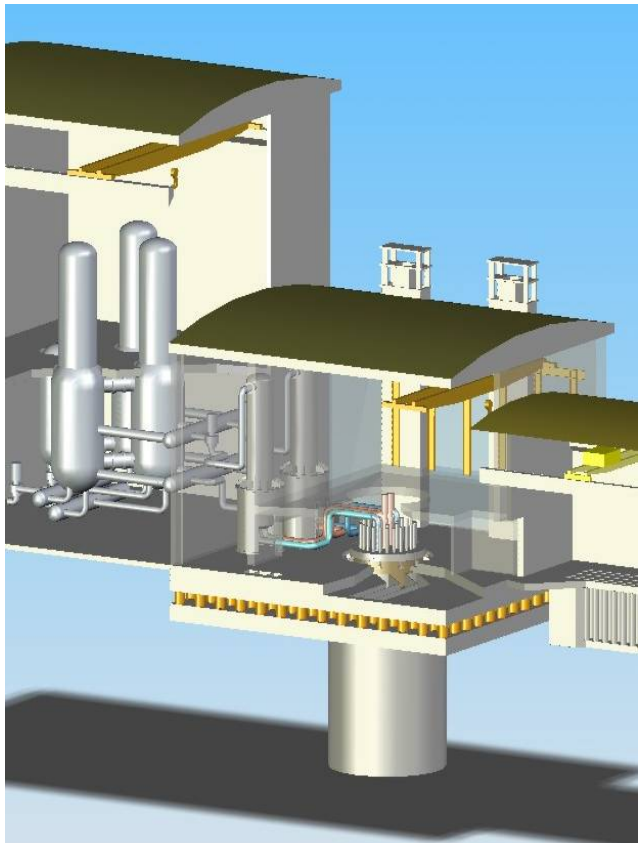
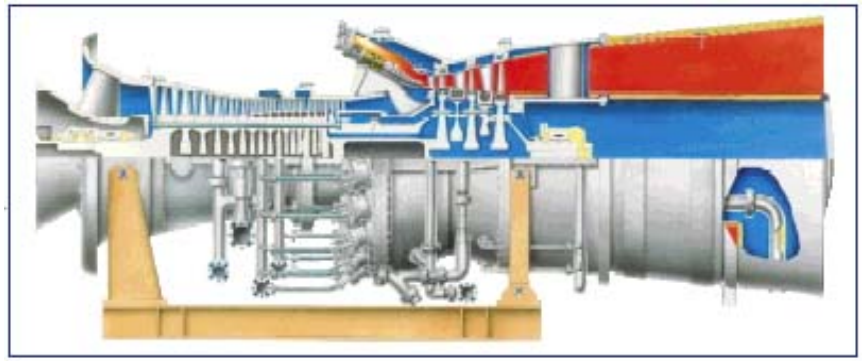
Salt-Cooled Reactors and the Advanced High-Temperature Reactor

Charles Forsberg
Oak Ridge National Laboratory
P.O. Box 2008; Oak Ridge, TN 37831-6165
E-mail: forsbergcw@ornl.gov
Tel: (865) 574-6783

National Tsing Hua University
December 13, 2005
Hsinchu, Taiwan





OAK RIDGE NATIONAL LABORATORY

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: TaiwanDec05AHTR

Abstract: Salt-Cooled Reactors and the Advanced High-Temperature Reactor

New non-nuclear technologies are creating new nuclear reactor options. Historically, the efficient power cycle to convert heat to electricity was the steam cycle with an upper temperature limit of 550ºC. The development of the higher-temperature Brayton cycles allows efficient conversion of higher-temperature heat to electricity. In parallel, there is a strong interest in processes to convert high-temperature heat and water to oxygen and electricity. These new technologies create a need for high-temperature heat and thus a demand for high-temperature reactors.

There are only two high-temperature fluids that have been developed for use in high-temperature reactors: high pressure helium and atmospheric-pressure liquid-fluoride salts. The use of liquid-fluoride-salt coolants in high-temperature reactors allows for large [2400-4000 MW(t)] reactors that use passive safety systems with safety characteristics that match modular [600 MW(t)] gas-cooled high-temperature reactors. Economic assessments indicate the potential for low capital costs. Three such reactors are described: the Advanced High-Temperature Reactor (AHTR) [liquid-salt coolant, coated-particle graphite fuel (same as in helium-cooled reactors)], the liquid-salt-cooled fast reactor (liquid-salt coolant and metallic-clad fuel), and the Molten Salt Reactor (fuel dissolved in salt). The AHTR is the near-term option that is being developed in the United States. A more detailed description of the AHTR is provided.

Why the New Interest in Salt-Cooled Reactors?

Why is the U.S. Examining Three Salt-Cooled Reactors?

Advanced High-Temperature Reactor
Liquid-Salt-Cooled Fast Reactor
Molten Salt Reactor

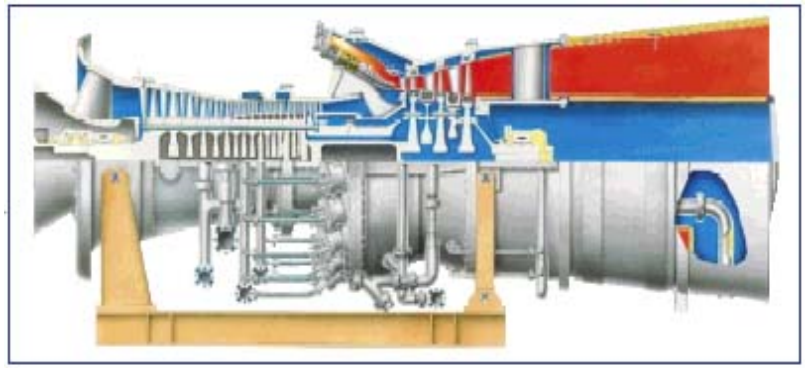
Liquid-Salt-Cooled Systems are Intrinsically High-Temperature Systems

- Useful salts for nuclear applications have freezing points between 350 and 500ºC and boiling points above 1200ºC

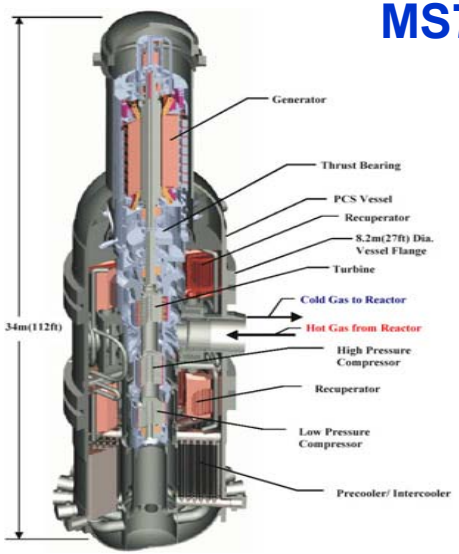
- Salt systems are only useful if supporting technologies can use high-temperature heat

Brayton Power Cycles Make High-Temperature Reactors Viable

- For electric utilities, high-temperature heat is only useful if it can be converted to electricity
- Steam turbines with a 550ºC peak temperature can not efficiently use high-temperature heat
- Development of large efficient high-temperature Brayton cycles *in the last decade* makes high-temperature heat useful



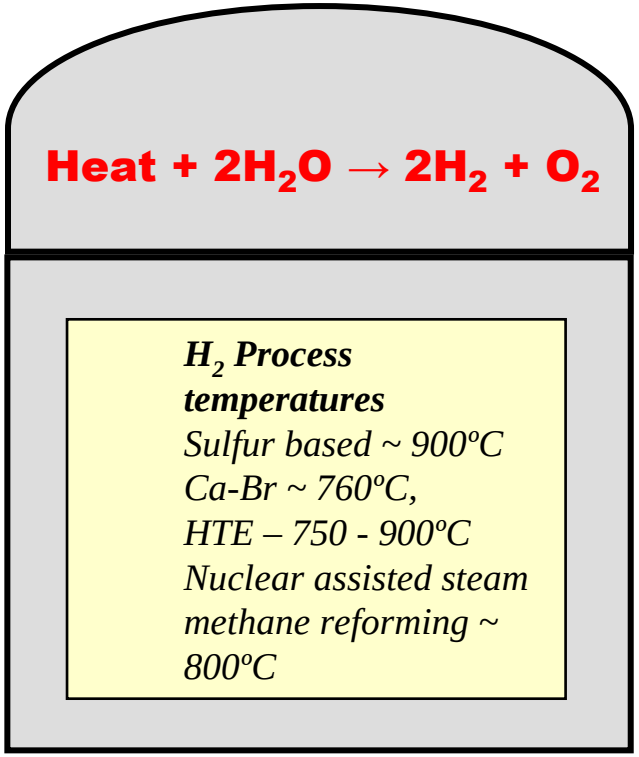
GE Power Systems MS7001FB



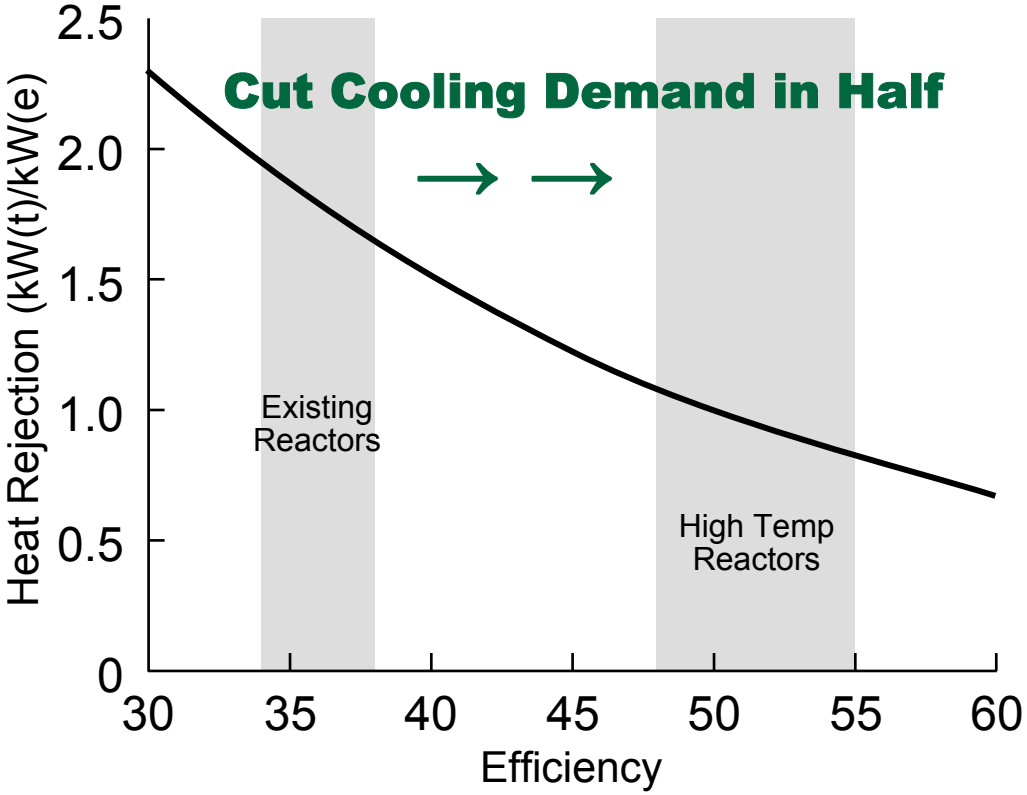
General Atomics GT-MHR Power Conversion Unit (Russian Design)

High-Temperature Reactors are Enabling Technologies

Hydrogen Production

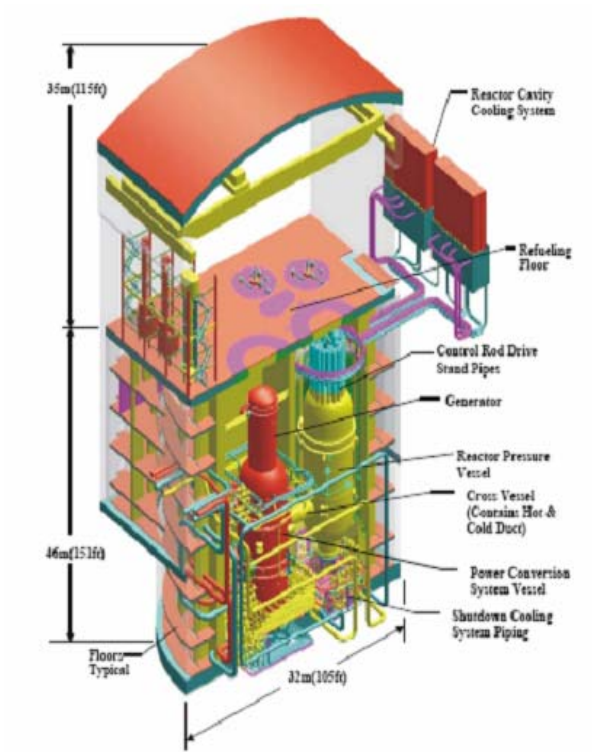


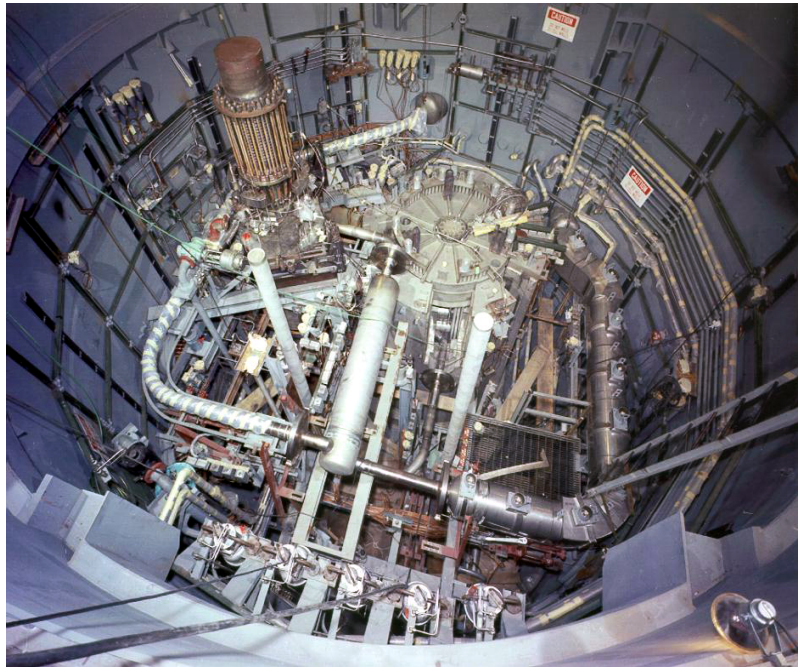
Dry Cooling for Electricity Generation



High-Temperature Reactor Options

There are Two Demonstrated High-Temperature Nuclear Reactor Coolants

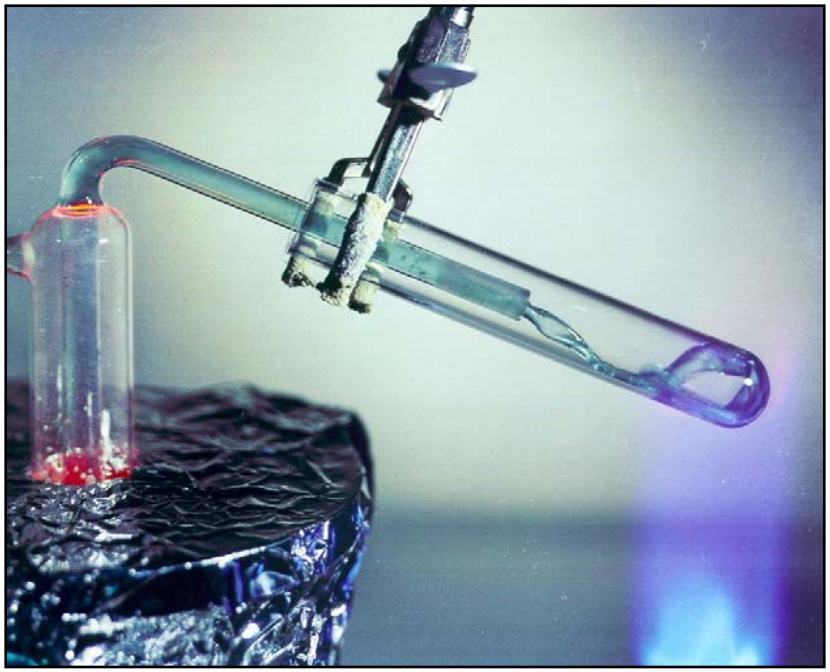




Helium: Multiple Reactors
(High-Temperature Reactors)

Liquid Fluoride Salts: Two Reactors
(Molten Salt Reactors)

There are Two Demonstrated High-Temperature Reactor Coolants



Helium

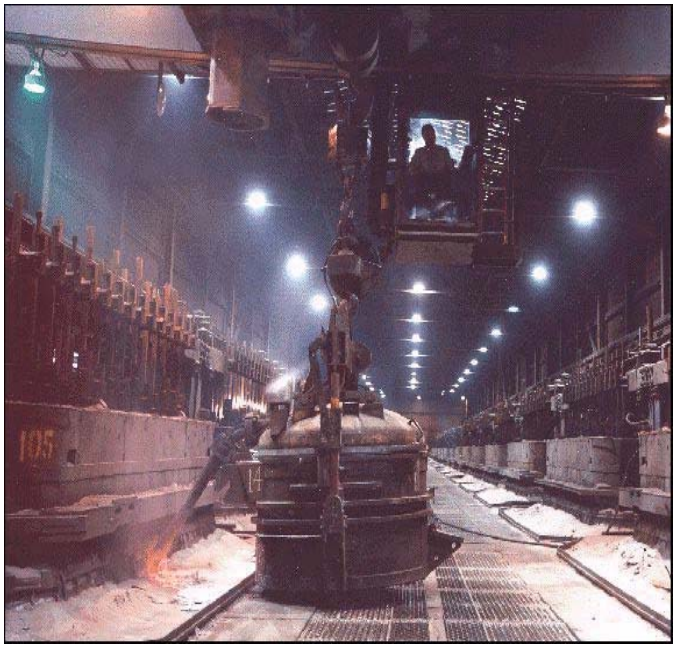
(High Pressure/Transparent)

Liquid Fluoride Salts

(Low Pressure/Transparent)

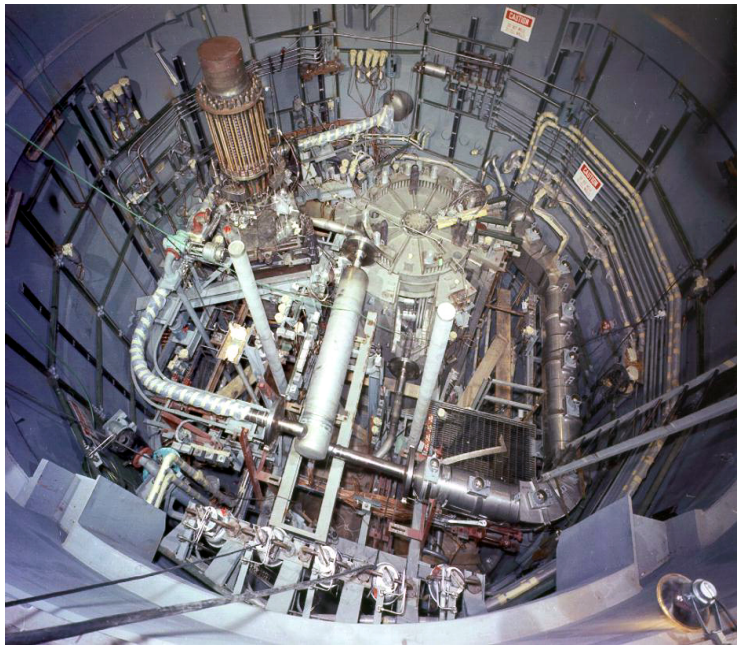
There is Significant Experience with Molten and Liquid Fluoride Salts

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



Molten Fluoride Salts are Used to Make Aluminum in Graphite Baths at 1000°C

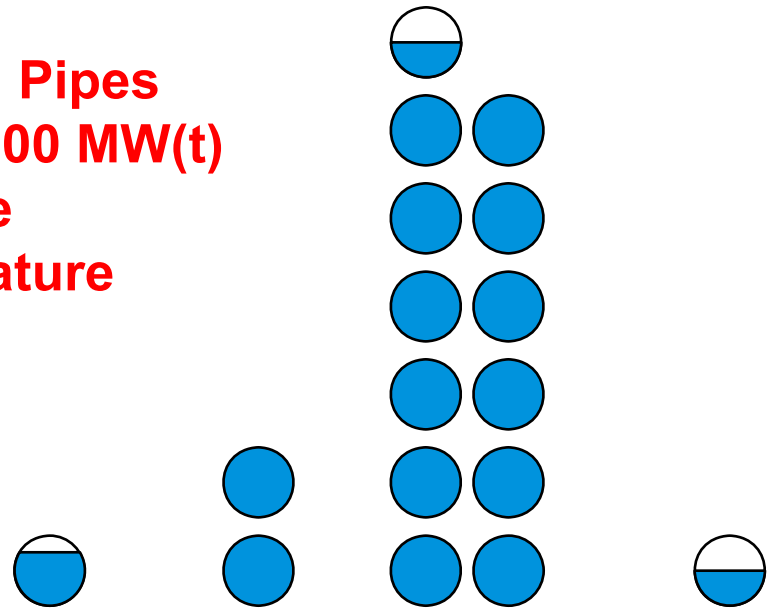
Liquid Fluoride Salts Were Used in Molten Salt Reactors with Fuel in Coolant (AHTR Uses Clean Salt and Solid Fuel)



Coolant Properties Impact Reactor Costs

(Determine Pipe, Valve, and Heat Exchanger Sizes)

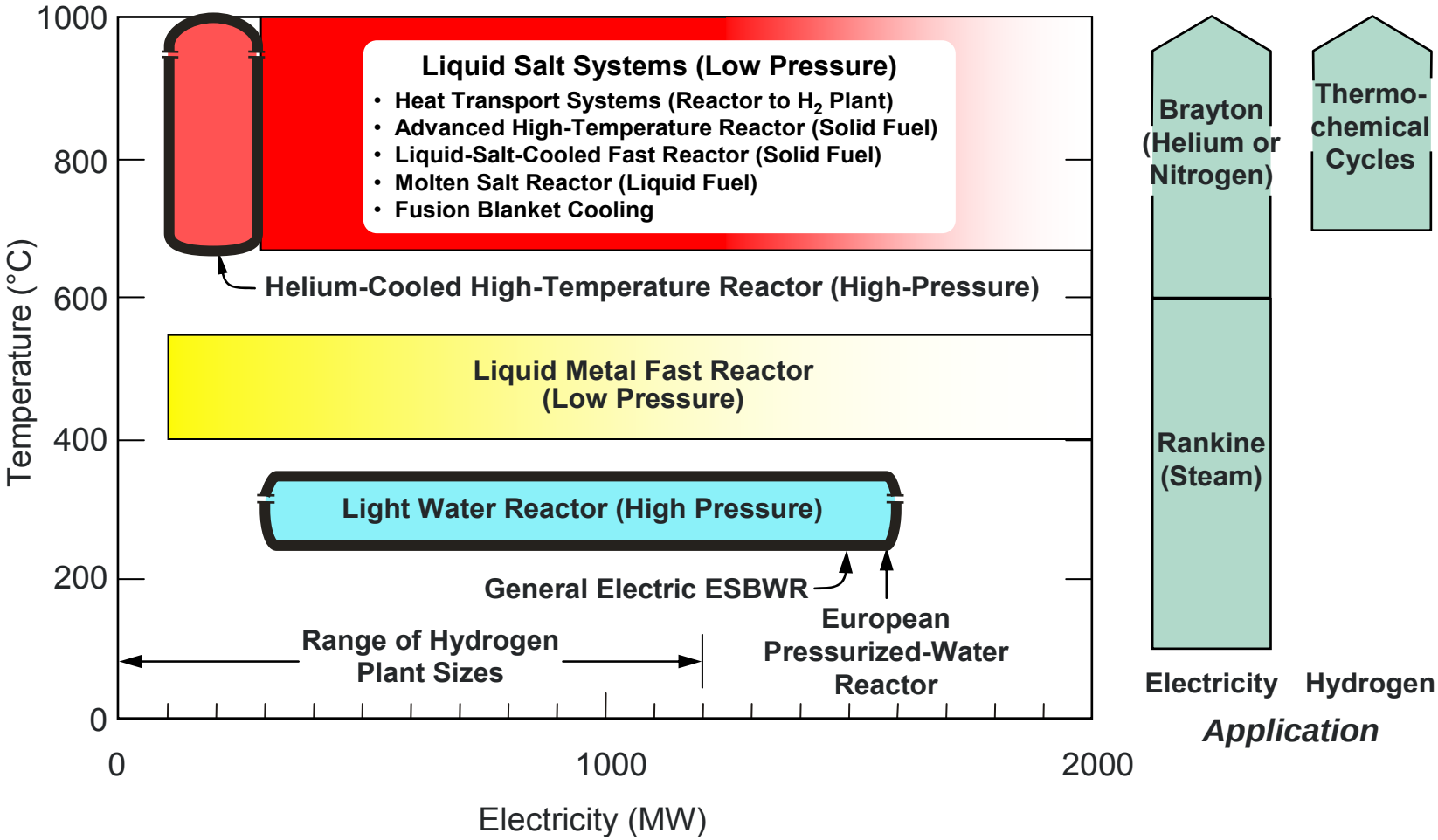
Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temperature



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

Liquid Salt Coolants Can be Used for Many High-Temperature Reactors

(Liquid Salt Reactors: Clean Coolant with Solid Fuel or Fuel in Coolant)



Advanced High-Temperature Reactor

(Liquid-Salt-Cooled Very High-Temperature Reactor)

Primary U.S. Salt-Cooled Reactor Program

(Funded as a GenIV VHTR Activity)

Reactor Characteristics

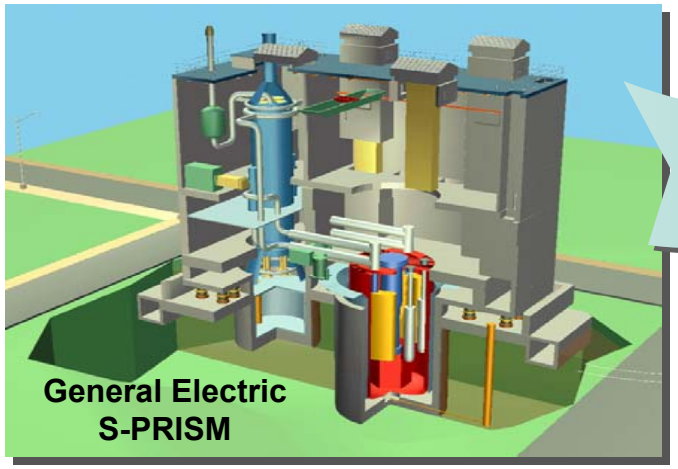
Clean liquid-salt coolant

Coolant temperature options: 700 to 1000ºC

Size range of interest: 2400 to 4000 MW(t)

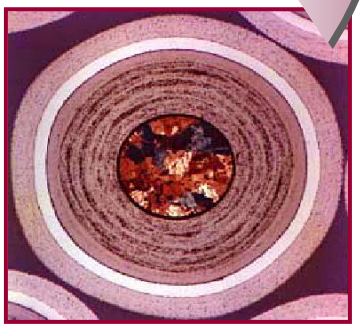
The Advanced High-Temperature Reactor

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 Liquid-Salt Coolant

AHTR Applications

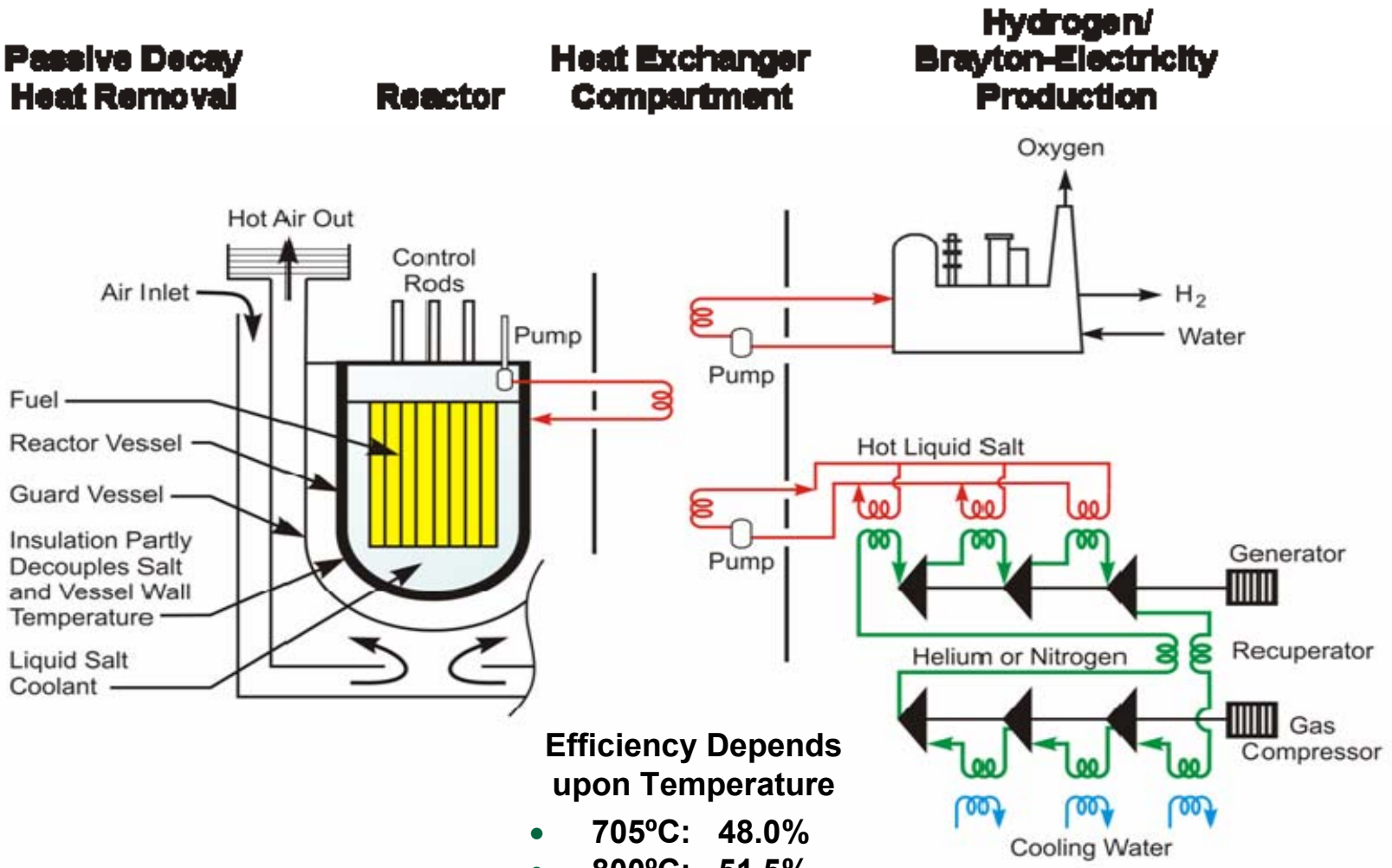
Hydrogen

- Government interest (primary)
- Requirement
  - Deliver heat to thermo-chemical H_2 cycle
  - Up to 950ºC
- Special capability
  - Smaller ΔT across heat exchangers than in gas-cooled reactors
  - Lower coolant temperatures for same temperature of delivered heat

Electricity

- Vendor interest
- Requirement: <$/kW(e)
- Market
  - Replace LWRs in 25 years
  - Match size of 2025 LWR [~2000 MW(e)]
- Goals
  - Large size [~4000 MW(t)]
  - Lower temperatures (700 to 800ºC) to minimize materials development

Schematic of Advanced High-Temperature Reactor

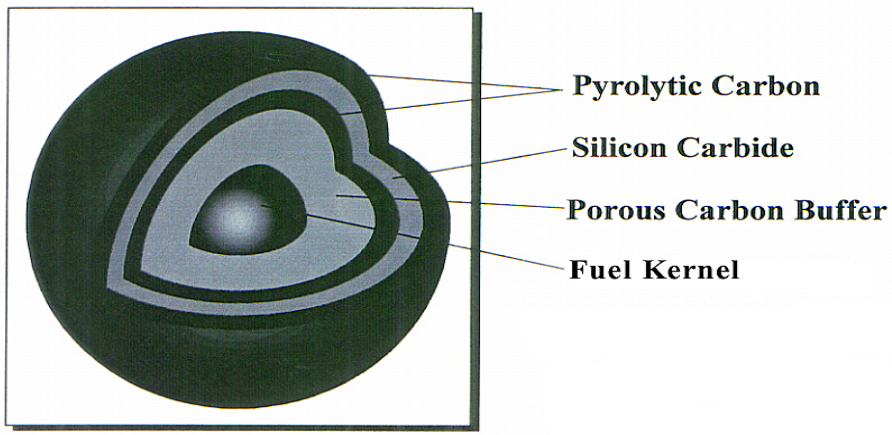


Efficiency Depends upon Temperature

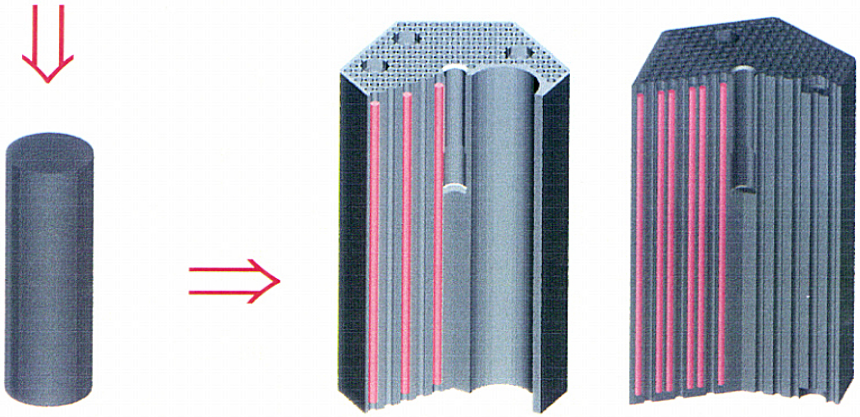
- **705ºC: 48.0%**
- **800ºC: 51.5%**

The AHTR Uses Coated-Particle Fuel

(Peak Operating Temperature: 1250ºC; Failure Temperature: >1600ºC)



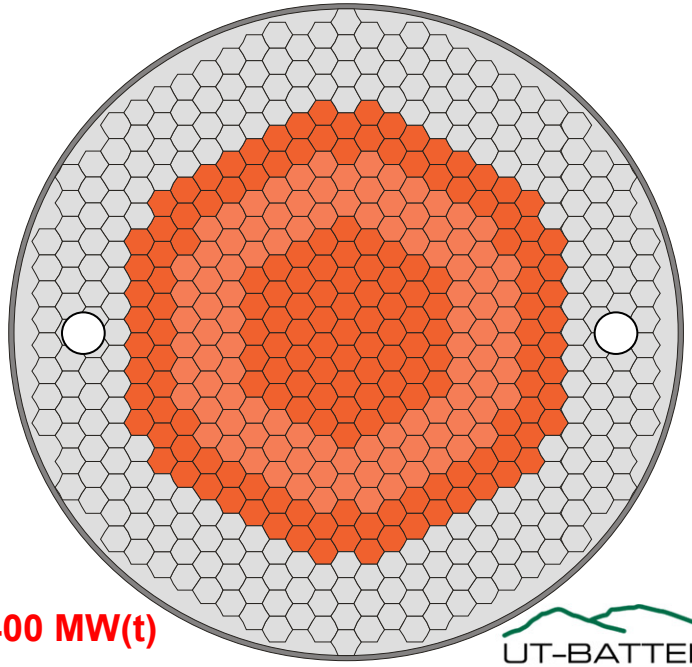
FUEL PARTICLE



FUEL COMPACT

FUEL ASSEMBLIES

Same Fuel as is Used in High-Temperature Gas-Cooled Reactors

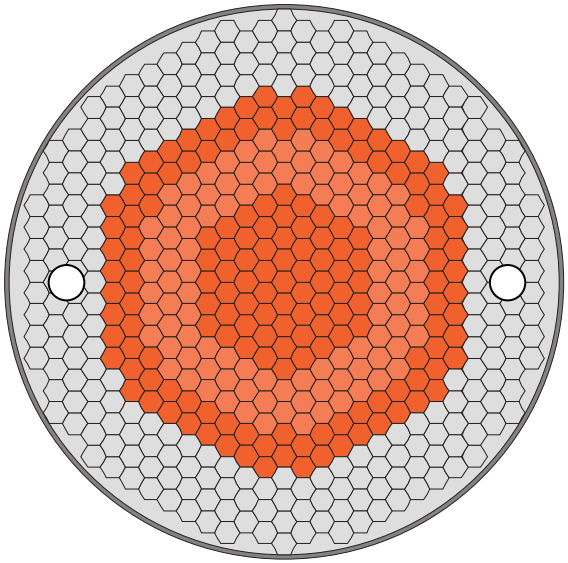


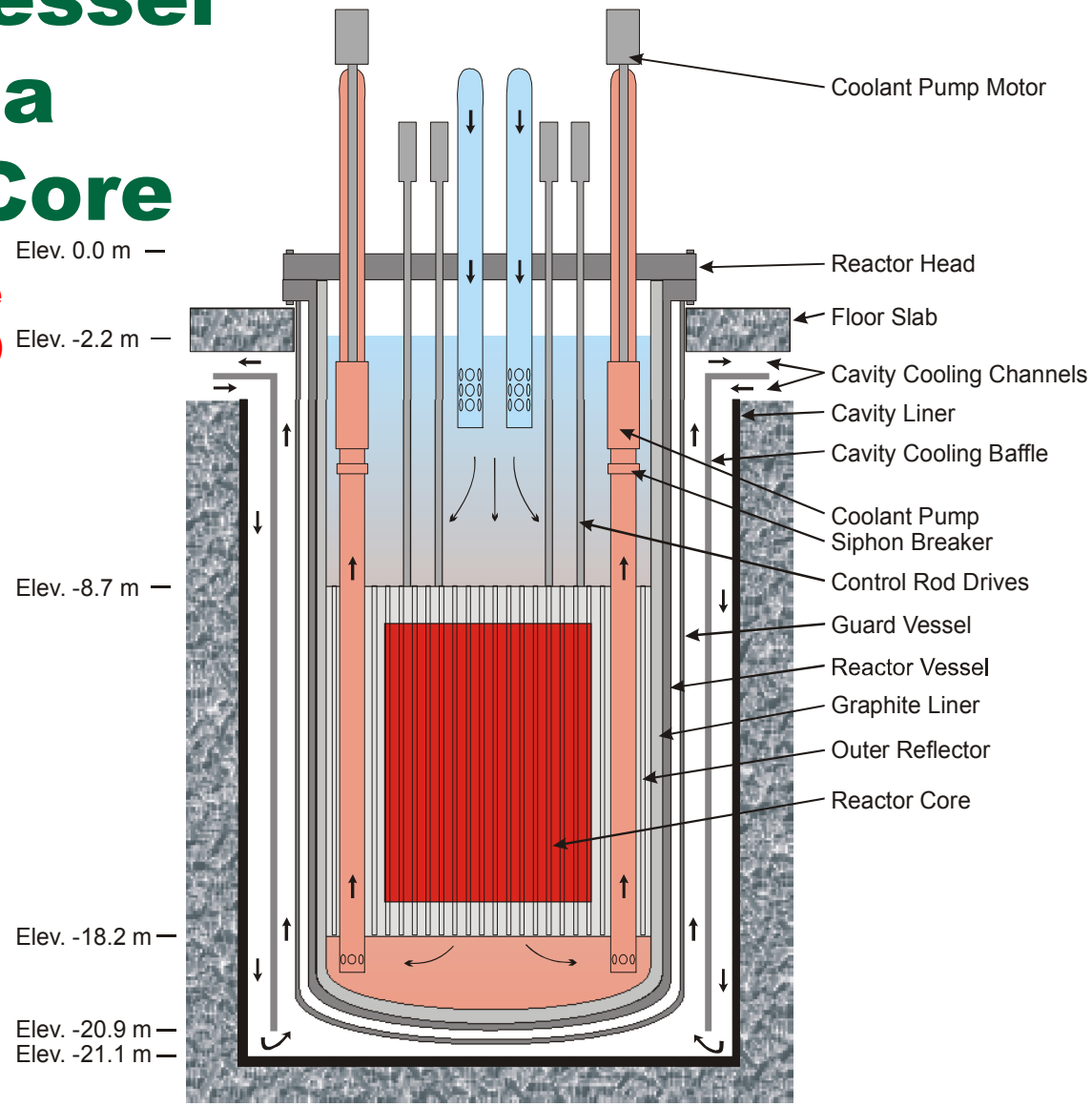
2400 MW(t)

AHTR 9.2-m Vessel Allows for a 2400-MW(t) Core

(Same Vessel Size as the S-PRISM Reactor Vessel)

102 GT-MHR fuel columns
163 Additional fuel columns
265 Total fuel columns

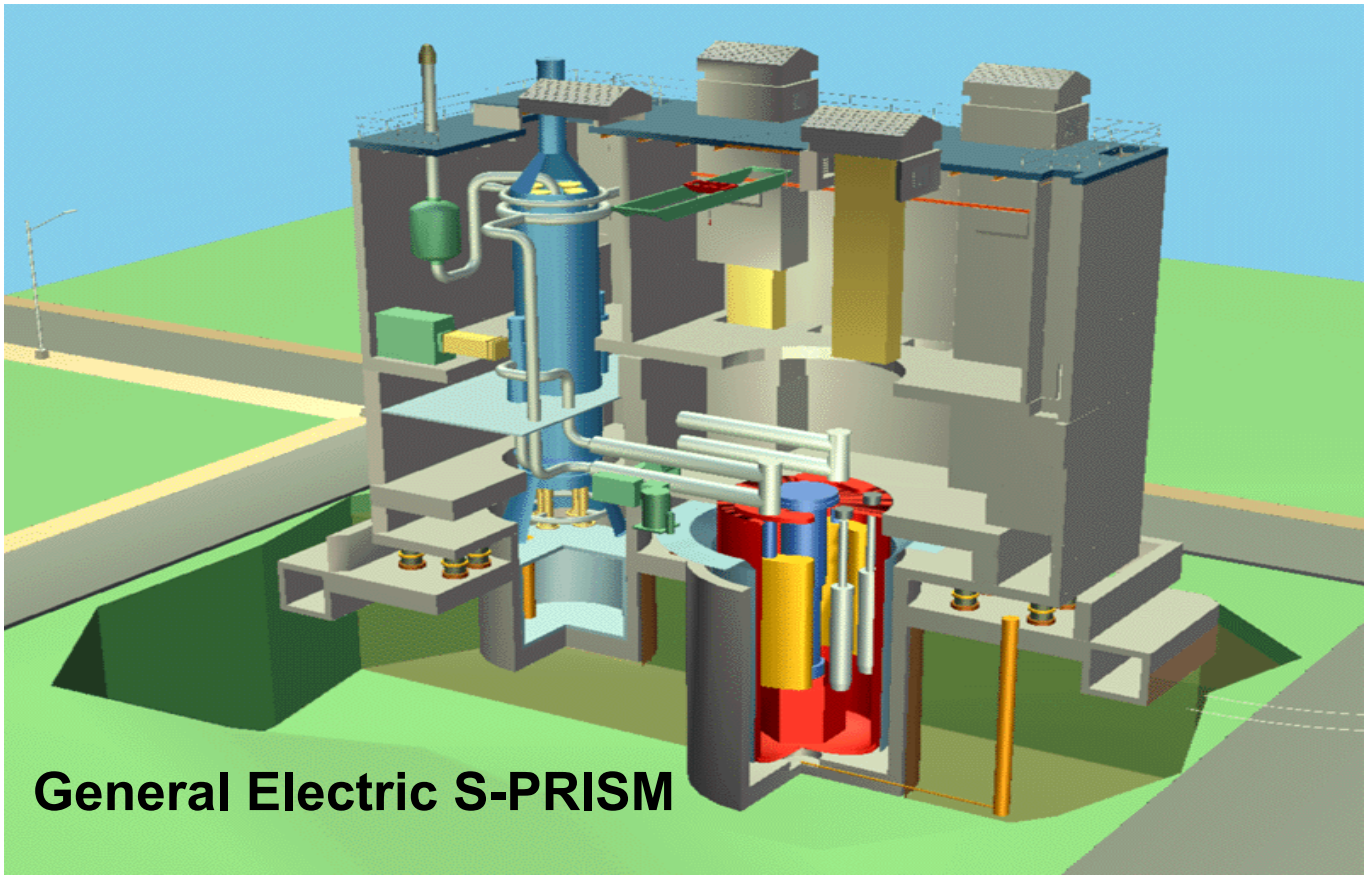




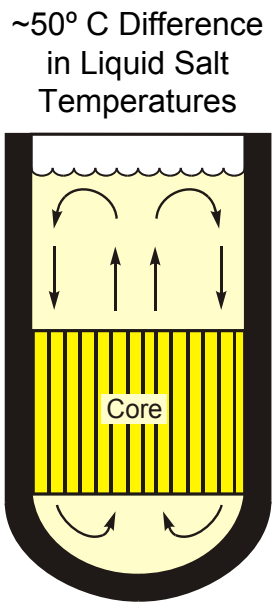
Power density = 10.0 MW/m^3

AHTR Facility Layouts are Based on Sodium-Cooled Fast Reactors

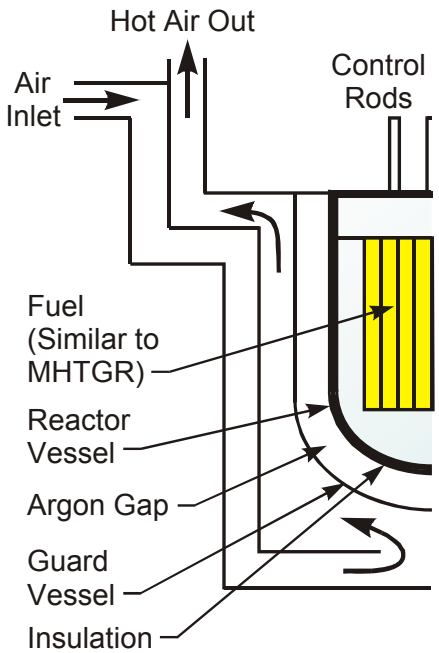
Low Pressure, High Temperature, Liquid Cooled



Decay Heat Removal System Similar to GE-SPRISM Fast Reactor System



Decay Heat from Core to Vessel Liner



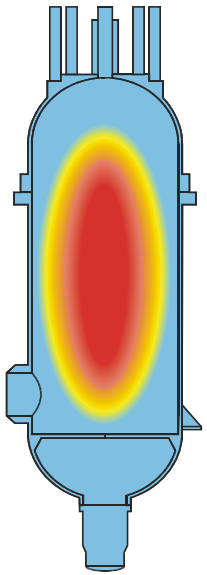
Decay Heat from Vessel to Environment

- 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: ~T^4
  - Thermal switch mechanism
- Vessel temperature determines heat rejection capabilities
  - LMR: 500-550ºC [~1000 MW(t)]
  - AHTR: 750ºC [~2400 MW(t)]
- Lower vessel temperatures possible
  - DRACS
  - Cost: Higher heat losses during normal operation

Liquid Cooling Allows Large Reactors with Passive Decay Heat Removed

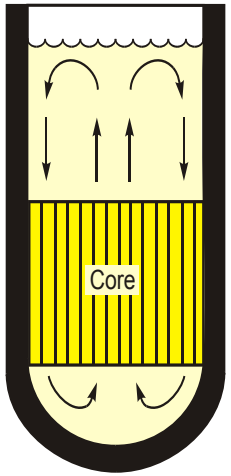
Alternative Decay Heat Removal Options to Move Heat to Vessel Surface or Heat Exchanger

Gas
[~600 MW(t)]



Conduction Cooling
(~1000ºC Difference in Fuel Temperature)

Liquid
[1000s of MW(t)]

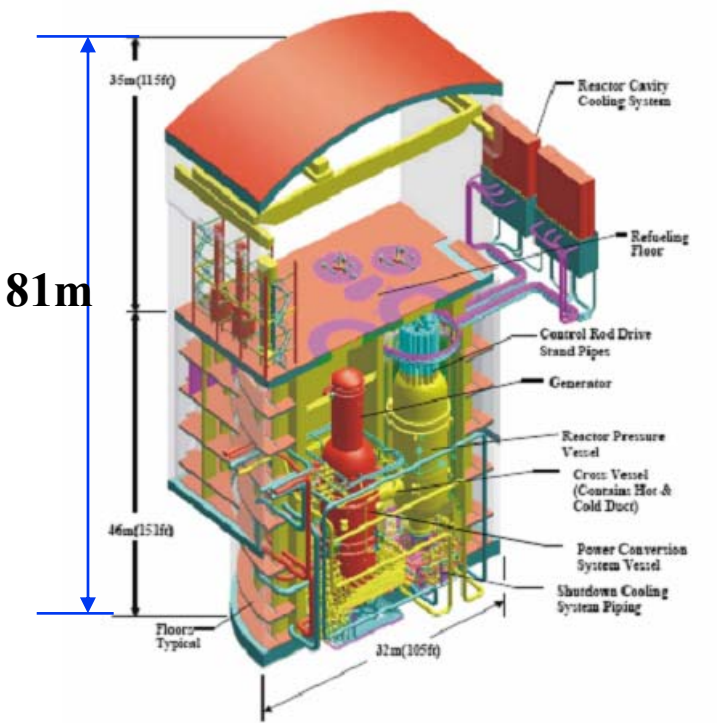


Convective Cooling
(~50ºC Difference in Liquid Temperature)

- **Passive decay-heat removal systems can remove heat from:**
  - **Vessel wall**
  - **Liquid coolant**
- **Passive decay-heat removal limited by heat transport from fuel to vessel or heat exchanger**
  - **Gas-cooled reactor: Conduction heat transfer: limited heat removal**
  - **Liquid-cooled reactor: Convective heat transfer: no power limit**

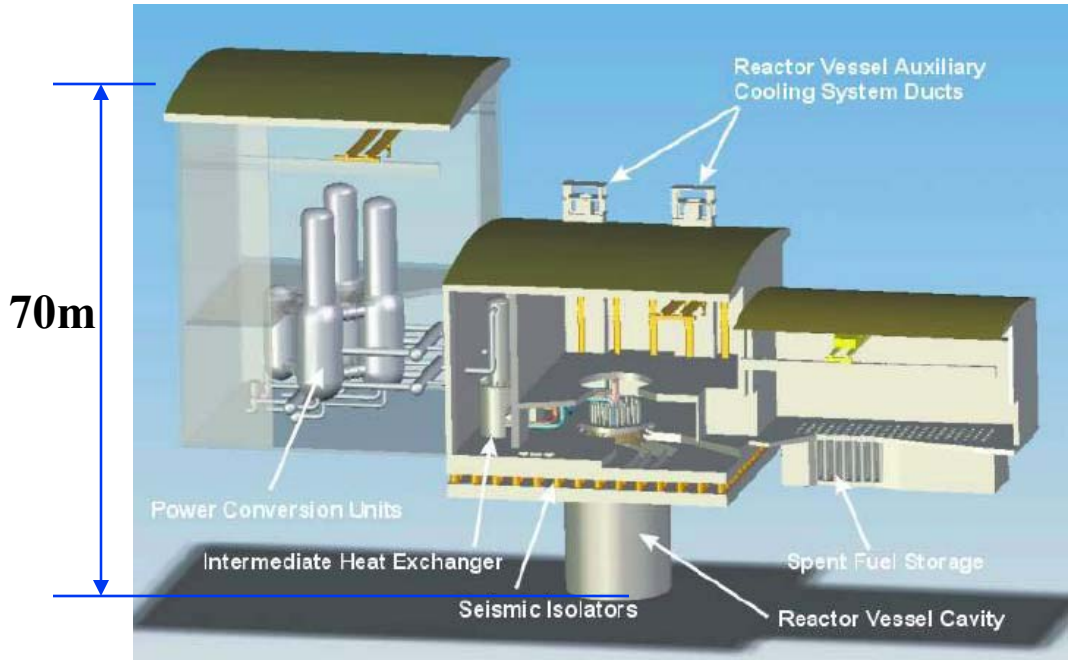
Liquid-Salt-Cooling Implies Smaller Reactors than with Gas-Cooled Cooling

(Figures to Scale)



Gas Cooling

GT-MHR (600 MW(t))



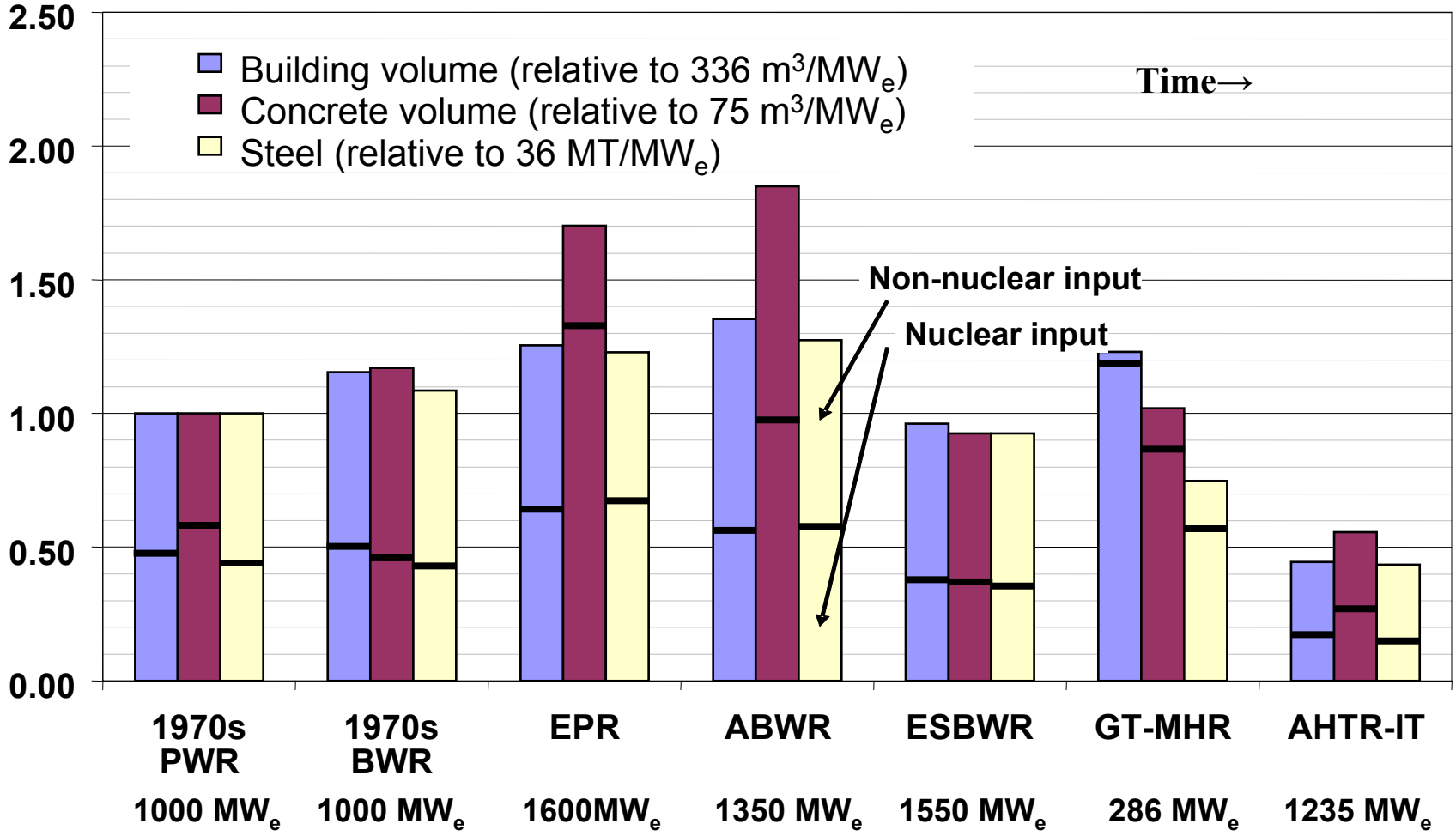
Liquid Cooling

AHTR (2400 MW(t))

Per Peterson (Berkeley): American Nuclear Society 2004 Winter Meeting

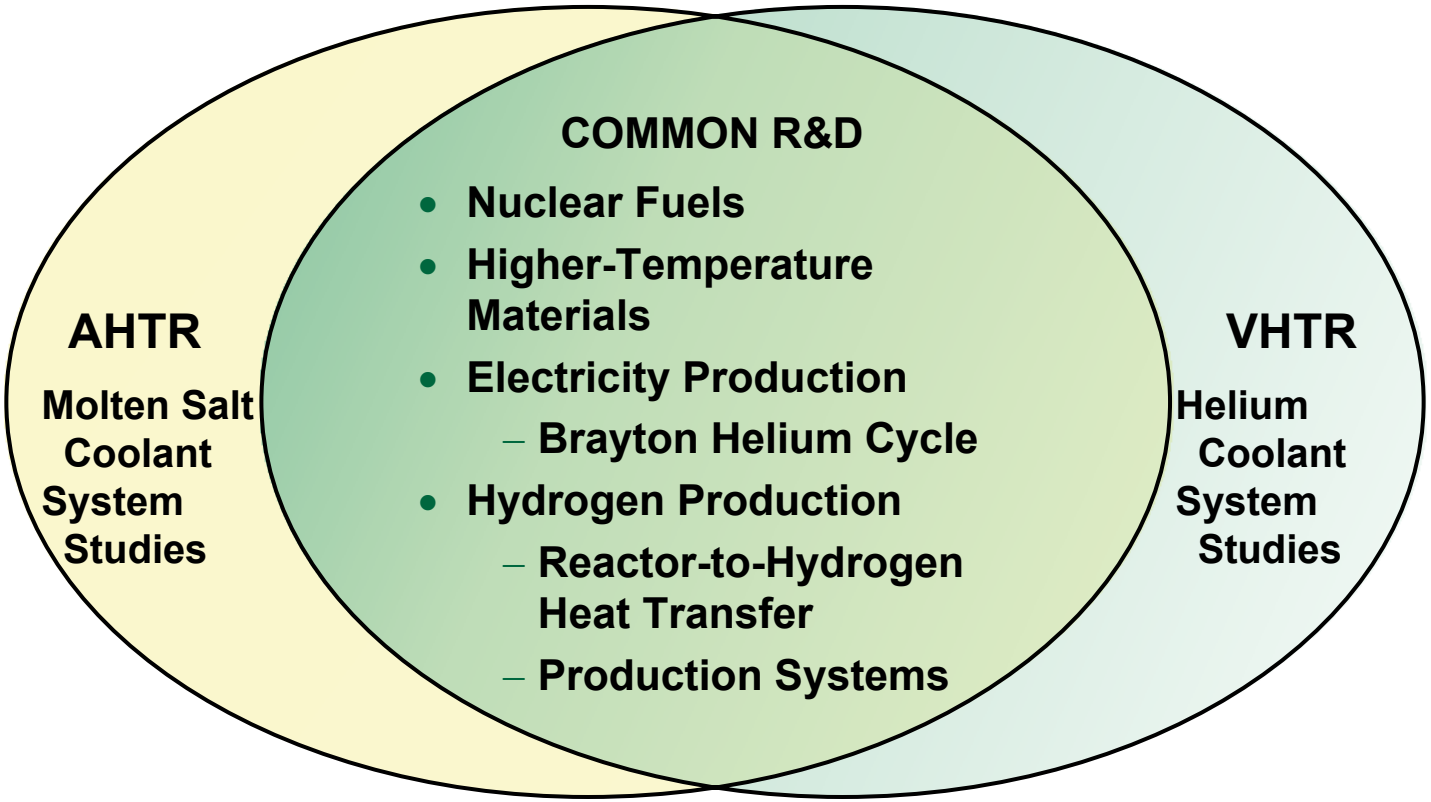
Reactor Comparison of Building Volume, Concrete Volume, and Steel Consumption

(Based on Arrangement Drawings)



Per Peterson (Berkeley): American Nuclear Society 2004 Winter Meeting

The R&D Requirements for the AHTR and the Helium-Cooled VHTR have Much in Common



AHTR Path Forward

- Rapidly growing program in the U.S.
  - Multiple laboratories: ORNL, INL, SNL, and ANL
  - Universities: University of Wisconsin and University of California at Berkeley
- Multiple reactor vendors examining concept
- Multiple activities underway
  - Core design
  - Alternative decay heat removal systems
  - Transient systems analysis
  - Balance of plant
  - Economic assessments
  - Process Identification and Ranking Table (PIRT)
  - Scaling studies to define future test reactor design

Liquid-Salt-Cooled Fast Reactor (LSFR)

(New Concept: Limited Analysis)

Address The Fast Reactor Challenge: High Costs

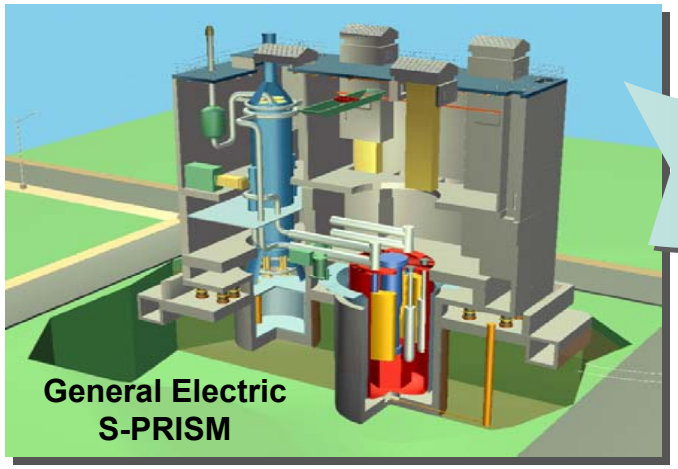
Plant Design is Similar to the AHTR
"Traditional" Fast Reactor Core
Coolant Temperatures: 700 to 800ºC

The Fast Reactor Challenge

- Fast reactor advantages
  - Generate fuel from fertile materials (^{232}Th and ^{238}U)
  - Destroy long-lived radionuclides
- Challenges
  - Sodium-cooled fast reactors cost ~25% more than light water reactors
  - Sodium-cooled fast reactor viability depends upon lowering cost
- Alternative strategy: Liquid salt-cooled fast reactor
  - Potential cost advantage
  - Technical viability issues

The Liquid-Salt-Cooled Fast Reactor

Higher-Temperature Liquid-Salt Coolant Replacing Sodium



Fast Reactor Facility Design

High Temperature Brayton Power Cycles

Fast Reactor Core

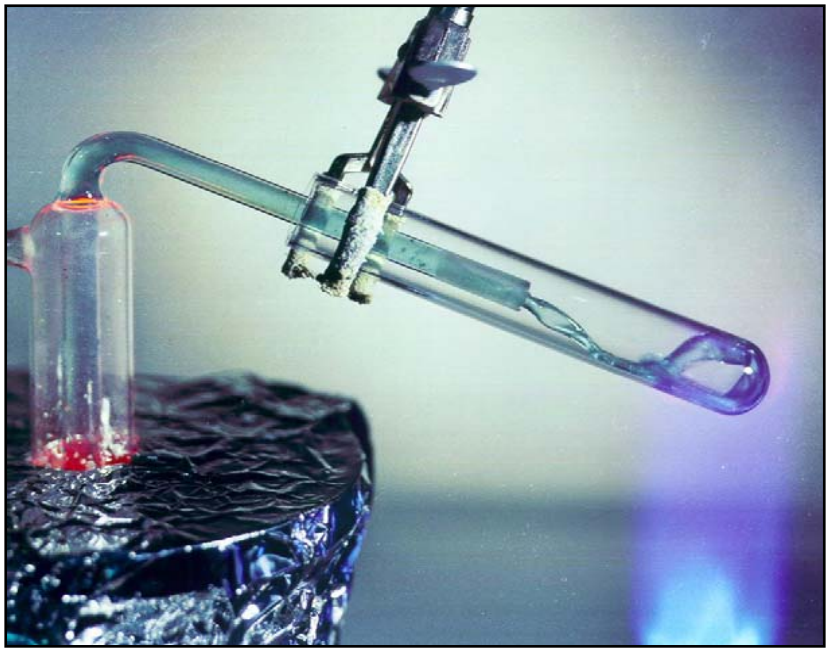
(Picture of PFR Core)

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

There are Significant Differences Between Liquid Salts and Sodium

Liquid Metal

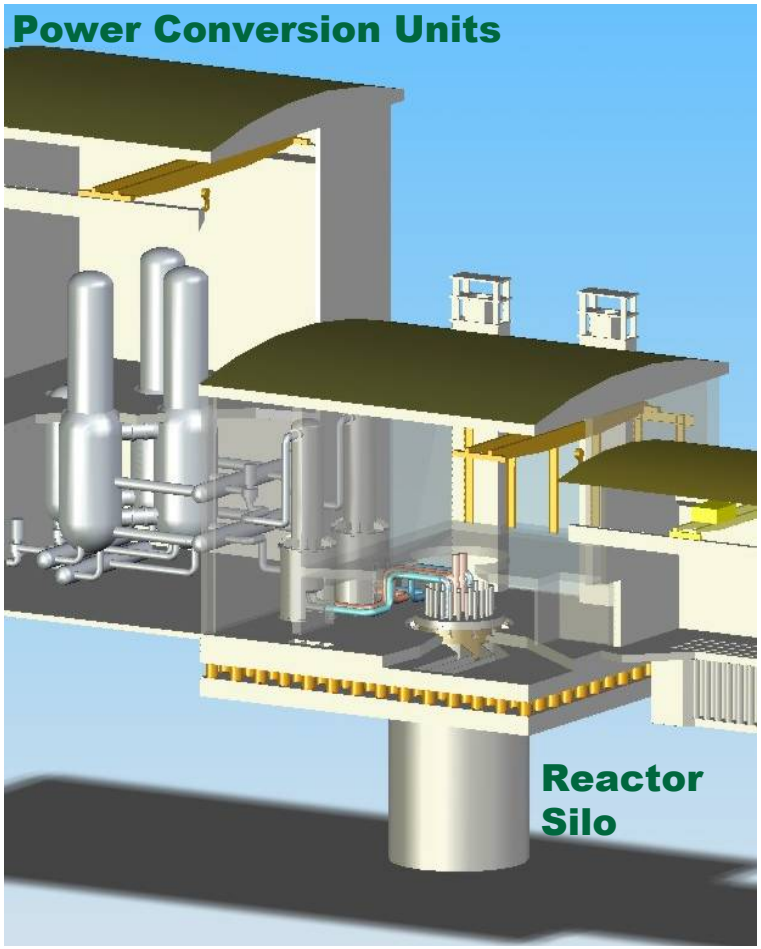
(Opaque; Na Boiling Point: 883ºC)



Liquid Fluoride Salts

(Transparent; Boiling Point >1200ºC)

LSFR Capital Costs Projected to be Less Than Sodium-Cooled Reactors



- 25% greater efficiency with high-temperature multi-reheat Brayton power cycle
- No sodium-water interactions (no steam cycle; no hydrogen)
  - Salt non-reactive with air
  - Slow reaction with water
- Smaller equipment size with high volumetric-heat-capacity fluid
- Transparent coolant to aid refueling and inspection
- Smaller heat rejection system with higher temperatures

There are Several Challenges Associated with the LSFR

(But Potentially Better Economics)

- Salt selection
  - Nuclear properties
  - Melting points (350 to 500ºC)
- Core design
  - Safety
  - Breeding
  - Waste Transmutation
- Clad materials of construction
  - Challenges
    - Higher temperatures
    - Liquid salt corrosion (can not use AHTR graphite core)
  - Candidate alloy clad systems
    - ODS alloys
    - Nickel alloys
    - Molybdenum alloys

Molten Salt Reactor (MSR)

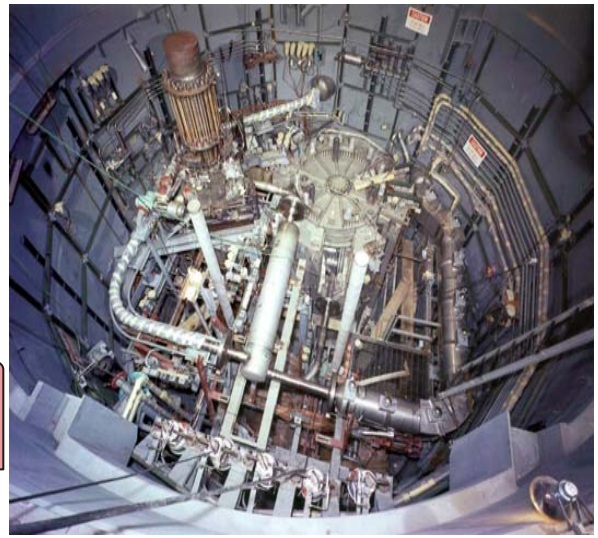
(Two Test Reactors Built)

Longer-Term Option

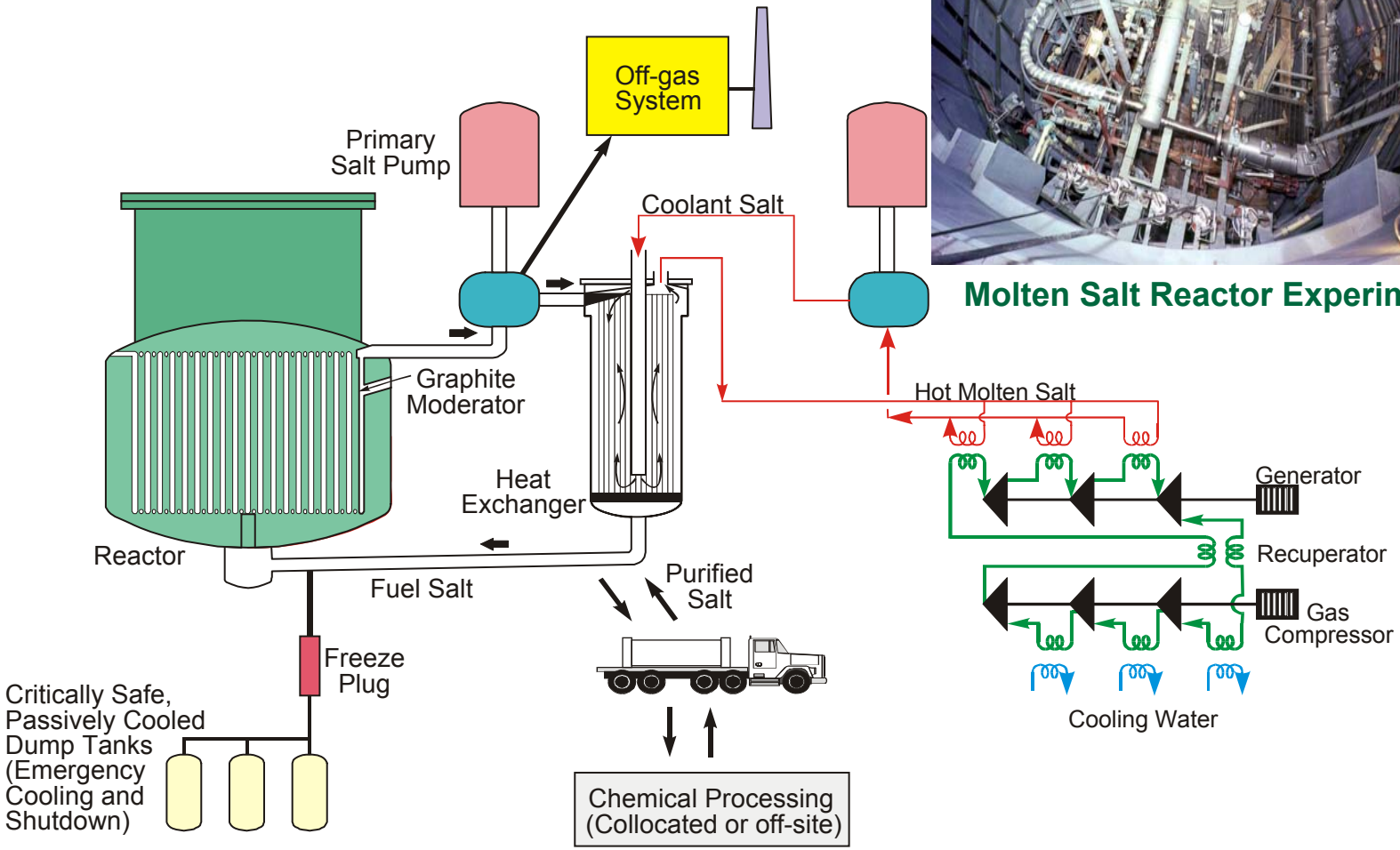
Fuel Dissolved in Coolant
Coolant Temperature: 700ºC
Size: 2400 to 4000 MW(t)

Molten Salt Reactor

(Modern Version with Brayton Power Cycle)



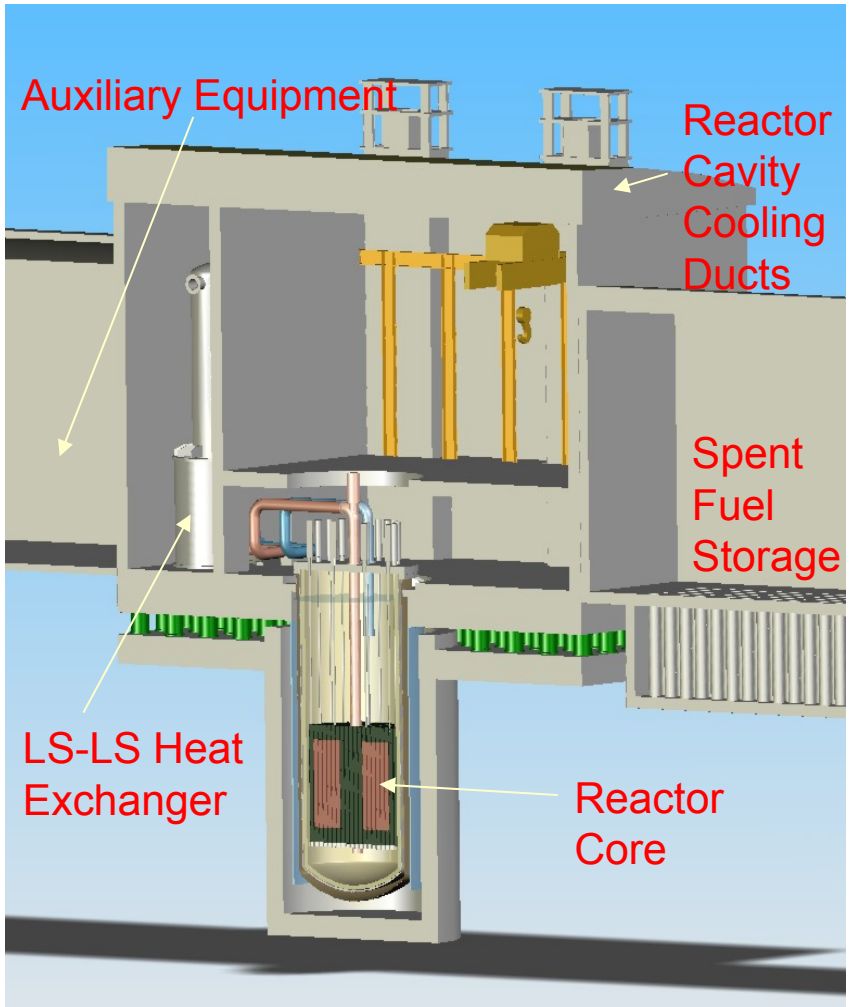
Molten Salt Reactor Experiment



Molten Salt Reactors are Unique

- General capabilities
  - High-temperature heat
  - Fissile fuel production (Breeding)
  - Waste transmutation
- Unique advantages
  - Minimum fissile inventory [kg fissile/kW(t)]
  - No fuel fabrication
  - On-line processing
    - Minimum accident source term
    - Unique fuel cycles
- Unique challenges: Fuel dissolved in the coolant
- Longer-term option

Conclusions



- **Incentives for high-temperature reactors**
  - Brayton power cycles
  - H_2 production
  - Dry cooling
- **AHTR: Near-term option**
  - Improved economics
  - Hydrogen production
  - Replacement for LWRs
- **Liquid-Salt Fast Reactor**
  - Potentially an economic fast reactor
  - Viability not studied
- **Molten-Salt Reactor**
  - Longer-term option
- **Significant R&D Required**

End

Backup Slides

End

Liquid Salt Coolants were Developed to Support Several Programs (1950–1970)

Molten Salt Reactors: Fuel Dissolved in Coolant; Intermediate Loop Used Clean Salts

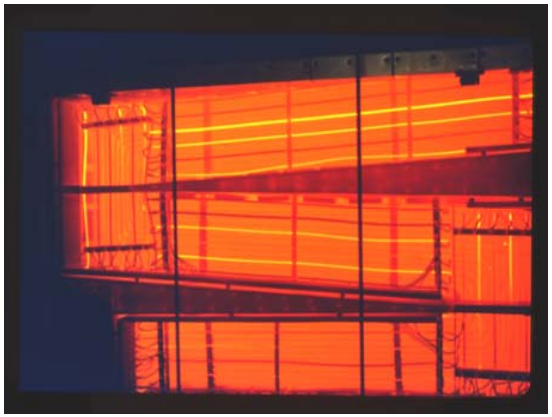
Aircraft Nuclear Propulsion Program

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

Molten Salt Breeder Reactor Program

ORNL Molten Salt Reactor Experiment
Power level: 8 MW(t); Peak Temperature: 650ºC
Fuel Salt: ^{7}Li/Be/F; *Clean Salt Secondary Loop*

Air-Cooled Heat Exchangers →

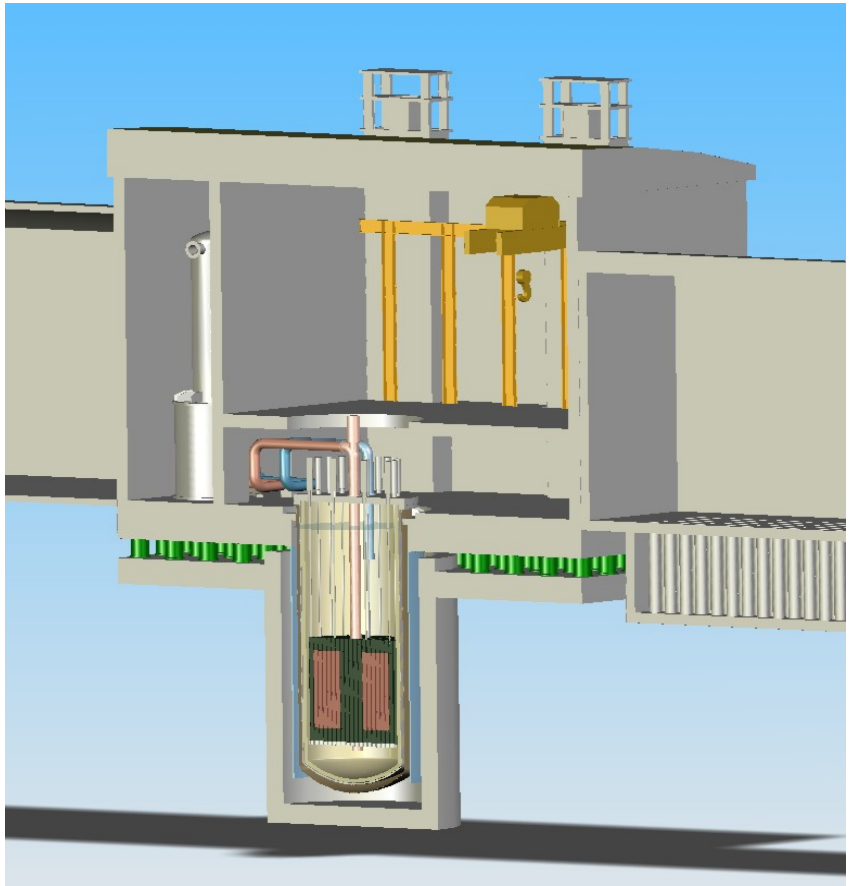


Materials and Fluoride Salts

- Graphite materials have been demonstrated to be stable in fluoride salts in radiation fields
- Hastelloy-N qualified to 750ºC in fluoride salts (but not in radiation fields)
- Testing required for higher-temperature materials
- Corrosion potential depends upon chemistry control
  - Nickel alloys have low corrosion
  - Impurities usually controls corrosion response (like in water and most other coolants)

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

AHTR Capital Costs per kW(e) are Estimated to be 50 to 60% of Gas-Cooled Modular Reactors



- **Economics of scale**
  - 2400 MW(t) vs 600 MW(t)
  - 1200 MW(e) vs 300 MW(e)
- **Smaller equipment size with high volumetric heat-capacity fluid**
- **Higher efficiency multi-reheat Brayton cycle**
- **No high-pressure vessel**

Pre-Conceptual AHTR Design Basis

System Parameters	Value
Power lever	2400 MW(t)
Coolant salt (Multiple Options)	$2LiF\text{-}BeF_2$
Fuel Type	Coated Particle Graphite Matrix
Outlet coolant temperature (Multiple options being examined)	950 °C
Inlet coolant temperature	≥ 850°C
Reactor vessel diameter	9.2 m
Power cycle (3-stage multi reheat)	Brayton
Working fluid	Helium (or Nitrogen)
Power output versus coolant temperature	(Helium, long-term)
Electric output 900ºC/1000ºC Coolant	1357 MW(e)
Electric output 700ºC/800ºC Coolant	1235 MW(e)
Electric output 670ºC/705ºC Coolant	1151 MW(e)
Decay Heat System (Multiple options)	Air
Discharge burnup	~150 GWd/t
Fuel cycle length	~18 months

Core Parameters	Value
Li-7 isotopic concentration	99.995%
Fuel kernel composition	$U_{1.0}C_{0.5}O_{1.5}$
Fuel kernel diameter	425 µm
Particle diameter	845 µm
U-235 enrichment	~ 15%
Particle packing fraction	≤ 25%
Fuel element (Hexagonal block)	
Graphite density	1.74 g/cm^3
Diameter (across flats)	36.0 cm
Height	79.3 cm
Fuel channel diameter	1.4 cm
Number of fuel channels	216
Coolant channel diameter	0.953 cm
Number of coolant channels	108
Pitch between channels	1.88 cm
Power density	10.0 MW/m^3
Number of fuel columns	265
Number of fuel blocks per column	10

EPR and Medium-Temperature AHTR Data

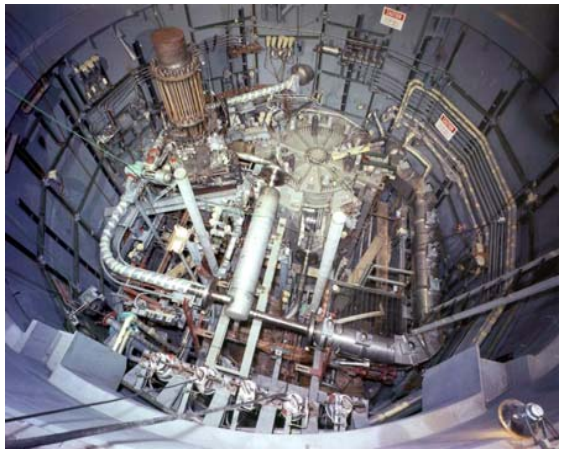
Parameter	AHTR-MI	EPR
Reactor thermal power / new electric power	2400 MW(t) / 1100 MW(e)	4500 MW(t) / 1650 MW(e)
Power conversion efficiency	~46%	36-37%
Primary coolant	flibe (?)	water
Core coolant inlet temperature / outlet temperature	~600°C / ~700°C	296°C / 327°C
Core power density	10.2 MW(t)/m^3	96.2 MW(t)/m^3
Primary coolant volumetric flow	7.5 m^3/hr MW(t)	25 m^3/hr MW(t)
Primary pump inlet pressure	0.5 bar	155 bar
Primary pump ΔP	~20 m	100 m
Number of primary pumps / pump power	4 / 1.46 kW/MW(t)	4 / 8.0 kW/MW(t)
Primary pumps rotational speed	1200 rpm	1485 rpm
Primary pumps specific speed	4486 rpm$(l/s)^{1/2}m^{-3/4}$	4160 rpm$(l/s)^{1/2}m^{-3/4}$
Primary coolant density	2030 kg/m^3	690 kg/m^3
Primary coolant Prandtl number	16.0	1.0
Primary loop hot leg total flow area	0.000879 m^2/MW(t)	0.0017 m^2/MW(t)
Primary hot leg flow velocity	2.4 m/s	4.1 m/s
Primary hot-leg diameter	0.82 m	1.14 m
Intermediate loop coolant	flinak (?)	water/steam
Intermediate loop: inlet temperature / outlet temperature	570°C / 670°C	230°C / 293°C
Intermediate heat exchanger*/SG power density	50 MW(t)/m^3	4.0 MW(t)/m^3
Intermediate heat exchanger*/SG surface area	__ MW(t)/m^2	0.141 MW(t)/m^2
Containment design pressure (EPR—hydrogen deflagration pressure spike)	~ 0 bar	5.5 bar

*AHTR uses printed-circuit heat exchangers

Oak Ridge National Laboratory Activities

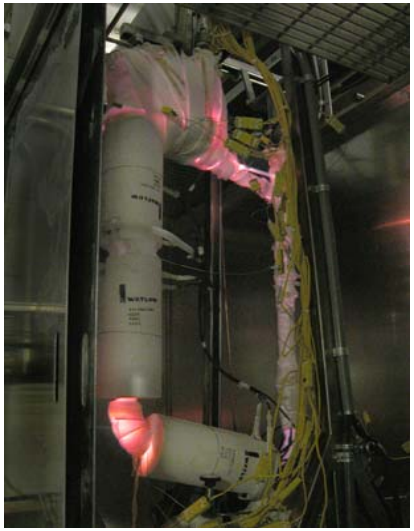
Historical

←ORNL Aircraft Reactor Experiment
ORNL Molten Salt → Reactor Experiment (MSRE)



Today

←MSRE Remediation Program
Constructing new salt test facilities →

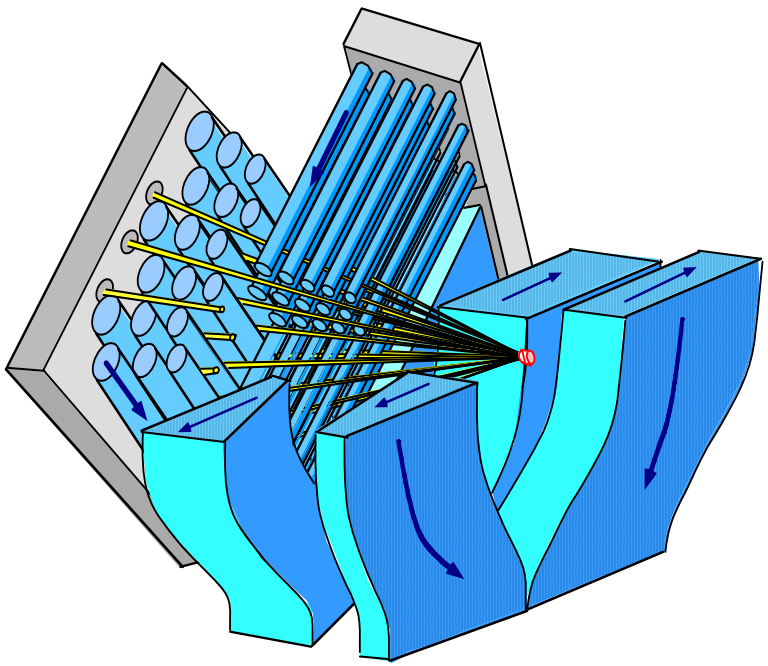


Fusion

(Longer-Term Option)

Magnetic

Inertial

Molten Salts are Candidates for Multiple Fusion Energy Systems

- Low-pressure coolant
- Tritium breeding
  - $^{6}Li + n \rightarrow {}^{3}H + {}^{4}He$
- First wall applications
  - "Liquid-wall" fusion machines
  - Replaceable radiation-damage-resistant wall
  - Withstand shock waves in inertial fusion (laser and particle beam) machines