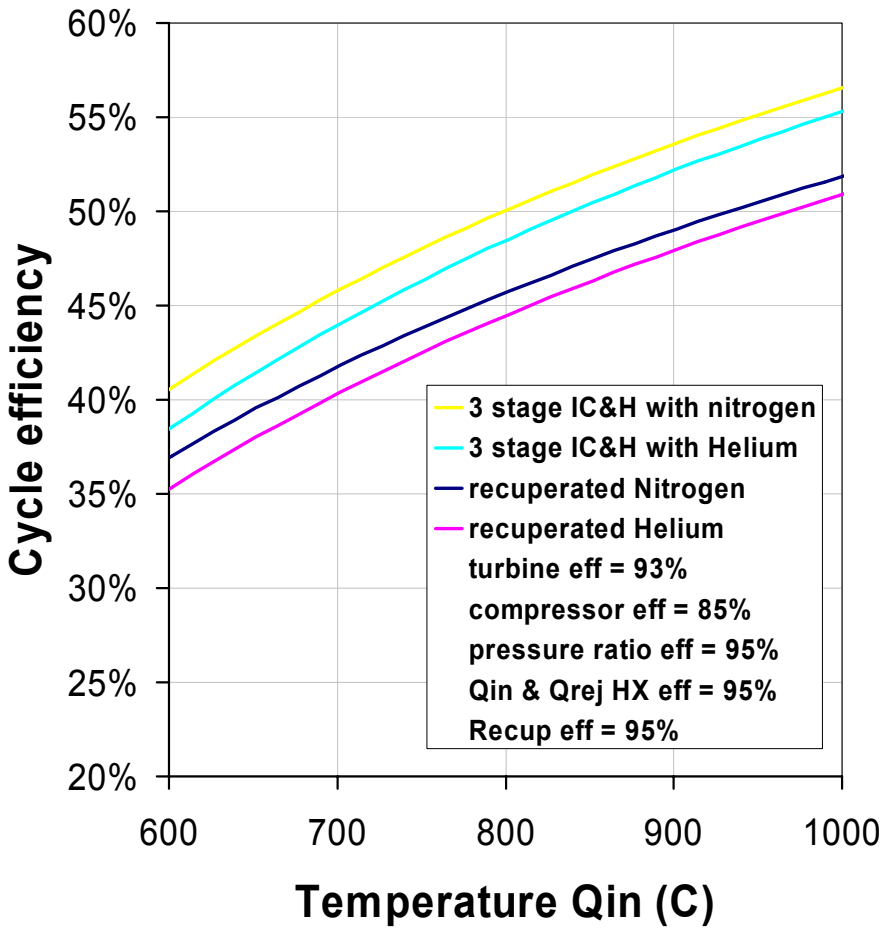
Energy Conversion

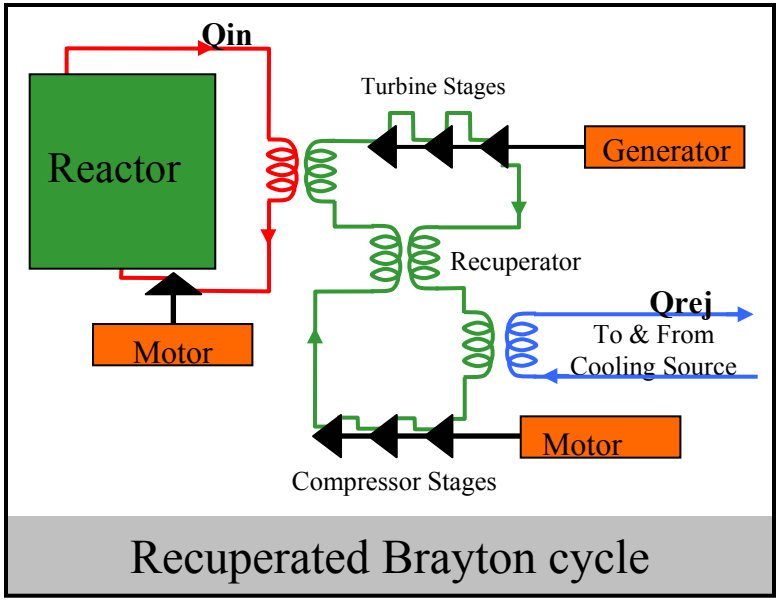
Electricity Generation
Hydrogen Production

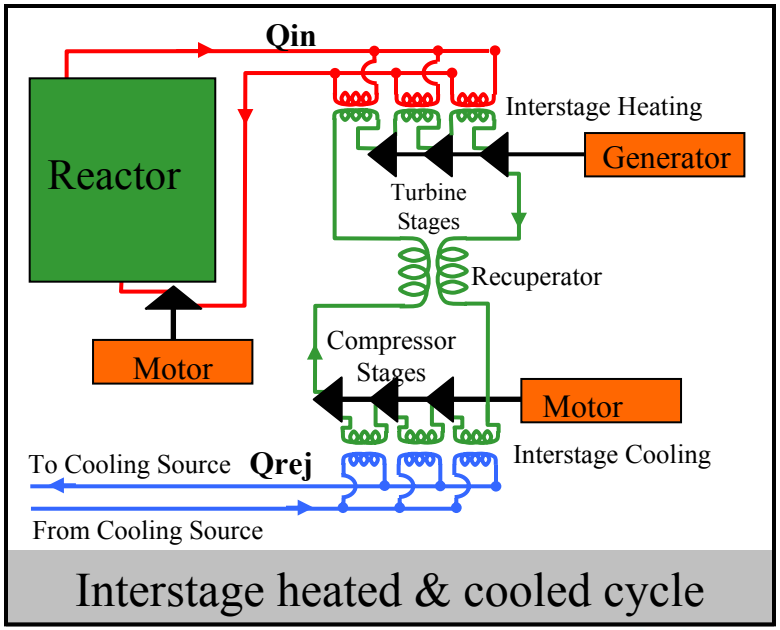
A *Multi-Reheat* Brayton Cycle Is Used for Efficient Electricity Production



Nitrogen and Helium Brayton Cycle Options Can be Considered for AHTR

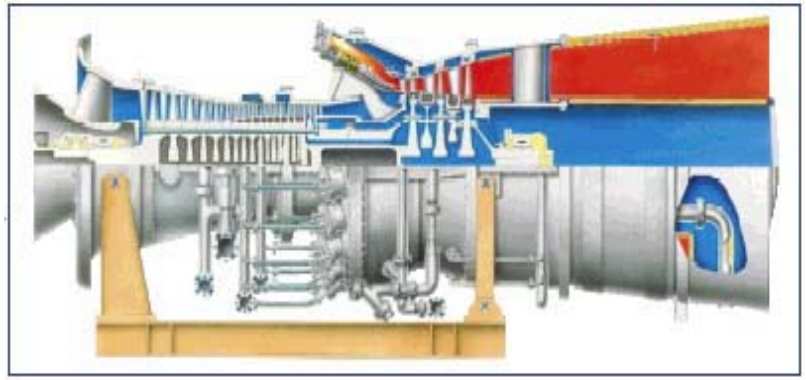




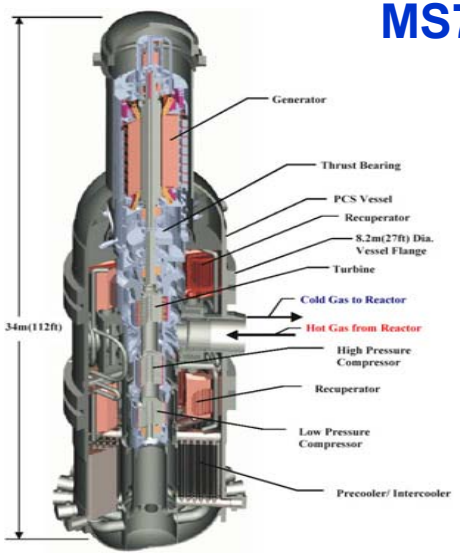


Near Term: Use Nitrogen Brayton Cycle (with minor amounts of helium)

- Same turbine technology as existing natural-gas-fired turbines
  - Lower temperatures than current commercial units
  - Option for small amounts of helium to improve thermal properties (reduce heat exchanger size)
  - Higher power density because low pressure (0.5-1.0 MPa) in the power cycle is not at 1 atm. (0.1 MPa)
- Helium Brayton Cycle
  - Second-generation option
  - Use if developed for helium-cooled reactor
- Minimize technical risk and development cost with little penalty

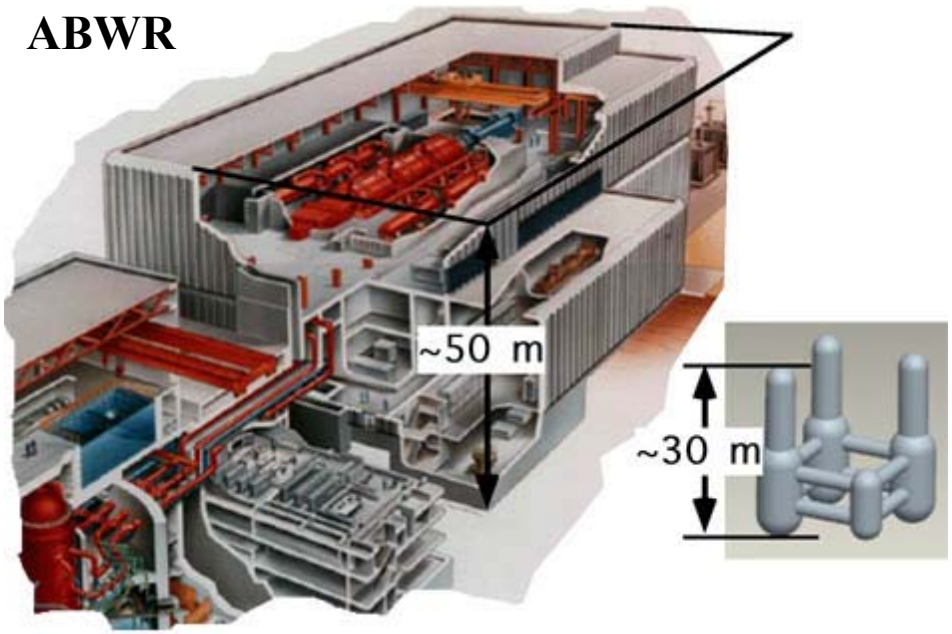


GE Power Systems MS7001FB



GT-MHR PCU (Russian Design)

Scaled Comparison of the 1380 MW(e) ABWR Turbine Building and ~1300 MW(e) AHTR



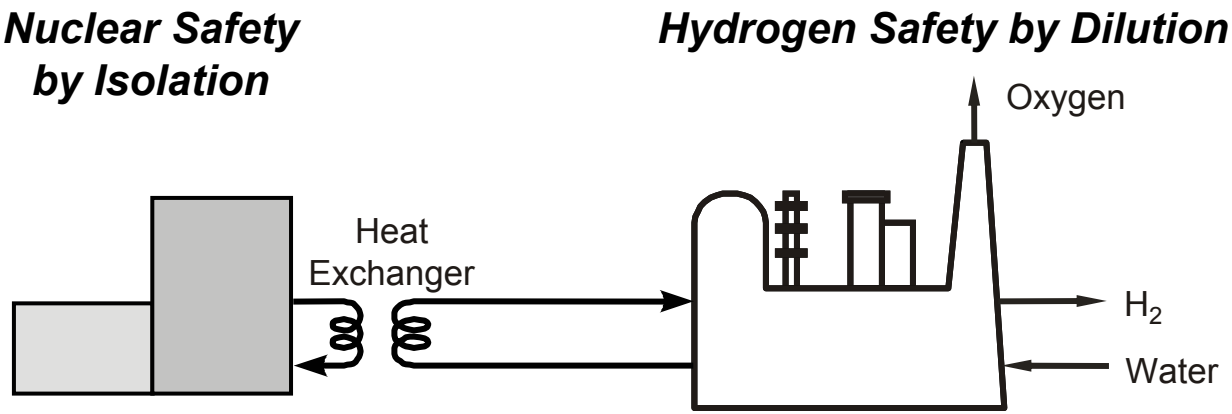
Advanced helium Brayton cycles can likely achieve a substantial reduction of the turbine building volume

He-Brayton Cycle With 3 Power Conversion Units Similar to GT-MHR

- **AHTR turbine building must also contain crane, turbine lay-down space, compressed gas storage, and cooling water circulation equipment**
- **AHTR requires ~1100 MW(t) of cooling water capacity, compared to 2800 MW(t) for ABWR; no low pressure turbines (steam)**

Hydrogen Production May Require Development of Molten Salt Coolant Technology

AHTR Couples Better to Such Systems



- **Smaller system (1 molten salt loop = 25 Helium loops)**
  - **Lower heat loses**
  - **Lower costs**
- **Chemical plant safety (German chemical industry evaluation)**
  - **No compressed-gas energy**
  - **Avoid toxic chemical release if heat exchanger failure**

Economics

Larger Reactors Have the Potential for Lower Capital and Operating Costs

Initial Cost Analysis Shows That AHTR Economics Is Favorable

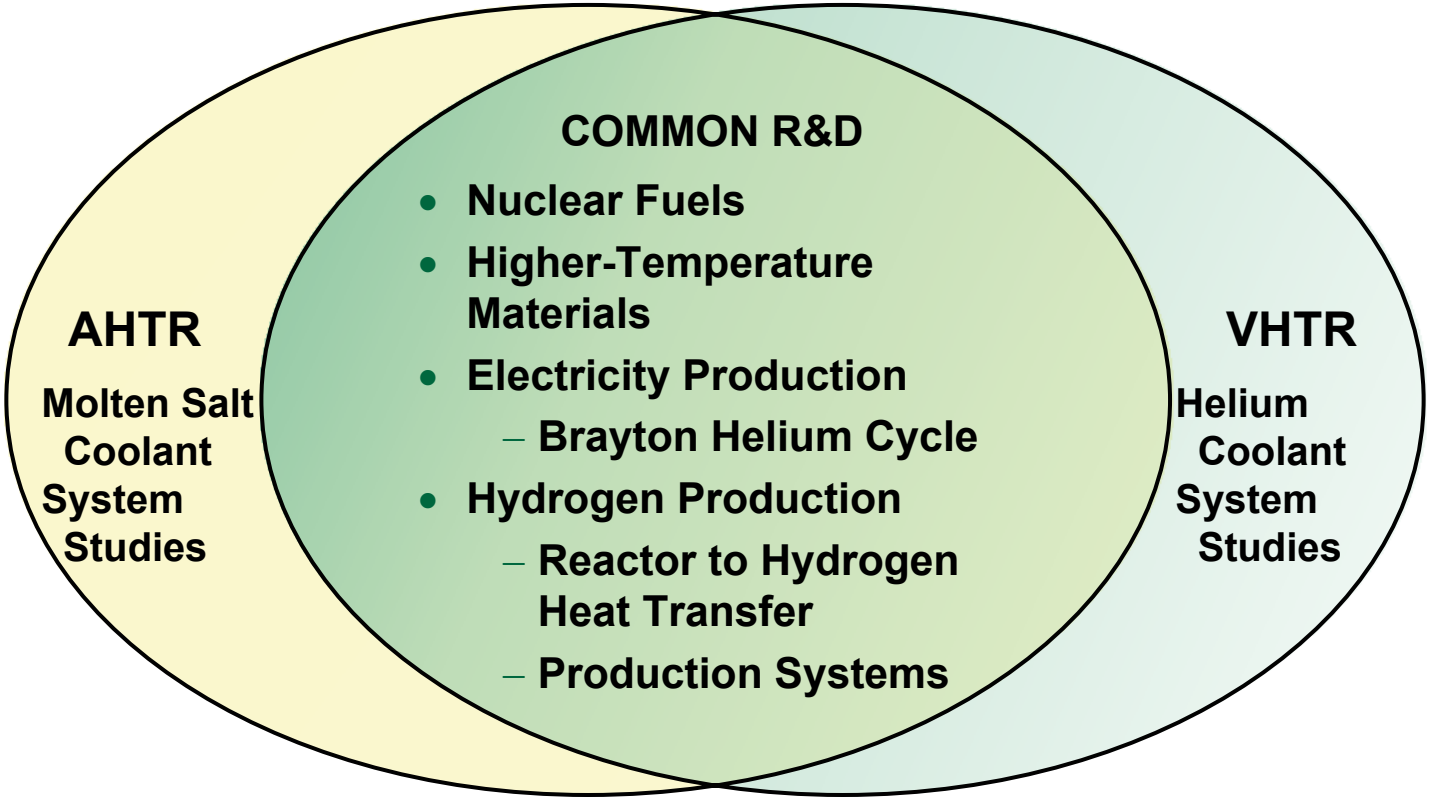
- Used scaled cost data from S-PRISM and GT-MHR
  - S-PRISM for reactor, construction, engineering, and contingency
  - GT-MHR for power conversion and heat rejection systems
- Included several cost elements for reactor, power conversion, and balance of plant systems
- Standard scaling laws used to normalize all three reactors to 2400 MW(t)
- Indicates that AHTR will be 50 to 75% of S-PRISM costs (dependent upon assumptions) and potentially even better economics than MHTGRs.

Research And Development

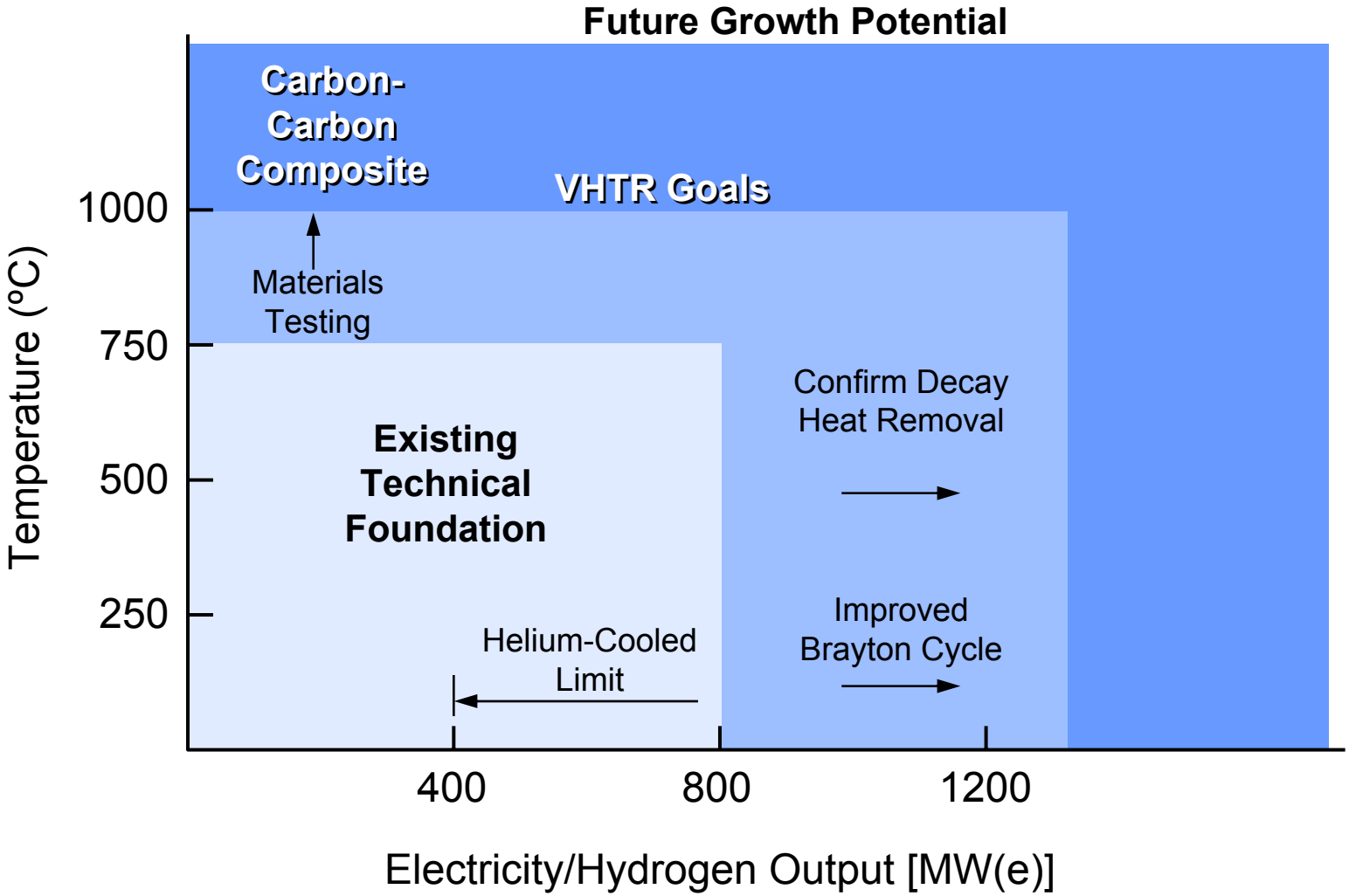
Overlap with Other High-Temperature Reactors

Some Unique Issues

The R&D Requirements for the Molten-Salt- Cooled AHTR and Helium-Cooled VHTR Have Much In Common



Global AHTR R&D Perspective



AHTR Conclusions

- Attractive features
  - High temperatures
    - Efficient power production
    - Hydrogen production
  - Economics
    - Large power output
    - Compact design
    - High efficiency
  - Passive safety
    - Match or exceed modular gas-cooled reactors
- Challenges
  - Point design
    - Salt selection
    - Decay heat removal system
    - Core design
  - Materials for higher-temperature operations
  - High melting temperatures