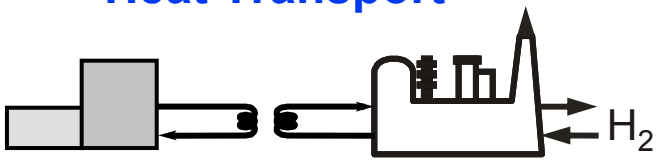
Reactors with Molten-Salts: Options and Missions

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

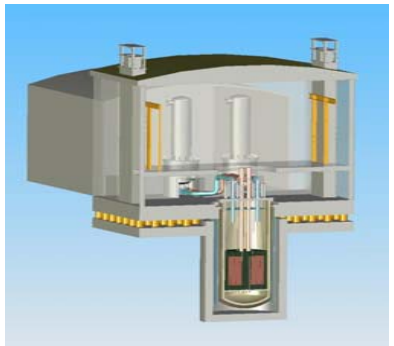
Frederic Joliot & Otto Han
Summer School on Nuclear Reactors
Cadarache, France
August 25–September 3, 2004

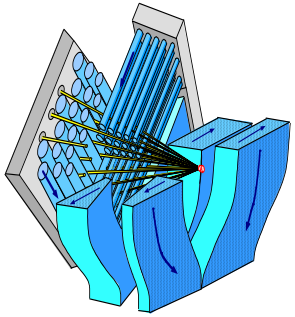
The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes. File: France2004.MoltenSaltOptionsView

Heat Transport

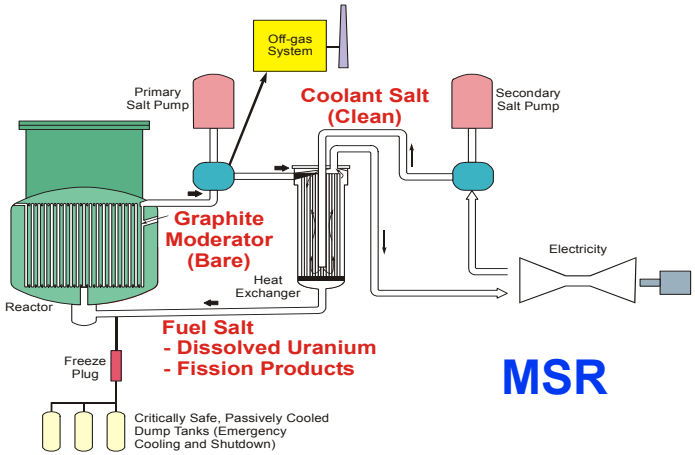


AHTR





Fusion



MSR

Contents

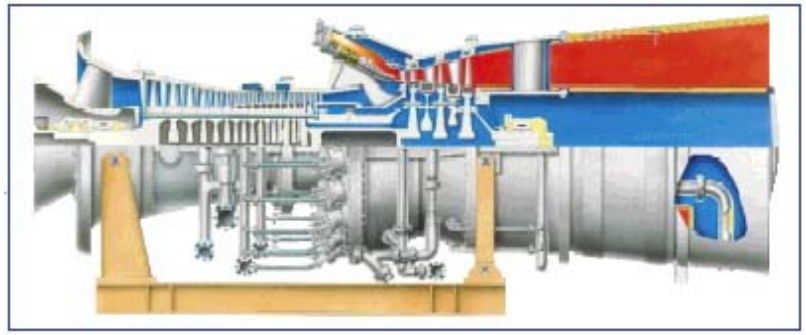
- **Introduction to molten salts**
- **Applications**
  - **Heat transport**
  - **Advanced high-temperature reactor**
  - **Molten salt reactor**
  - **Fusion**
- **Molten salt characteristics**
- **Power cycles**

Introduction

Molten Fluoride Salts

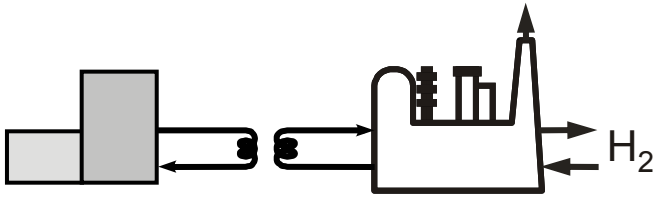
A High-Temperature Coolant

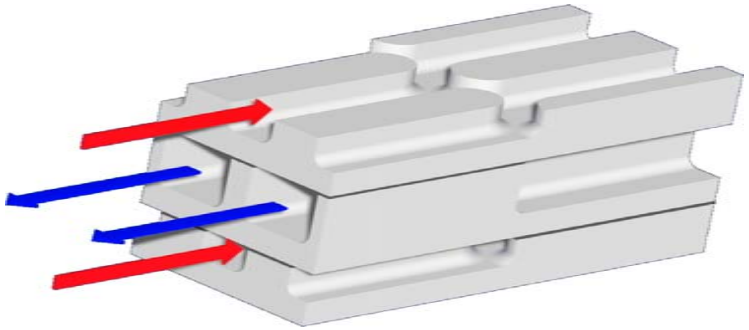
There Has Been a Rebirth of Interest in High-Temperature Nuclear Reactors



Brayton power cycles that efficiently convert heat to electricity (vs. steam cycle limits at ~500°C)

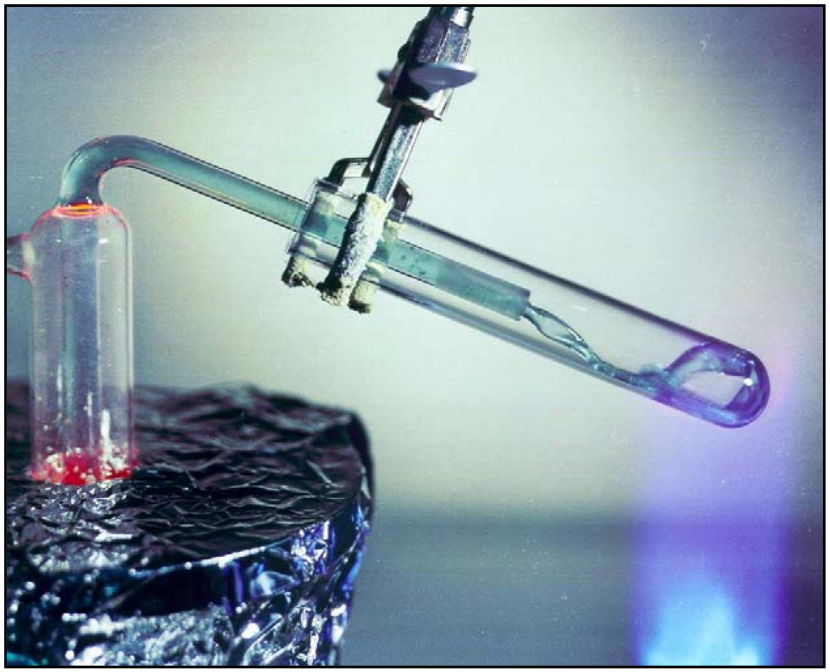
Thermochemical hydrogen production: Requires high temperatures: 700 to 850°C





Increased availability of carbon-carbon composites and other high-temperature materials

Only Two Coolants Have Been Demonstrated to be Compatible with High-Temperature Operations



Helium

(High Pressure/Transparent)

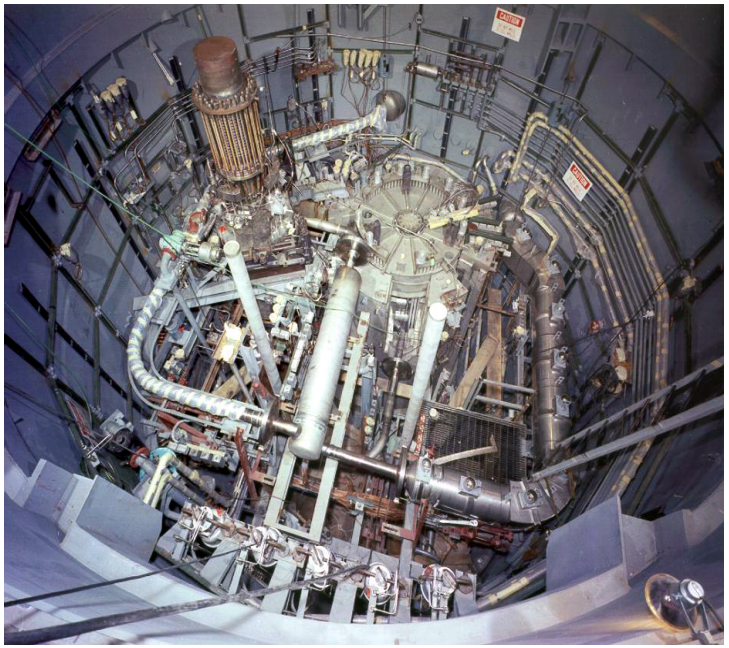
Molten Fluoride Salts

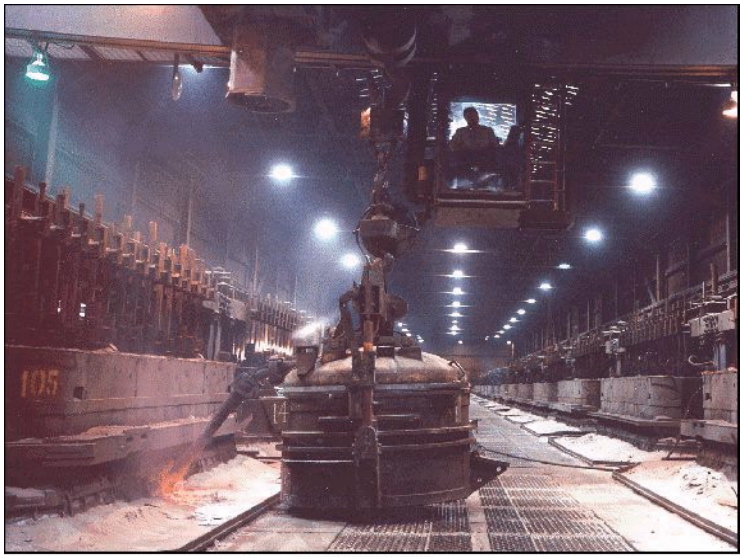
(Low Pressure/Transparent)

Mankind has Large-Scale Experience with Only 3 High-Temperature Liquids

Iron, Glass, and Fluoride Salts)

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



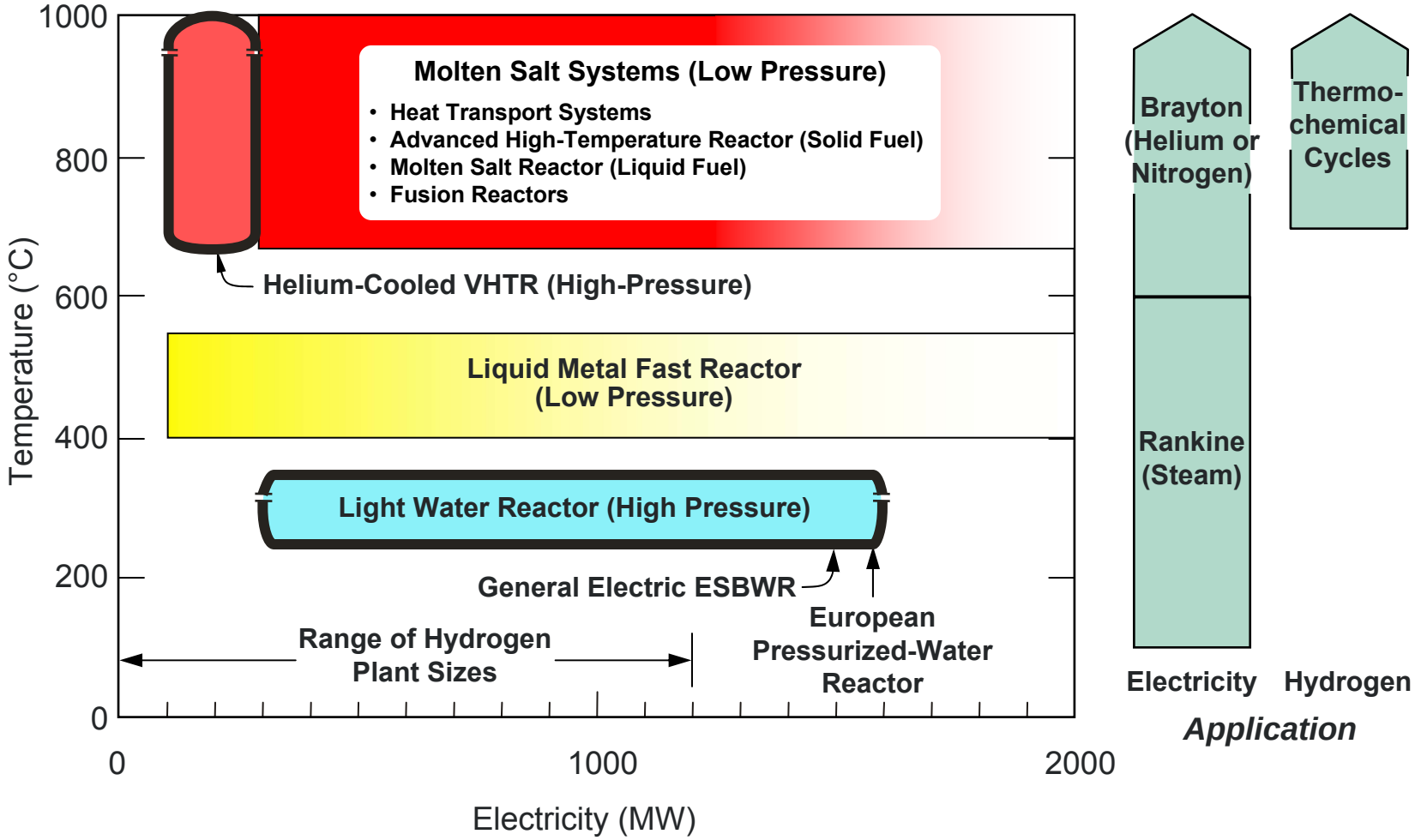


Tapping aluminum

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

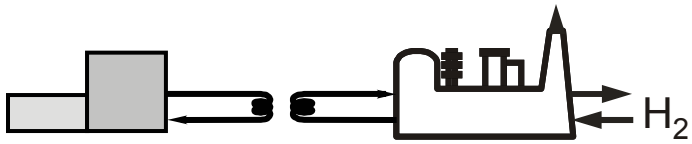
Reactor Peak Temperatures and Power Outputs

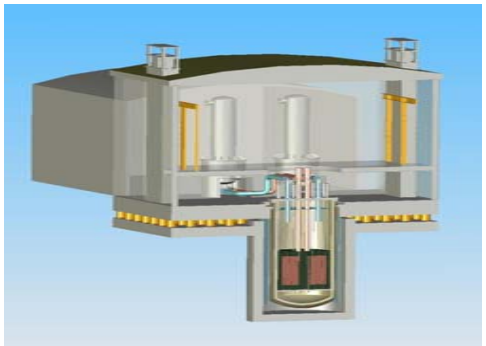


Molten Salt Nuclear Applications

Molten-Salt Nuclear Applications

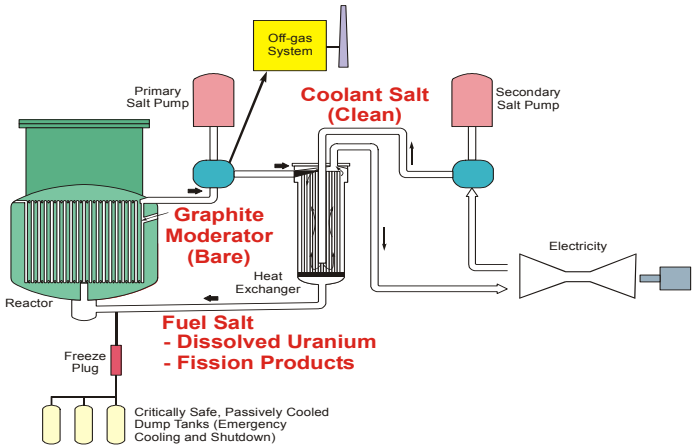
High-temperature heat transport→ from nuclear reactors to thermochemical hydrogen facilities

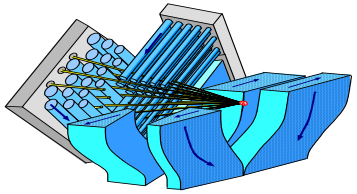




←Advanced high-temperature reactor with solid fuel and a molten-salt coolant

Molten salt reactor (MSR)→ with fuel dissolved in a molten salt





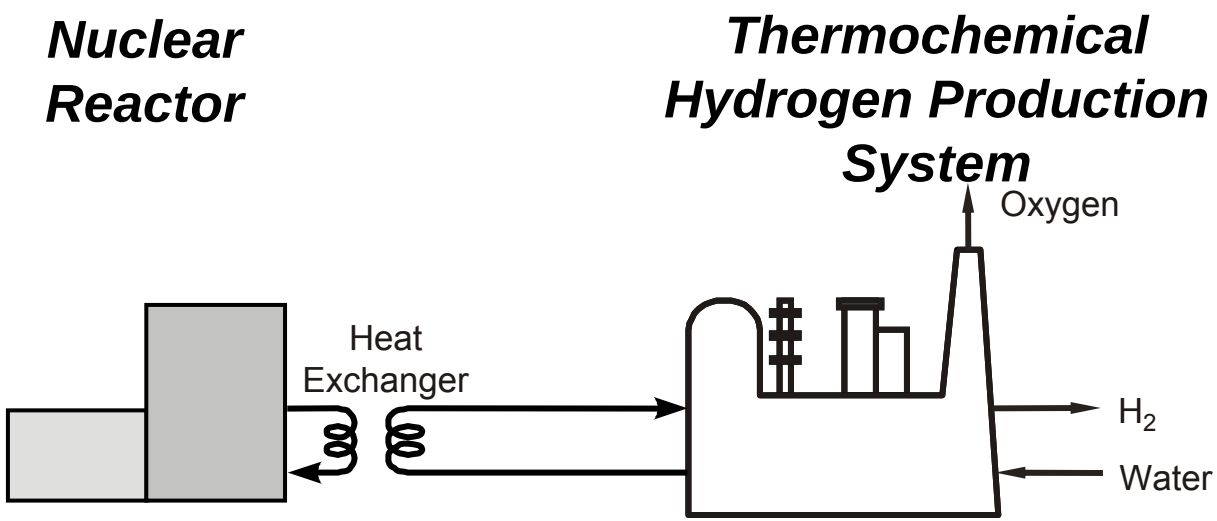
←Fusion: Molten salt coolant for heat transfer and tritium breeding

High-Temperature Heat Transport

Heat Transport From Nuclear Reactors to Thermochemical Hydrogen Facilities

Heat Transport Systems for Hydrogen Production

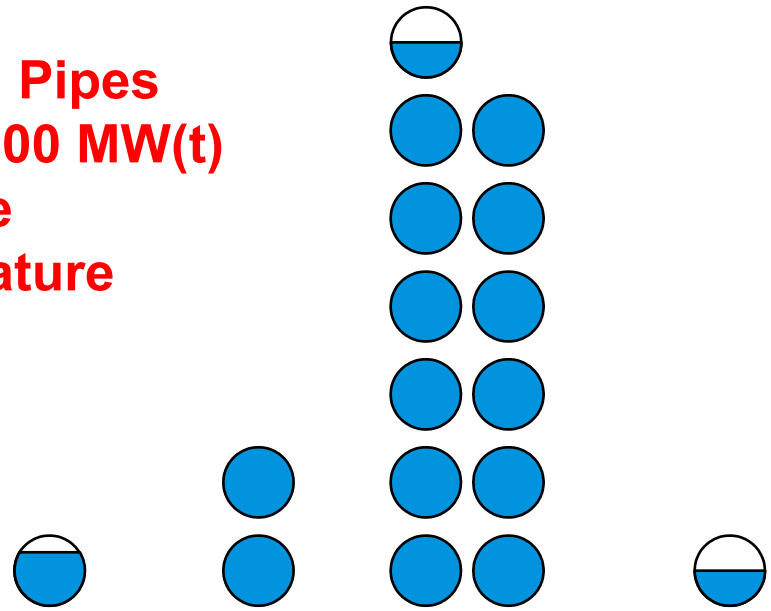
(Heat + Water → Hydrogen + Oxygen)



- **Heat must be transported from the reactor to the hydrogen production plant [1000s of MW(t)]**
- **Significant transport distances are involved because of the size of the chemical plants and safety (100s of meters)**
- **Temperature of delivered heat: 700 to 850ºC**
- **Other molten salts used in the chemical industry to 600ºC**

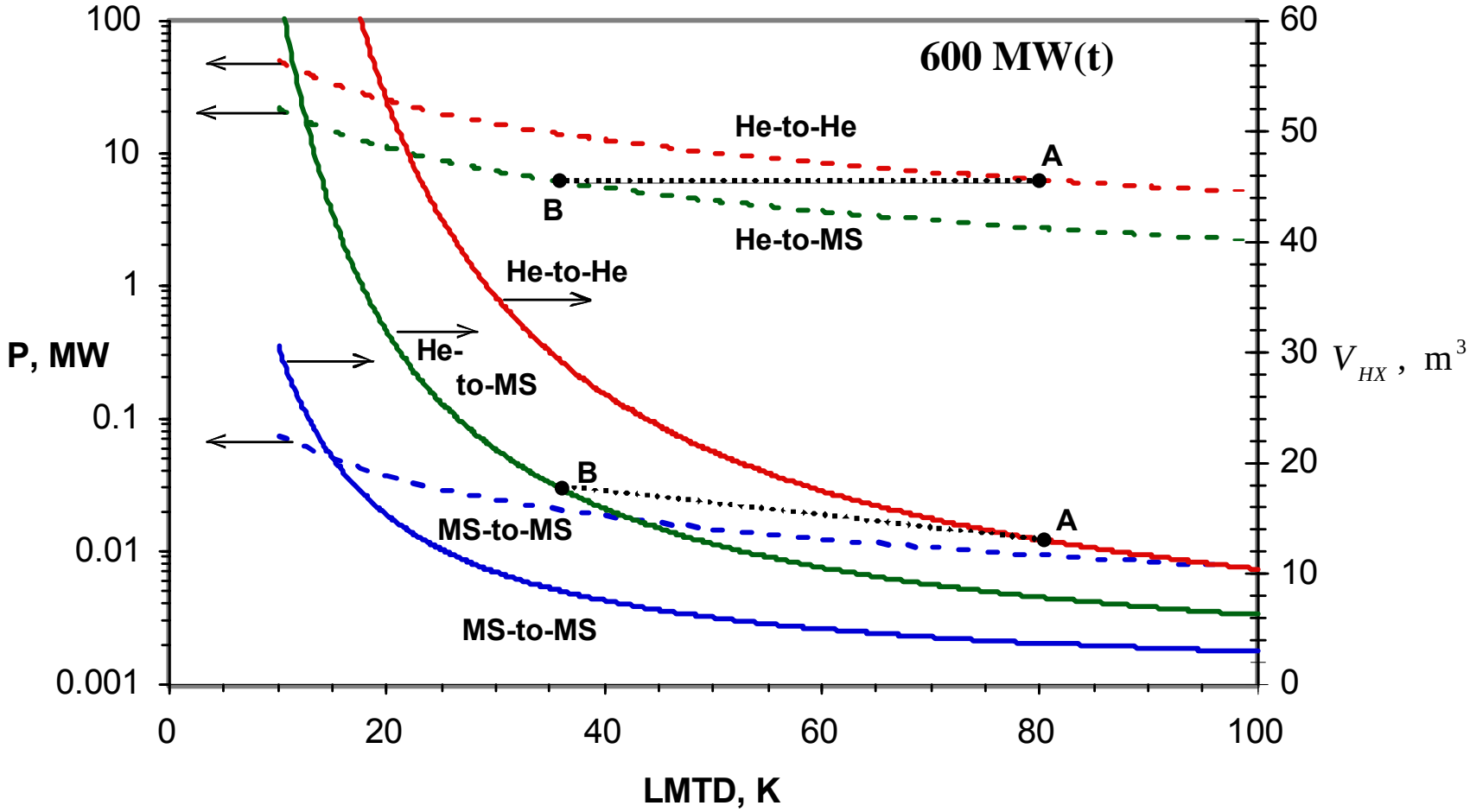
Molten Salts Have Superior Capabilities for the Transport of Heat

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 Velocity (m/s)	6	6	75	6

Molten Salt Intermediate Heat Exchangers (IHXs) have Lower Temperature Drops, Smaller Heat Exchangers, and Less Power Consumption than Helium IHXs



Optimized Compact Off-set Strip-Fin IHX

High-Temperature Heat-Transport Research-and-Development Challenges

- **Materials of construction, if operating temperatures are above 750ºC**
- **Optimized choice of salt**
- **System engineering of salt with a freeze point between 350ºC and 500ºC**

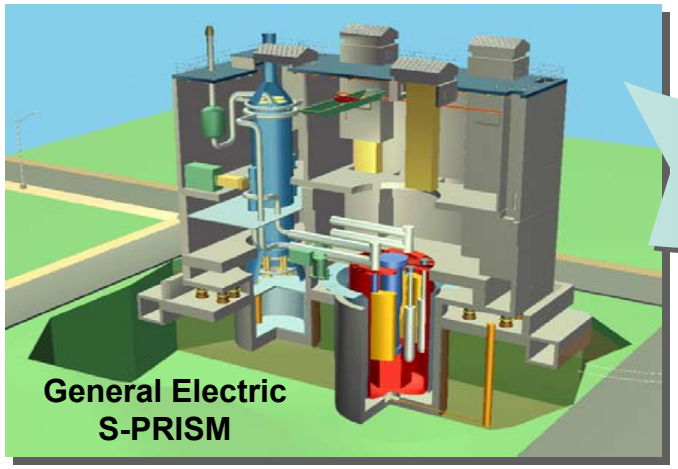
The Advanced High-Temperature Reactor (AHTR)

Solid Fuel

Clean Molten Salt Coolant

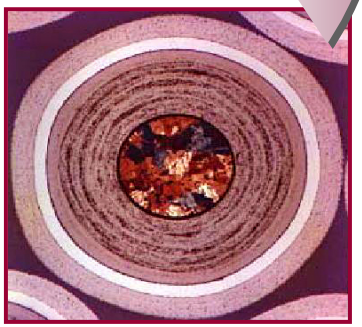
The Advanced High-Temperature Reactor

Combining Existing Technologies in a New Way



Passively Safe Pool-Type Reactor Designs

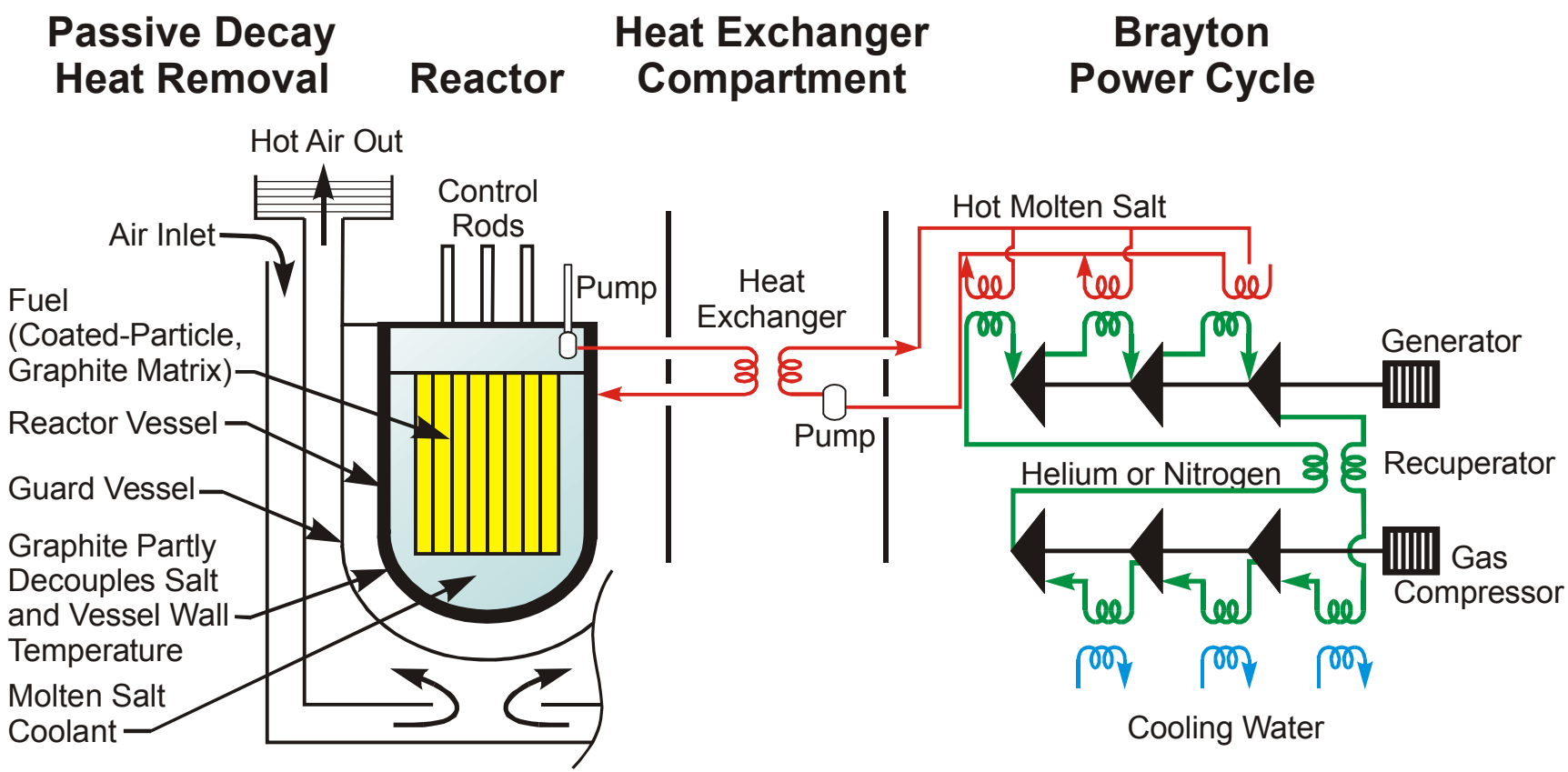
Brayton Power Cycles



High-Temperature Coated-Particle Fuel

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

The Advanced High-Temperature Reactor



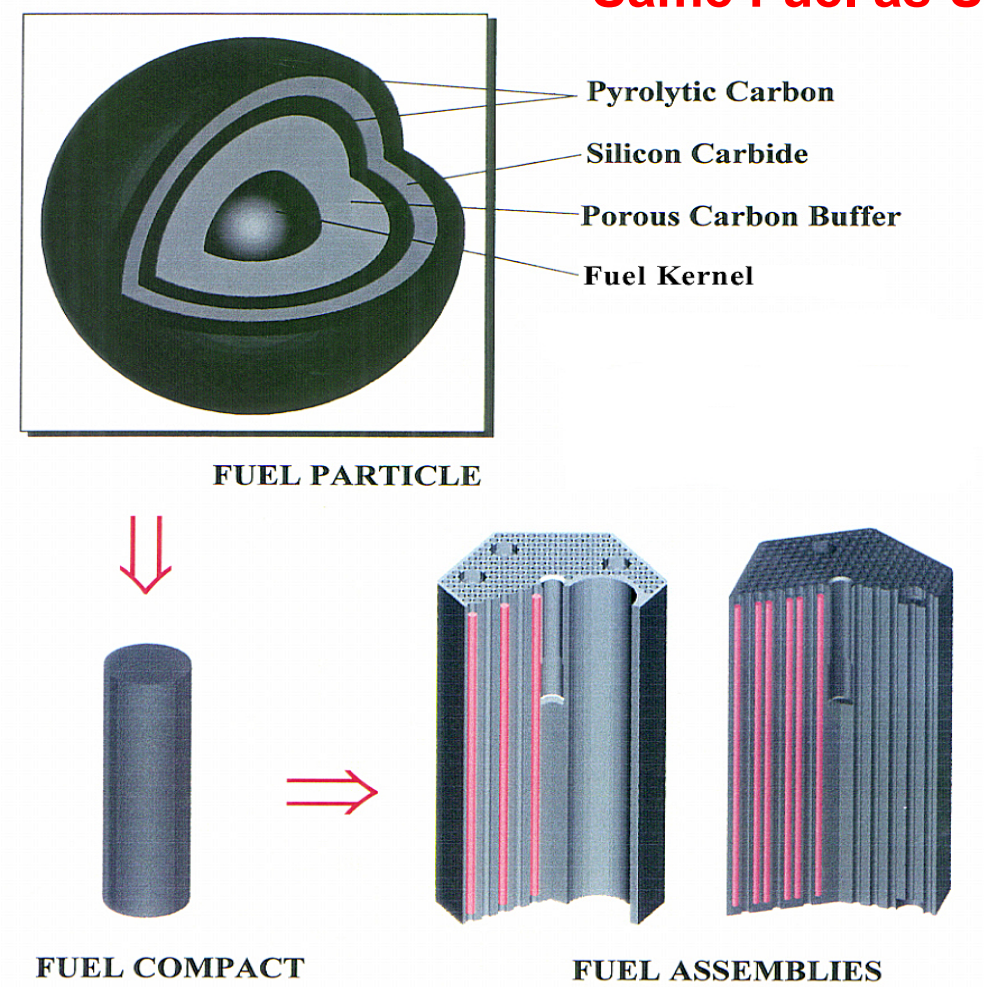
AHTR Fuels and Coolant

Graphite-Matrix, Coated Particle Fuel

Clean Molten-Salt Coolant

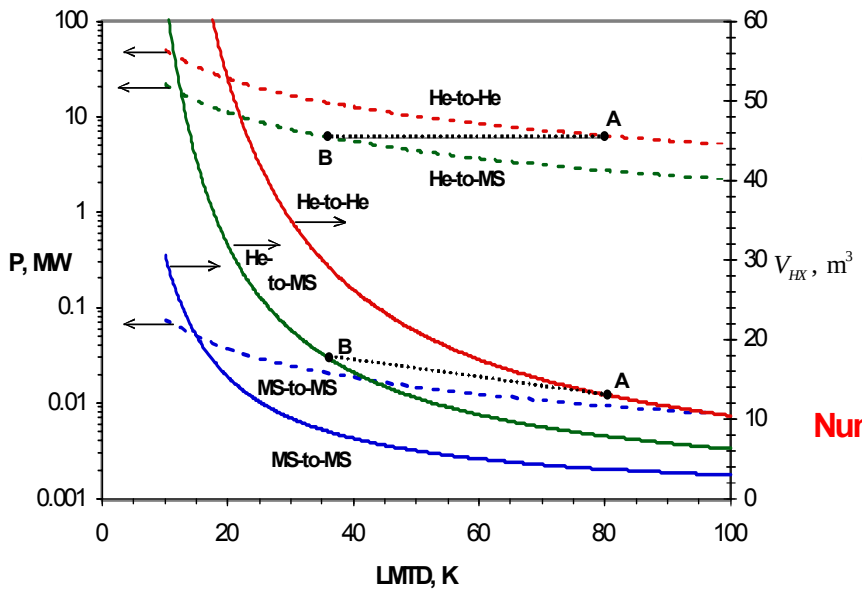
The AHTR Uses Coated-Particle Graphite Fuel Elements
(Peak Operating Temperature: 1250ºC; Failure Temperature: >1600ºC)

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

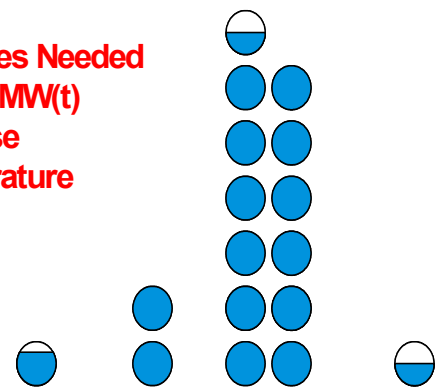
Molten Salt Coolant Reduces AHTR Temperatures and Equipment Sizes Relative to Helium Reactors



←Better Heat Transfer

(Smaller Temperature Drops in Heat Exchanger with Lower Peak Temperatures)

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

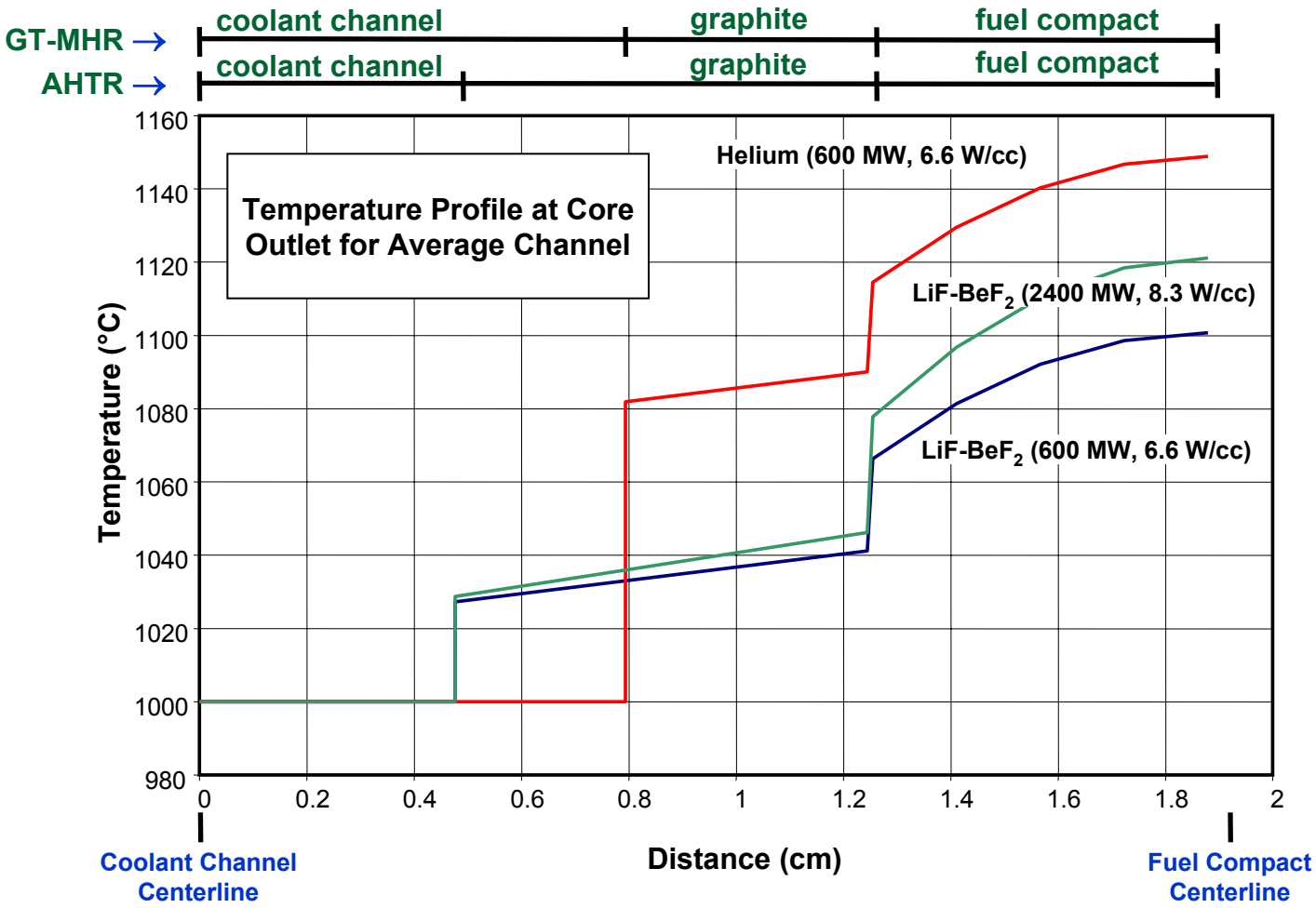


	Water (PWR)	Sodium (LMR)	Helium	Molten Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocities (m/s)	6	6	75	6

Smaller Pipes, Valves, Heat Exchangers, and Other Components→

Liquids Remove Heat More Effectively than Gas:

Cooler Fuel for the Same Coolant Exit Temperatures

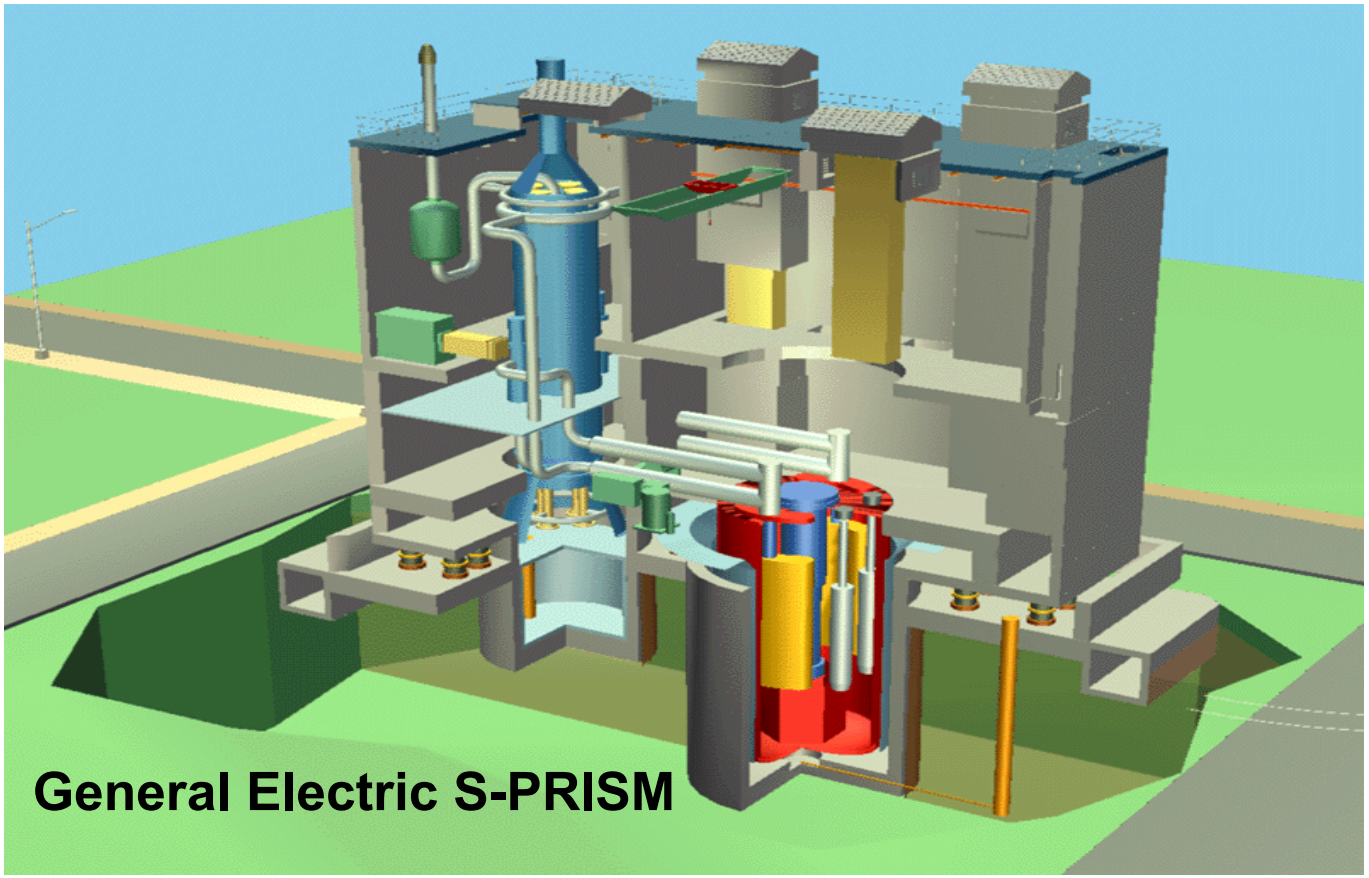


AHTR Facility Design

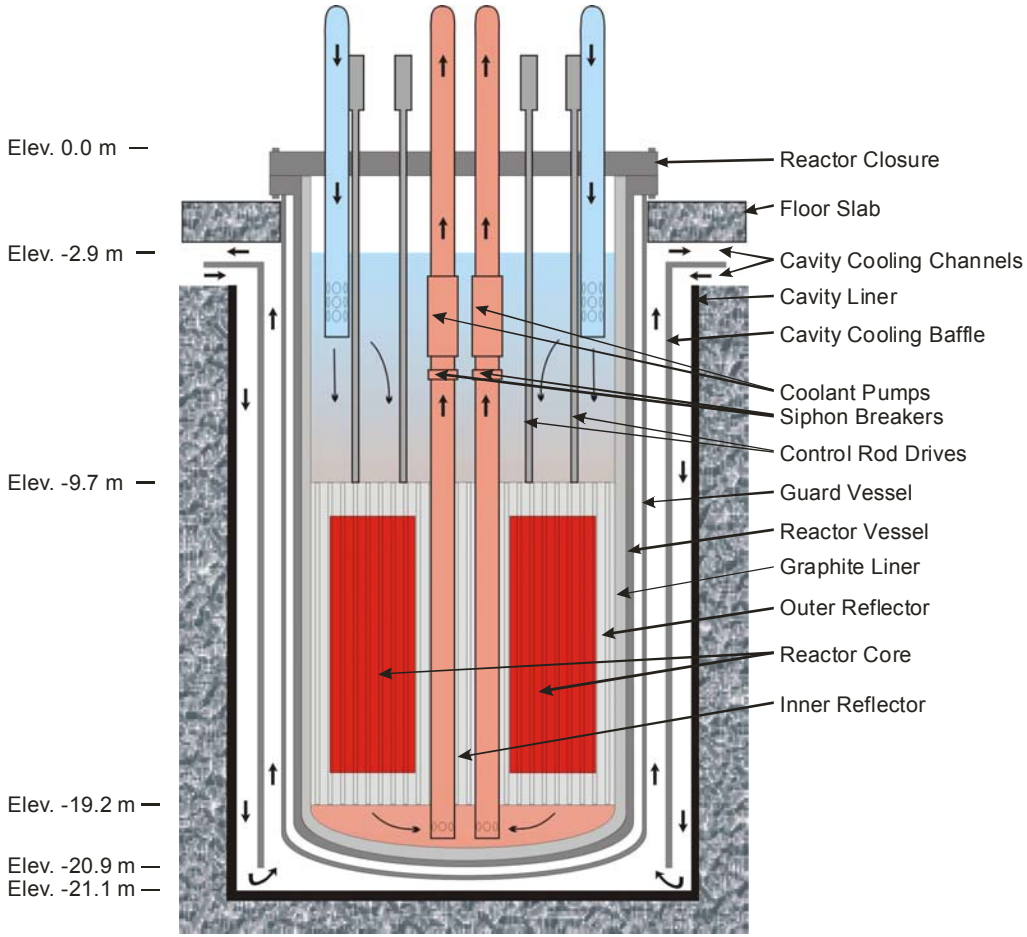
A Low-Pressure,
High-Temperature Liquid-Cooled Reactor

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

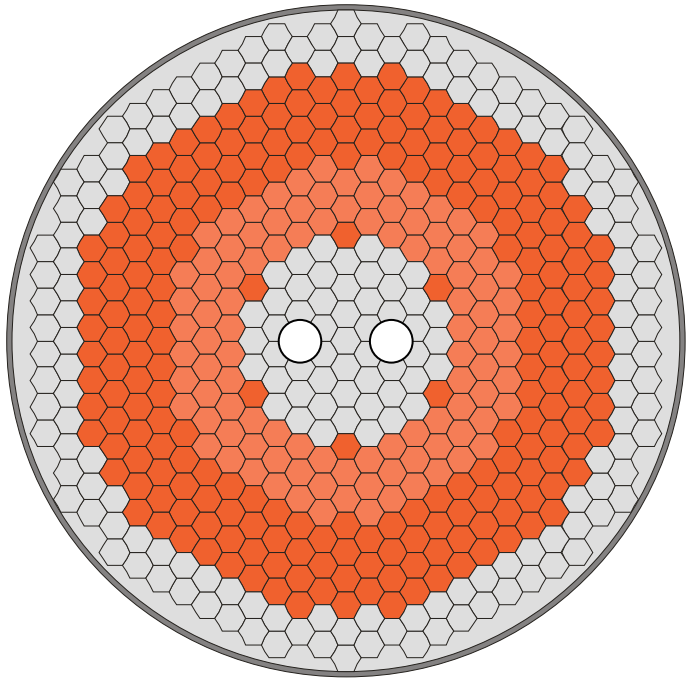
Low Pressure, High Temperature, Liquid Cooled



AHTR 9.0-m Vessel Allows 2400-MW(t) Core

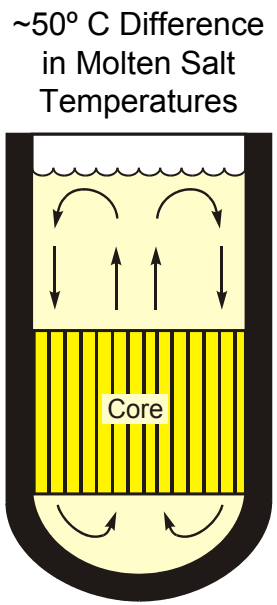


102 GT-MHR fuel columns
222 Additional fuel columns
324 Total fuel columns

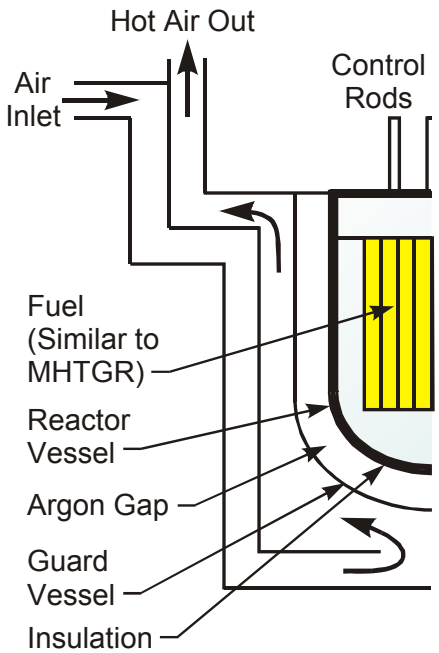


Power density = 8.3 MW/m^3
(26% larger than 600-MW GT-MHR)

In an Emergency, Decay Heat is Transferred to the Reactor Vessel and then to the Environment



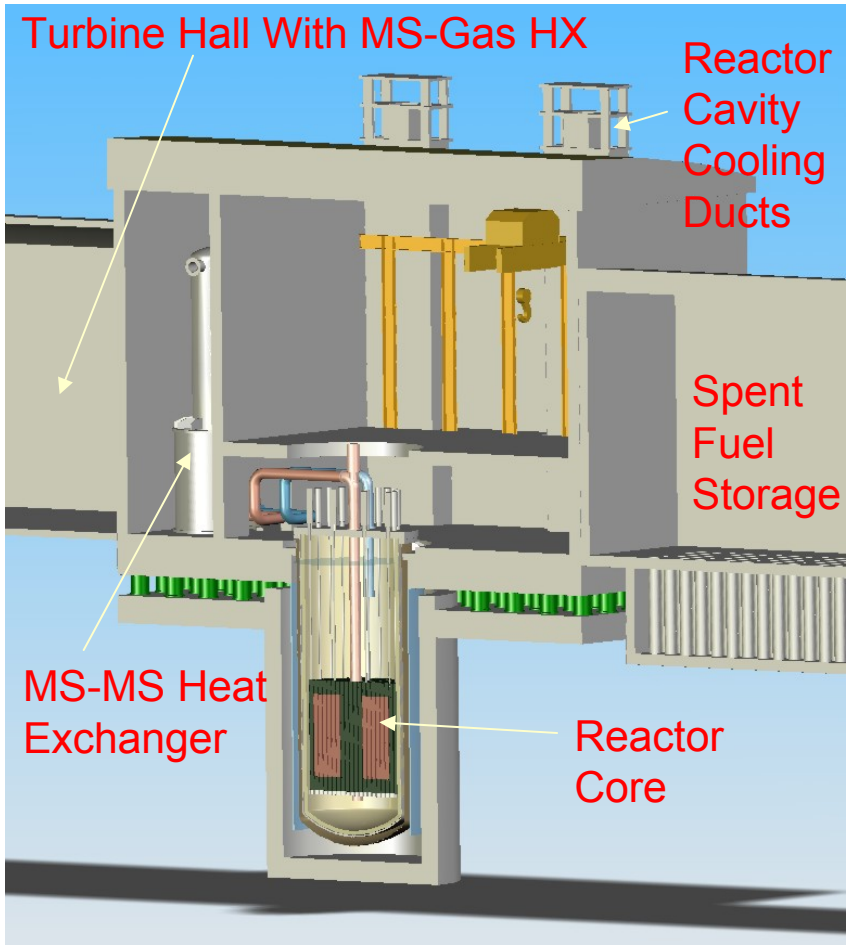
Decay Heat from Core to Vessel Liner



Decay Heat from Vessel to Environment

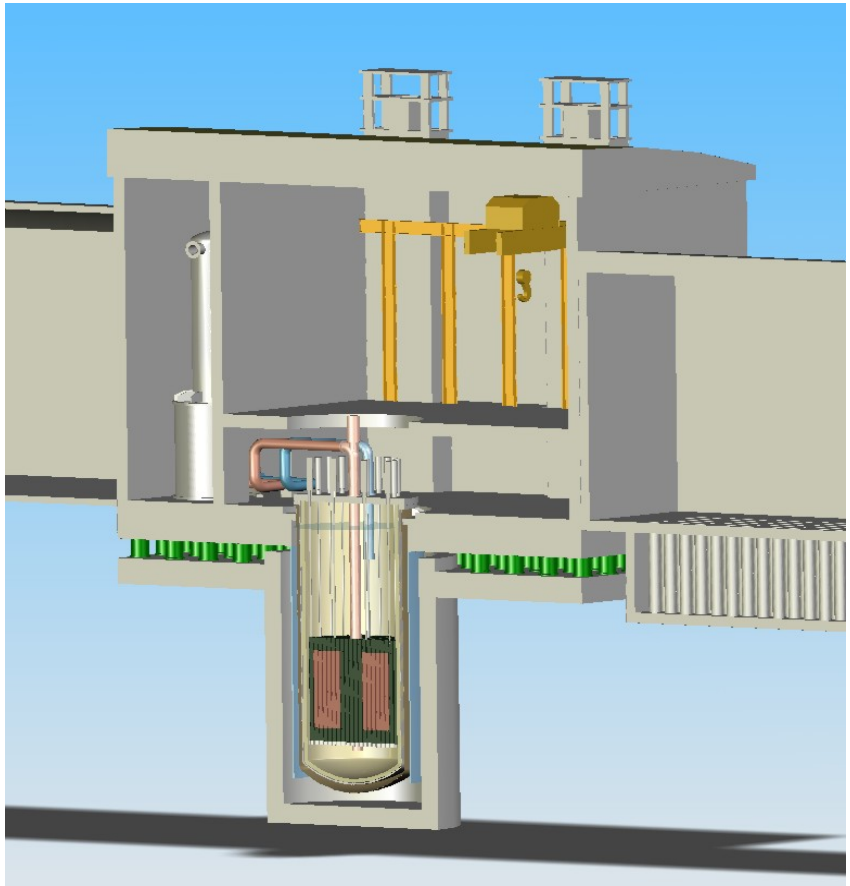
- Similar to GE S-PRISM (LMR)
- Liquid transfers heat from fuel to wall with small temperature drop (~50ºC)
- Argon gap: Reactor to guard vessel
  - Heat transfer: ~T^4
  - Thermal switch mechanism
- Heat rejection: Vessel temperature dependent
  - LMR: 500-550ºC [~1000 MW(t)]
  - AHTR: 750ºC [~2400 MW(t)]
- Other decay heat cooling options

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 (low pressure)**
  - **Space for 2400-MW(t) AHTR core with low power density**
- **Similar equipment size**
  - **Molten salt volumetric heat capacity > than that for sodium**
- **Higher-capacity decay heat removal system**
  - **750ºC vessel under accident conditions for nominal 1000ºC salt exit temperature**
- **Higher electrical output**
  - **S-PRISM: 380 MW(e)**
  - **AHTR: >1200 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 temperature (750ºC) vessel increases heat rejection**
- **Higher efficiency multi-reheat Brayton cycle**
- **No high-pressure vessel**

AHTR Research and Development Challenges

- **New reactor concept with associated uncertainties**
- **No qualified materials of construction if operating temperatures are above 750ºC**
- **Reactor core design**
- **Refueling temperatures near 500ºC (Avoid salt freezing)**

Molten Salt Reactor (MSR)

Fuel Dissolved In Molten Salt

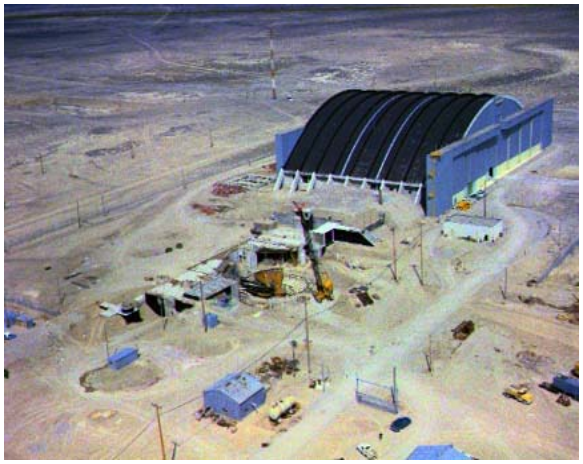
MSRs Were Developed to Support Several Large Programs (1950–1970)

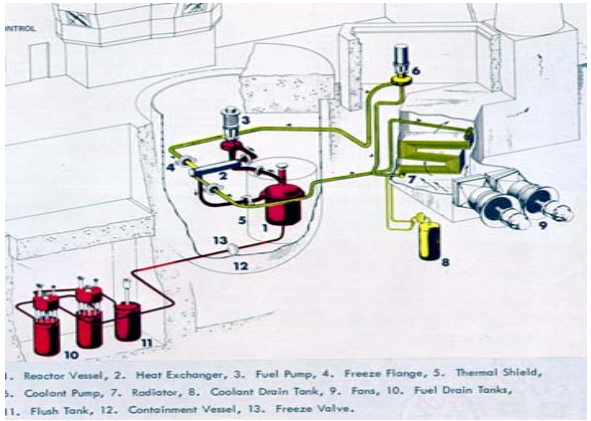
Molten Salt Reactors: Fuel Dissolved in Coolant

Aircraft Nuclear Propulsion Program

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

INEEL Shielded Aircraft Hanger→

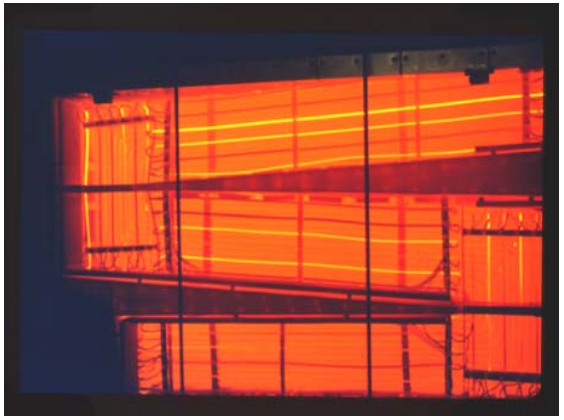




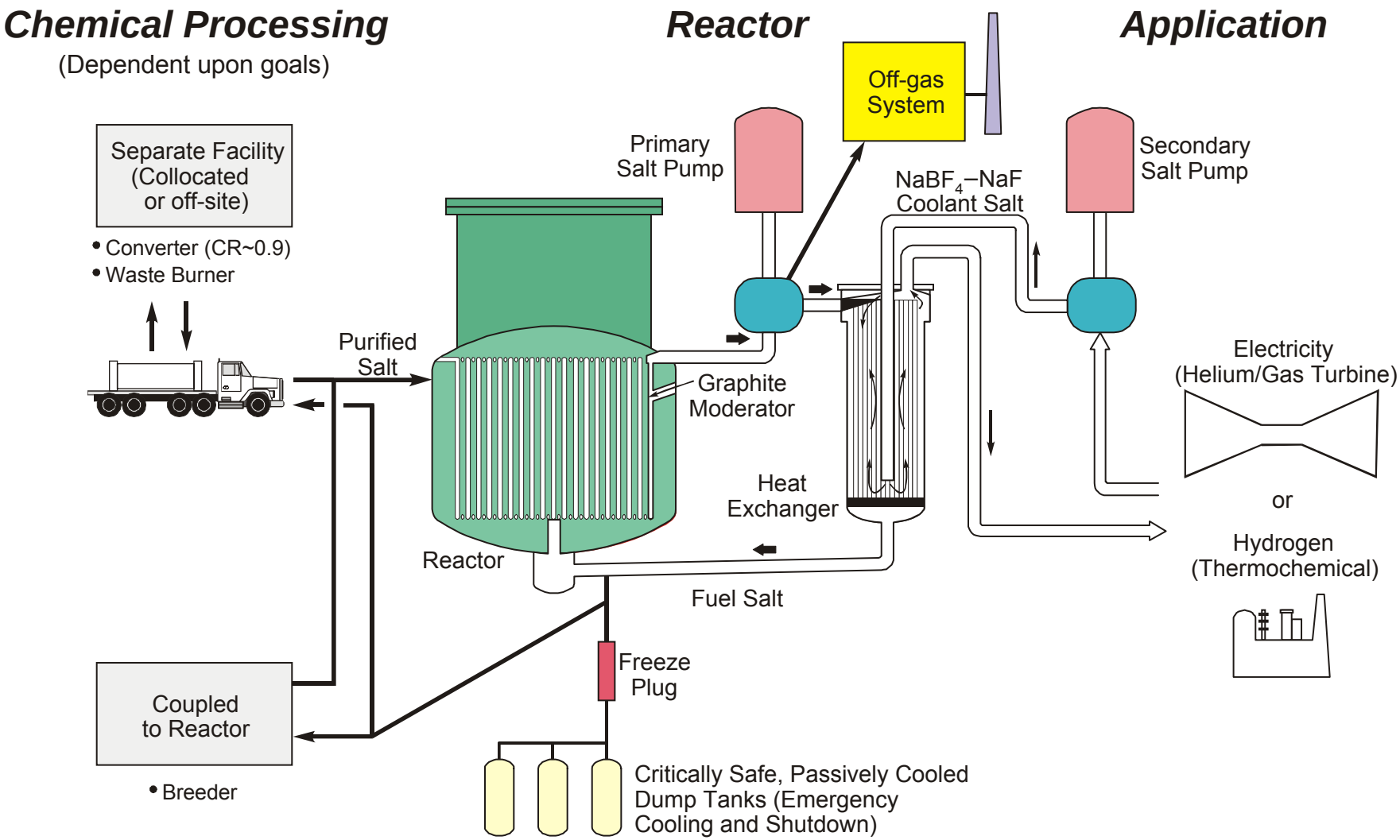
Molten Salt Breeder Reactor Program

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

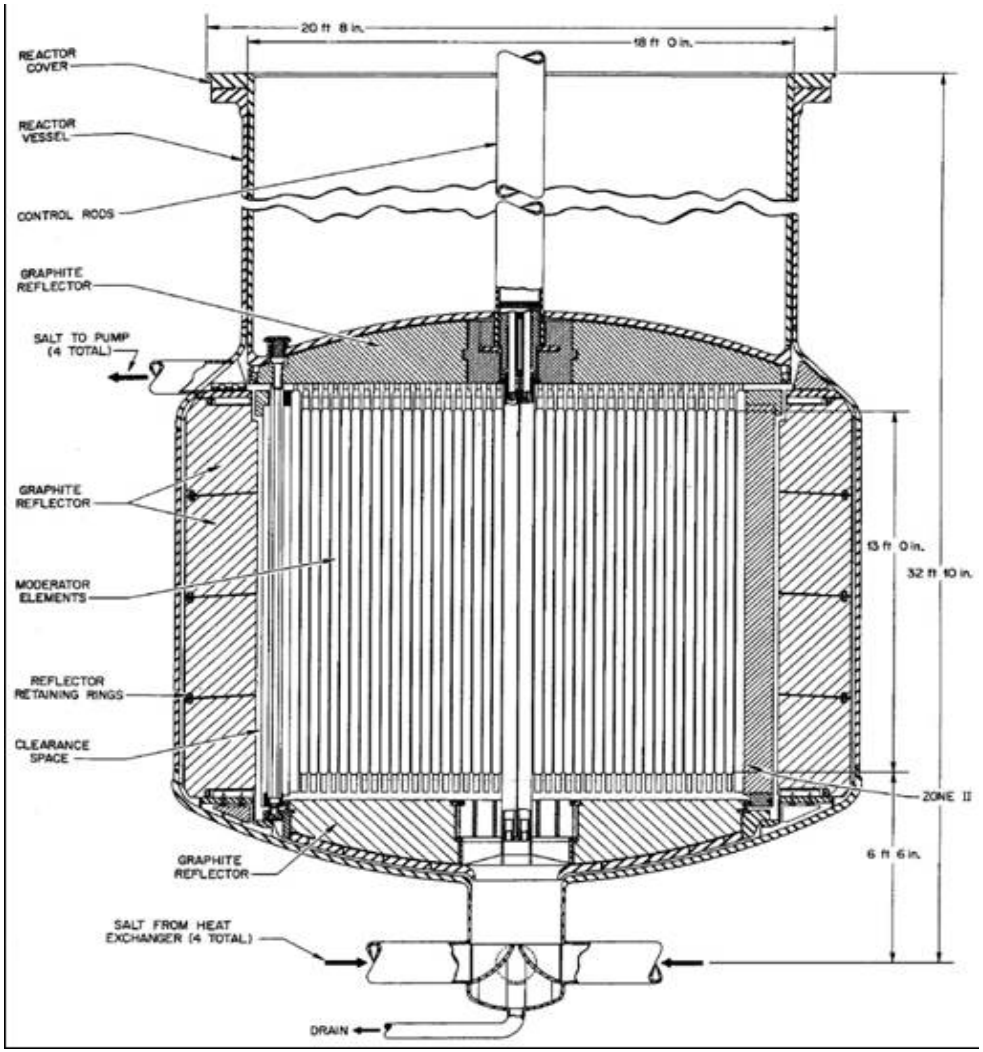
Air-Cooled Heat Exchangers →



Molten Salt Reactor



Cross Section of 1970s 2250-MW(t) MSR Design



The Molten Salt Reactor Experiment Demonstrated the Concept

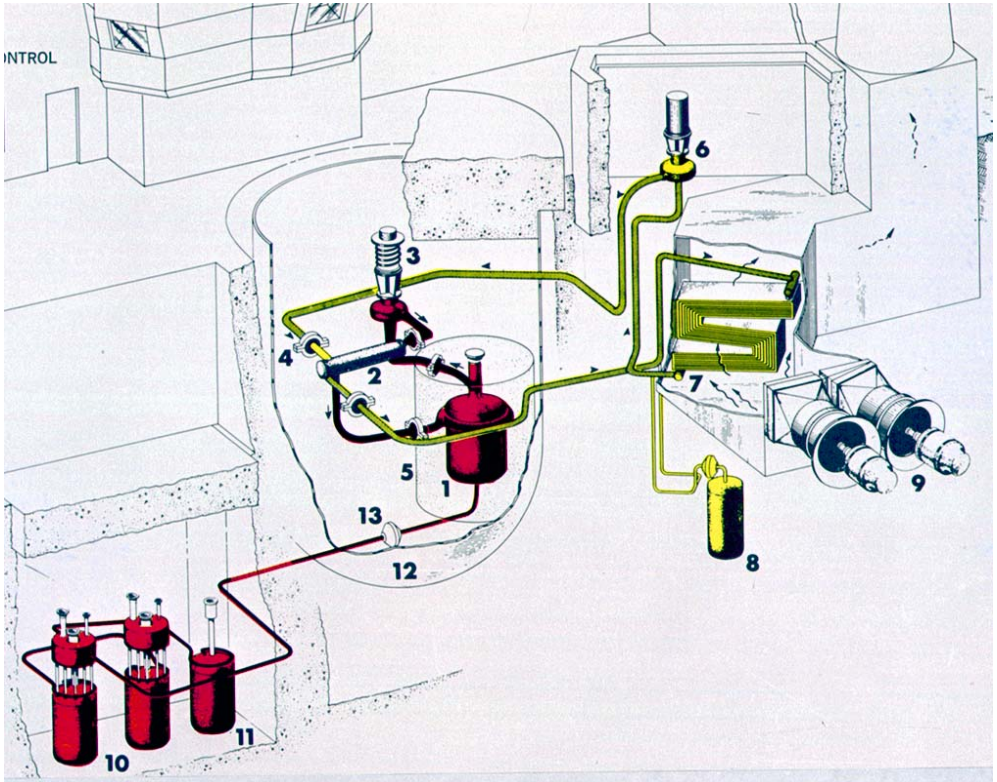
Hours critical	**17,655**
Circulating fuel loop time (hours)	**21,788**
Equiv. full power hrs w/ ^{235}U fuel	**9,005**
Equiv. full power hrs w/ ^{233}U fuel	**4,167**

1960s Goal: Breeder

- **Base technology established**

Today's Option

- **Actinide burning**
- **New requirements**
- **Changes in the base technology**



1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

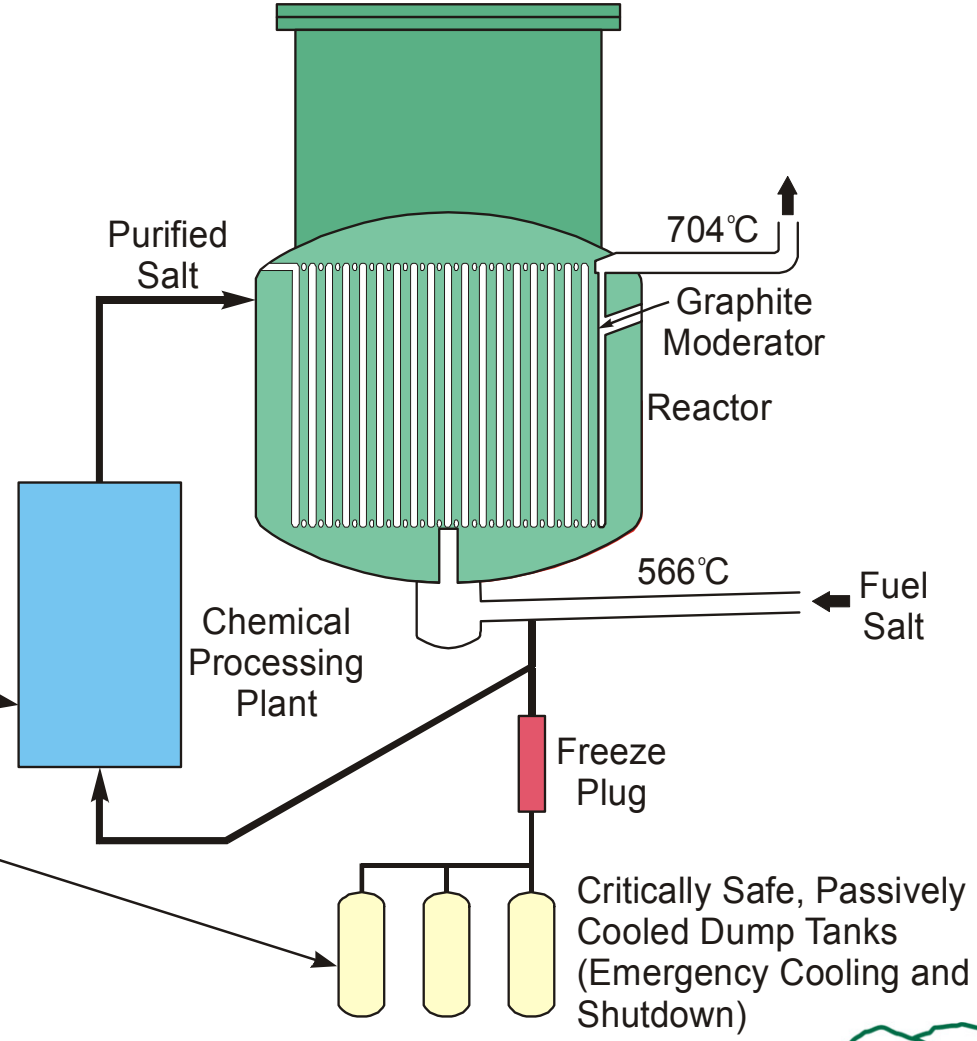
MSRE power = 8 MW(t)
Core volume <2 cubic meters

Renewed Interest in MSRs

- **Changing goals**
  - **Passive safety in very large reactors**
  - **Low fissile fuel inventory, no requirement for large breeding ratio**
  - **Wastes without long-lived actinides**
  - **Burning actinides from light-water reactors**
- **New technologies that may significantly lower costs and technical challenges**
  - **Brayton cycles (higher efficiency and avoid steam/salt mismatch)**
  - **Compact heat exchangers (minimize volume of fuel salt)**

MSRs Have a Different Safety Approach that Allows Passive Safety in Very Large Reactors

- **Low pressure (molten salt boiling point ~1400°C)**
- **Low chemical reactivity**
- **Low accident source term with continuous removal of mobile fission products**
- **Passive cooling by dumping fuel to cooled tanks**



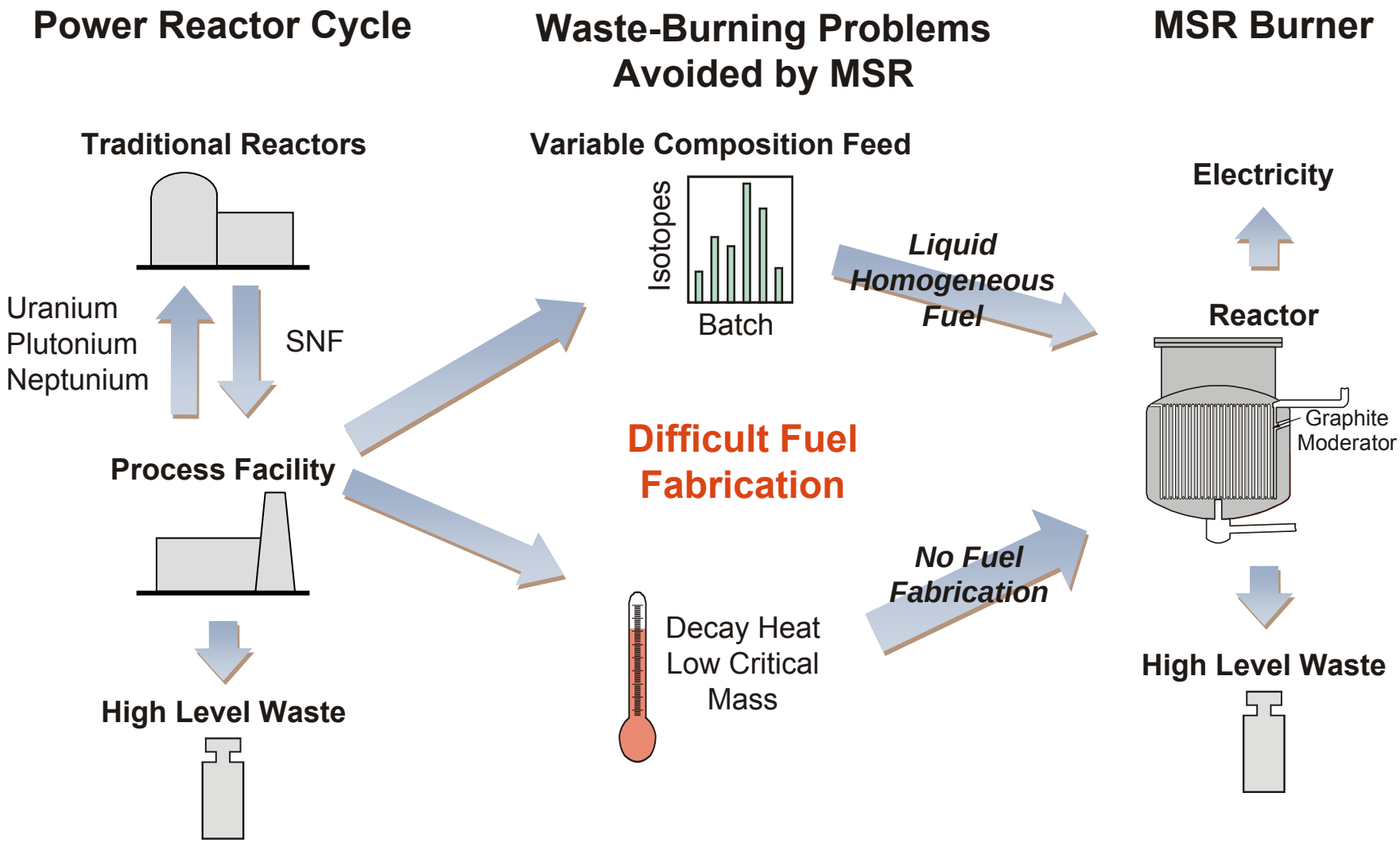
Multiple Fuel Cycle Options Exist
(Process and Preferred Salt May Differ)

Fuel Cycle	On-line Processing	Molten Salt
Actinide burning	Optional	NaF, ZrF_4, other
Once-through	Optional	NaF, ZrF_4, other
Denatured (^{238}U)	Limited	NaF, ZrF_4, other
^{233}Th-^{233}U Breeder	Required	^{7}LiF, BeF_2

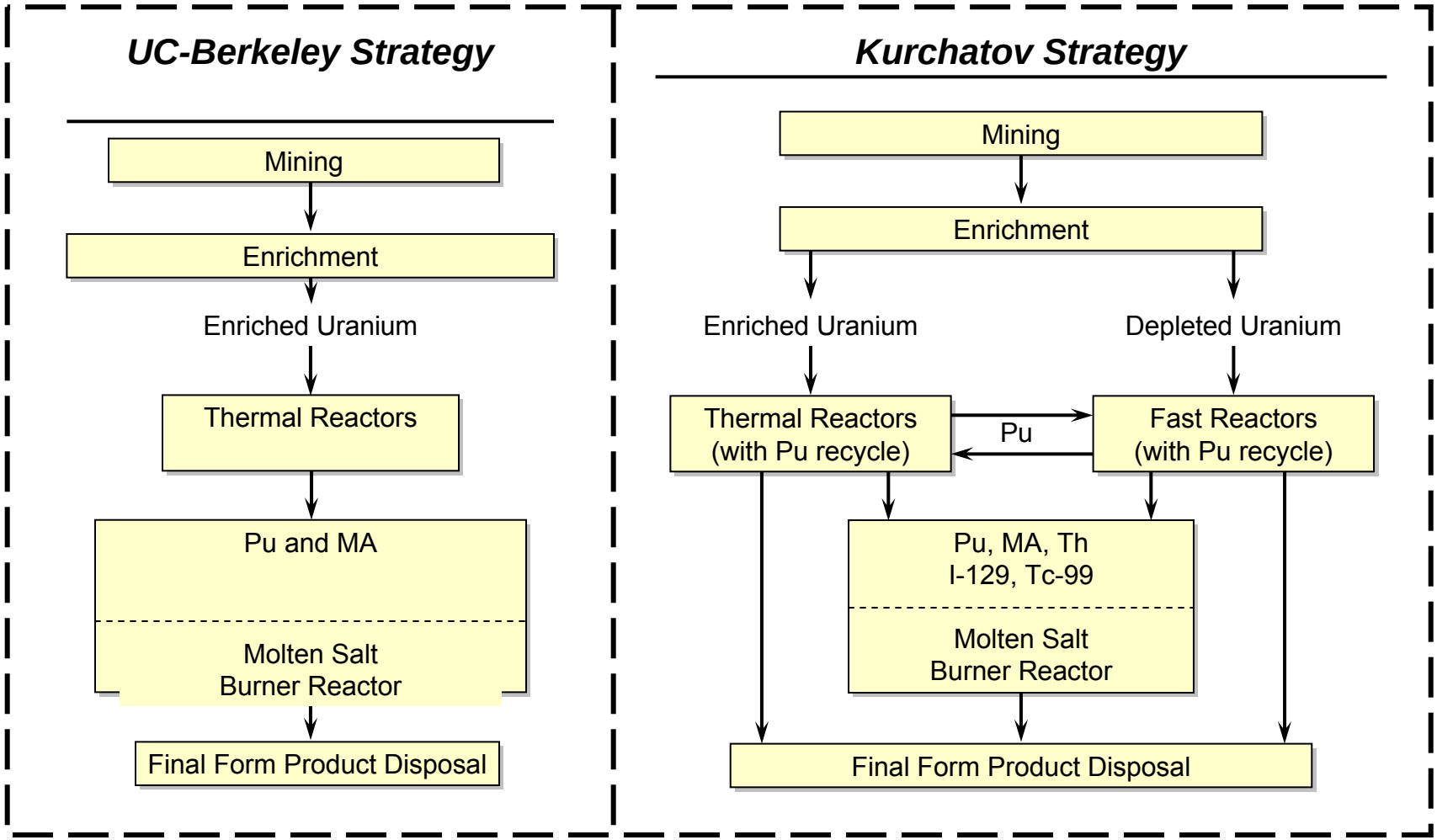
MSR Thorium Cycle: Low-Fissile-Inventory Reactor with Low-Actinide Waste

- **Epithermal neutron breeder reactor**
  - $^{232}Th + n \rightarrow {}^{233}Pa \rightarrow {}^{233}U$
  - **Maximum breeding ratio: 1.06**
- **Very low actinide content waste**
  - **Fissile materials burnout before generating significant actinides (^{233}U, ^{235}U, ^{239}Pu, etc.)**
- **Very low fissile inventory**
  - **MSR: 2 kg fissile/MW(e)**
  - **LWR: 3-5 kg fissile/MW(e)**
  - **Fast reactor: 25 kg fissile/MW(e)**

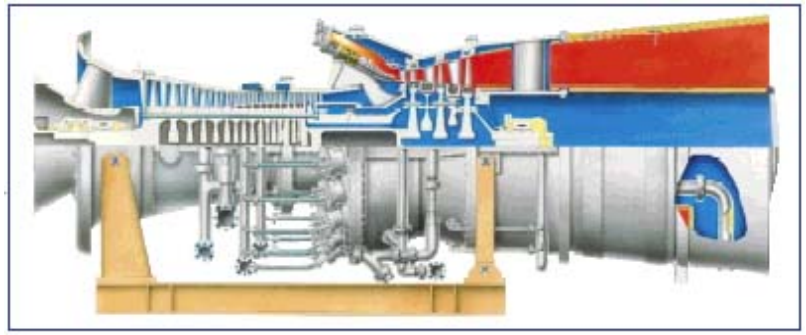
MSRs Avoid Several Solid-Fuel-Reactor Problems with Burning LWR Actinides (High-Burnup Pu, Am, Cm)



MSR Actinide Burning Strategies

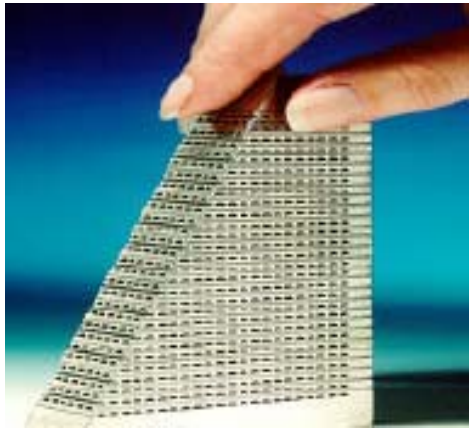


New Technologies may Significantly Improve the Viability of MSRs



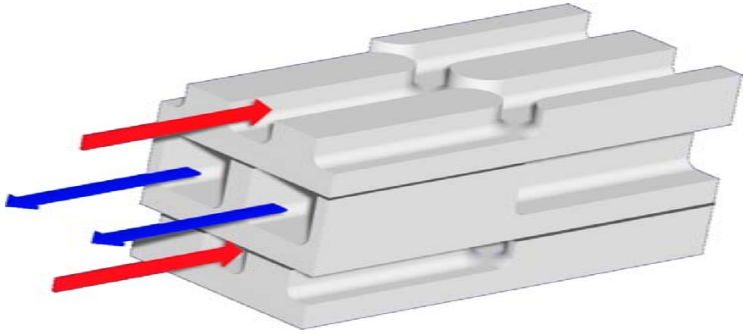
←Brayton Power Cycles

Major efficiency gain
No salt-water interactions
(salt freeze, tritium, etc.)



Compact Heat Exchangers→

(Reduced fuel salt inventory)



←Better materials

Carbon-carbon composites

MSR Research and Development Challenges

- **Update concept to understand impacts of new technologies**
  - **Brayton cycles**
  - **Compact heat exchangers**
  - **Carbon-carbon composites**
- **Develop modern fuel cycles**
  - **Actinide burning (High actinide inventory)**
  - **Simplified salt processing**
- **Reactor core design for different fuel cycles**
- **Refine online chemistry control**
  - **Noble metal plate out**

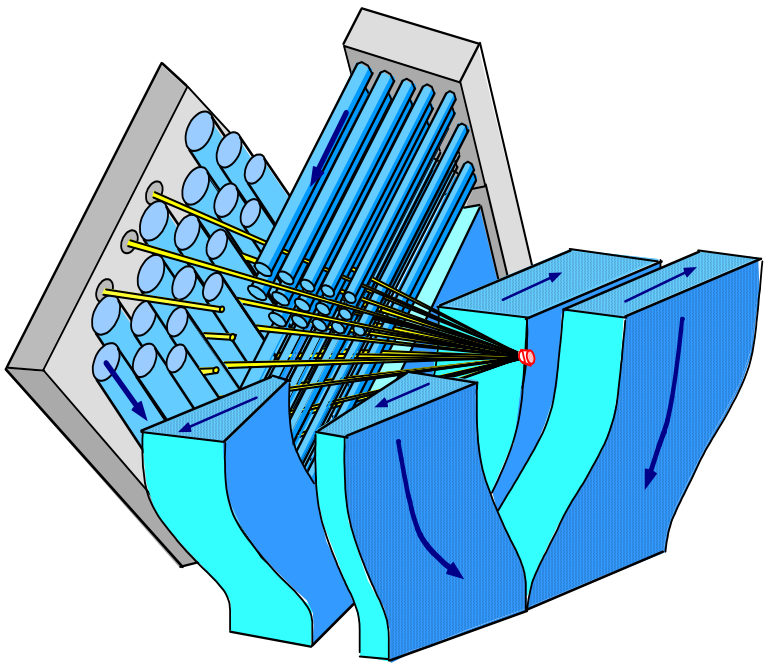
Fusion

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**

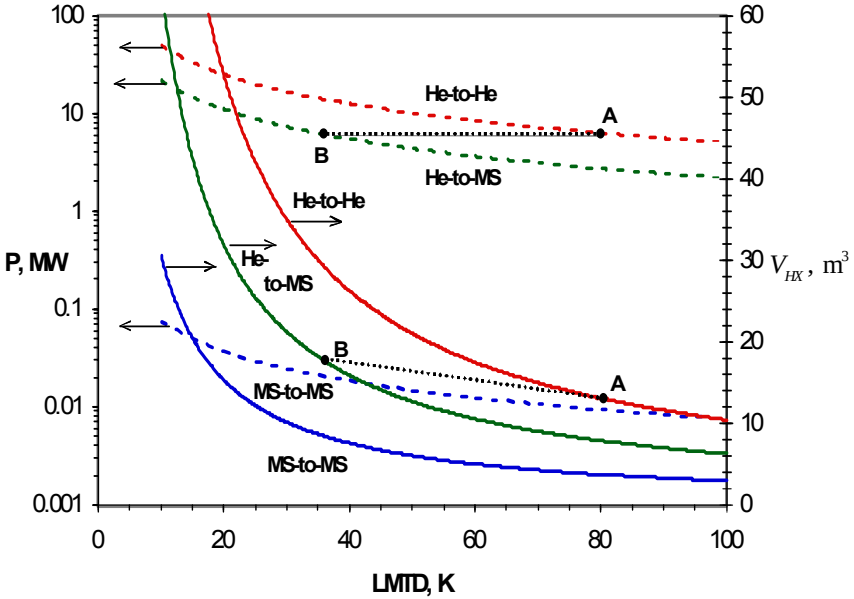


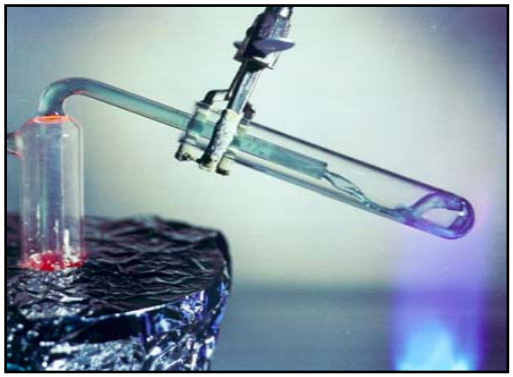
Molten Salt Characteristics

Neutronics, Chemistry, and Physical Properties Determine the Choice of Molten Salt

Advantages of Molten Salt Coolants

Low-Pressure, Transparent Coolants→

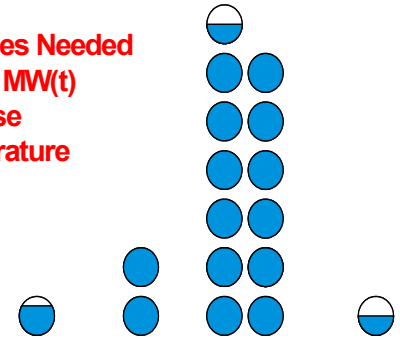




←Better Heat Transfer

(Smaller Temperature Drops)

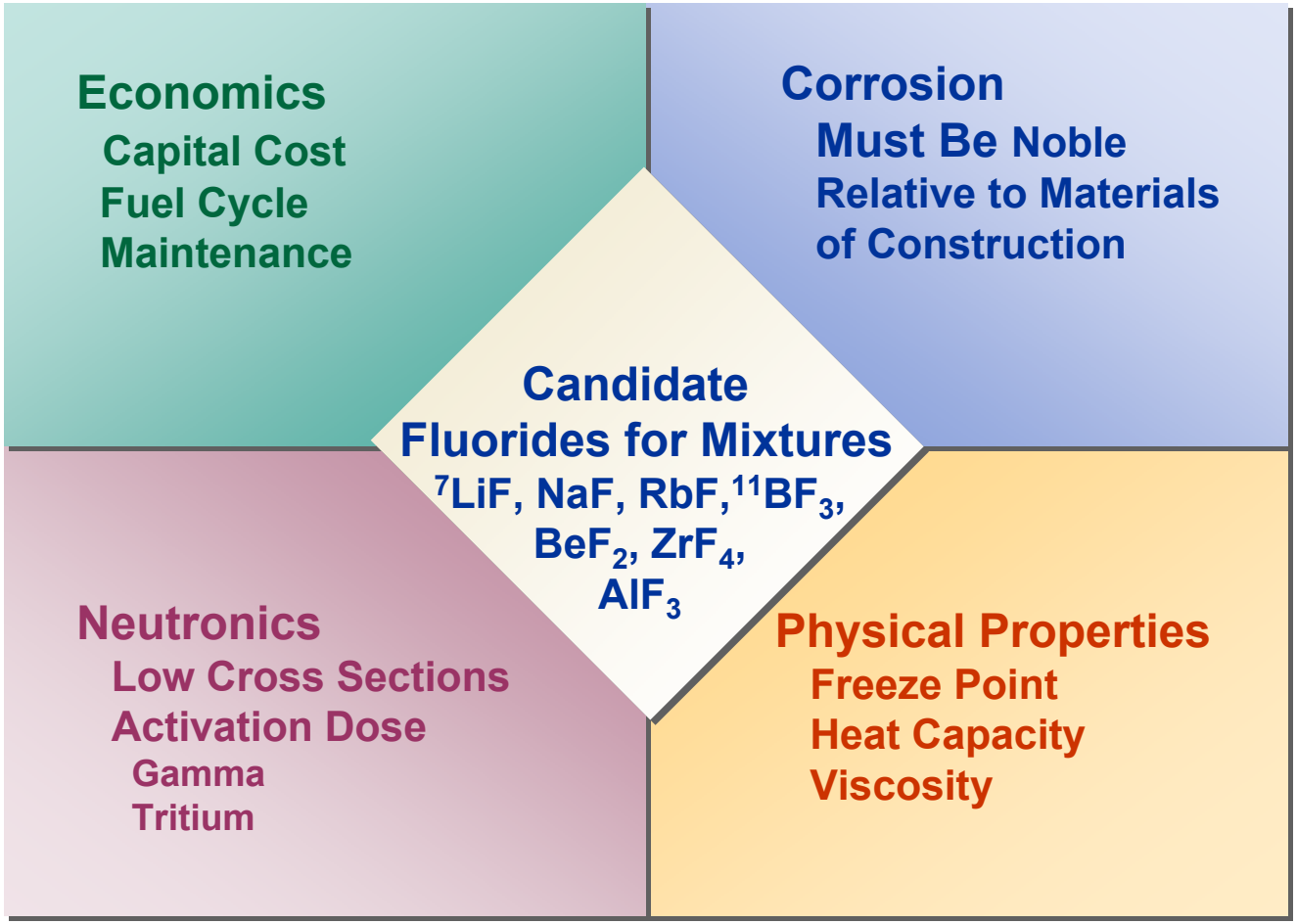
Number of 1-m-dia. Pipes Needed To Transport 1000 MW(t) With 100ºC Rise In Coolant Temperature



	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

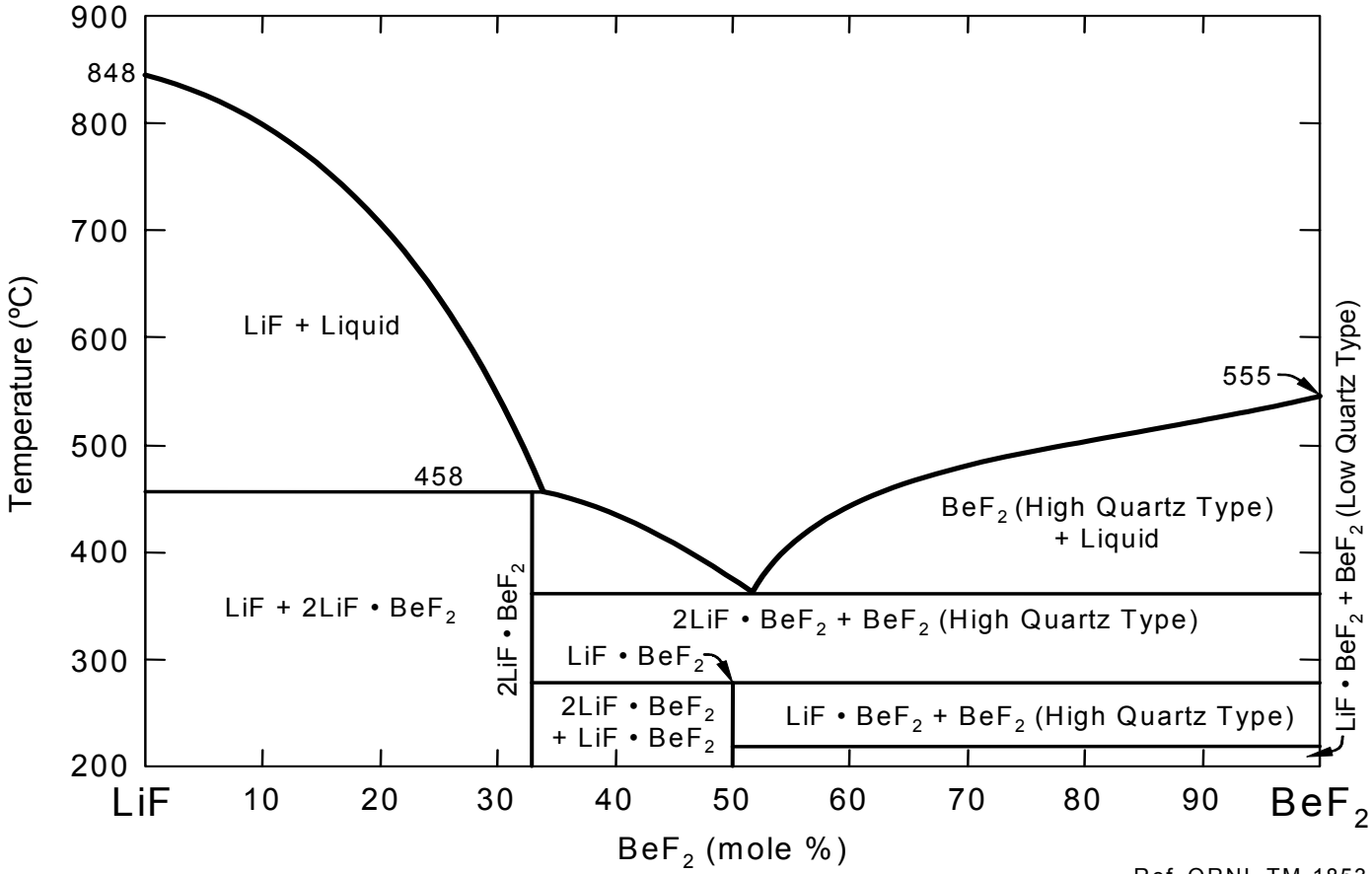
Better Transport of Heat→

The Choice of Molten Salt Mixture Involves Complex Tradeoffs



Multi-Component Salt Mixtures are Used to Improve Physical Properties

(Lower Freezing Points, Viscosity, Vapor Pressure)



Ref. ORNL-TM-1853

Materials

Existing metals to 750ºC

Graphite fully compatible

Hastelloy-N Qualified to 750ºC; Testing Required for Higher Temperature Materials

- 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 chemical conditions
    - Materials challenges in MSR are significantly larger because of fission products
- Test program required for high temperatures (>750ºC)
  - Flow loop corrosion testing
  - Some high-temperature corrosion mechanisms depend upon temperature differences

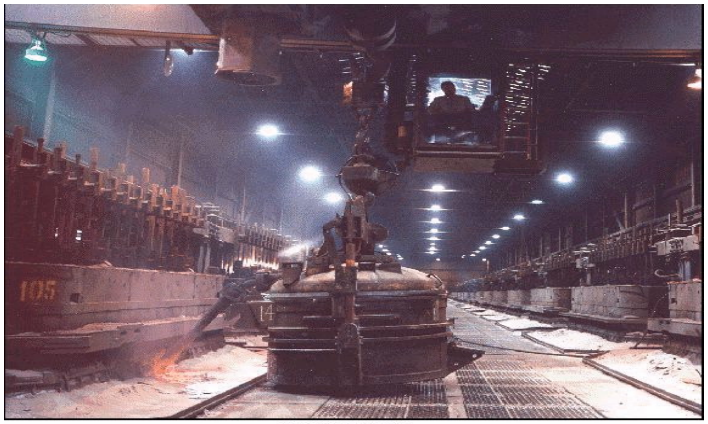
3000 hours at 815ºC with minimal corrosion by fluoride salt (Williams: Global 2003)

Materials of Construction Must be Chemically Noble Relative to the Molten Salts

Constituent	Free energy of formation at 1000°K (kcal/mol-F)	Cation thermal capture cross section (barns)
Fluoride Salt Constituents		
^{7}LiF	-125	0.033 (^{7}Li)
NaF	-112	0.52
BeF_2	-104	0.01
ZrF_4	-94	0.18
$^{11}BF_3$	~-95	0.05 (^{11}B)
Structural Metal Constituents (Fluoride Must Be Less Stable Than Salt)		
CrF_2	-75.2	3.0
FeF_2	-66.5	2.5
NiF_2	-55.3	4.5
MoF_6	-50.9	2.5

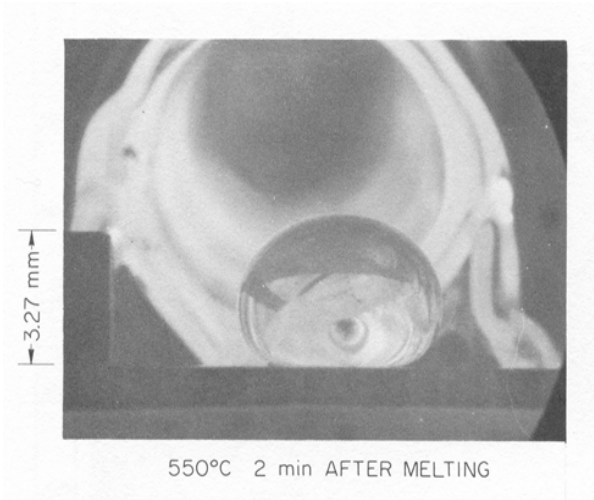
Molten Fluoride Salts are Fully Compatible with Graphite

- **Century of experience in the aluminum industry (1000ºC)**
- **Tested in high radiation fields**
- **Tests to 1400ºC**
- **Does not wet graphite (right)**



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.



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

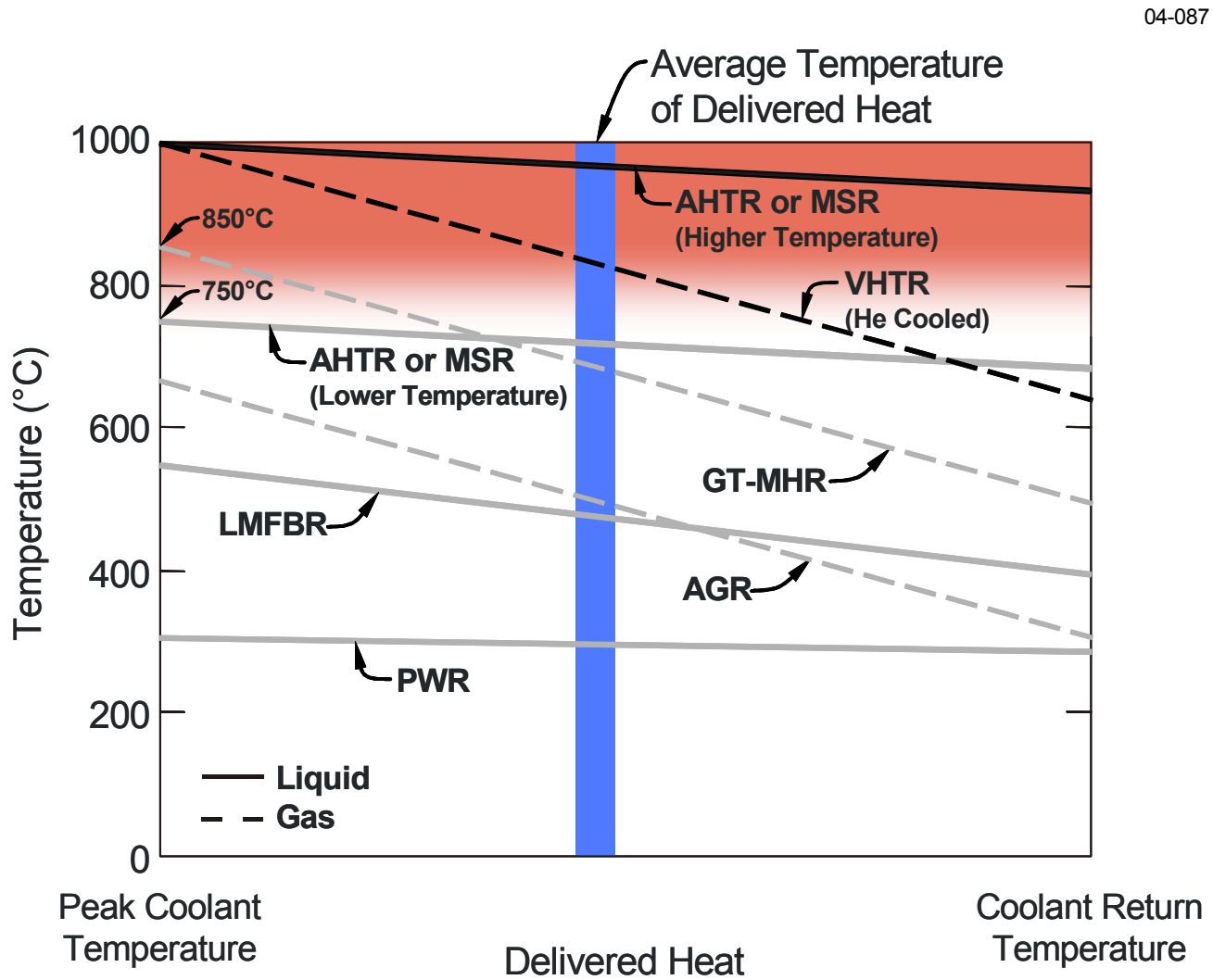
***Salts Used in Reactors.** **Examples of fluoride salts with lower melting points: Li-Na-Be (22-44-33): ~300ºC; Na-K-Zr (10-48-42): 385ºC**

Partial List of Candidate Salt Systems

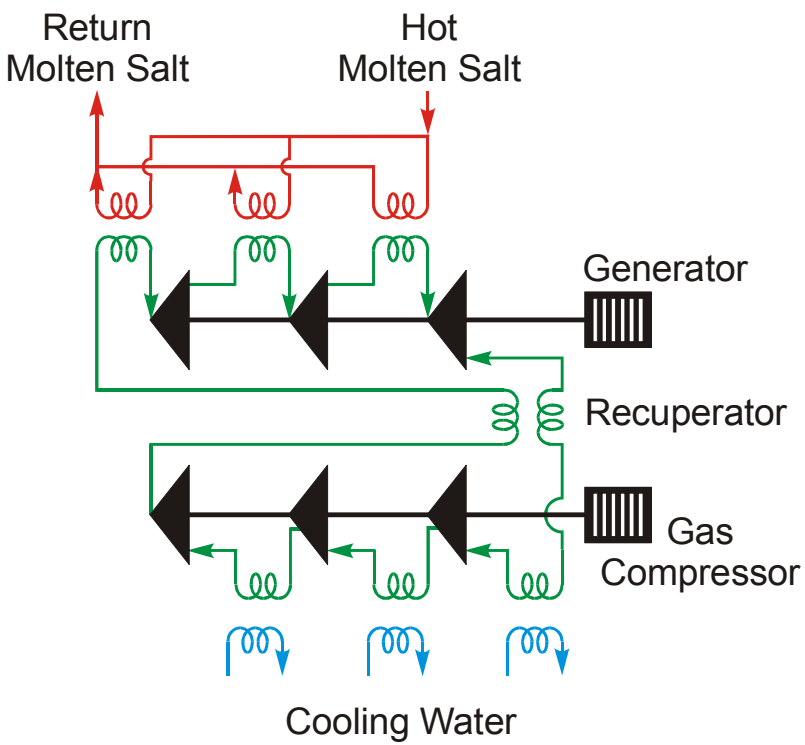
Family	Example (mole %)	Pressure at 1000ºC (Atm.)	Melting Point (ºC)
Alkali Fluorides	LiF-NaF-KF 11.5/46.5/42	0.01	454
Fluoro-Borates	KBF_4/KF	0.7	460
Zirconium Fluorides	NaF-KF-ZrF_4 10/48/42	<0.1	385

Energy Conversion

Liquid-Cooled Reactors Deliver Heat at Higher Temperatures than Gas-Cooled Reactors



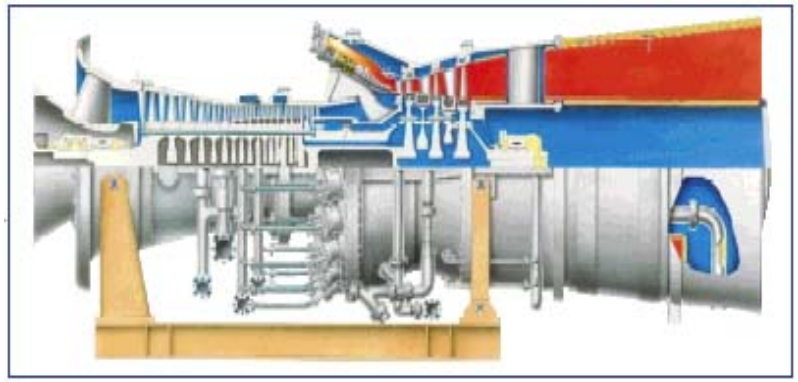
Delivering Heat at a Nearly Constant High Temperature Allows the Use of Advanced Electric Power Cycles

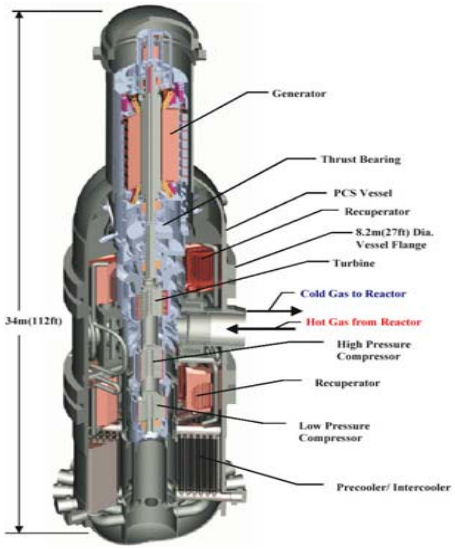


- **Multi-reheat helium Brayton cycle**
- **Cycle requirements**
  - **High temperature**
  - **All heat delivered at a high temperature**
  - **4 to 8% more efficient than simple gas-cooled Brayton cycle with same peak temperatures**

Brayton Cycles: An Enabling Technology for High-Temperature Salt-Cooled Reactors

- **No steam-cycle temperature limit**
- **Brayton cycle efficiencies**
  - **48% efficiency at 705ºC**
  - **51.5% efficiency at 800ºC**
  - **56.6% efficiency at 1000ºC**
- **High temperatures match salt properties (avoid freezing)**
- **No salt interactions if a heat- exchanger failure occurs**
  - **Steam and salt slowly react**
  - **Helium or nitrogen does not react with salt**



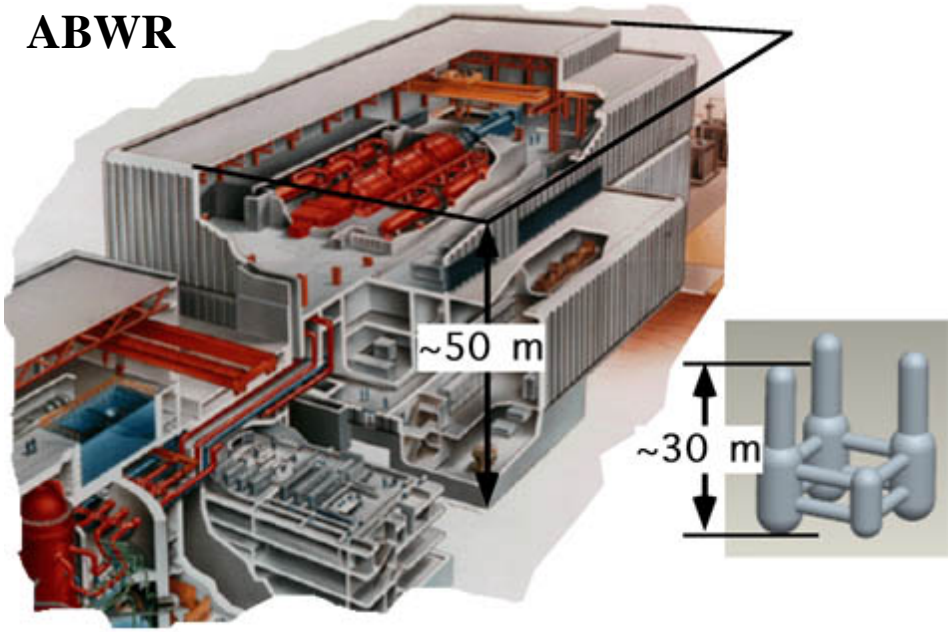


Above: GE Power Systems MS7001FB

Left: GT-MHR Power Conversion Unit (Russian Design)

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

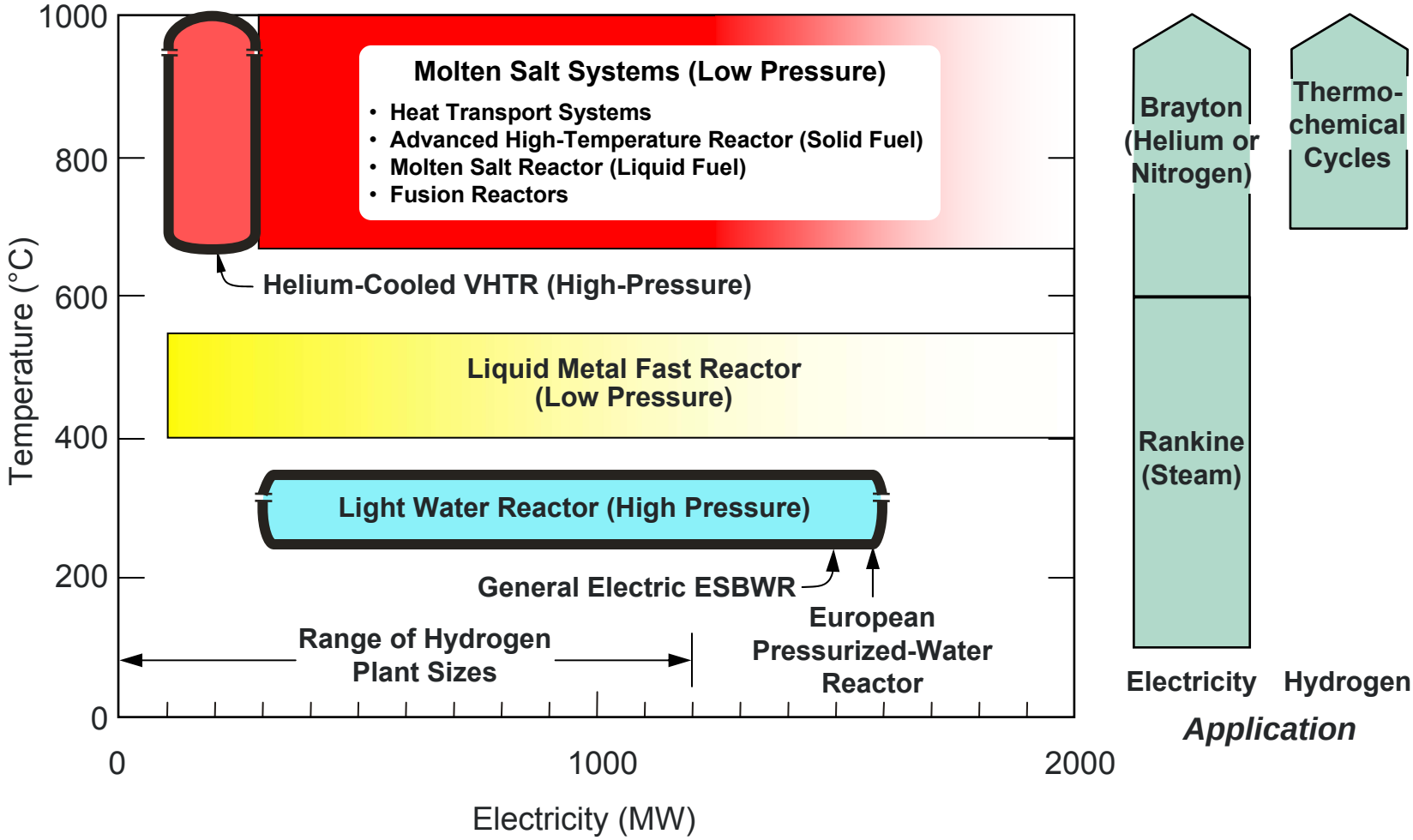
ABWR



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

Helium-Brayton Cycle with Three Power Conversion Units (Similar to GT-MHR)

- **No low-pressure steam turbines (Brayton cycle operates at higher pressures)**
- **Brayton cycle requires ~1100 MW(t) of cooling water capacity, compared with 2800 MW(t) for ABWR**

Conclusions

Molten Salts may be the Enabling Technology for Economic High-Temperature Reactors