# Overview of Nuclear Salt Applications
## (Liquid Salt Temperature >700$^{o}$)

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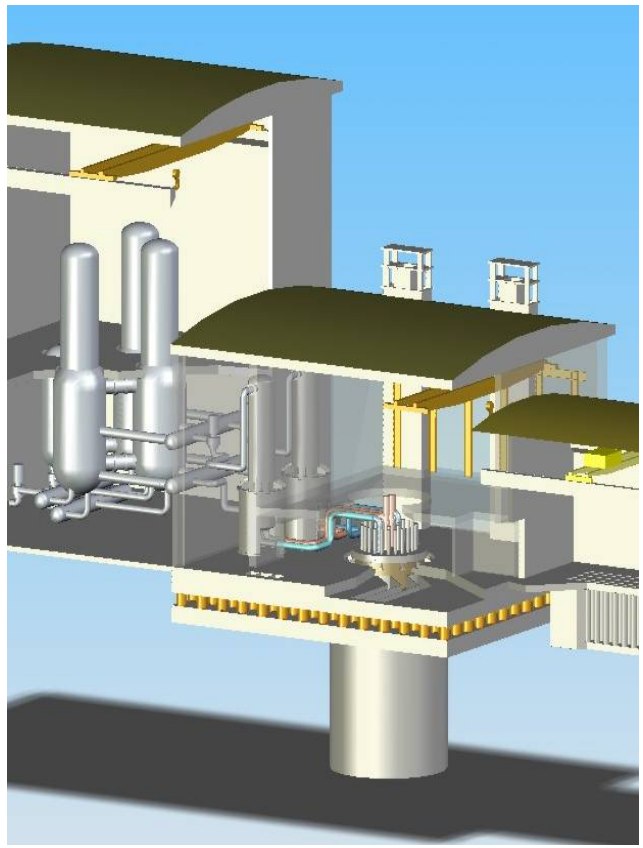
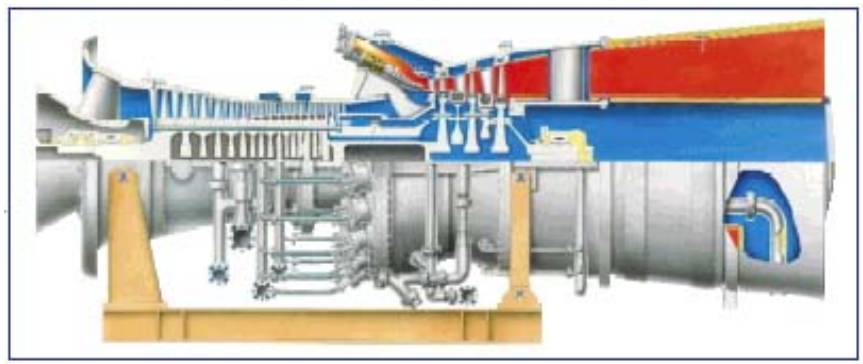
**Liquid Salt Technology Working Group**
**Friday, October 28, 2005**
**Los Angeles, California**





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# Molten/Liquid Salt Timeline

- Aircraft Nuclear Propulsion Program:
  - 1950s-1960s
  - Money is no objection
- Molten Salt Breeder Reactor Program
  - 1960s-1973
- Basic Science R&D
- Molten Salt Reactor Experiment Remedial Action Program
  - 1995-today
- Advanced Reactors and Hydrogen Production
  - 2000 onward

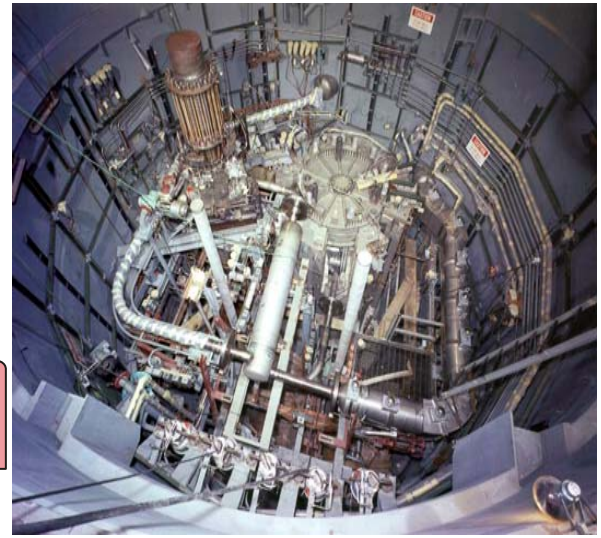
# Molten Salt Reactor (MSR)

**Goal: Unlimited-Range Nuclear-Powered Bomber**
**ORNL Concept and Lead Laboratory**
**Lower Weight Than Other Reactor Options**
**Billion Dollar Program (1950s-1960s)**

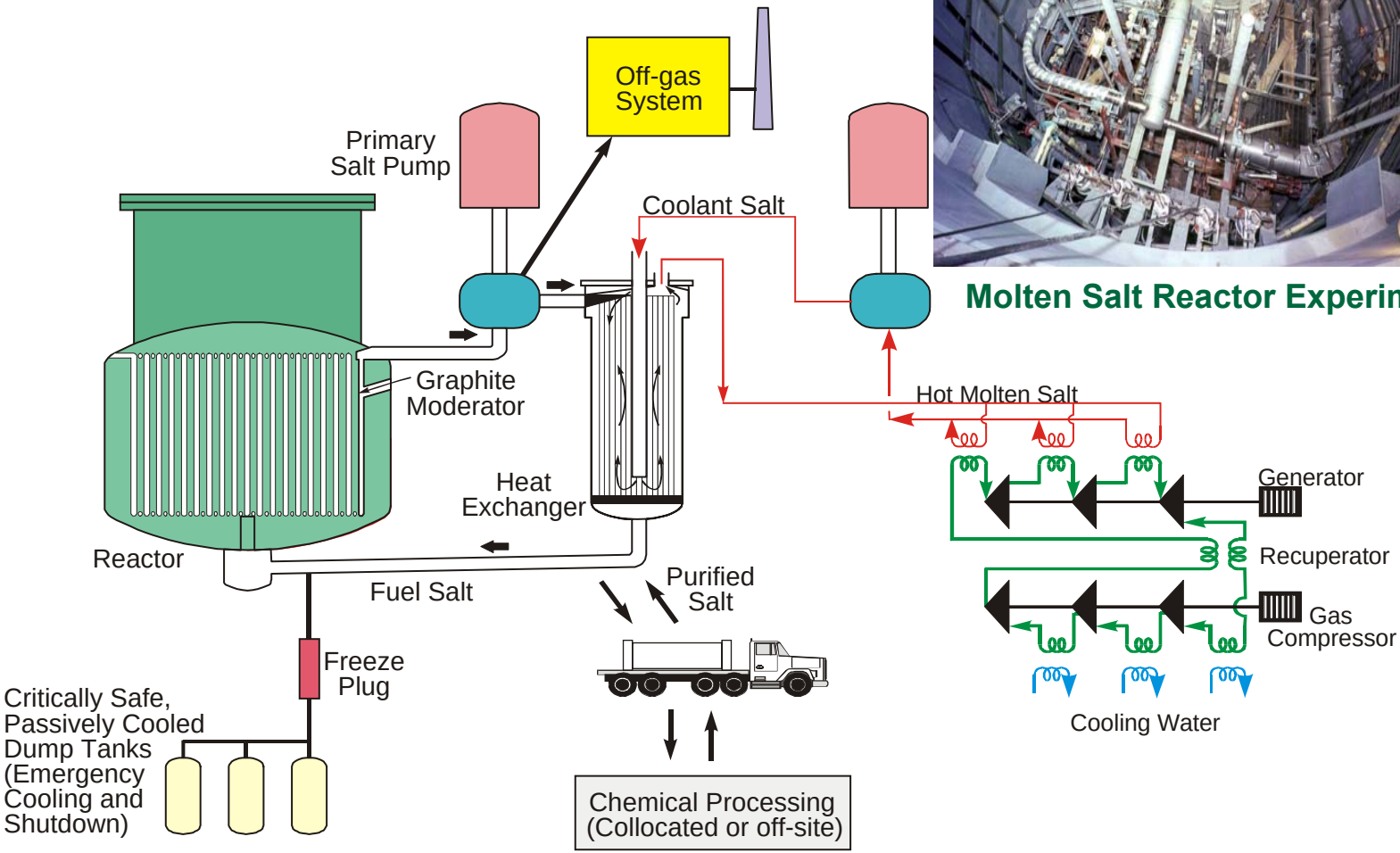
**Goal: Breeder Reactor**
**ORNL Concept and Lead Laboratory**
**Liquid-Fuel Reactor With Unique Capabilities**
**Smaller Program (1960s)**

# Molten Salt Reactor

## (Modern Version with Brayton Power Cycle)



Molten Salt Reactor Experiment



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

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

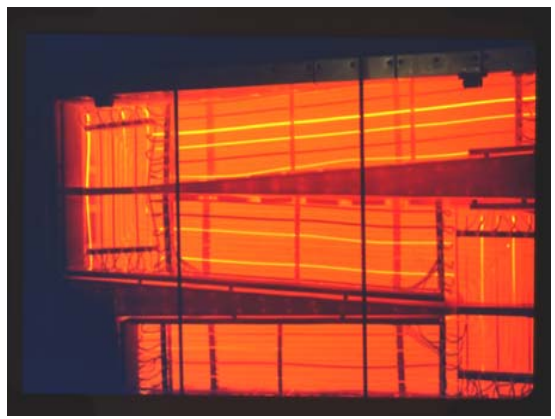
### Aircraft Nuclear Propulsion Program

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

### Molten Salt Breeder Reactor Program

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

Air-Cooled Heat Exchangers →

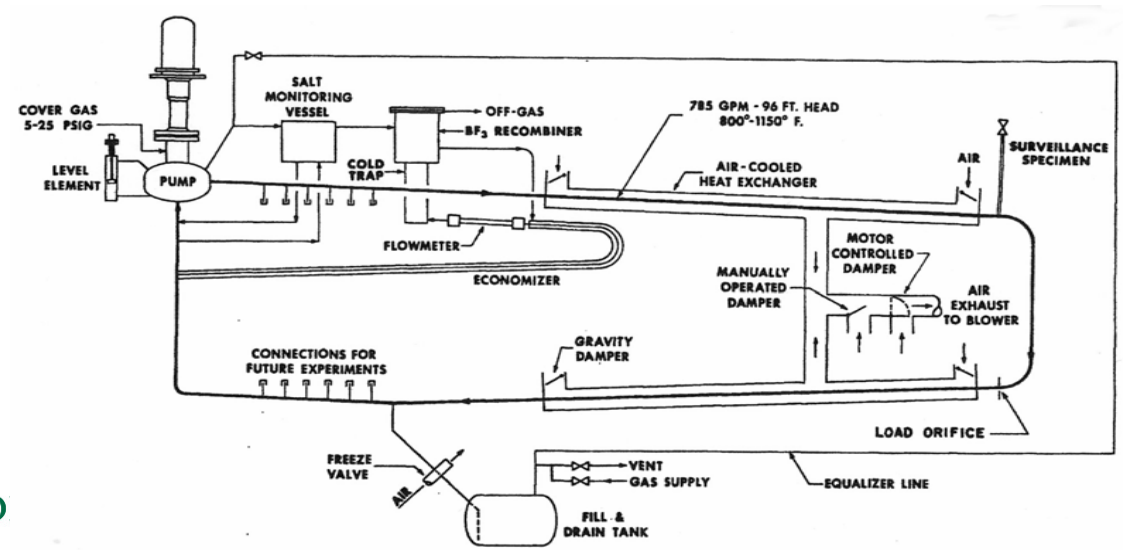


# Status of Salt Technology at the End of the ORNL Molten Salt Reactor Program

- Two test reactors
- Massive data base of salt properties
- 750,000 hours of pump loop test data
- Preliminary design of 1000 MW(e) molten salt reactor
- Start of development of large-scale pumps, valves, and bearings by industrial partners

## 1970s ORNL Coolant Salt Technology Facility

- Pump: 850 gal/minute
- Piping: 5-in Sch 40
- Material: Hastelloy N
- Temperature: 850-1100ºF
- Run time: 9300 hours



# Molten Salt Reactor Experiment Remediation Project (Ongoing)

# Molten Salt Reactor Experiment Remediation Program

2600 kg Coolant Salt in Original Tank

Coolant Salt Removed to Transfer Tanks

**Products from the Remediation:**

- 2600 kg of non-radioactive coolant salt ($^{7}Li_2BeF_4$) in 5 tanks
- More complete understanding of the radiolysis mechanism
- Limited reestablishment of pilot-plant scale handling operations

U-233 Hot Cell Conversion

# What Has Changed?

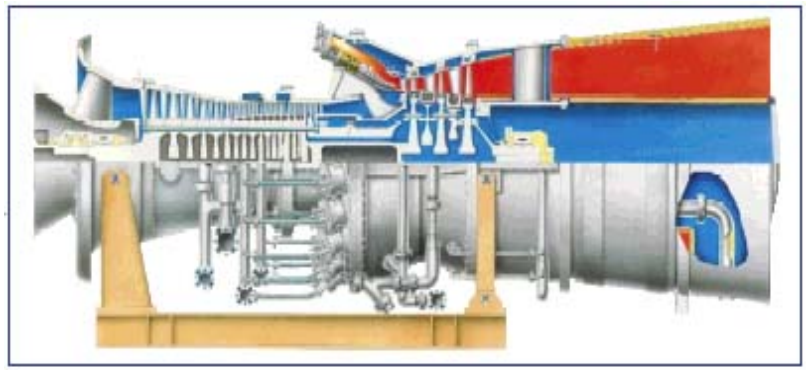
## Why the New Interest in Liquid Salt Coolants?
## Why the New Interest in Salt-Cooled Reactors?

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

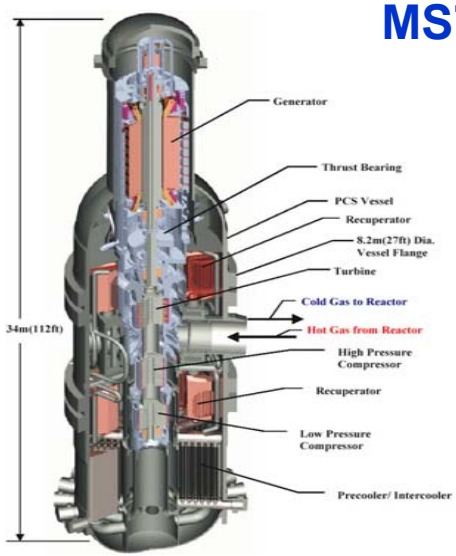
- Salt freezing points are between 350 and 500ºC
  - Fluoride salts
  - Freezing point dependent on salt composition
- Not suitable for a low-temperature reactor
- Only useful if supporting technologies to use the high-temperature heat

# Brayton Power Cycles May Make High-Temperature Reactors Viable

- High-temperature heat for a utility is only useful if it can be converted to electricity
- Steam turbines (with a 550ºC peak temperature) have been the only efficient, method to convert heat to electricity
- Development of large efficient high-temperature Brayton cycles *in the last decade* makes high-temperature heat useful



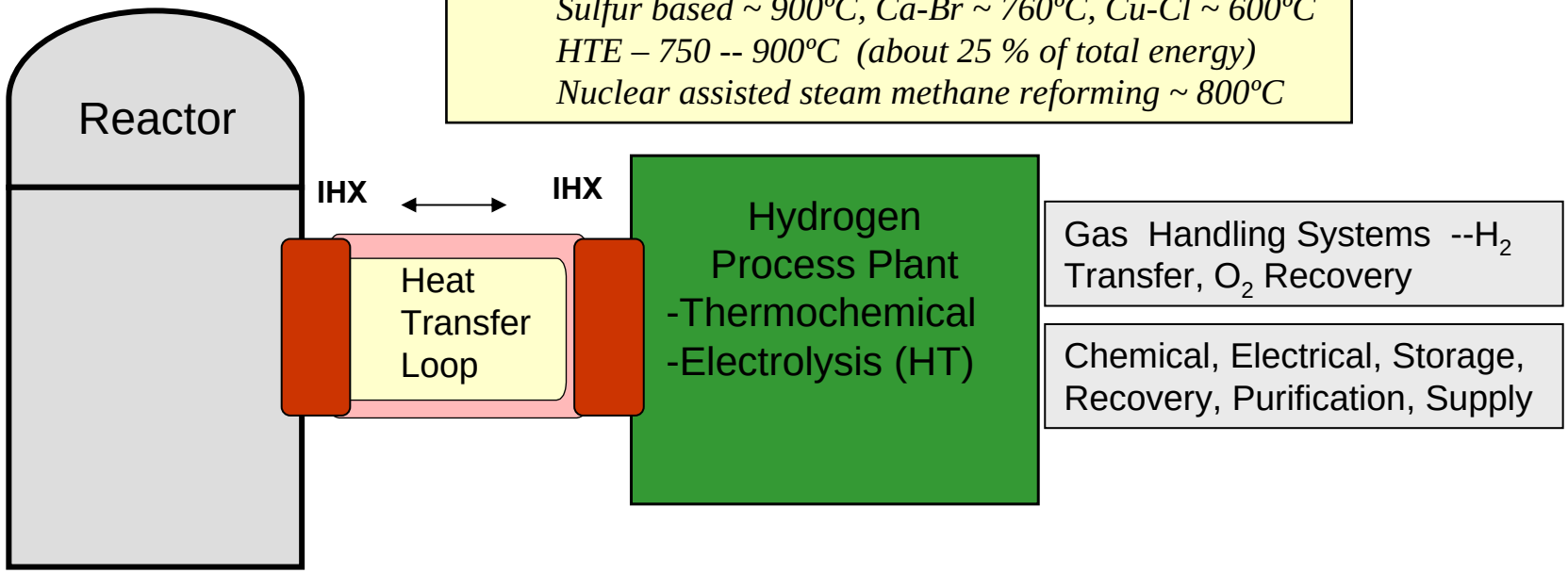
GE Power Systems MS7001FB




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

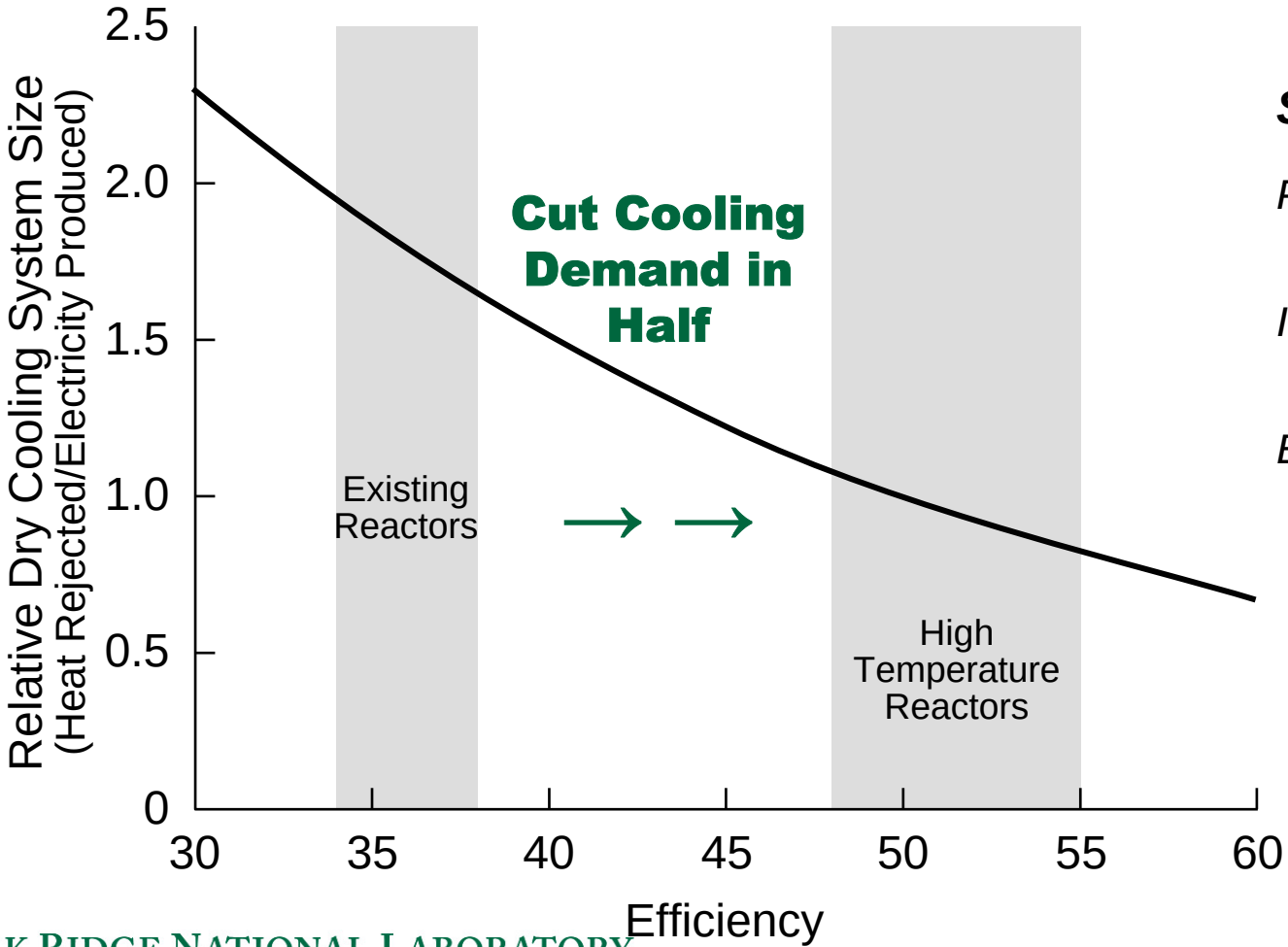
# Hydrogen Production Requires High-Temperature Heat Transport Loops

***$H_2$ Process temperature requirements***
*Sulfur based ~ 900ºC, Ca-Br ~ 760ºC, Cu-Cl ~ 600ºC*
*HTE – 750 -- 900ºC (about 25 % of total energy)*
*Nuclear assisted steam methane reforming ~ 800ºC*



# High-Temperature Reactors May Make Dry-Cooling Practical

## Water Is A Major Resource Constraint




***Simplified Siting***

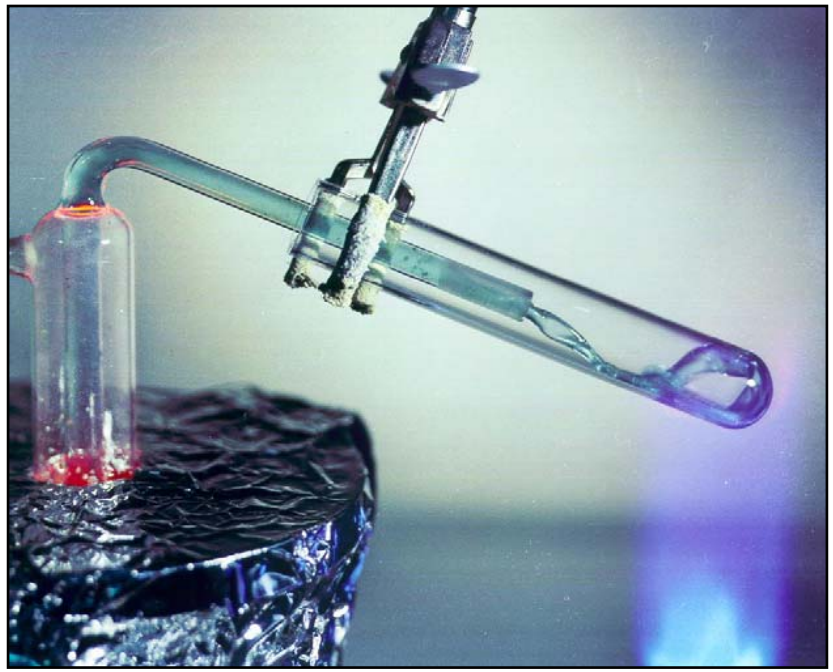
*People live near water*

*Ideal nuclear site is far from people*

*Examples of good west-coast sites: east of coastal mountains (close to cities, far from people, but no water)*

# Options for High-Temperature Reactors

# There are Two Demonstrated High-Temperature Nuclear Reactor Coolants



**Helium**

**(High Pressure/Transparent)**

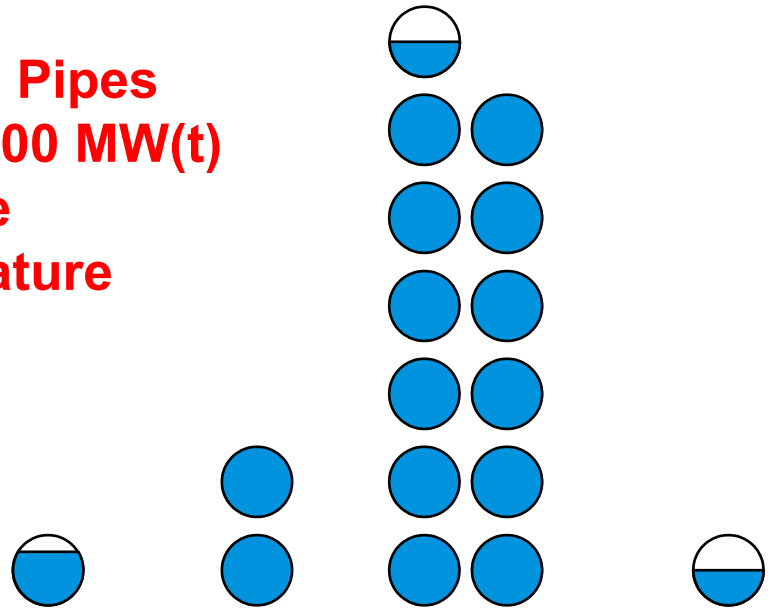
**Liquid Fluoride Salts**

**(Low Pressure/Transparent)**

# Coolant Properties Determine Pipe, Valve, and Heat Exchanger Sizes

## (Small Equipment [lower costs] with Liquid Coolants)

**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 |

# Classes of Salt-Cooled Reactors

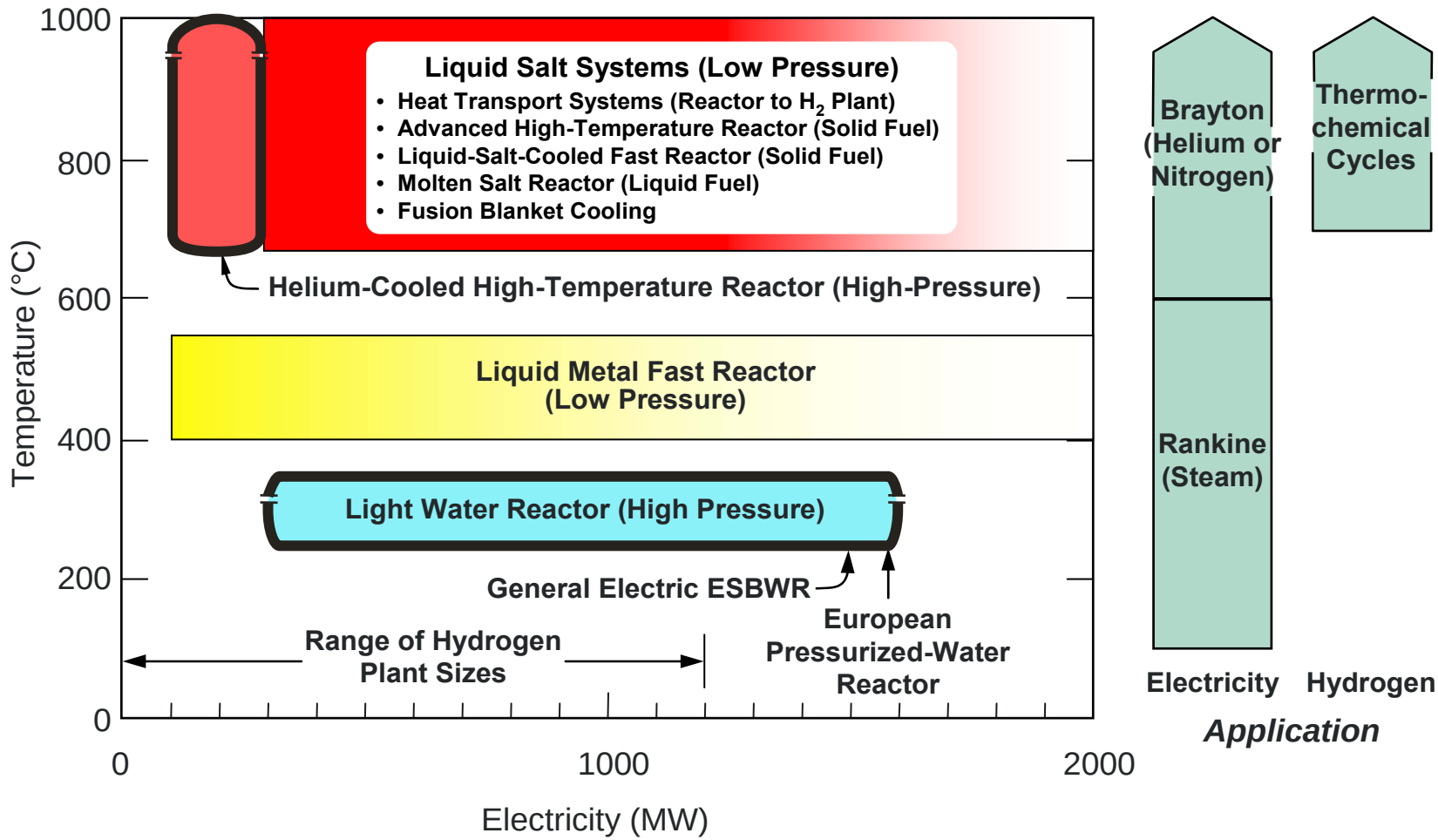
**Advanced High-Temperature Reactor**

**Salt-Cooled Fast Reactor**

**Molten Salt Reactor**

# Liquid Salt Coolants can be Used for Many High-Temperature Reactors

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



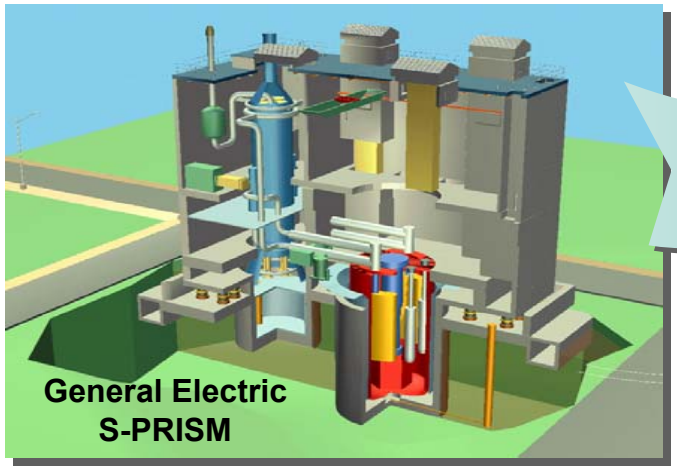
# Advanced High-Temperature Reactor

## Salt-Cooled Reactor Option I

**Clean Salt Coolant**
**Coolant Temp. Options: 700 to 1000ºC**
**Graphite-Matrix Coated-Particle Fuel**
**Size: 2400 to 4000 MW(t)**

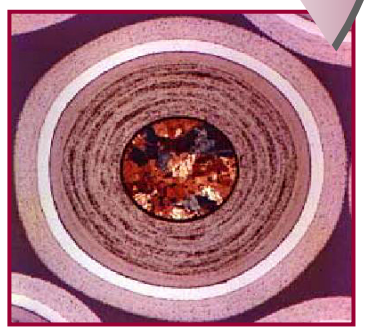
# The Advanced High-Temperature Reactor

## 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**

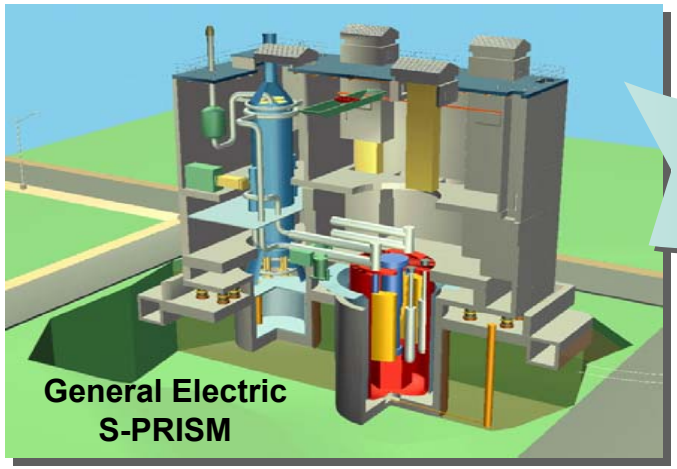
# Liquid-Salt-Cooled Fast Reactor (LSFR)

## Salt-Cooled Reactor Option II

**Clean Salt Coolant**
**Coolant Temp. Options: 700 to 800ºC**
**Traditional Fast Reactor Core**
**Size: 2400 to 4000 MW(t)**
**(Significant materials and physics uncertainties)**

# 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

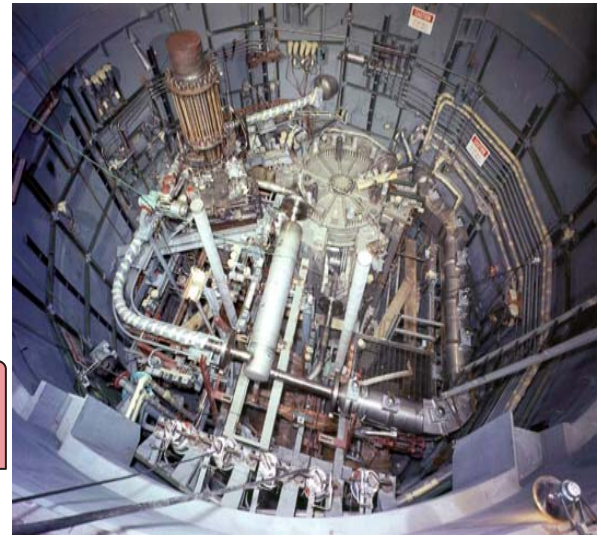
# Molten Salt Reactor (MSR)
## (Two Test Reactors Built)

### Salt-Cooled Reactor Option III

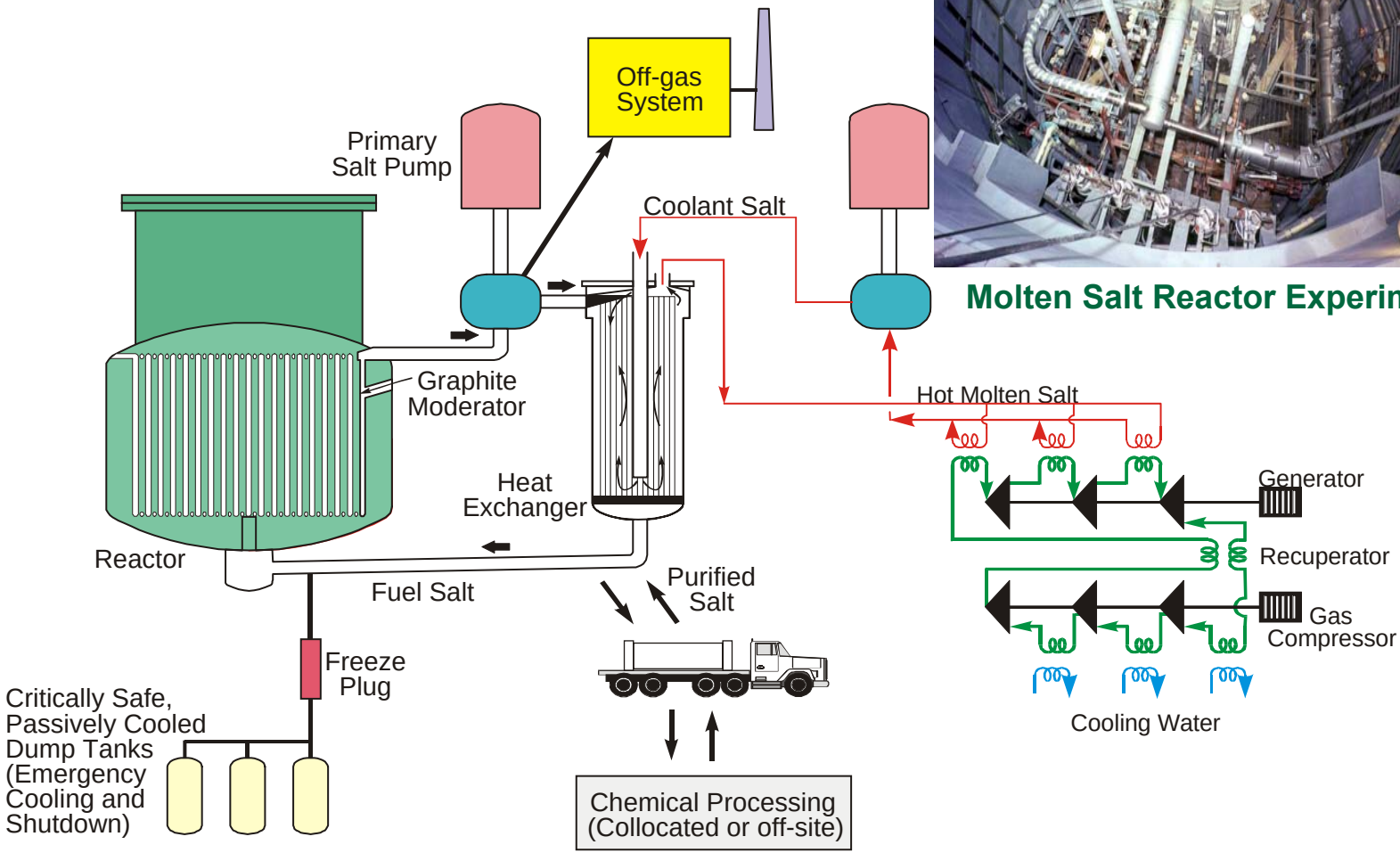
**Fuel Dissolved in Coolant**
**Coolant Temperature: 700ºC**
**Size: 2400 to 4000 MW(t)**

# Molten Salt Reactor

## (Modern Version with Brayton Power Cycle)



Molten Salt Reactor Experiment



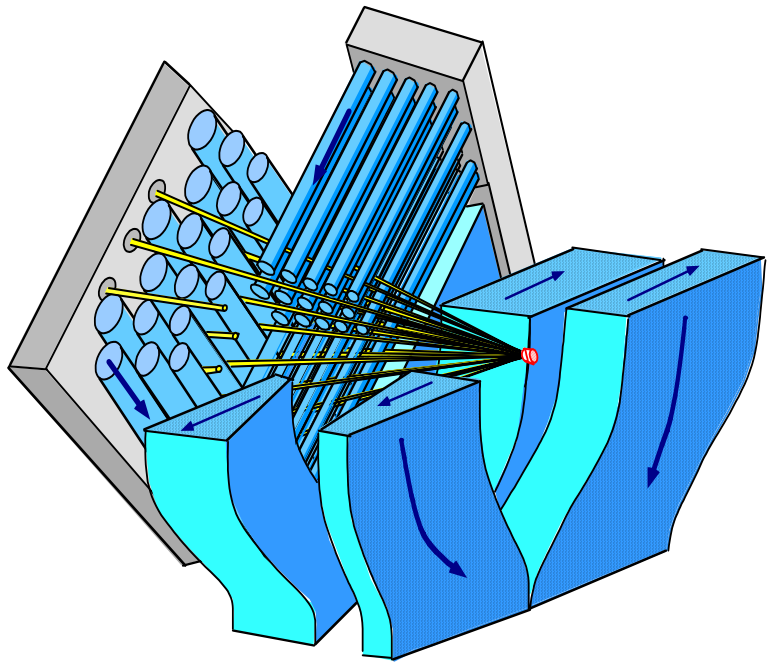
# Fusion

**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



# The Advanced High-Temperature Reactor

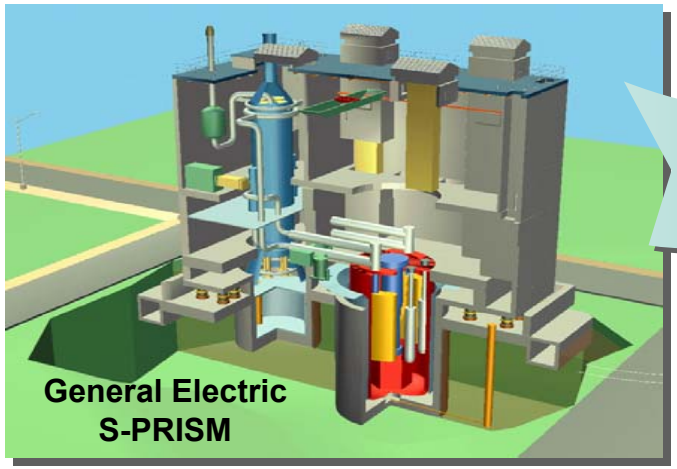
## The Near-Term Salt-Cooled Reactor Option

## Within GenIV Program Defined As Liquid-Salt-Cooled Very High-Temperature Reactor

Demonstrated Fuel
Code-Qualified Materials to 750ºC; Existing Materials to Potentially 850ºC

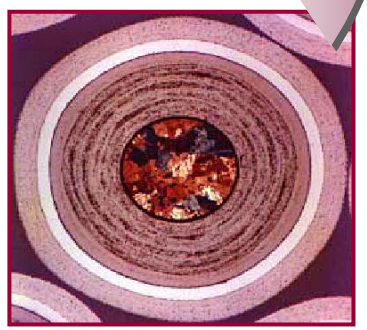
# The Advanced High-Temperature Reactor

## Combining Existing Technologies in a New Way




**Passively Safe Pool-Type Reactor Designs**

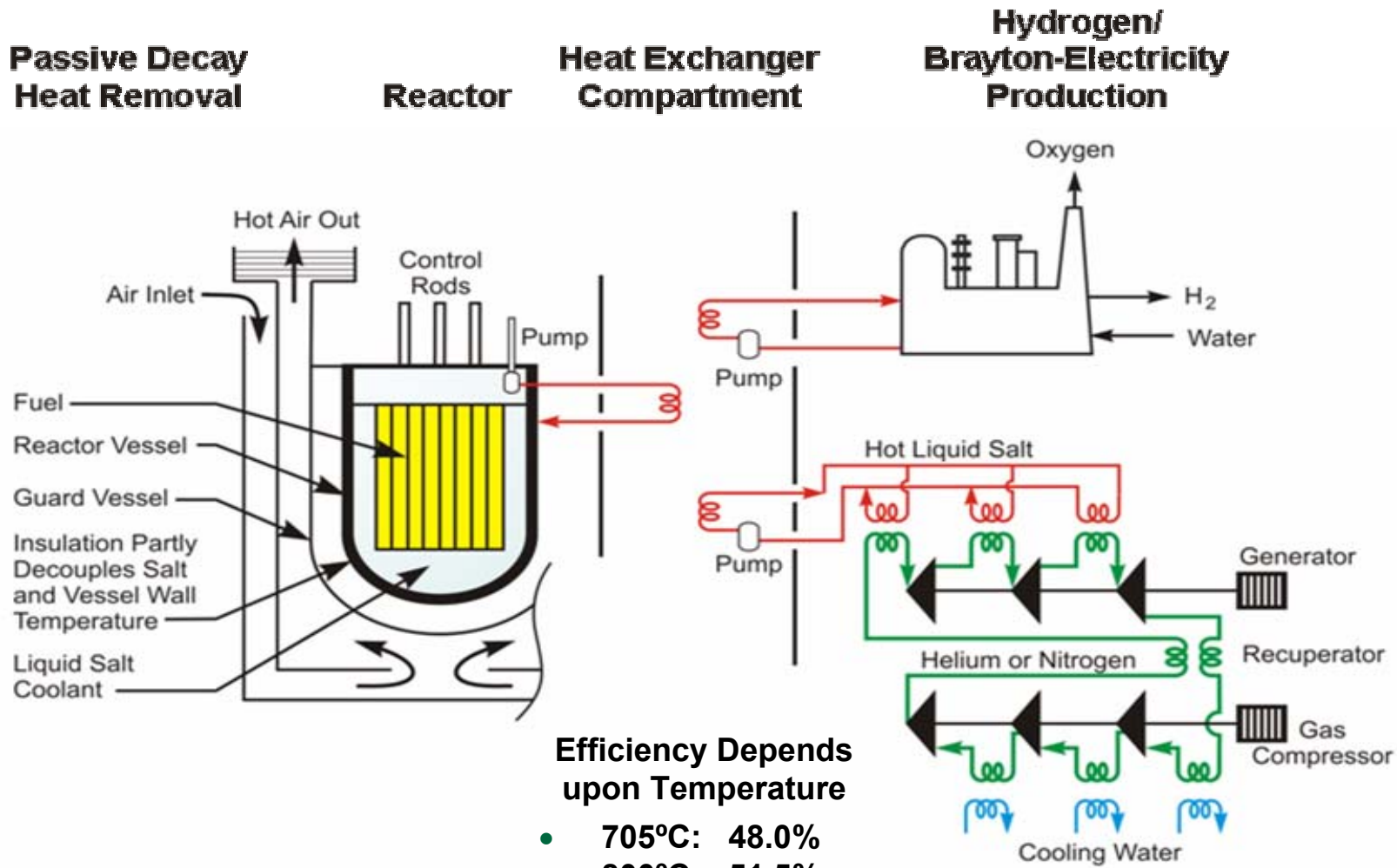
**Brayton Power Cycles**



**High-Temperature Coated-Particle Fuel**

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

# Schematic of Advanced High-Temperature Reactor



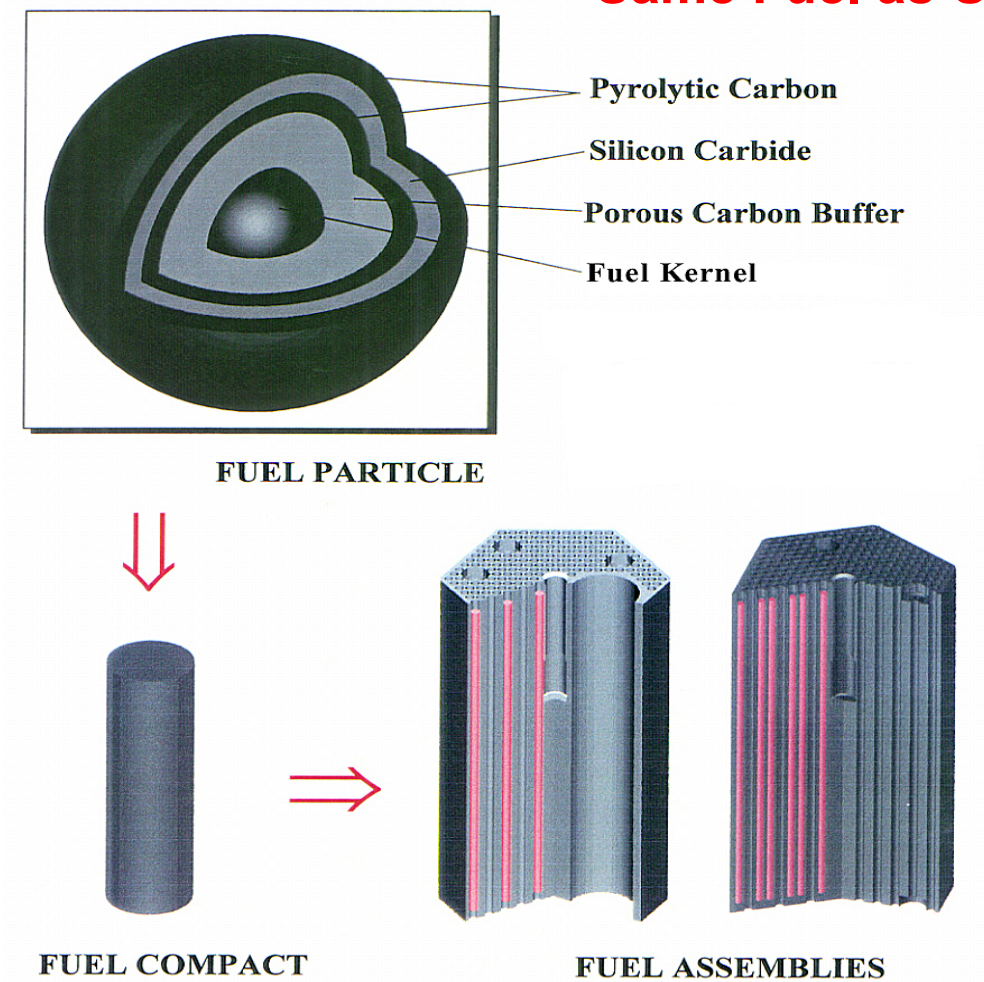

**Efficiency Depends upon Temperature**

- **705ºC: 48.0%**
- **800ºC: 51.5%**

# The AHTR Uses Coated-Particle Fuel Elements

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

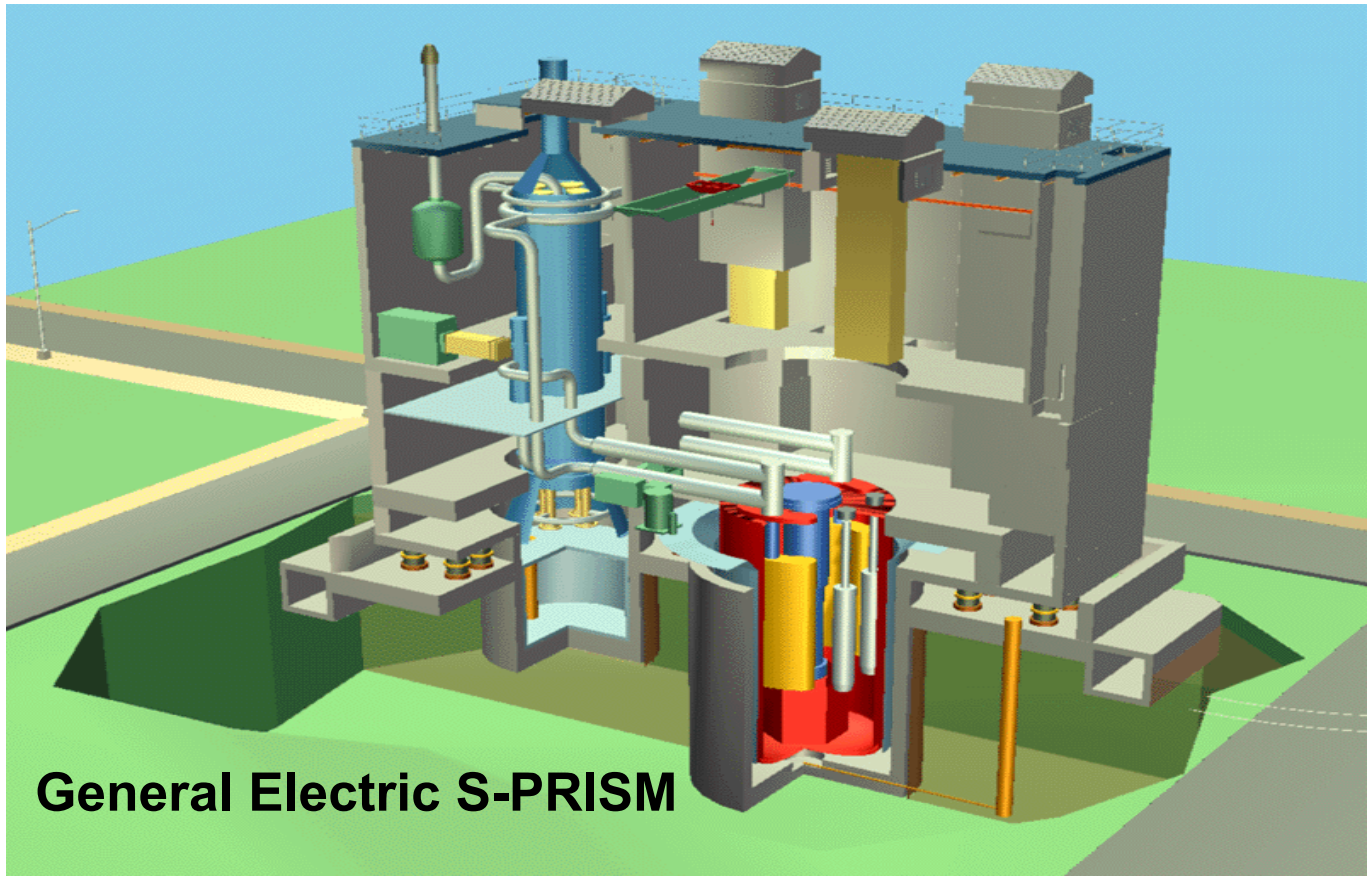
**Same Fuel as Used in Gas-Cooled Reactors**




- 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

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

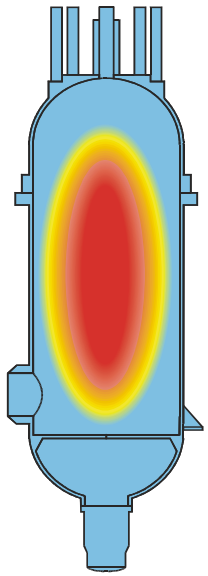
*Low Pressure, High Temperature, Liquid Cooled*



# Liquid Cooling Allows Large Reactors With Passive Decay Heat Removed

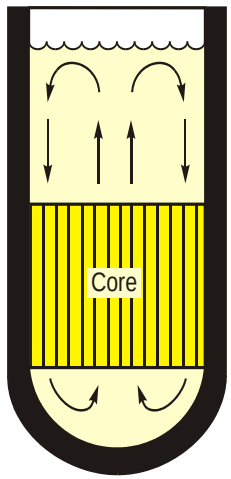
***Alternative Decay Heat Removal Options to Move Heat to Vessel Surface or Heat Exchanger***

**Gas**
**(~600 MW(t))**



Conduction Cooling
(~1000º C Difference
in Fuel Temperature)

**Liquid**
**(1000s of MW(t))**

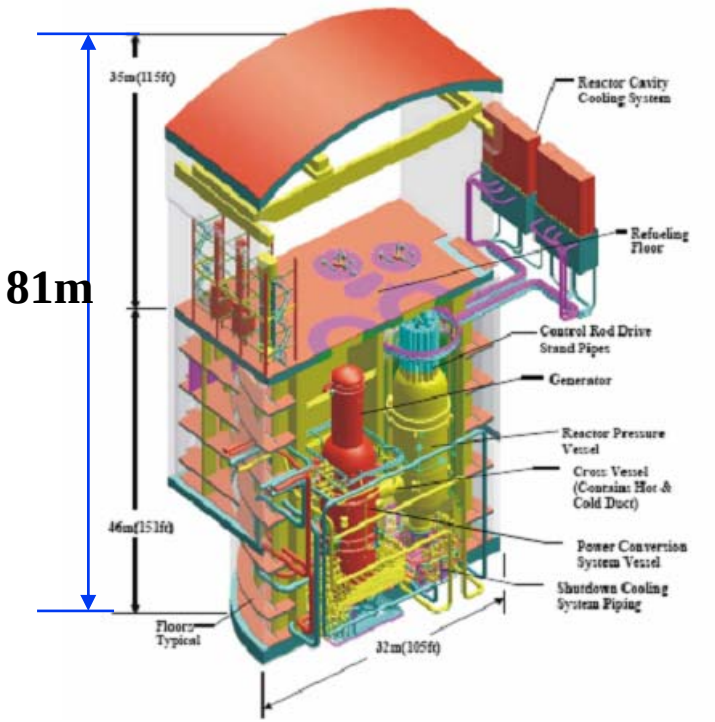


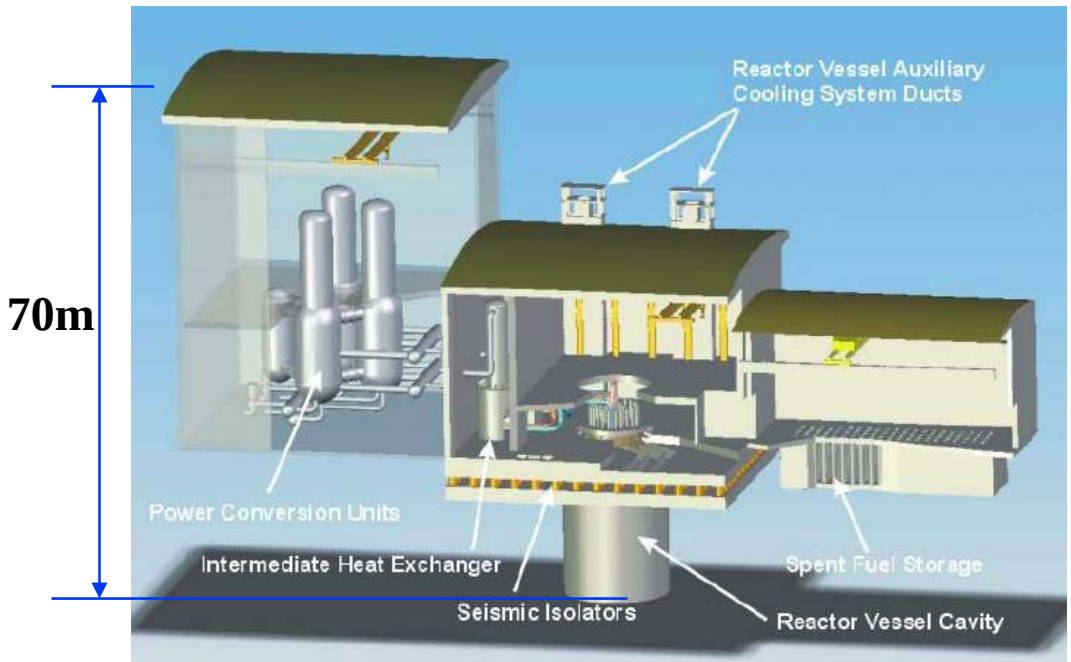

Convective Cooling
(~50º C Difference in
Liquid Temperature)

- **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**

# Salt Cooling Aids Economics

## (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**

# AHTR Status

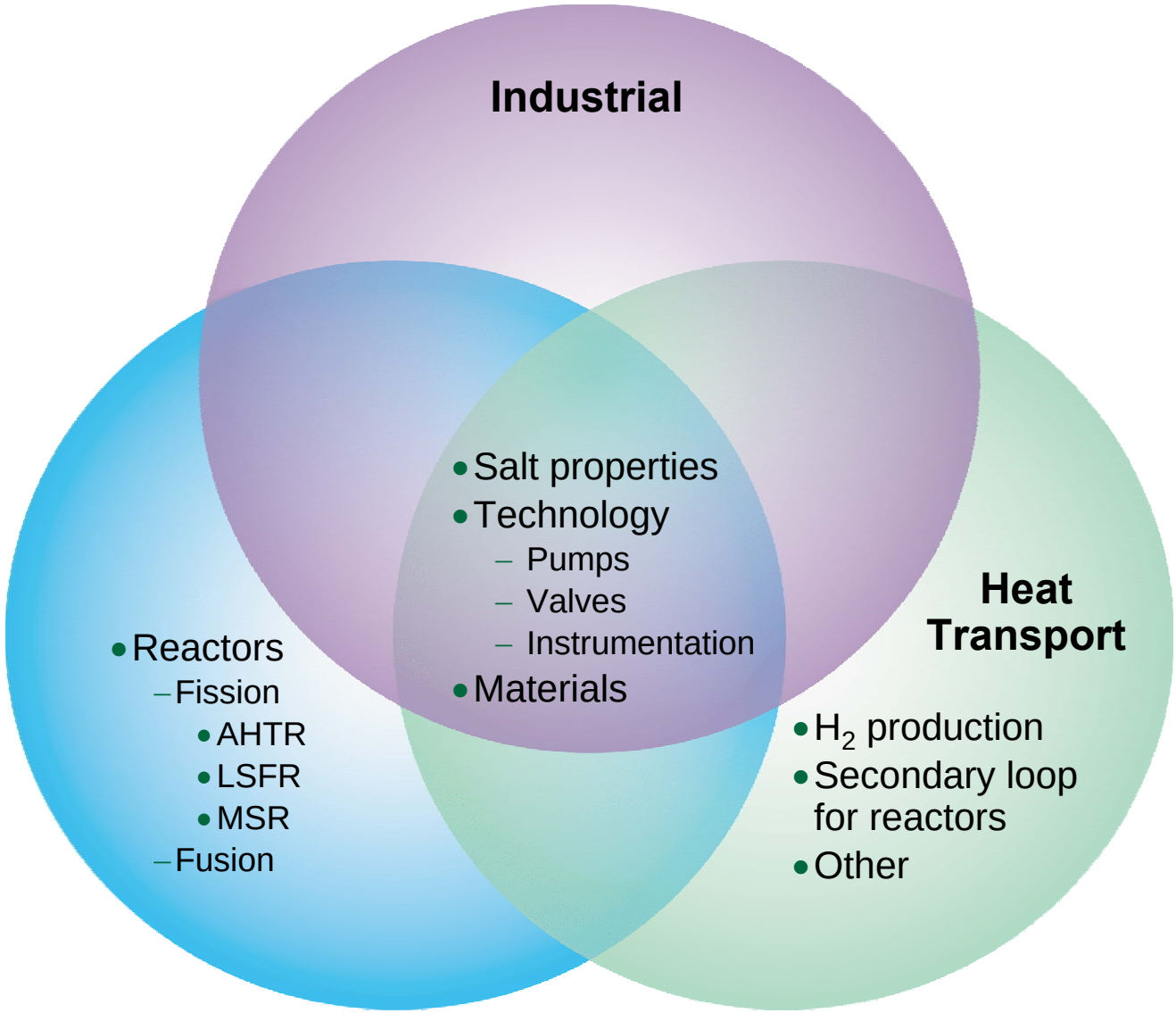
- New concept (4 years) with associated uncertainties
- Vendor interest in the AHTR
  - Potentially superior economics relative to MHTGRs/LWRs
  - Vendor interest in large reactors [1800 MW(e)]
- Accelerating program
- Partners
  - Laboratories: ORNL, INL, SNL, ANL
  - Universities
  - Vendors

# Salt Technology Worldwide

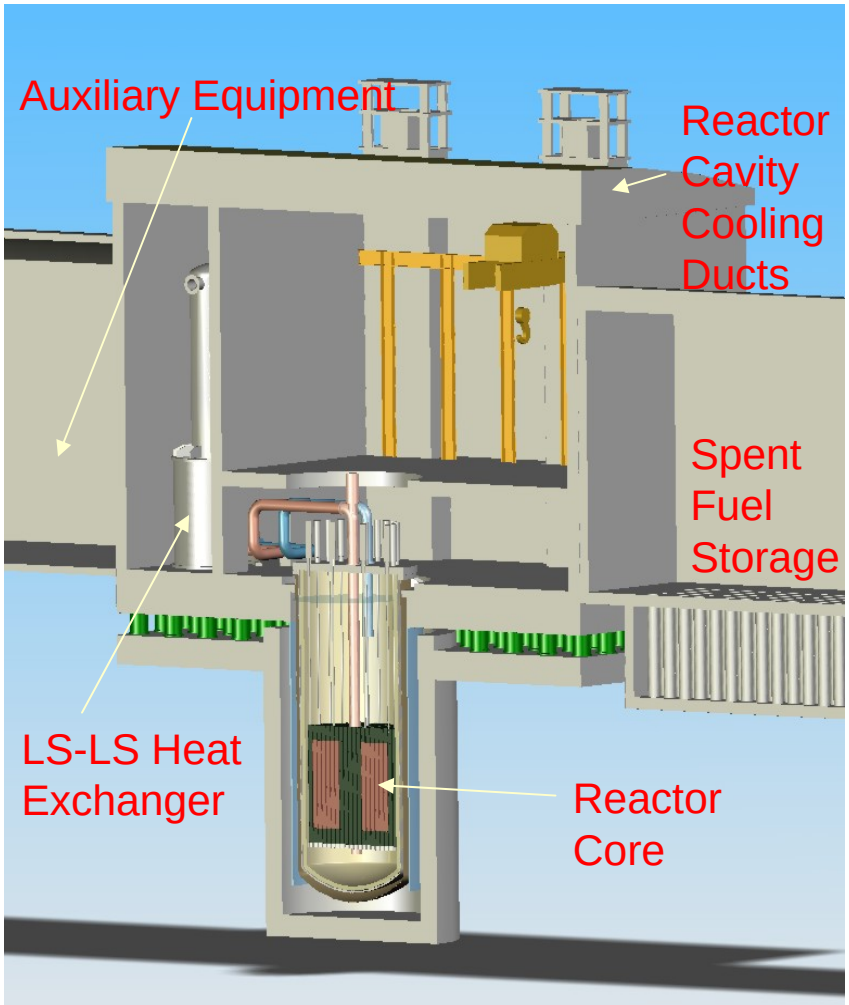
# High-Temperature Salt Technology (>700°C)

- United States
  - GenIV: AHTR and MSR
  - NHI: Hydrogen
  - Industry (Commercial non-nuclear)
- France (MSR and AHTR)
- Czech Republic (MSR)
- Netherlands (Pebble bed AHTR)
- Russia
  - Very small pebble bed small reactor

# Common Salt Research and Development



# Conclusions




- **Incentives for high-temperature reactors**
  - **Brayton power cycles**
  - **$H_2$ production**
  - **Dry cooling**
- **AHTR – The near term reactor option**
- **NHI – Heat transport to hydrogen plants**
- **Commercial non-nuclear applications**
- **Growing foreign programs**

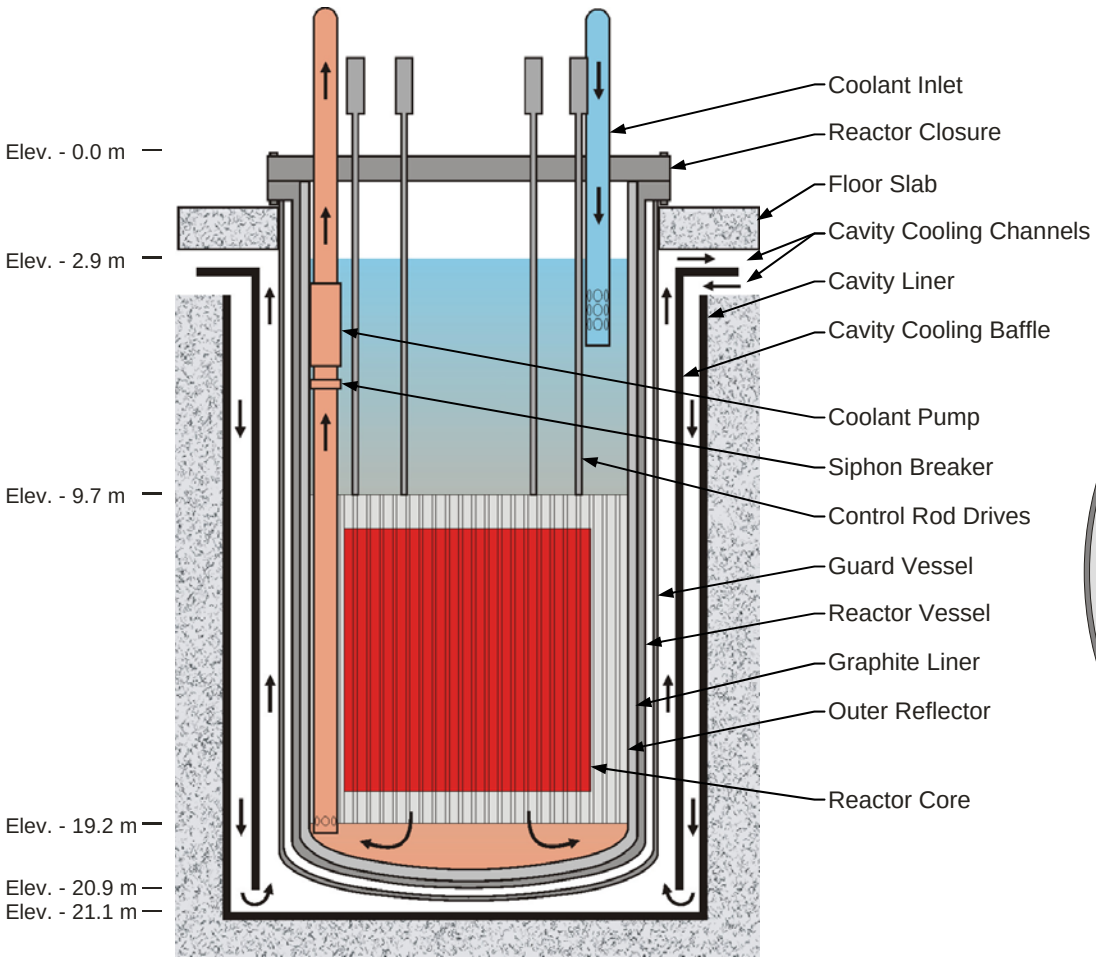
# End

# End

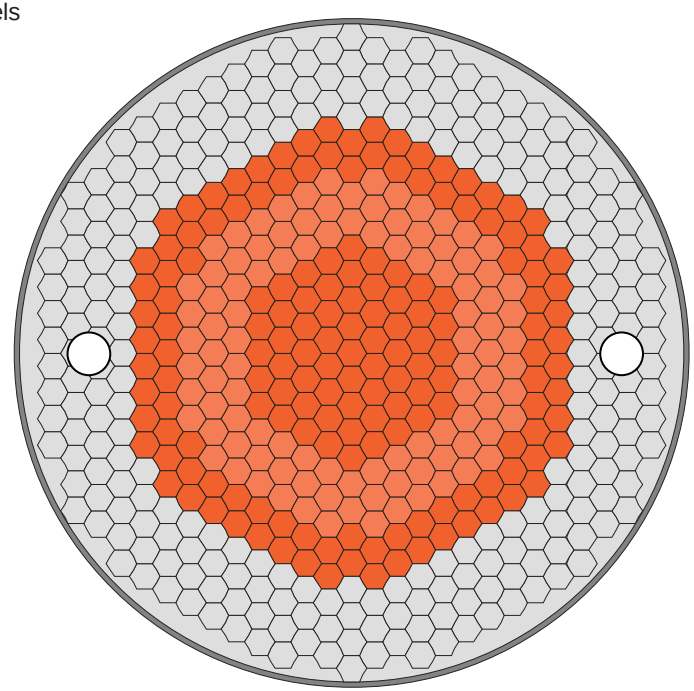
# End

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

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

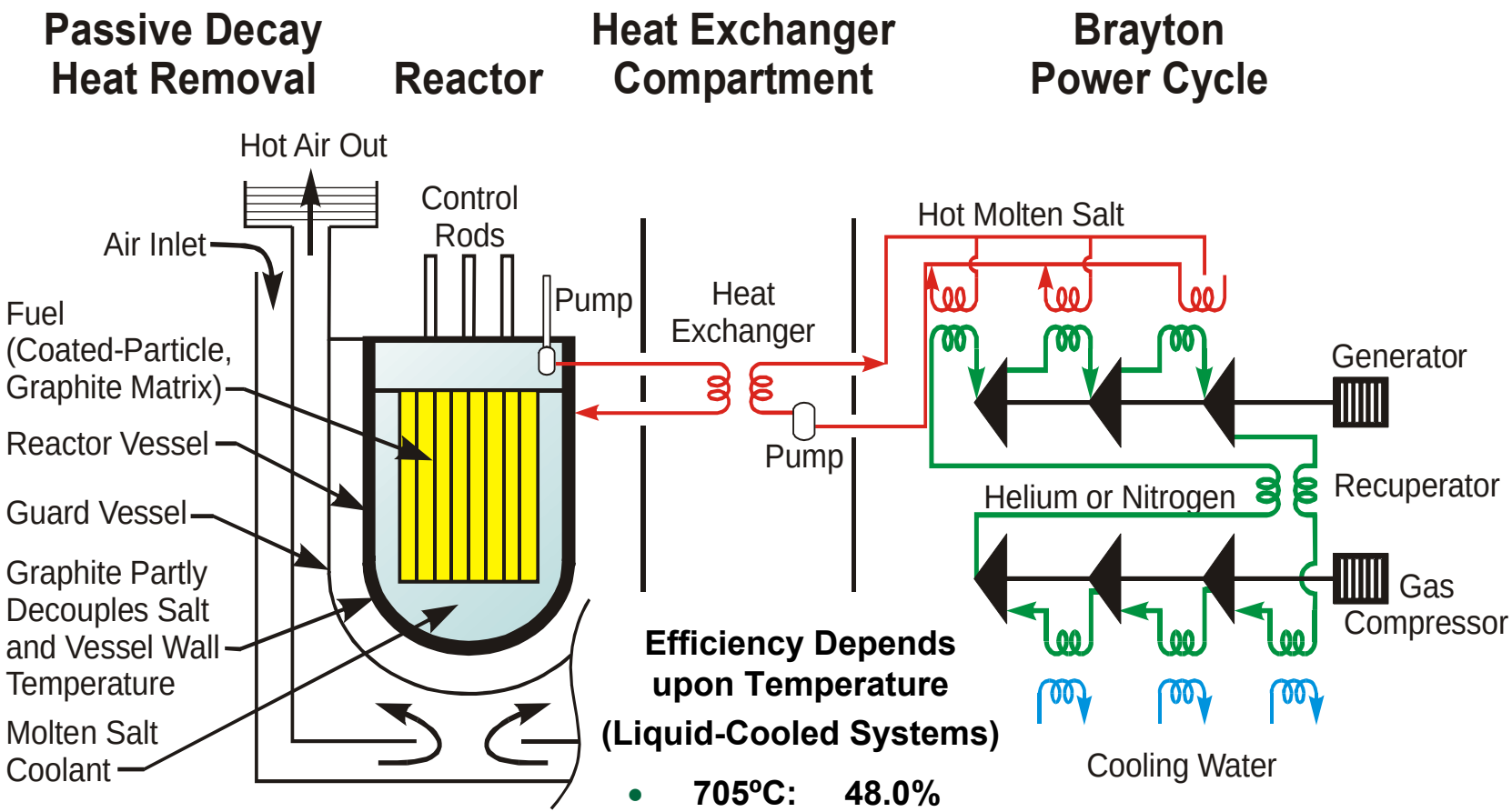



102 GT-MHR fuel columns
163 Additional fuel columns
265 Total fuel columns



Power density = 10.0 MW/m$^3$

# *Multi-Reheat* Brayton Cycles Enable the Efficient Use of High-Temperature Heat

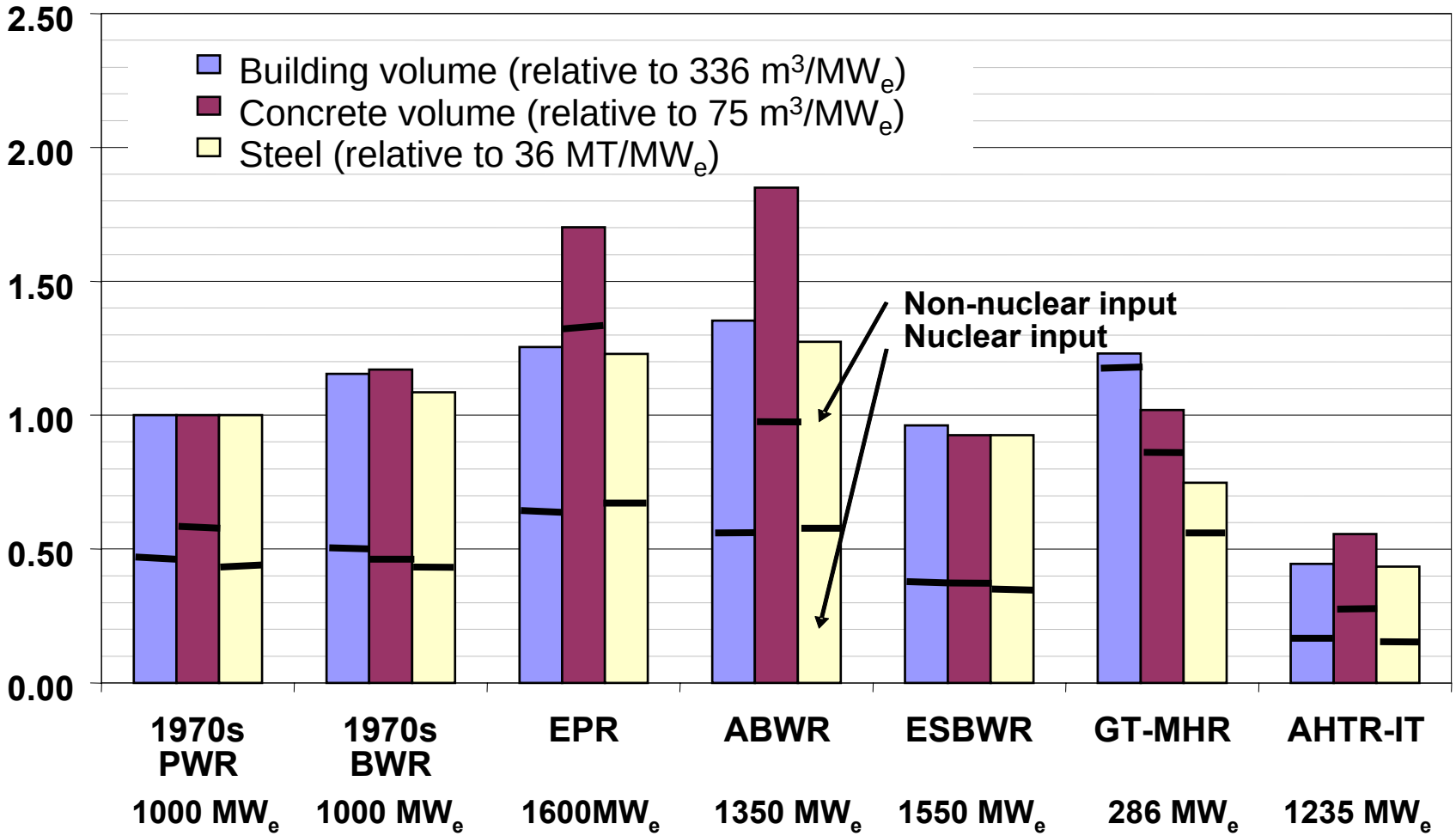



**Efficiency Depends upon Temperature (Liquid-Cooled Systems)**

- **705ºC: 48.0%**
- **800ºC: 51.5%**
- **1000ºC: 56.6%**

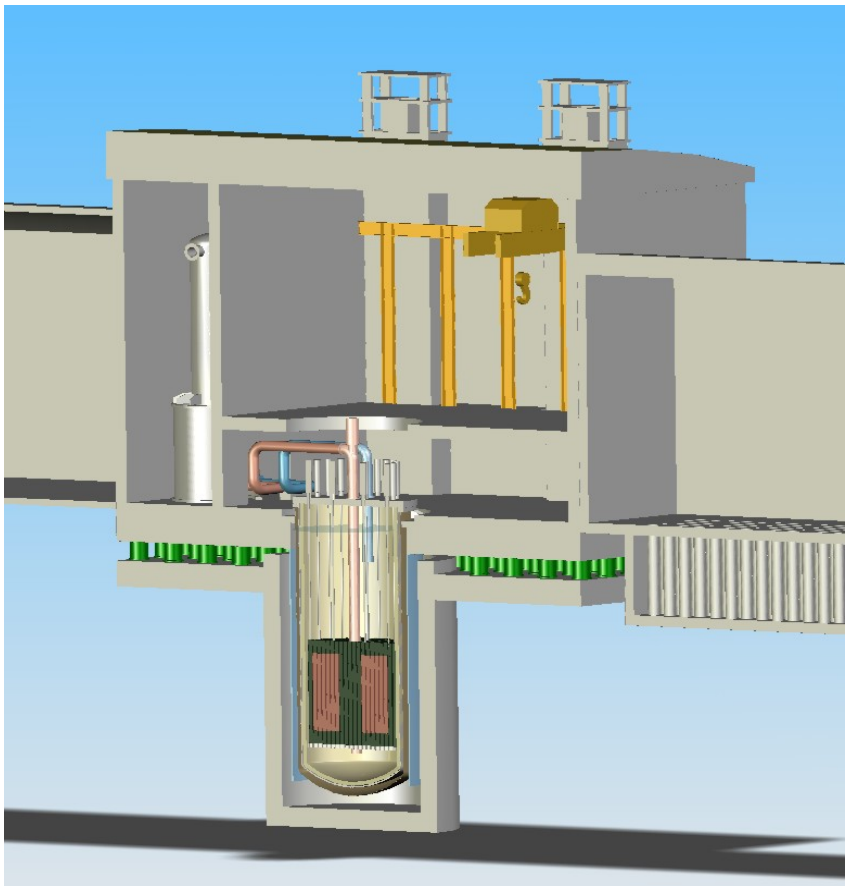
# Reactor Economics: Comparison of Building, Concrete, and Steel Consumption

## (Based on Arrangement Drawings)




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

# 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