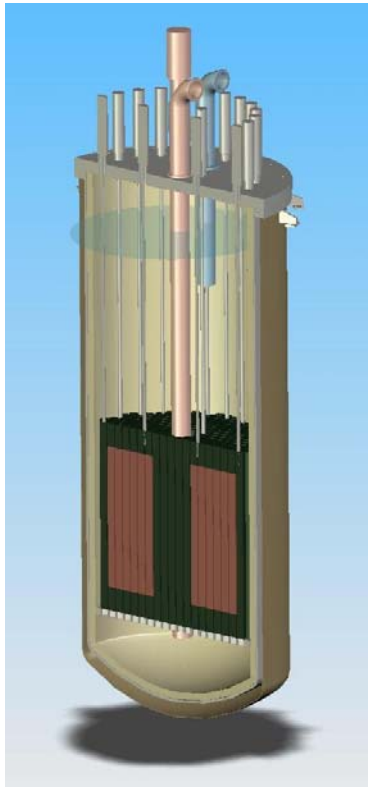
Maximizing Temperatures of Delivered Heat from the Advanced High-Temperature Reactor

Dr. Charles Forsberg
Oak Ridge National Laboratory

Professor Per Peterson
University of California, Berkeley

Dr. Paul Pickard
Sandia National Laboratories



2004 International Congress on Advances in
Nuclear Power Plants (ICAPP 04)
Pittsburg, Pennsylvania
June 13–17, 2004

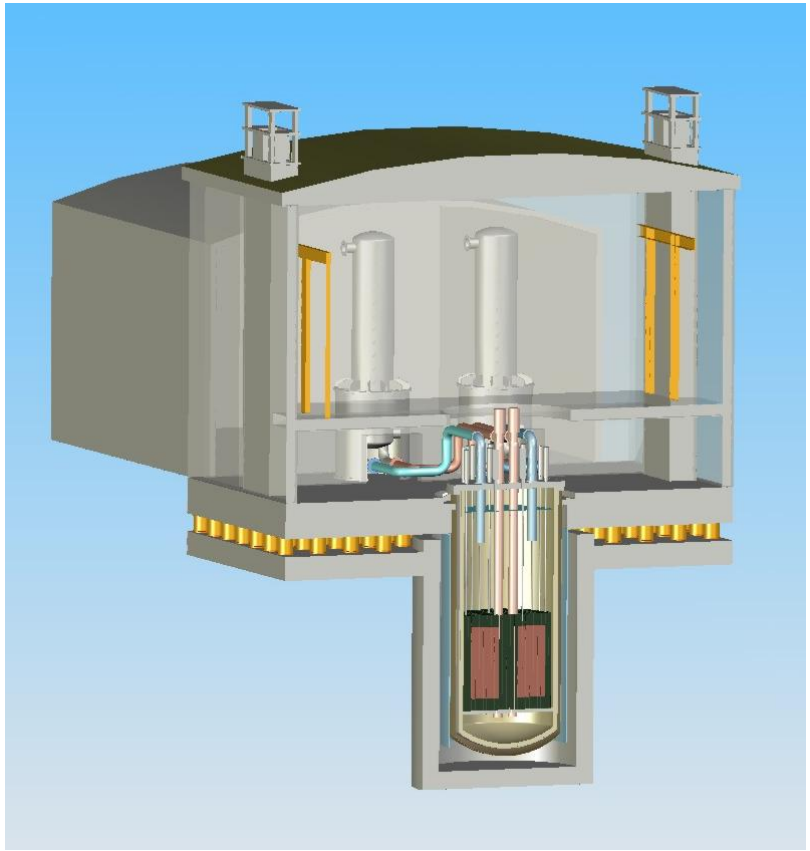
The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. File: ICAPP.2004.Hightemp.View

OAK RIDGE NATIONAL LABORATORY

Sandia National Laboratories

UC Berkeley NUCLEAR ENGINEERING

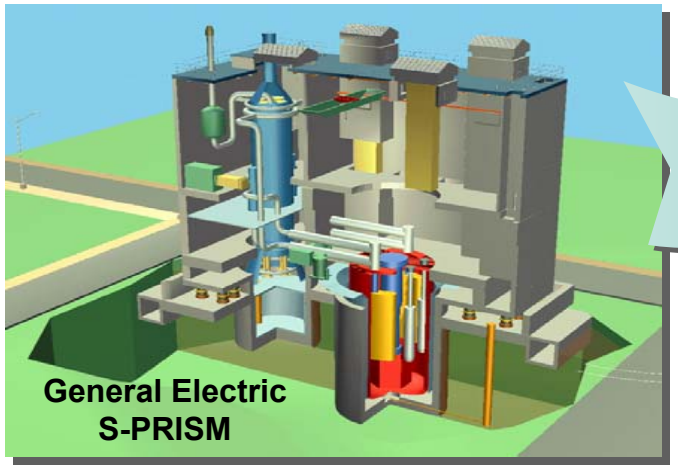
Outline



- Introduction
- Fuels
- Molten Fluoride Salt Coolants
- Facility Design
- Conclusions

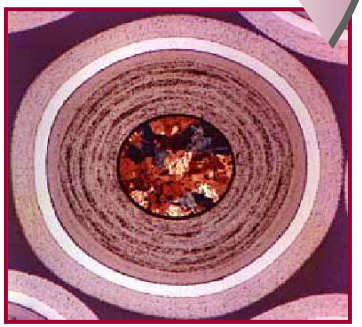
The Advanced High-Temperature Reactor

Combining Existing Technologies in a New Way



Passively Safe Pool-Type Reactor Designs

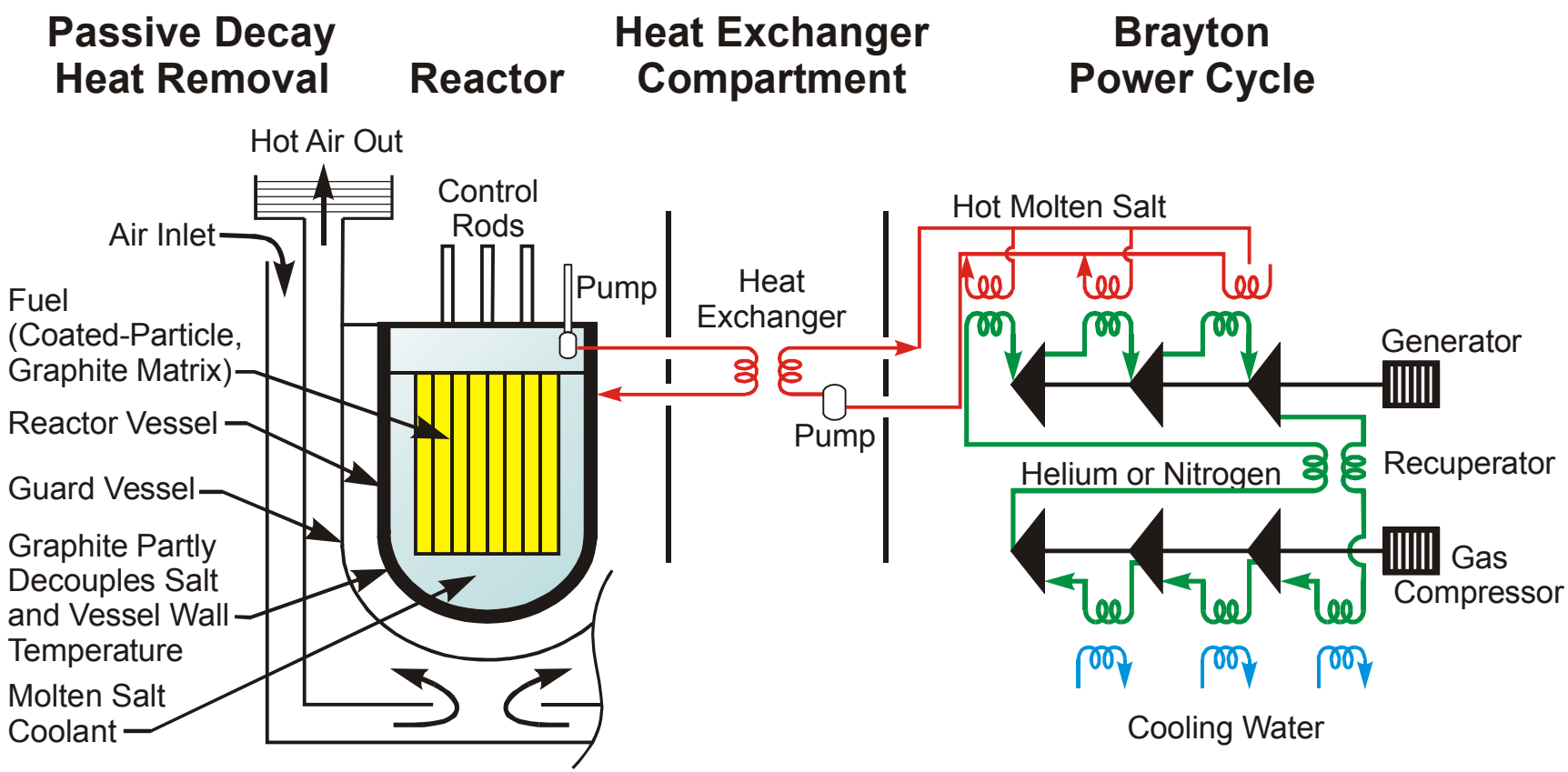
Indirect Brayton Power Cycles



High-Temperature Coated-Particle Fuel

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

The Advanced High-Temperature Reactor

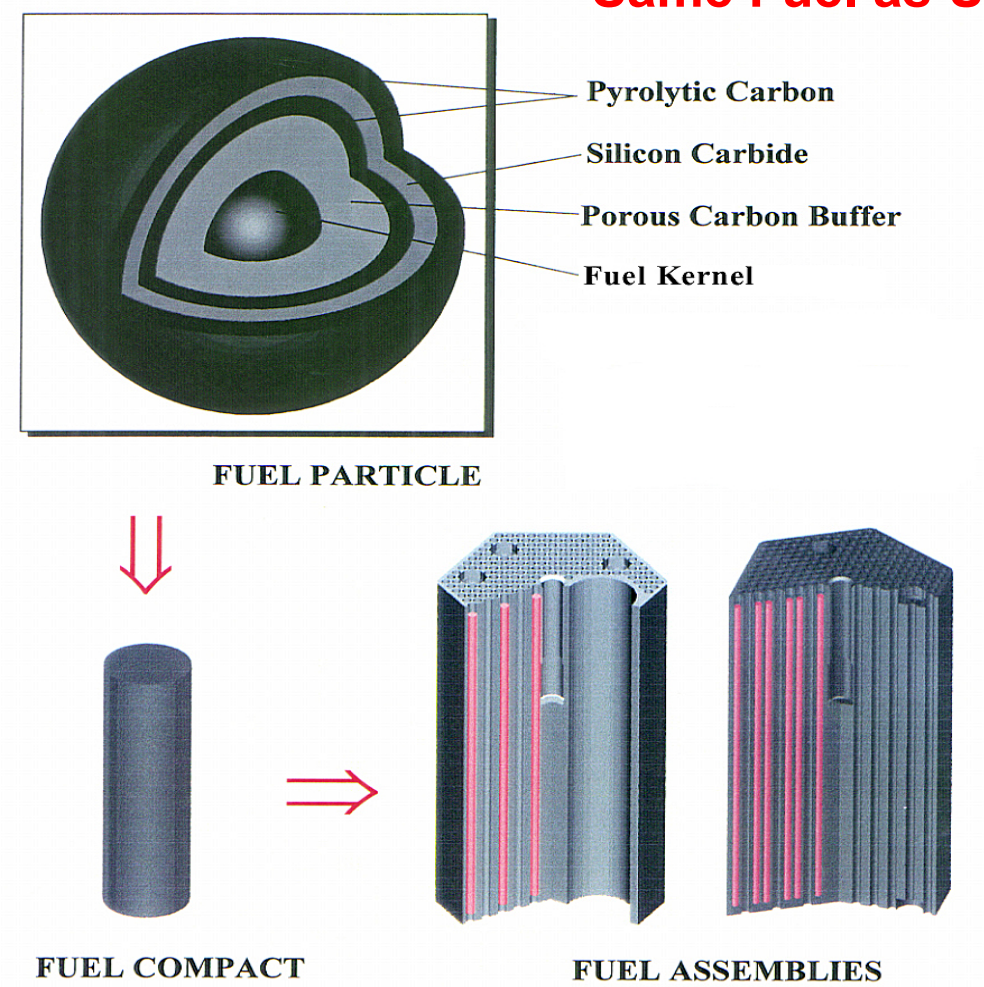


Fuels

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)

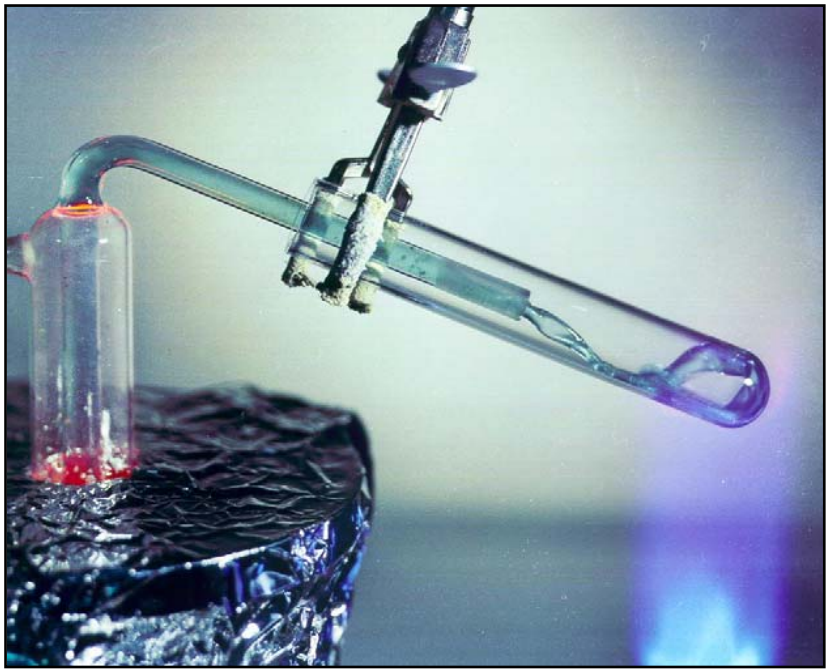
Same Fuel as Used in Gas-Cooled Reactors



- Fuel particle 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 are viable
- Graphite blocks provide neutron moderation and heat transfer to coolant

Molten Fluoride Salt Coolants

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



Helium

(High Pressure/Transparent)

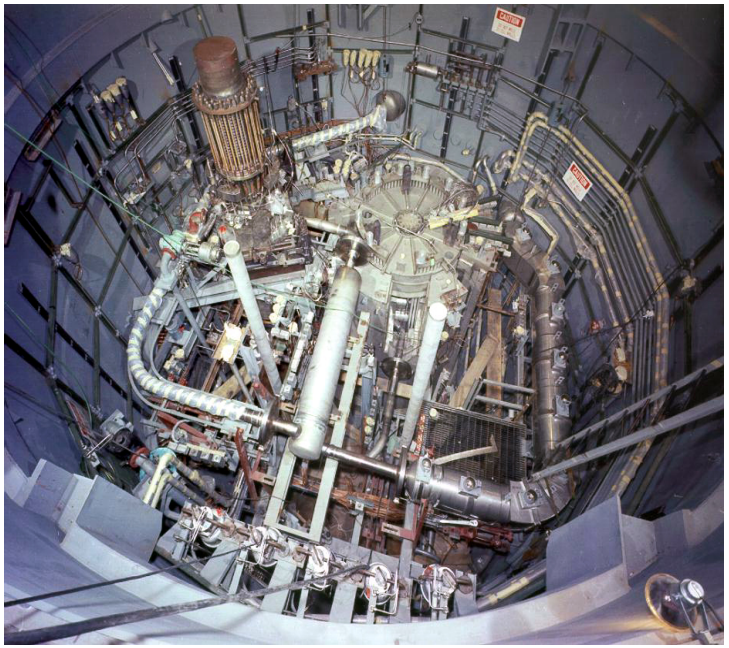
Molten Fluoride Salts

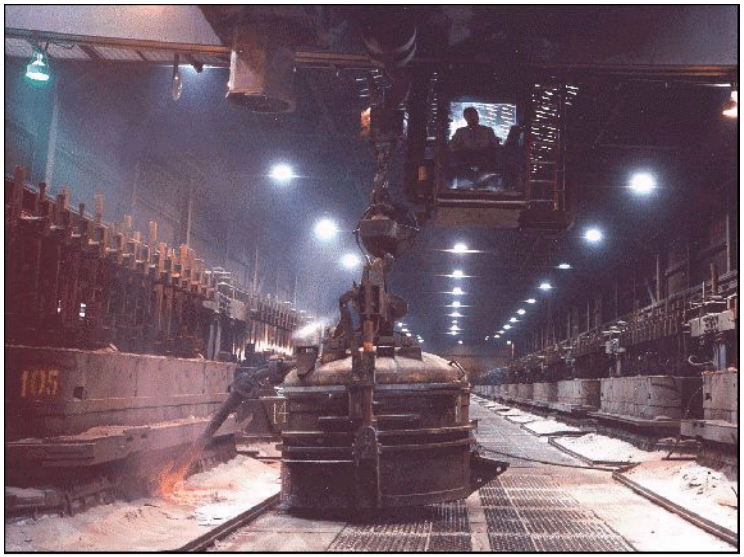
(Low Pressure/Transparent)

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)





Tapping aluminum

Aluminum is tapped from a Kitimat Works electrolytic-reduction cell into a steel vessel called a crucible. The crucible holds approximately 4,000 kg of aluminum and is used to transfer the molten aluminum to the furnaces in the casting department.

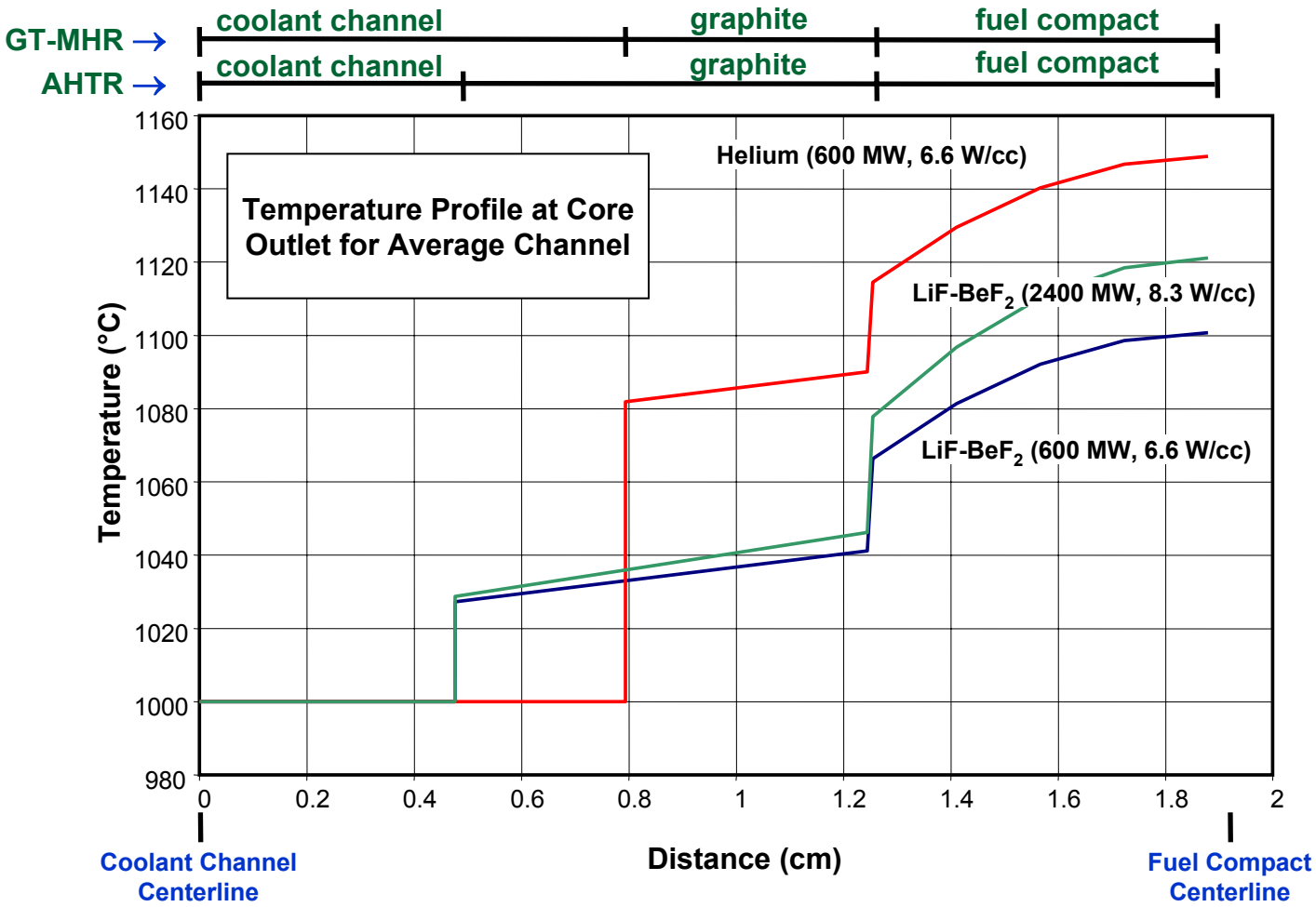
Molten Fluoride Salts Have Been Used for a Century to Make Aluminum in Graphite Baths at 1000°C

The AHTR Is Not a Molten Salt Reactor

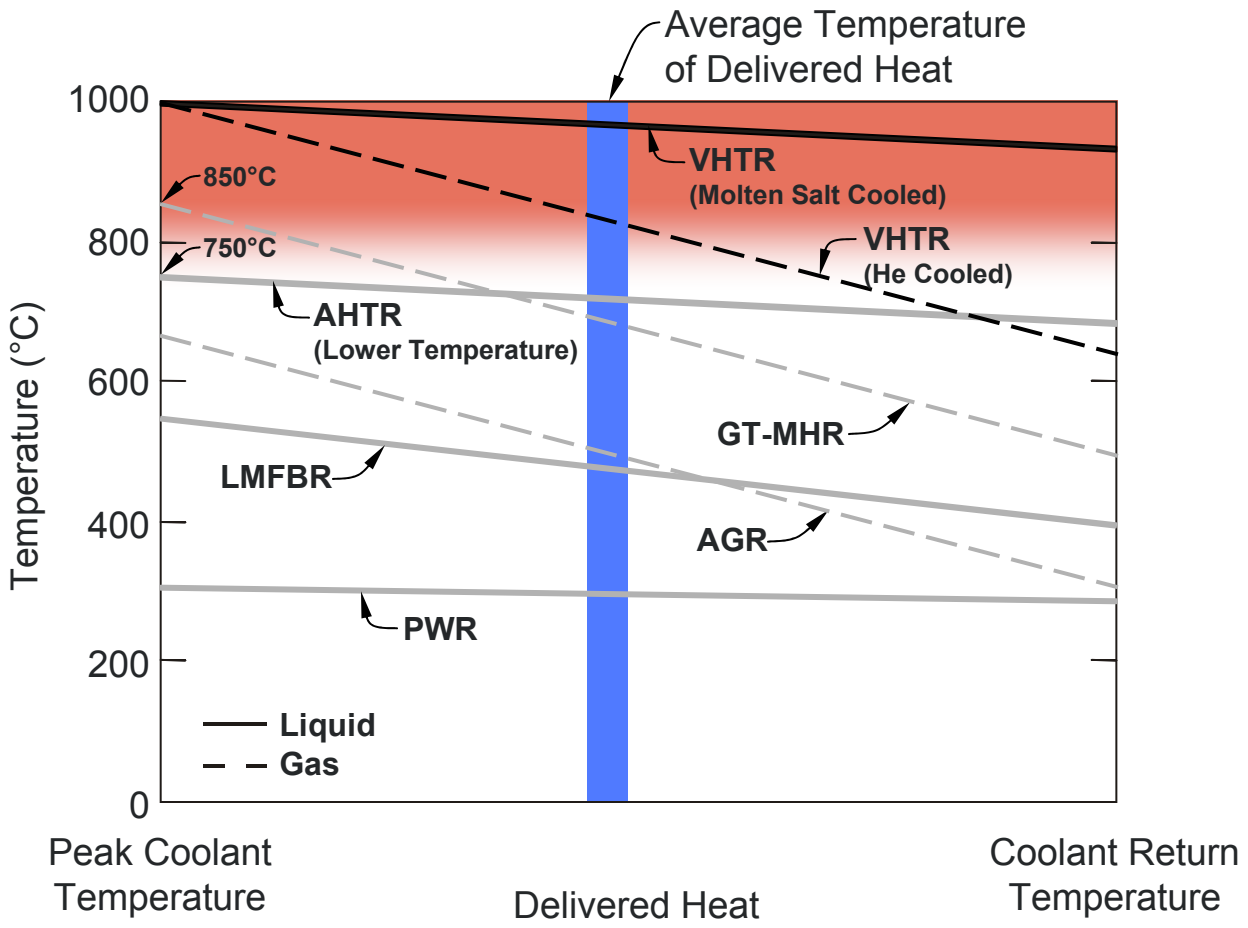
Cooled with a Clean Molten Salt, Not Fuel in Salt

Liquids Remove Heat More Effectively than Gas:

Cooler Fuel for the Same Coolant Exit Temperatures

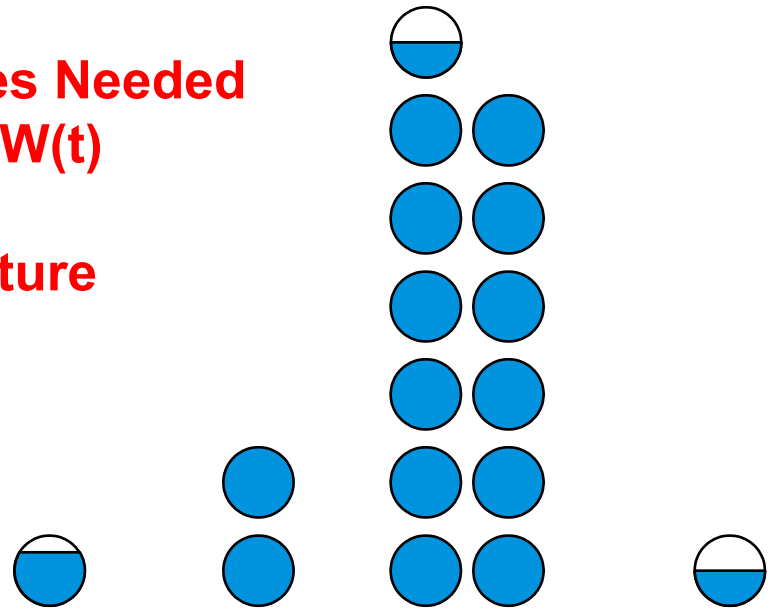


For Any Coolant Exit Temperature, the Average Temperature of Delivered Heat (the Product) Is Higher with Liquid Coolants than with Gas Coolants



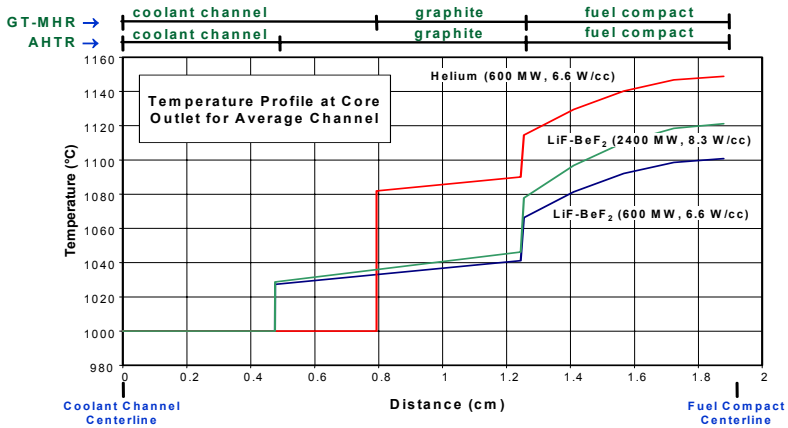
Molten Salts Have Superior Capabilities for Transport of Heat

Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temperature



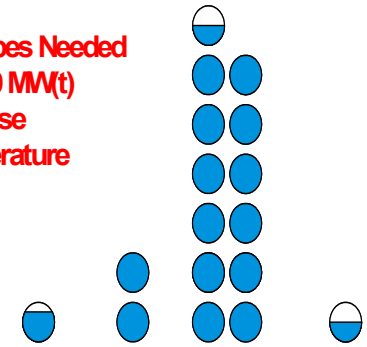
	Water (PWR)	Sodium (LMR)	Helium	Molten Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocities (m/s)	6	6	75	6

AHTR Peak Temperatures Are Much Lower Than Gas-Cooled Reactors for Heat *Delivered At the Same Temperatures*



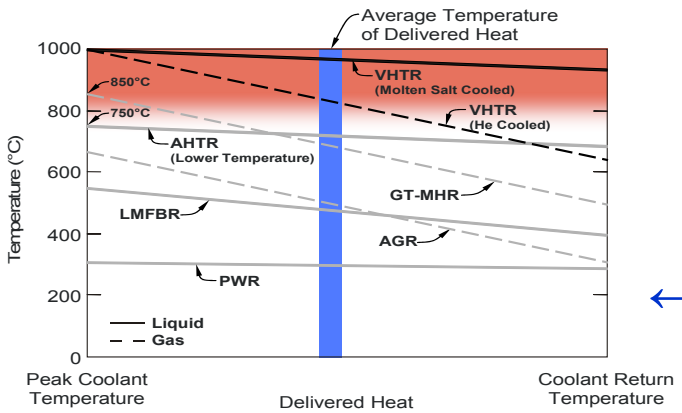
←Better Heat Transfer

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



Better Transport of Heat→

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



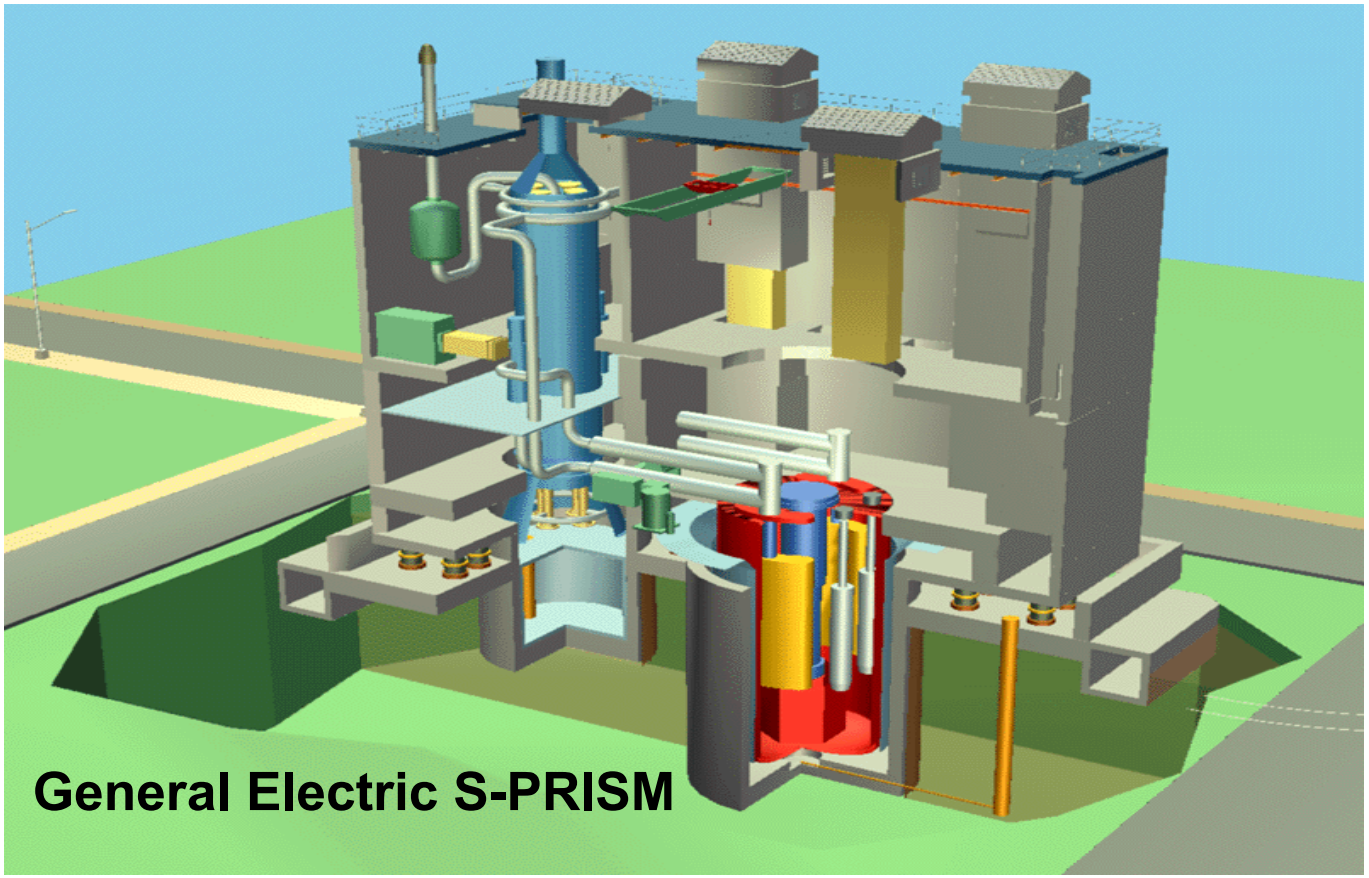
←Heat Delivered at Higher Temperatures

Facility Design

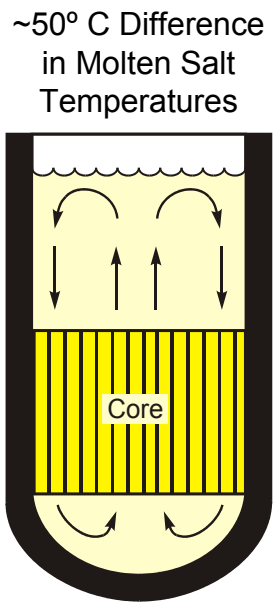
AHTR: A Low-Pressure, High-Temperature Liquid-Cooled Reactor

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

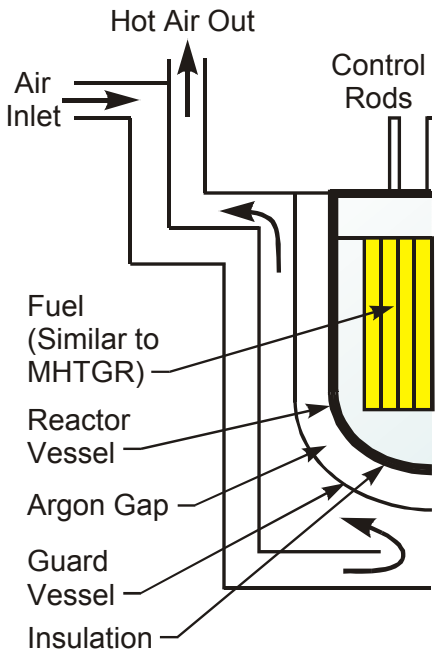
Low Pressure, High Temperature, Liquid Cooled



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



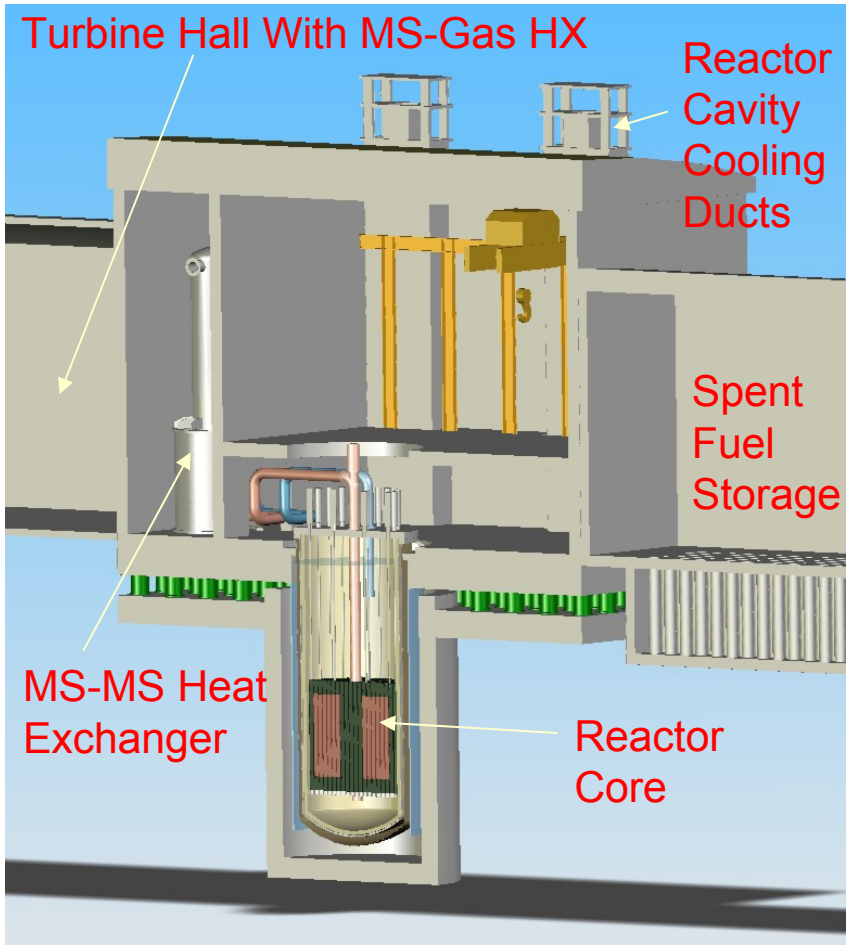
Decay Heat from Core to Vessel Liner



Decay Heat from Vessel to Environment

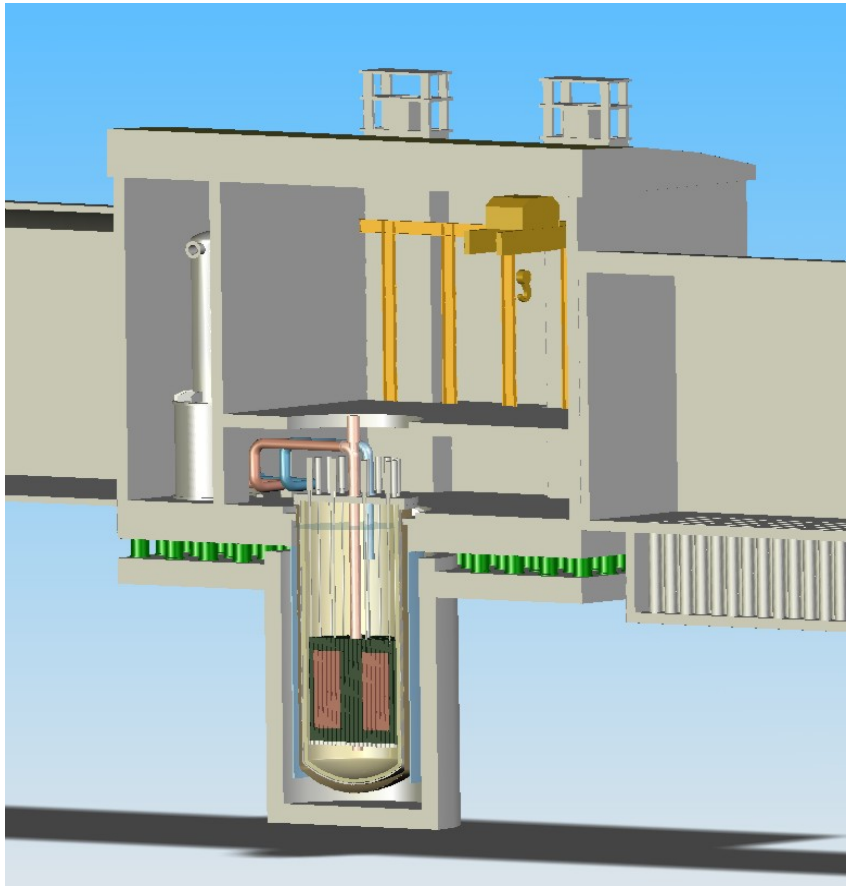
- Similar to GE S-PRISM (LMR)
- Liquid transfers heat from fuel to wall with small temperature drop (~50ºC)
- Argon gap: Reactor to guard vessel
  - Heat transfer: $\sim T^4$
  - Thermal switch mechanism
- Heat rejection: Vessel temperature dependent
  - LMR: 500-550ºC [~1000 MW(t)]
  - AHTR: 750ºC [~2400 MW(t)]
- Lower vessel temperatures possible
  - DRACS
  - Cost: Higher heat losses during normal operation

2400-MW(t) AHTR Nuclear Island Is Similar in Size to 1000-MW(t) Sodium-Cooled S-PRISM Plant



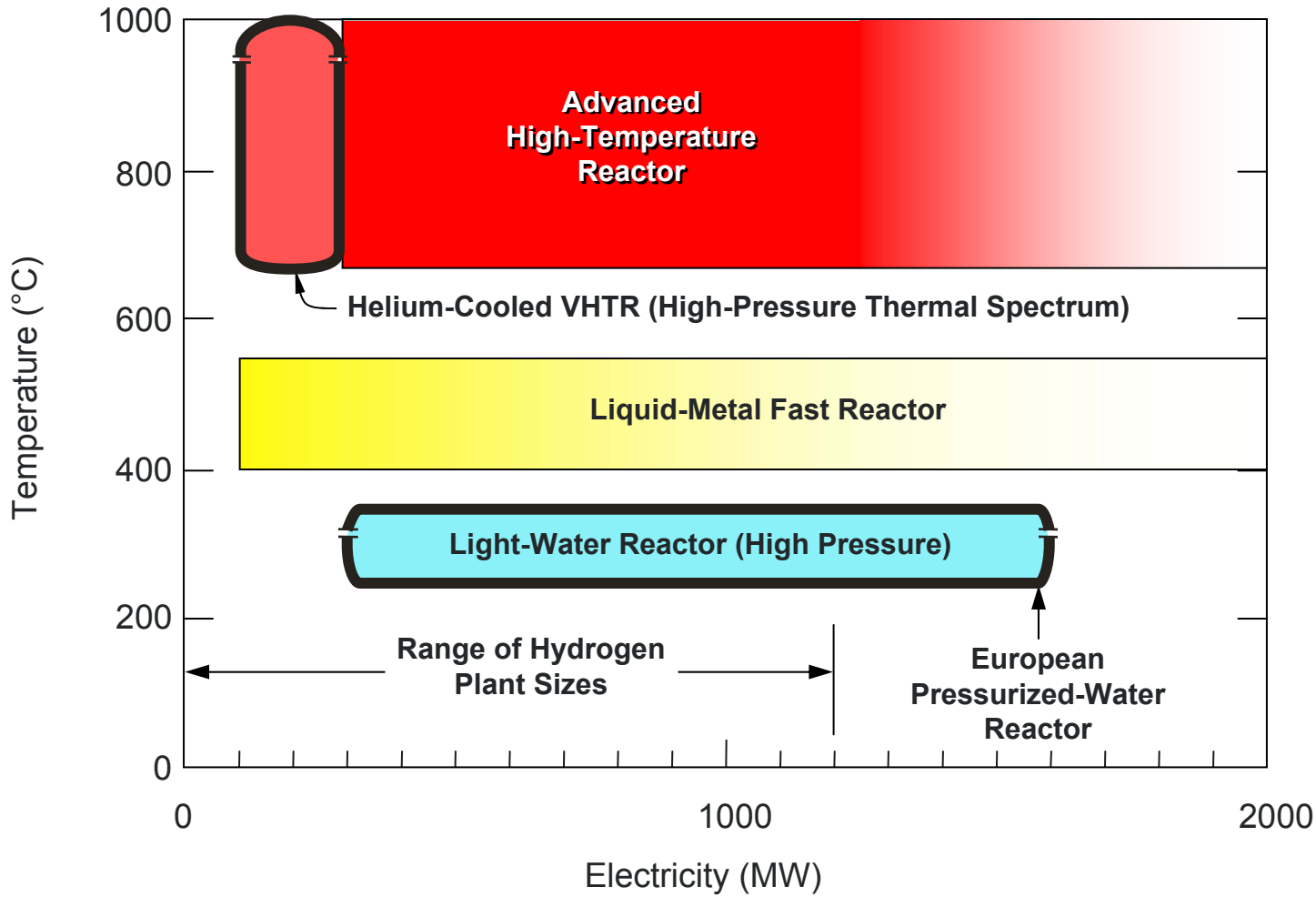
- **Differences from S-PRISM facility layout:**
  - **No SNF storage in vessel**
  - **No heat exchanger inside vessel**
  - **Molten salt-to-gas heat exchanger in turbine hall**
- **Same vessel size**
  - **Space for 2400-MW(t) AHTR core with low power density**
- **Similar equipment size**
  - **Molten salt volumetric heat capacity > sodium**
- **Higher-capacity decay heat removal system**
  - **Higher vessel temperatures**
- **Higher electrical output**
  - **S-PRISM: 380 MW(e)**
  - **AHTR: 1300 MW(e)**

The Preliminary Economic Analysis Indicates Capital Costs of 50 to 60% per kW(e) Relative to S-PRISM and MHTGRs



- **Economics of scale**
  - **2400 MW(t) vs 600 to 1000 MW(t)**
  - **1300 MW(e) vs 300 to 380 MW(e)**
- **Passive safety in a large reactor**
  - **Liquid heat transport inside reactor vessel**
  - **Higher temperatures (750ºC) increase heat rejection**
- **Higher efficiency (multi-reheat Brayton cycle)**
- **No large pressure vessel**

AHTR Characteristics Relative to Other Reactor Concepts

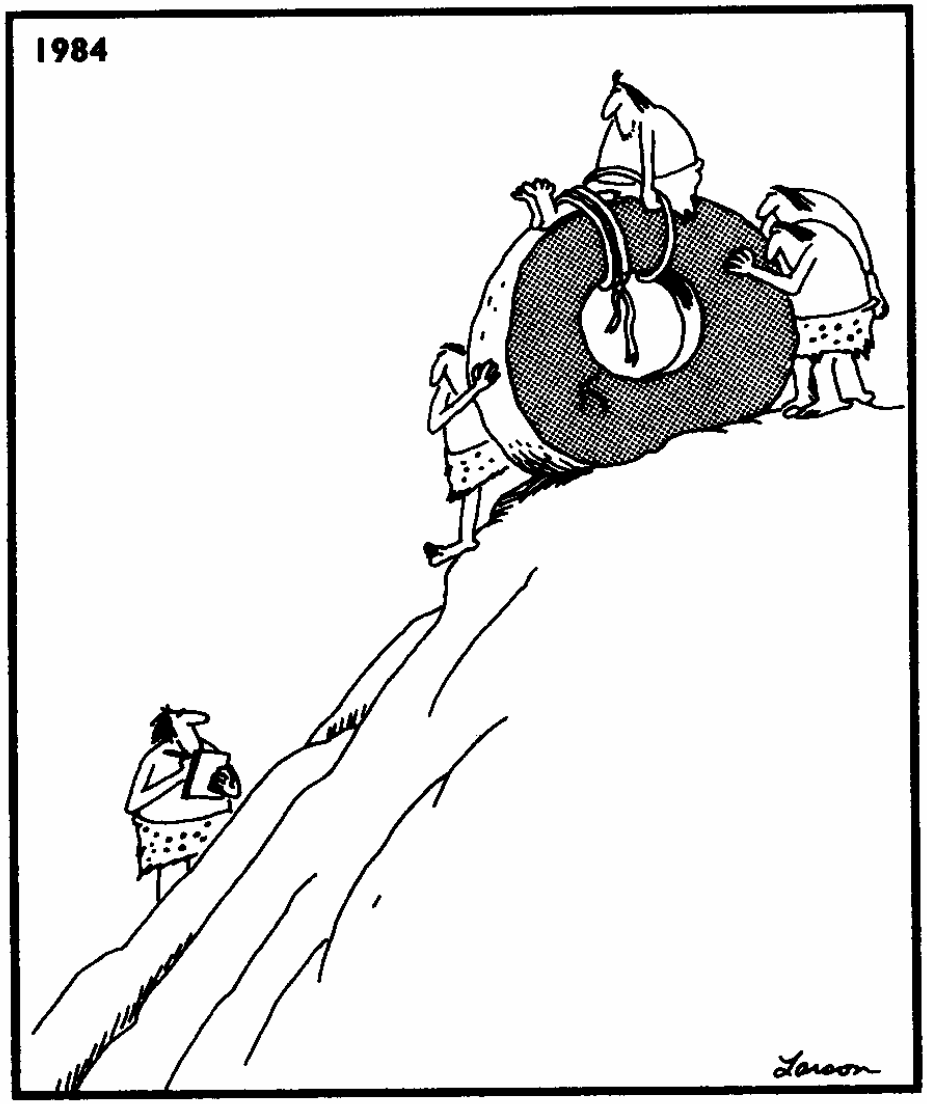


AHTR Summary

- **Goals: Develop an economic reactor (the AHTR) with three characteristics**
  - **High temperatures (efficient)**
  - **Large (economics)**
  - **Passive safety (match or exceed MHTGR)**
- **Technical approach to reach goals**
  - **High-temperature graphite coated-particle fuel**
  - **Molten salt coolant**
  - **Passive decay-heat cooling system**
  - **Brayton power cycle**
- **New concept: Significant work remains**

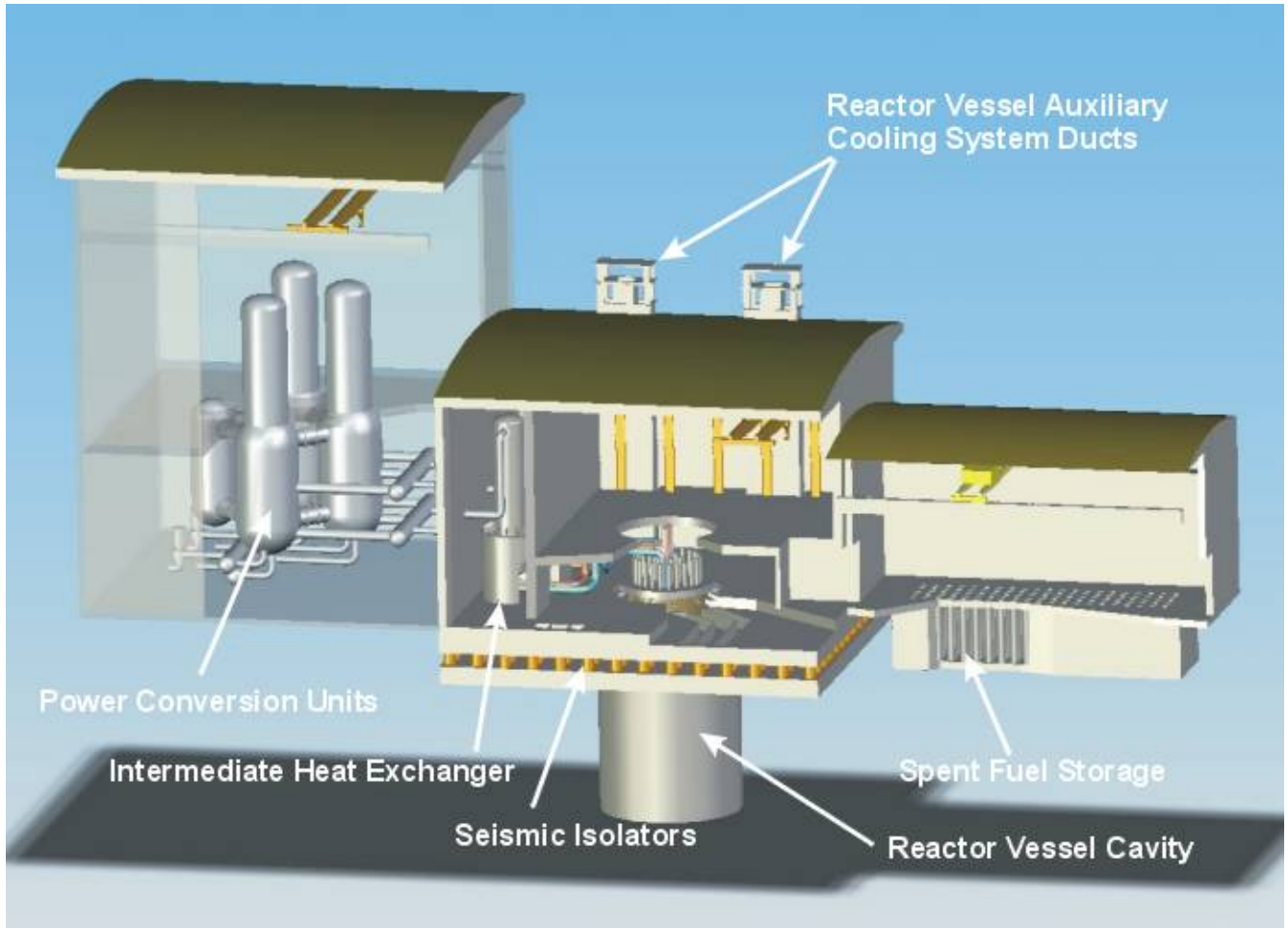
The AHTR:

A good idea that still needs some work



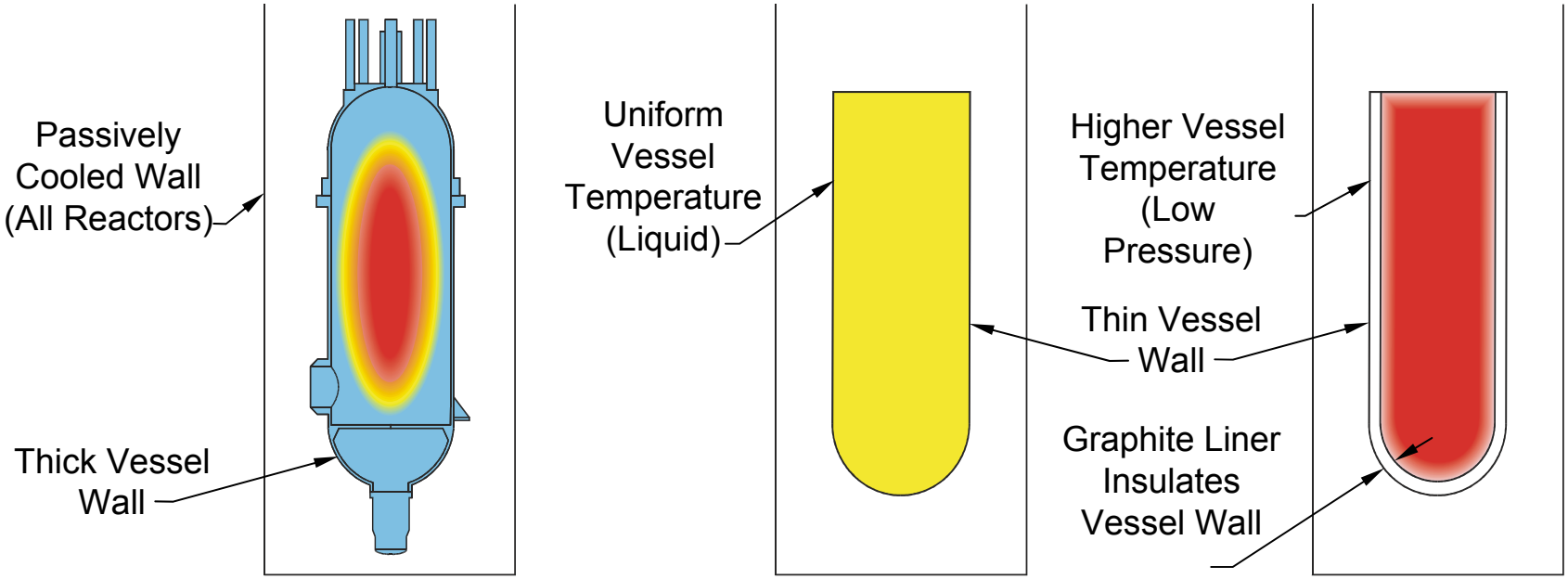
Backup Slides

Advanced High-Temperature Reactor

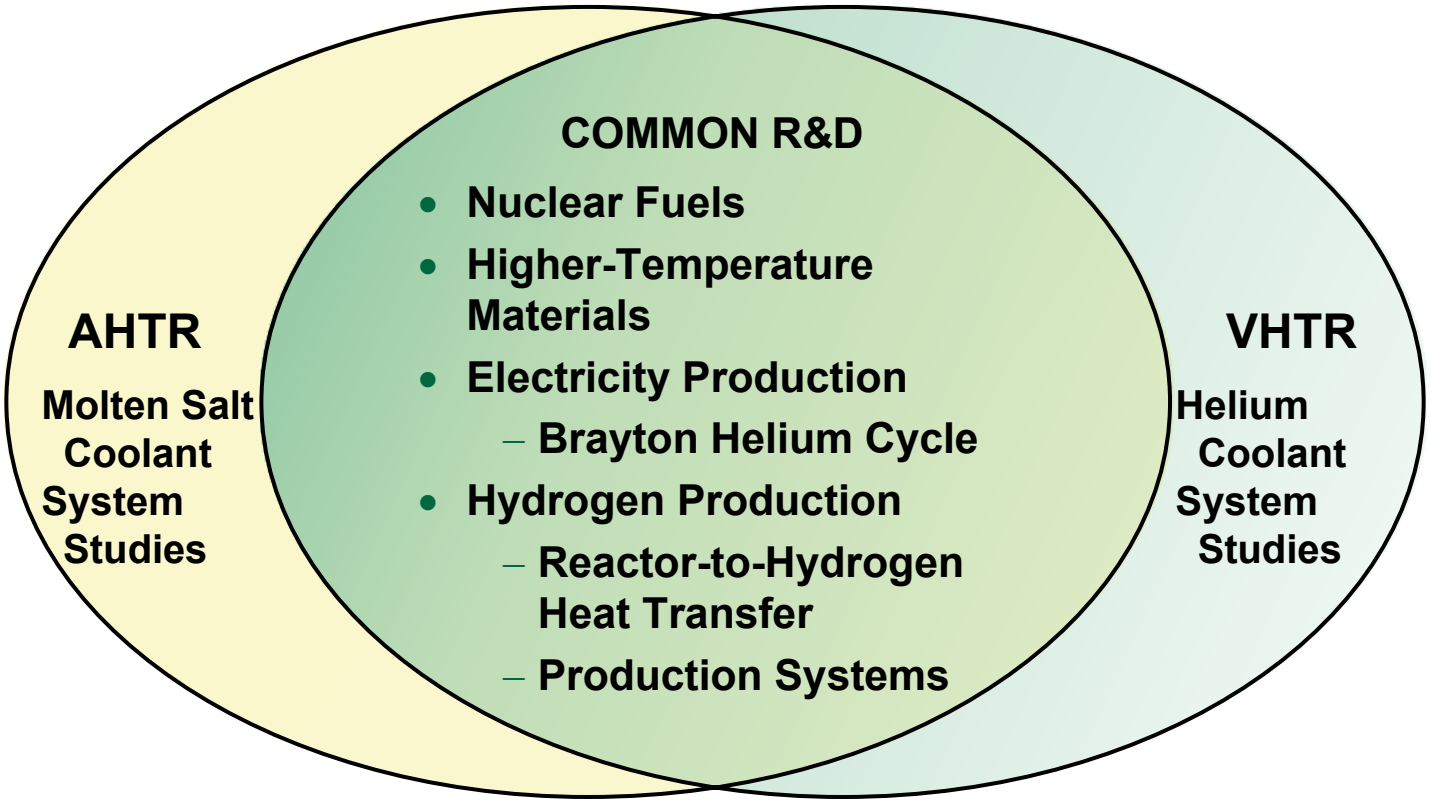


High-Temperature, Low-Pressure Liquid Coolants Enable the Design of Large Reactors with Passive Safety

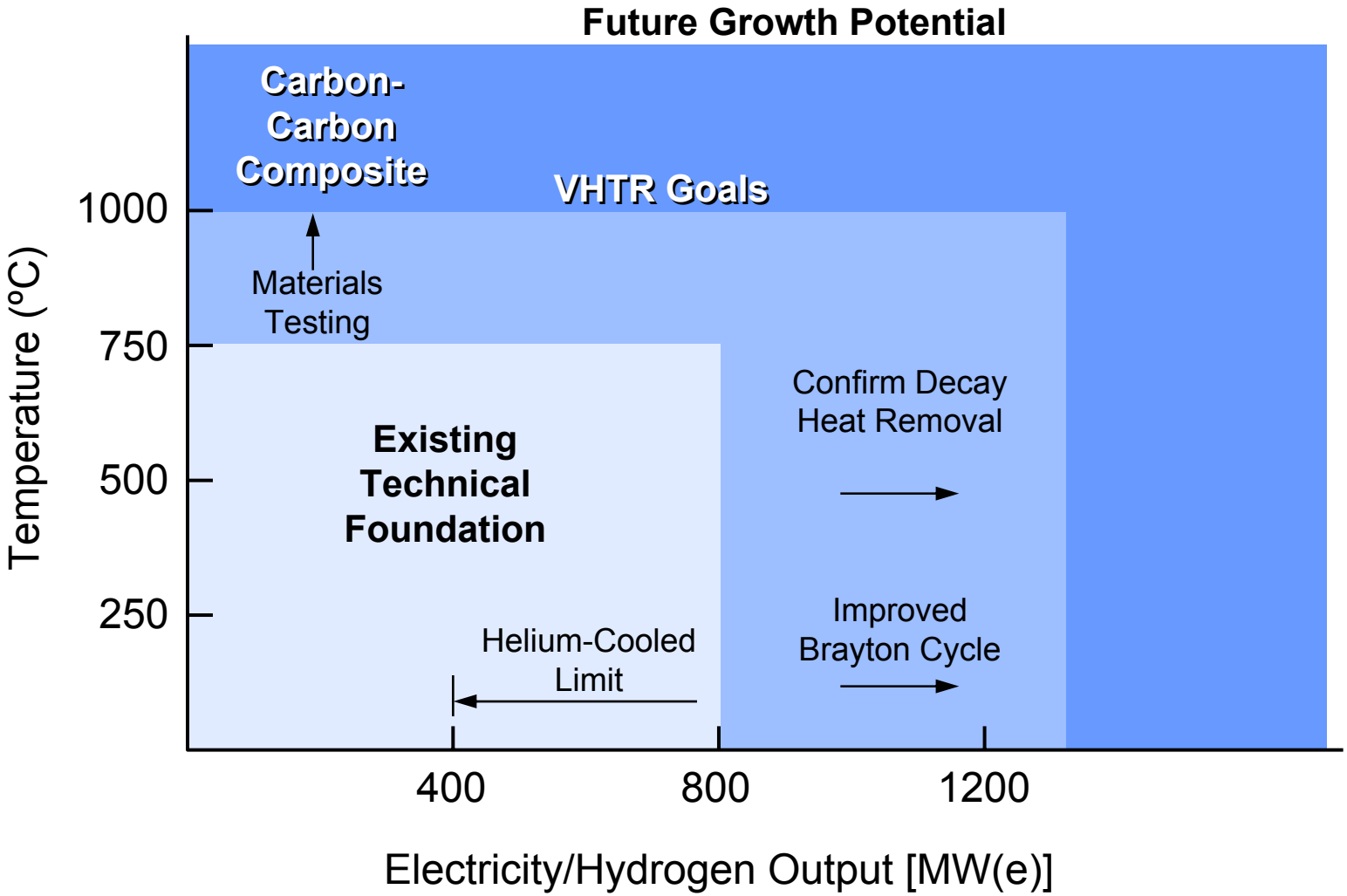
Reactor:	MHTGR	S-PRISM	AHTR
Coolant:	Helium	Sodium	Molten Salt
Power:	600 MW(t)	1000 MW(t)	2400 MW(t)
Constraint:	Conduction	Sodium Boiling Point	Vessel



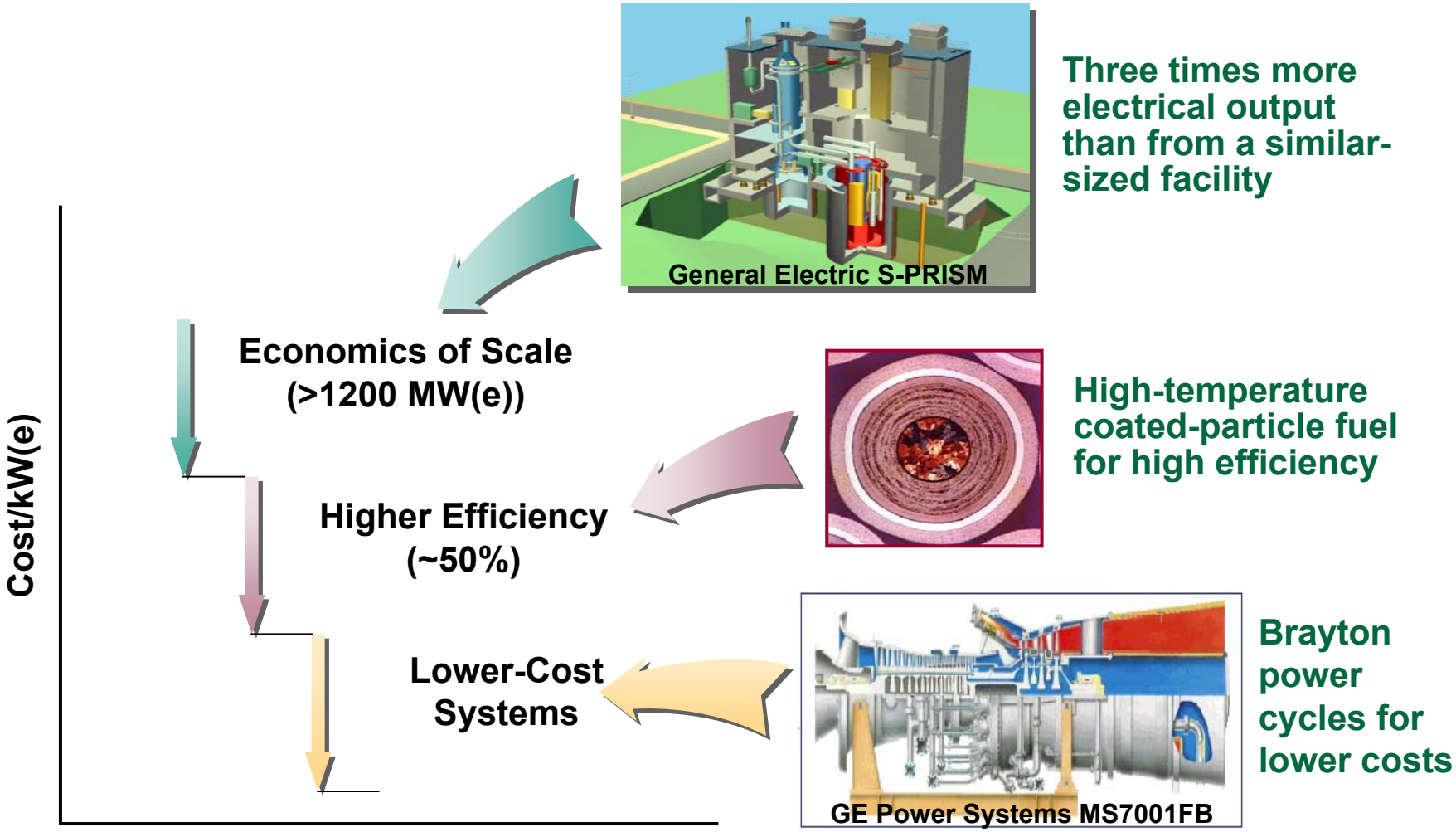
The R&D Requirements for the Molten-Salt- Cooled AHTR and the Helium-Cooled VHTR Have Much In Common



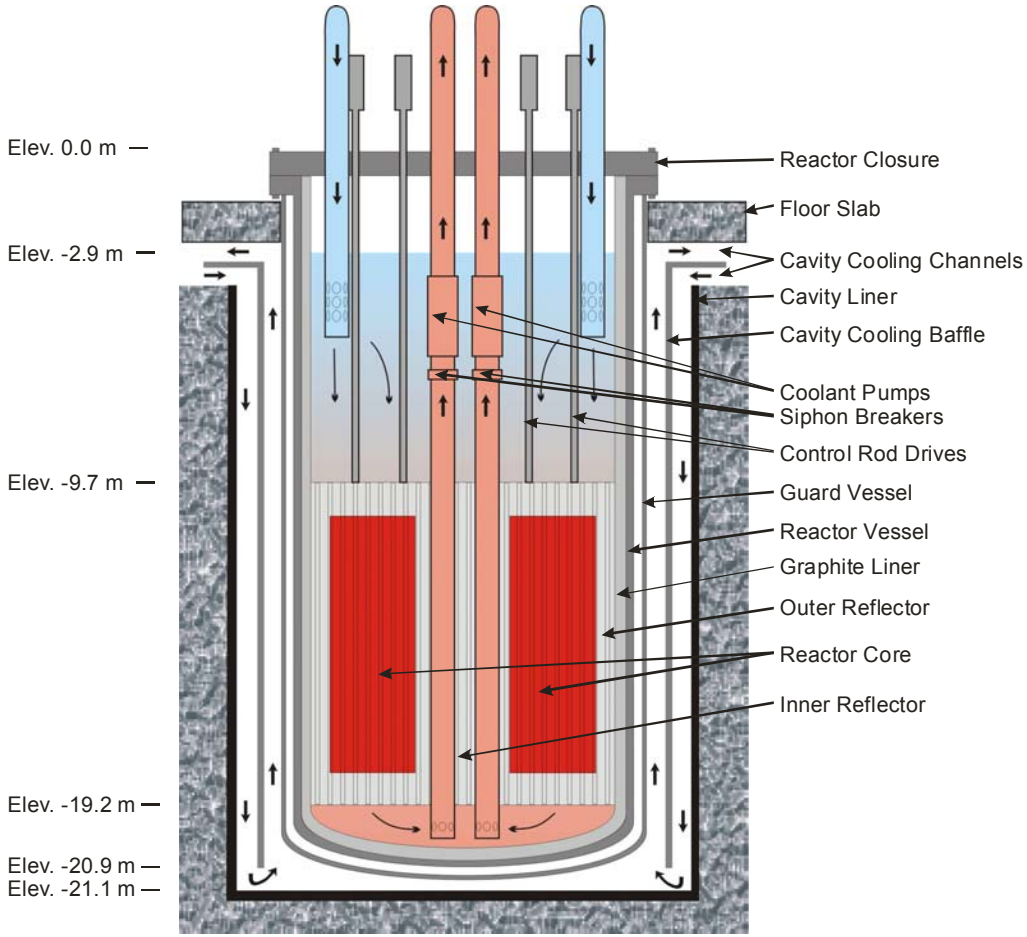
Global AHTR R&D Perspective



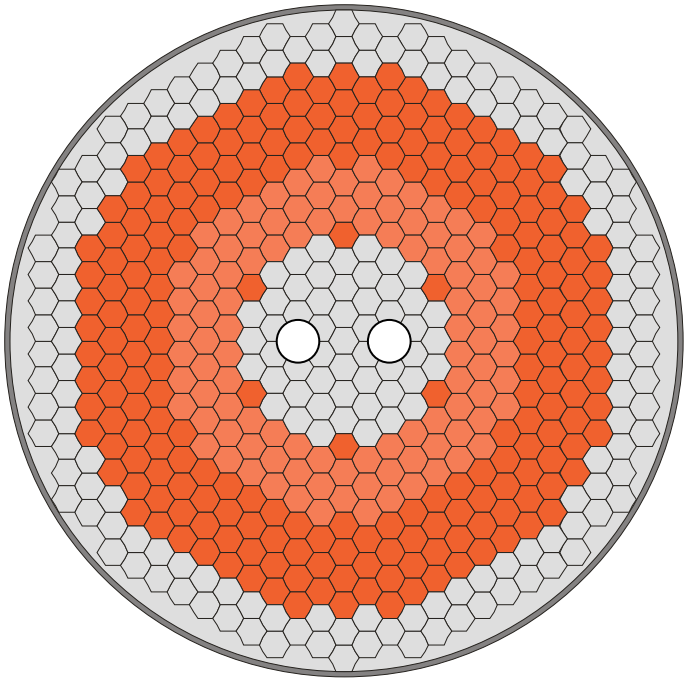
The Economic Goal Is To Drive Costs Significantly Below $1000/kW(e)



AHTR 9.0-m 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)