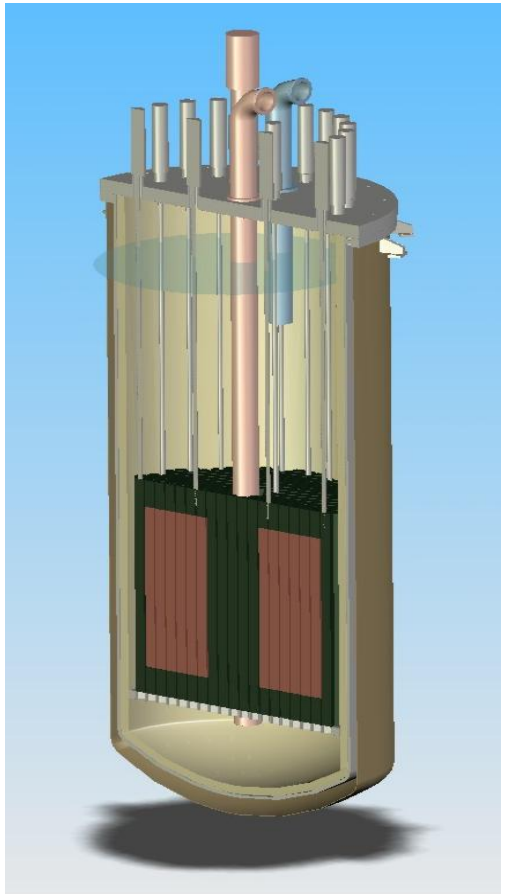
Sustainability, Water, Dry Cooling, and the Advanced High-Temperature Reactor



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November 15, 2004

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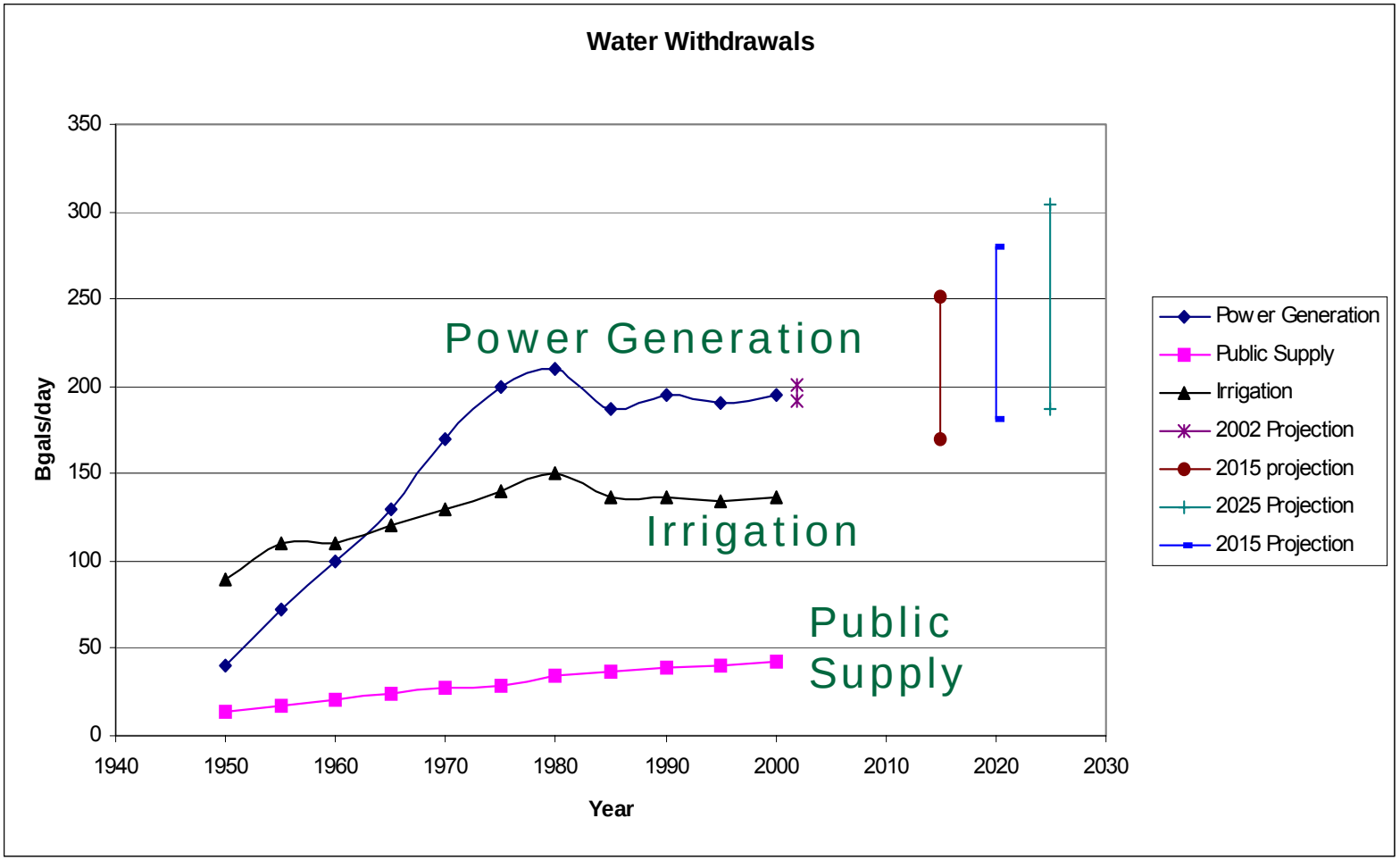
OAK RIDGE NATIONAL LABORATORY

UC Berkeley NUCLEAR ENGINEERING

Power Generation is the Largest User of Water in the United States



Nuclear Power Plant Heat Rejection is a Key Issue for Future Plants

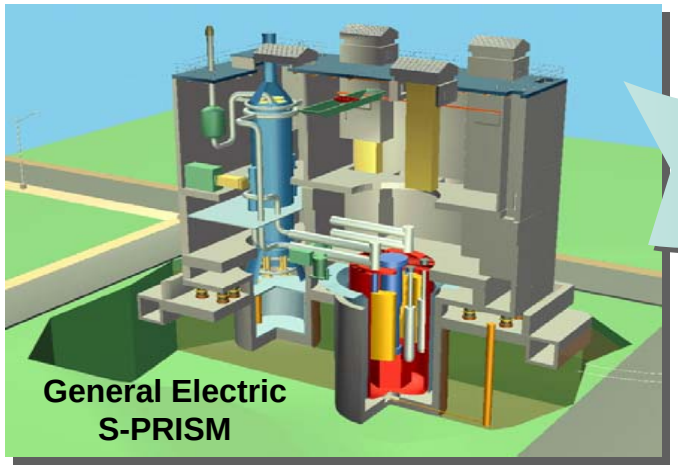
- **Growing national water shortages**
- **Nuclear power plant siting is limited by availability of water**
  - **Where there is water, there are people**
  - **The ideal nuclear power plant site has no neighbors but is close to large cities**
  - **Example: ideal west-coast nuclear sites are just east of the coastal mountains in the desert**
- **Eliminating water for cooling would greatly benefit nuclear energy**

The Advanced High-Temperature Reactor

Designed to Maximize Efficiency and Minimize Dry Cooling Costs

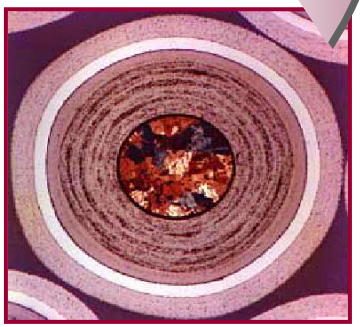
The Advanced High-Temperature Reactor

Combining Existing Technologies in a New Way



Passively Safe Pool-Type Reactor Designs

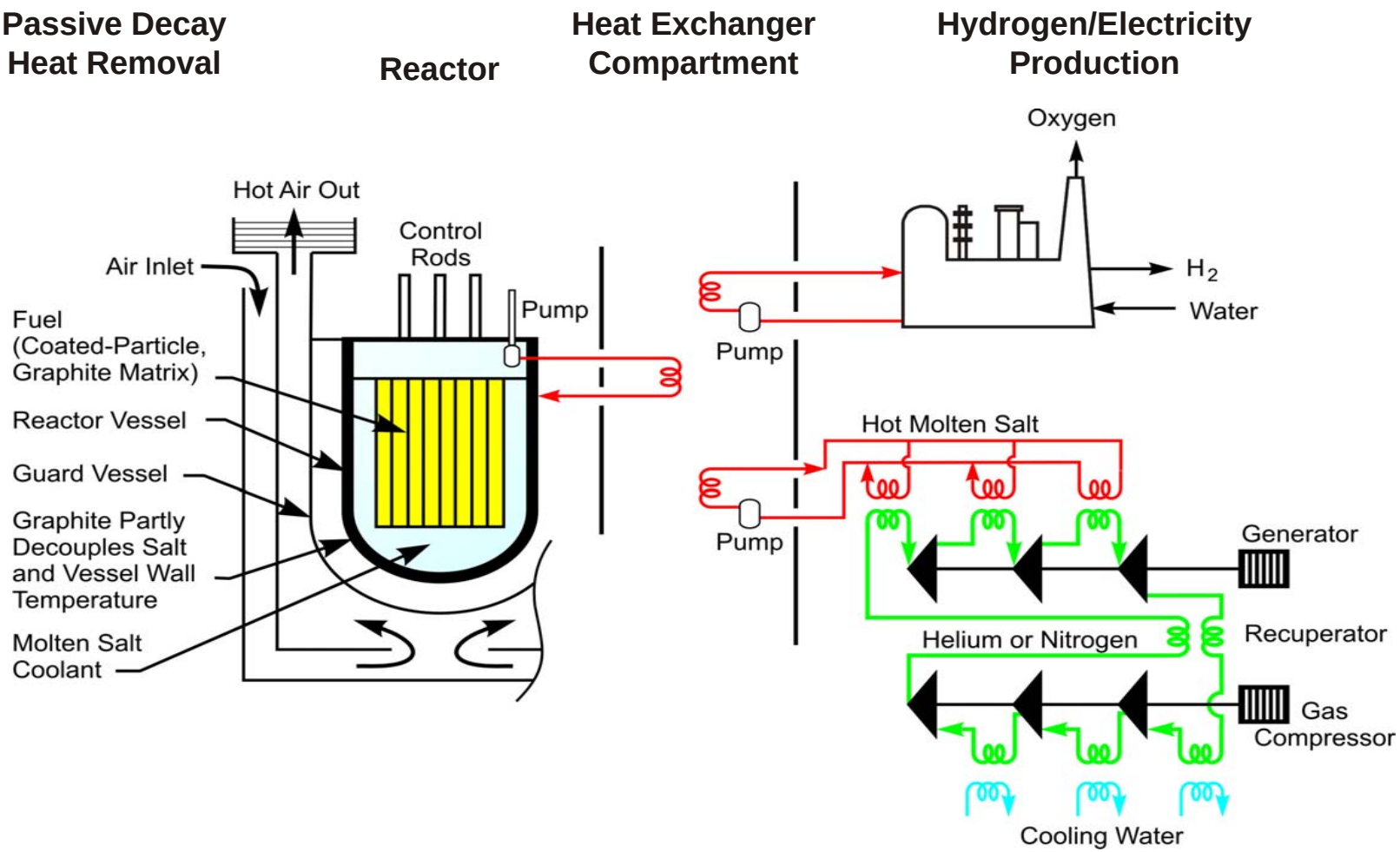
Brayton Power Cycles



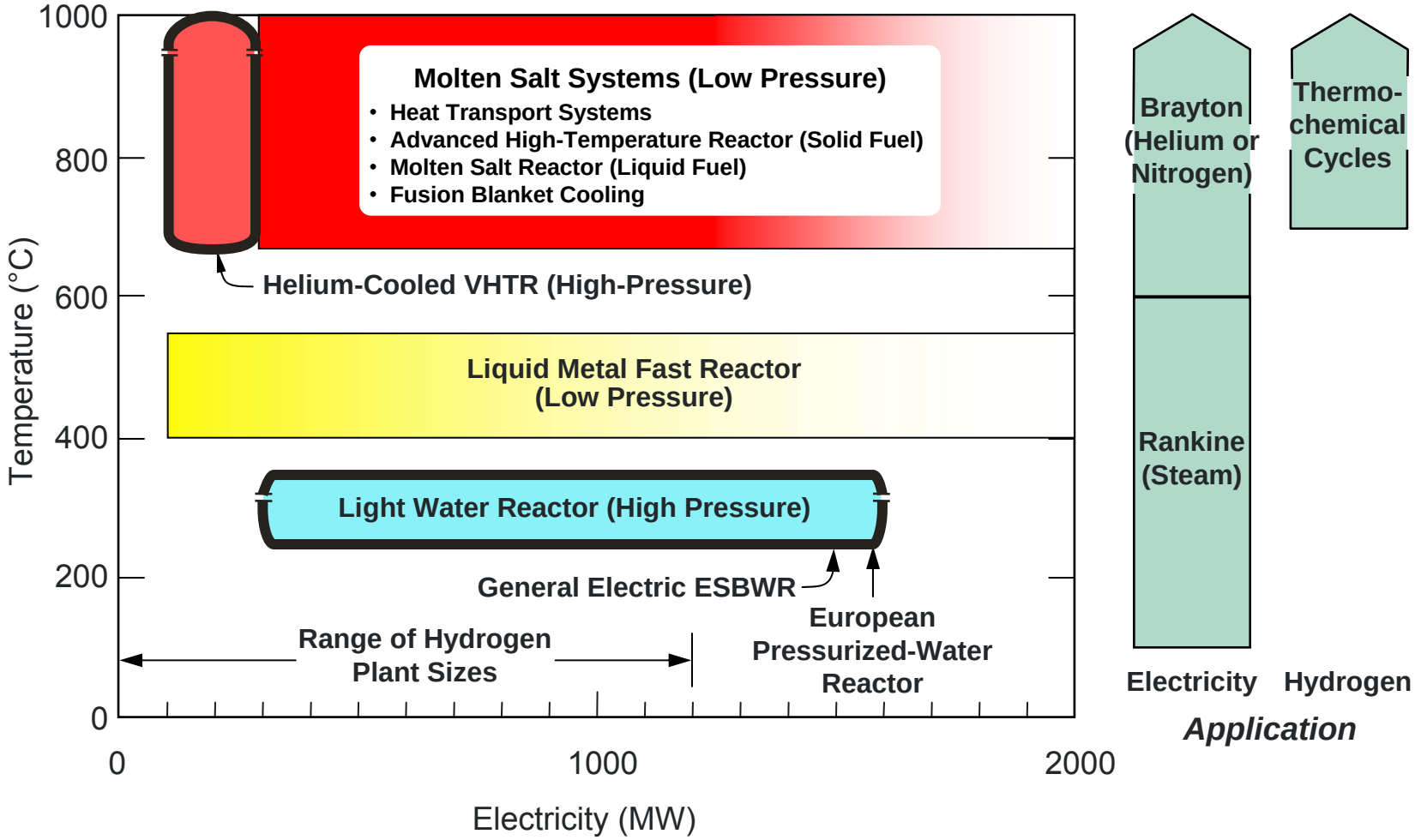
High-Temperature Coated-Particle Fuel

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

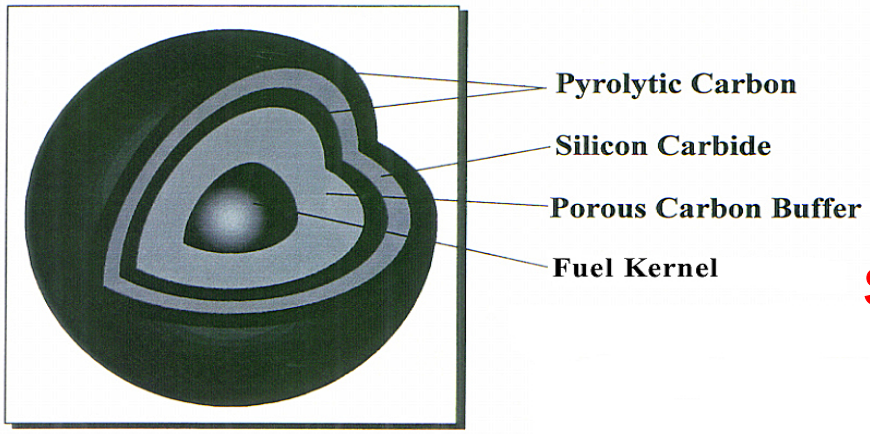
Advanced High-Temperature Reactor



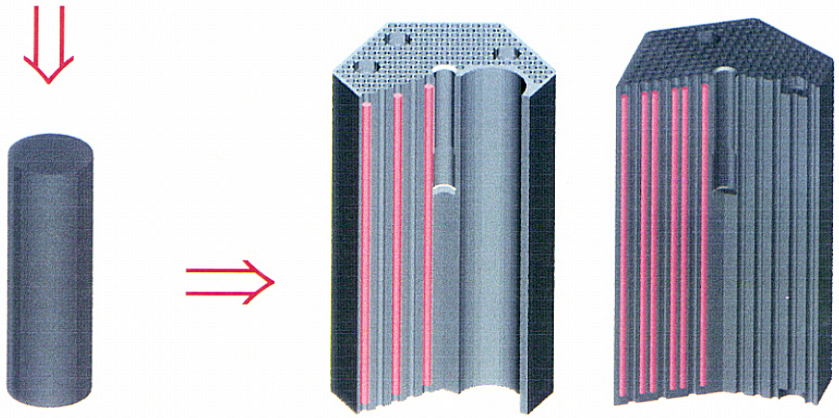
The AHTR is a Large High-Temperature Reactor



The AHTR Uses Coated-Particle Graphite-Matrix Fuel Elements



FUEL PARTICLE

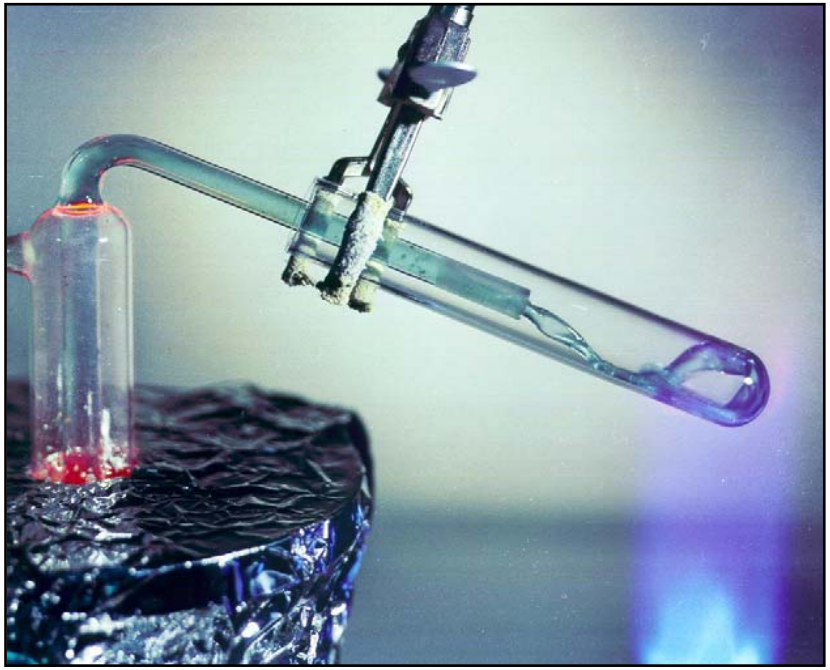


FUEL COMPACT

FUEL ASSEMBLIES

Same Fuel as Used by High-Temperature Gas-Cooled Reactors

Two Coolants are Compatible with Graphite Materials and High-Temperature Operations



Helium

(High Pressure/Transparent)

Molten Fluoride Salts

(Low Pressure/Transparent)

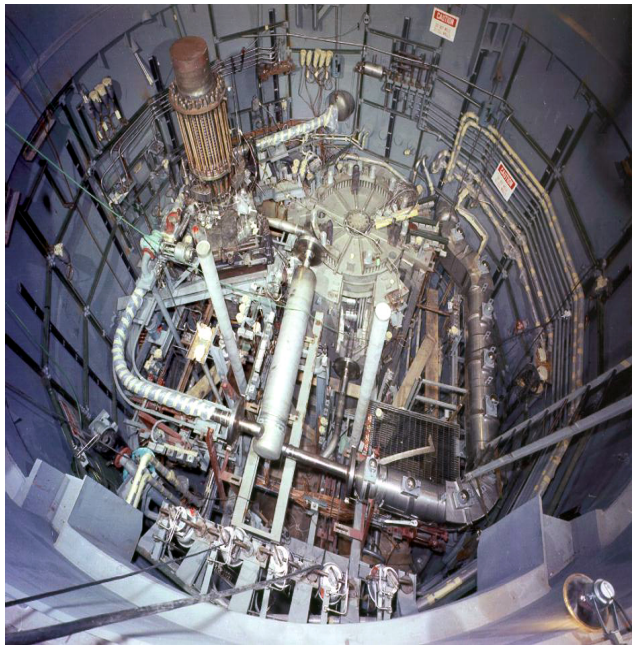
Molten-Fluoride Salts have been Used in Industrial and Nuclear Applications

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.

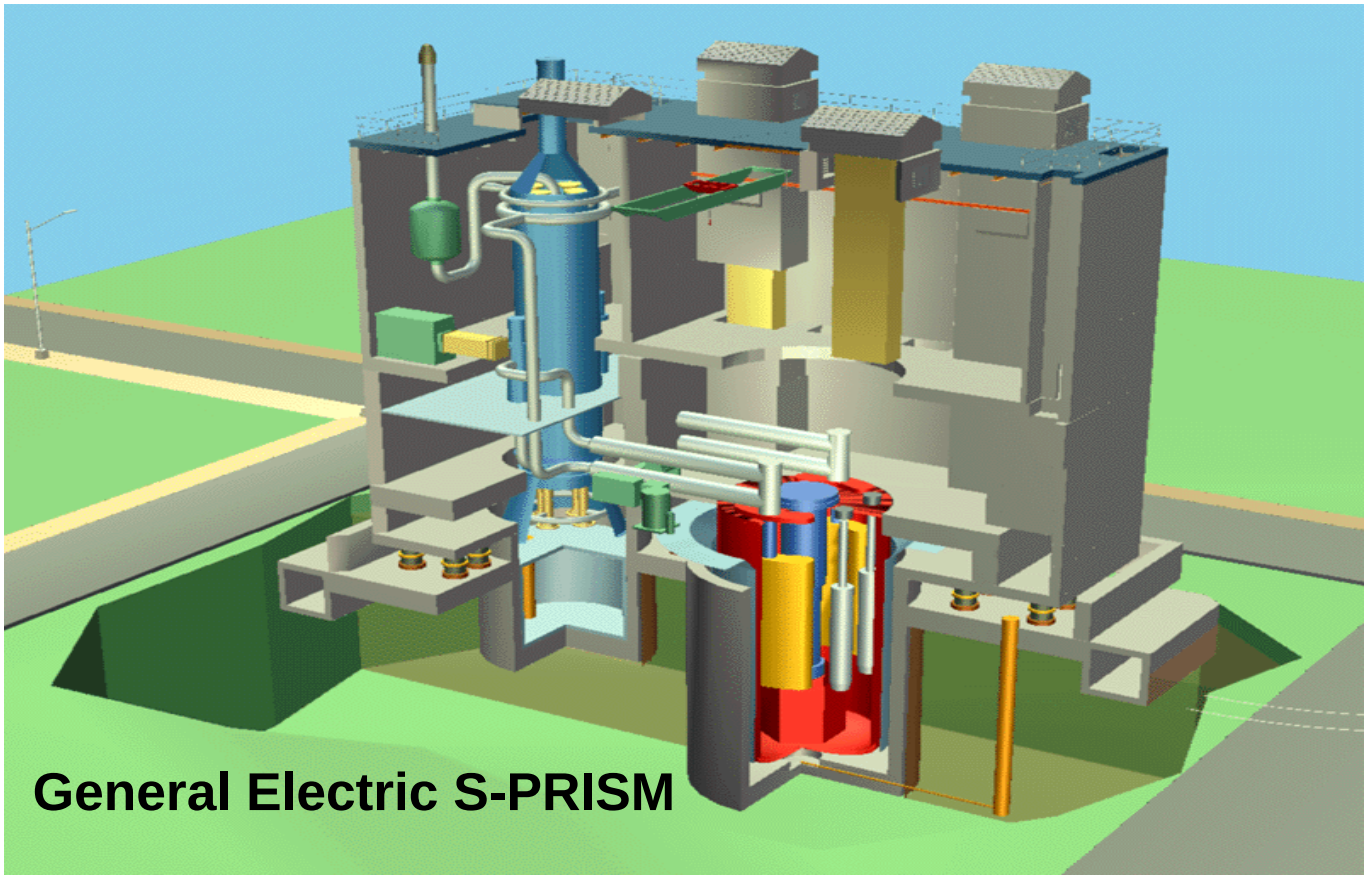
Molten Fluoride Salts Are Used to Make Aluminum in Graphite Baths at 1000°C

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

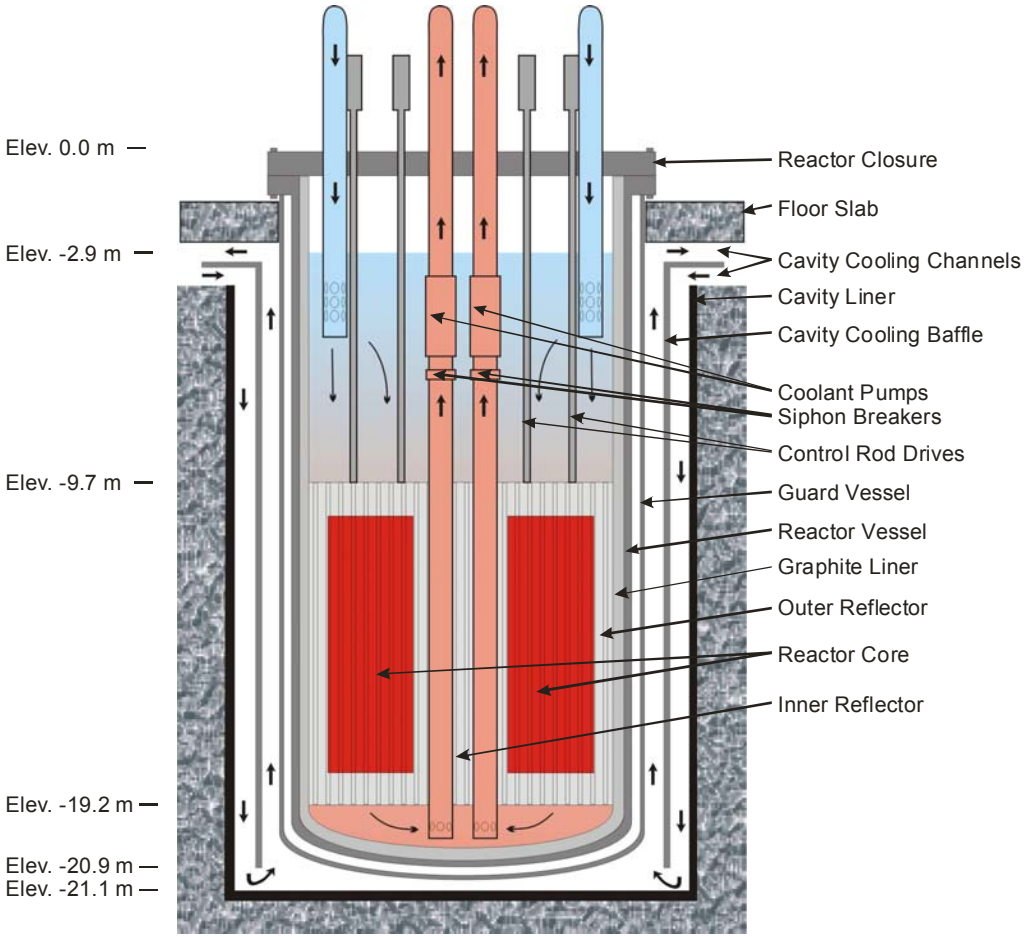


AHTR Facility Layouts are Based on Sodium-Cooled Fast Reactors

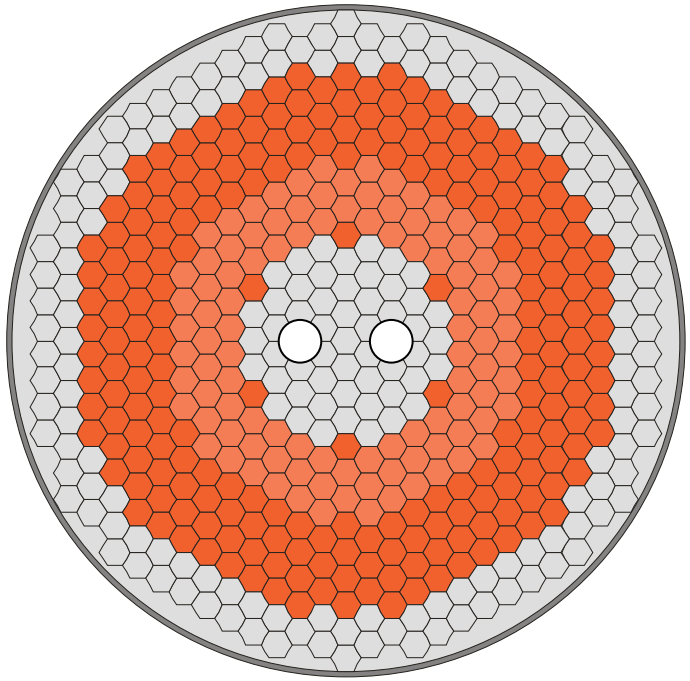
Low Pressure, High Temperature, Liquid Cooled



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



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

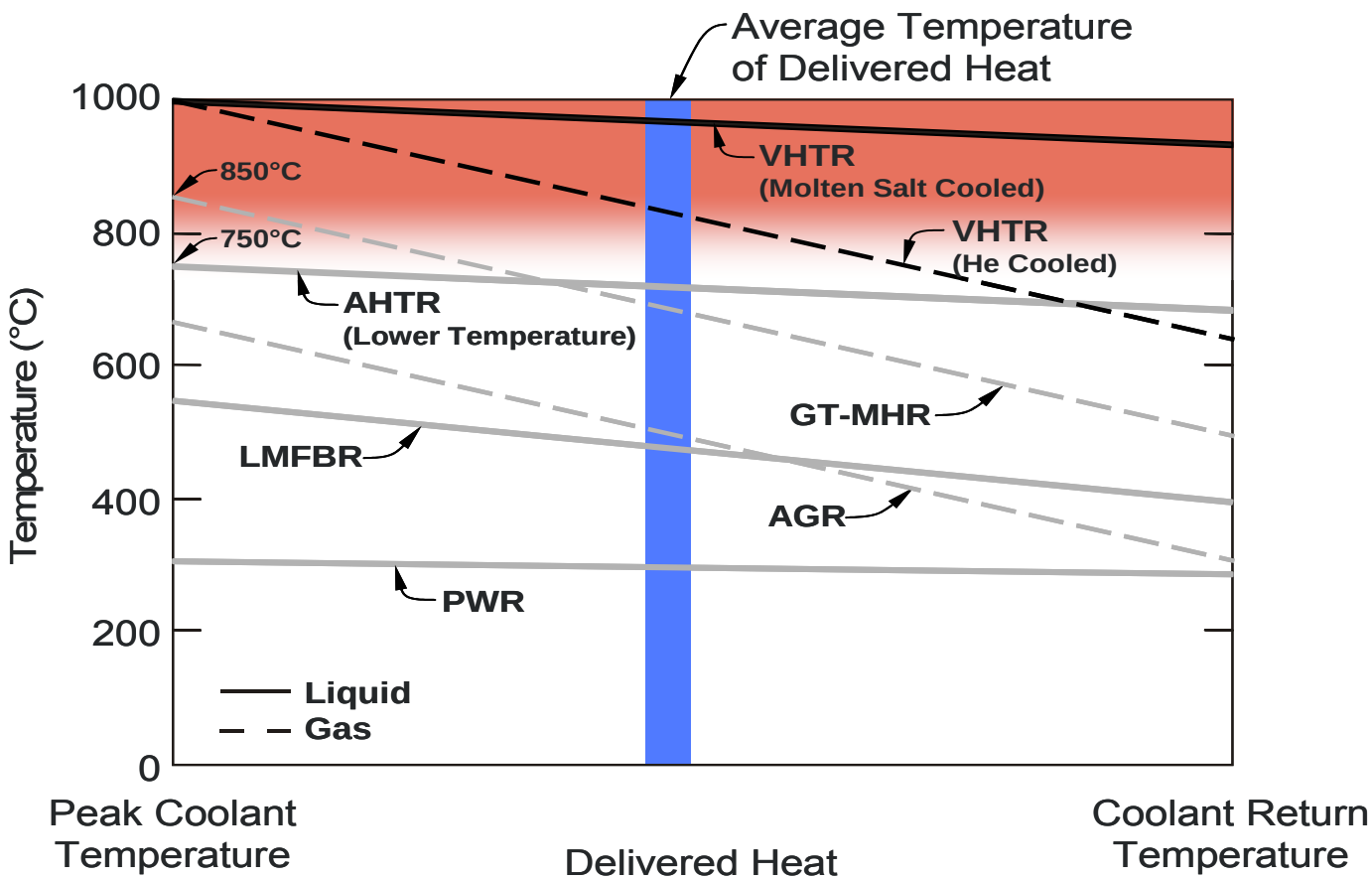


Power density = 8.3 MW/m^3
(26% larger than 600-MW GT-MHR)

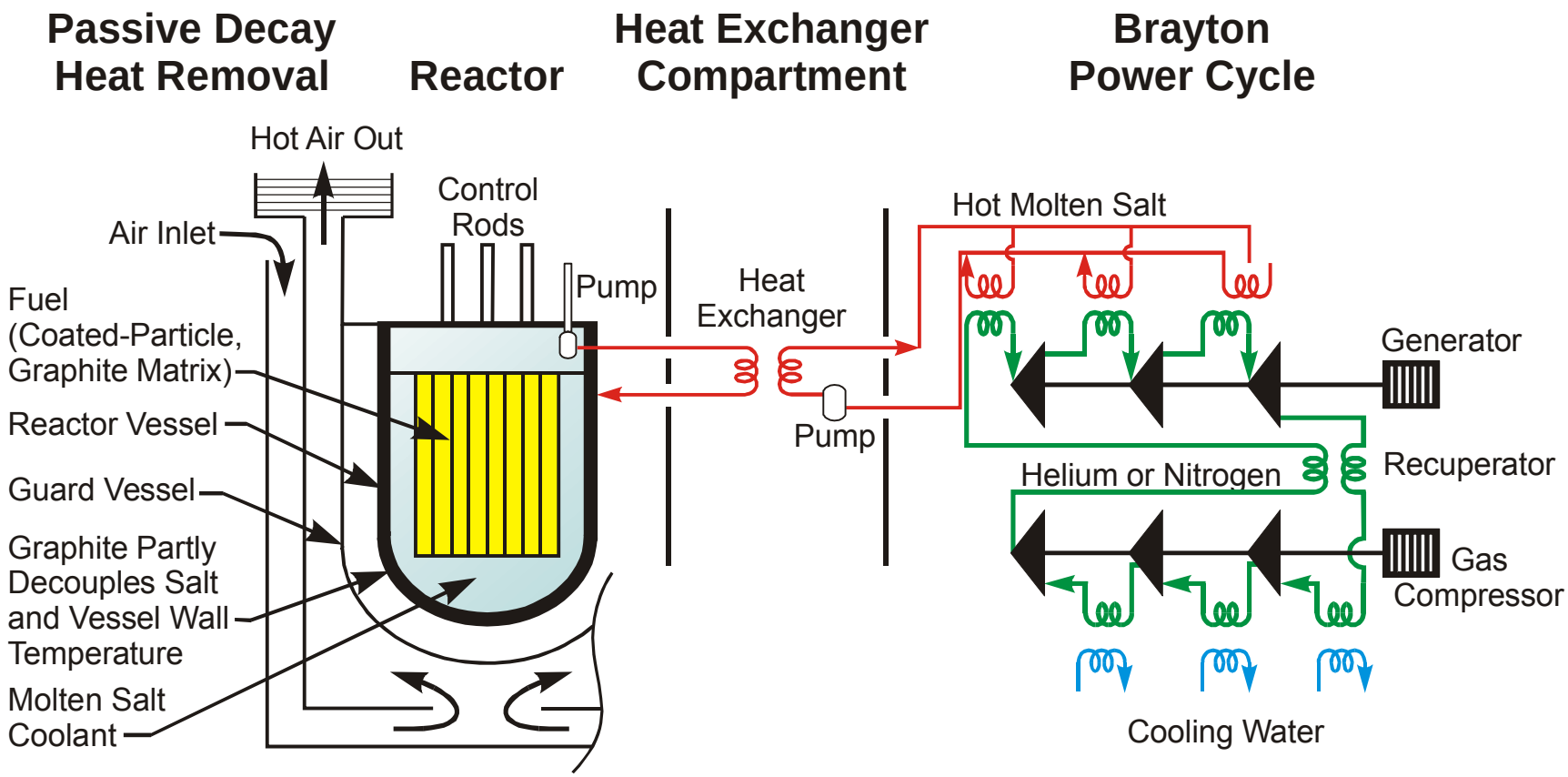
Power Cycles and Dry Cooling

Liquid Cooling Maximizes High-Temperature Heat to the Power Cycle

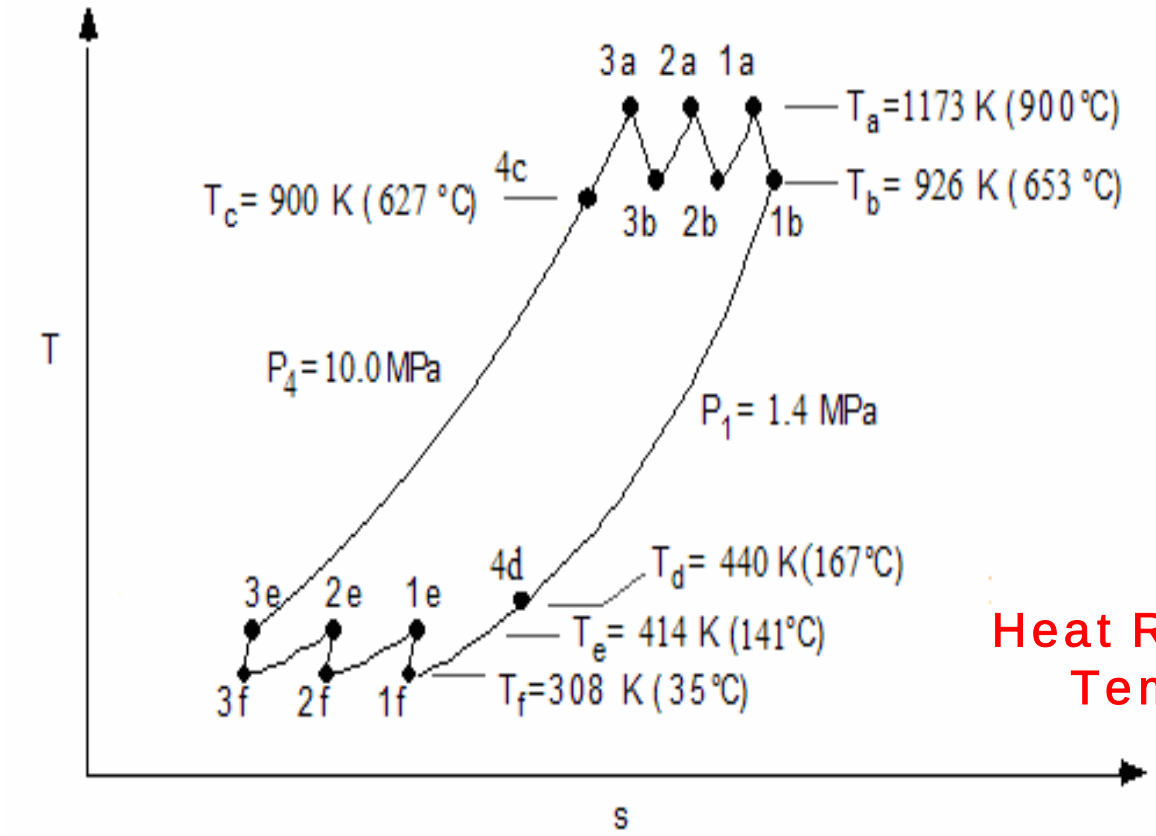
(4 to 8% More Efficient than Gas-cooling for the Same Peak Temperature)



A *Multi-Reheat* Brayton Cycle Efficiently Uses the High-Temperature Heat



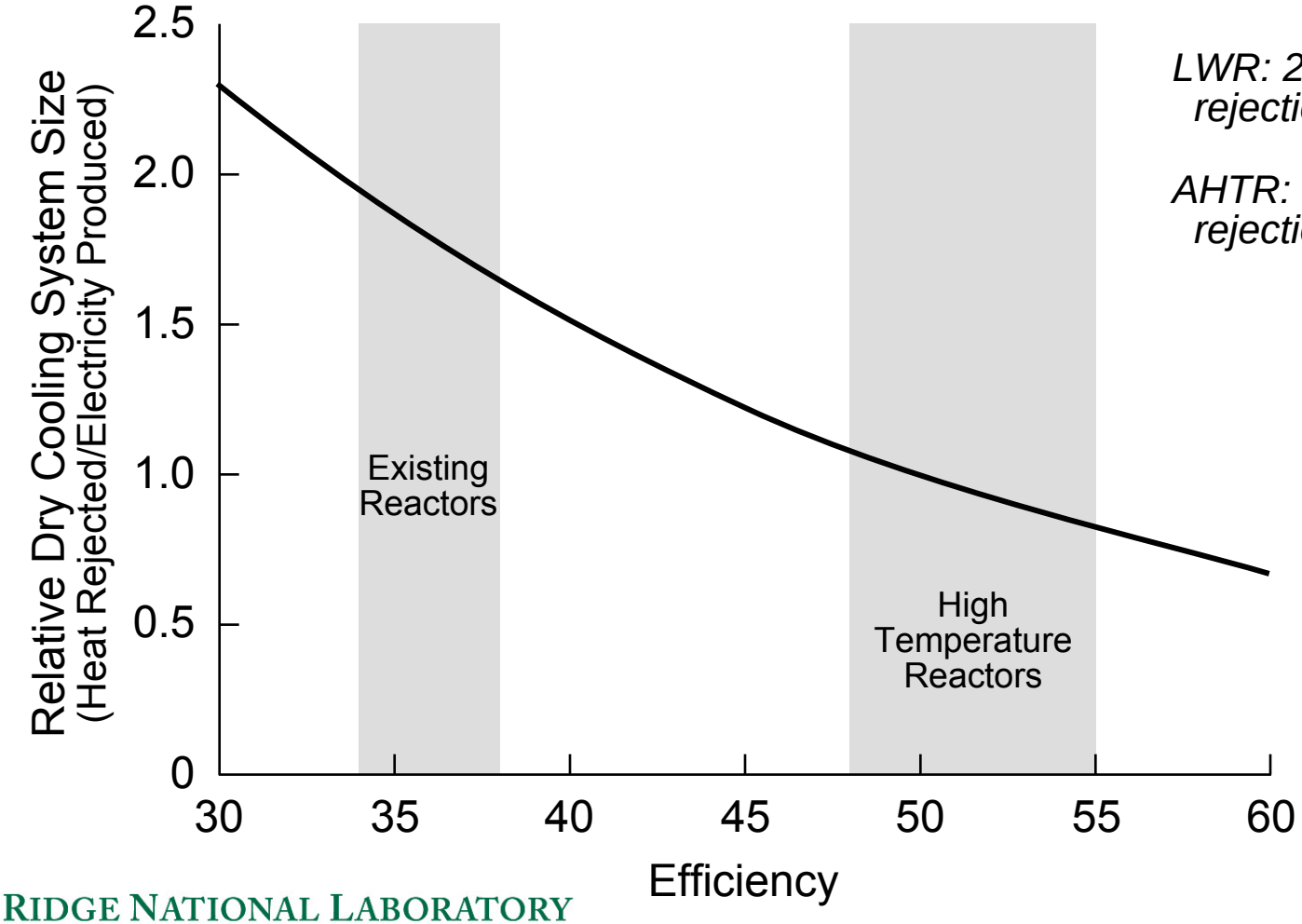
Liquid-Cooled Multi-Heat Brayton Cycles Approach Ideal Carnot Cycles



Heat Inputted Over Small Temperature Range

Heat Rejected Over Small Temperature Range

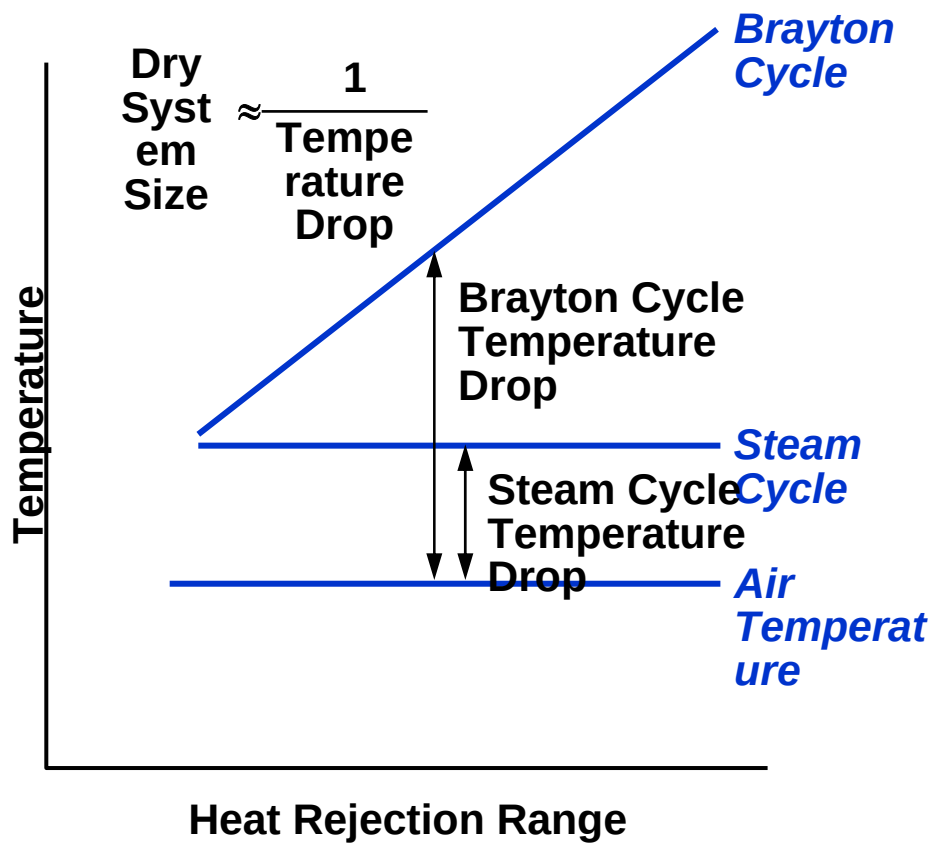
AHTR Reduces Dry-Cooling System Costs by Reducing Heat Rejection



LWR: 2 kW(t) heat rejection per kW(e)

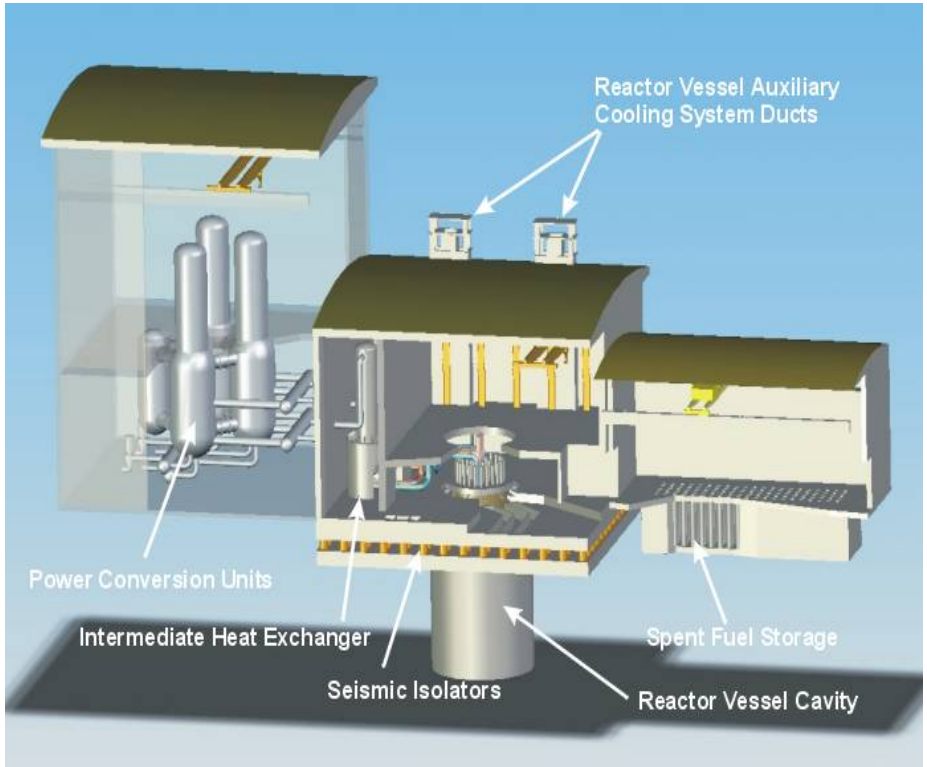
AHTR: 1 kW(t) heat rejection per kW(e)

Brayton Cycles Match Dry Cooling Characteristics and Requirements



- **Wet Cooling**
  - Wet cooling towers evaporate water at ~constant temperatures
  - Matches steam cycle that rejects heat at a constant temperature
- **Dry Cooling**
  - Dry cooling towers heat air over a temperature range
  - Brayton power cycles reject heat over a temperature range

The AHTR may Enable the Use of Economical Dry Cooling Systems

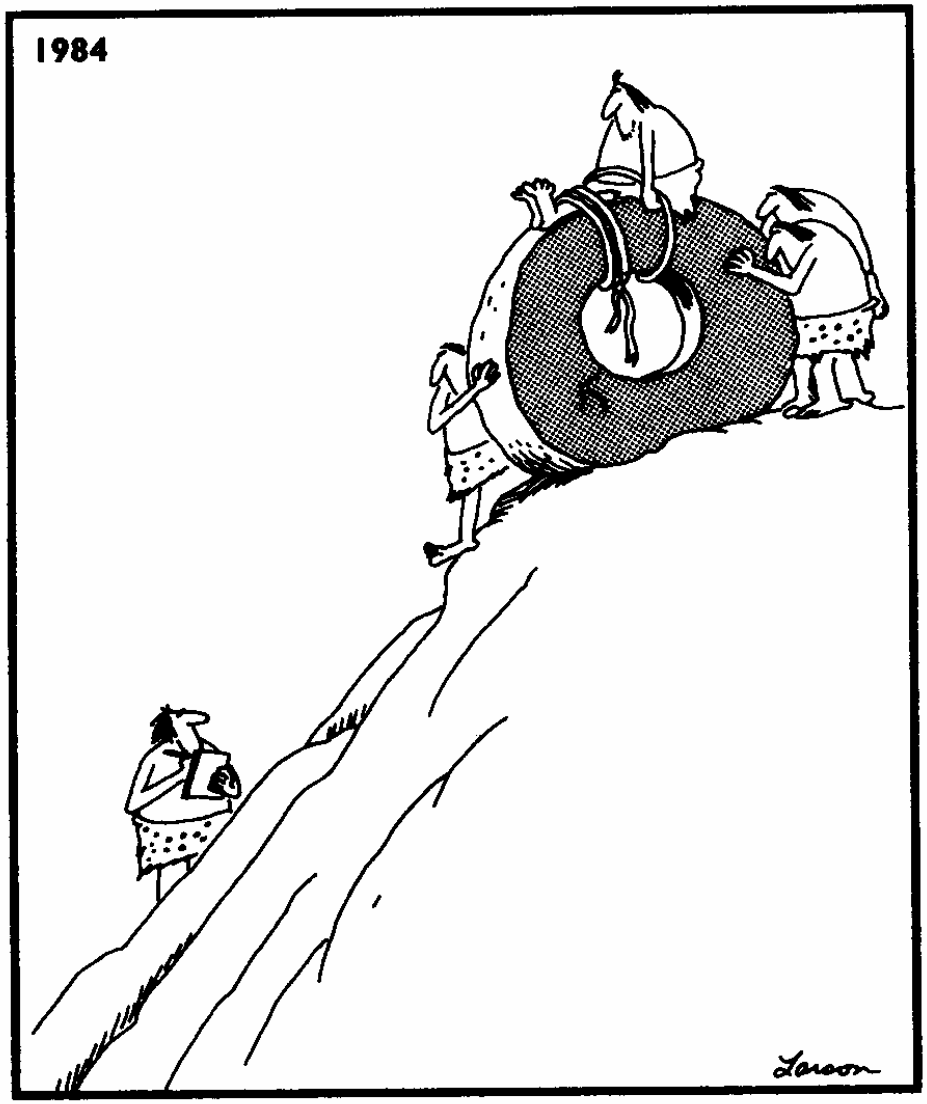


- **Dry cooling costs reduced**
  - **Half the heat rejection per unit of electricity produced compared to an LWR**
  - **Heat rejected over a temperature range to match dry cooling tower requirements**
- **Dry cooling has major beneficial impacts**
  - **Freedom in siting nuclear power plants**
  - **No competition for water**

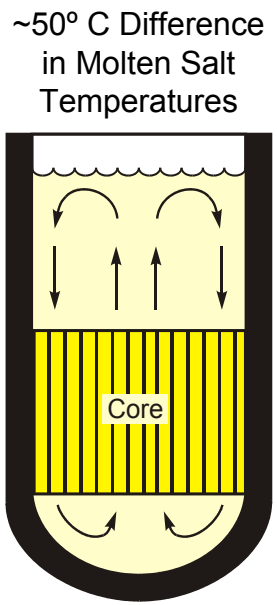
Backup
Backup
Backup

The AHTR:

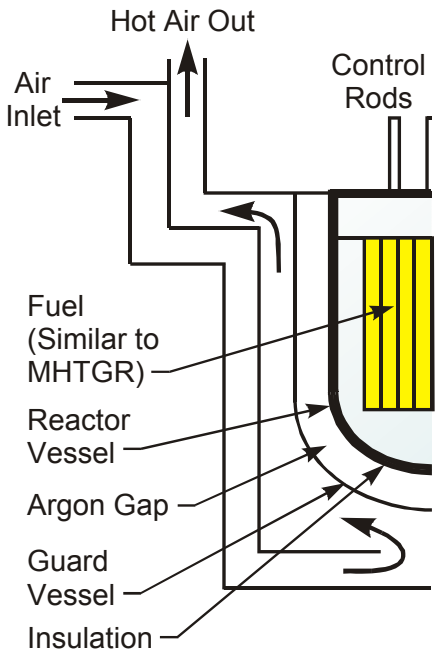
A good idea that still needs some work



Shutdown Decay Heat is Transferred to the Reactor Vessel and Then to the Environment



Decay Heat from Core to Vessel Liner

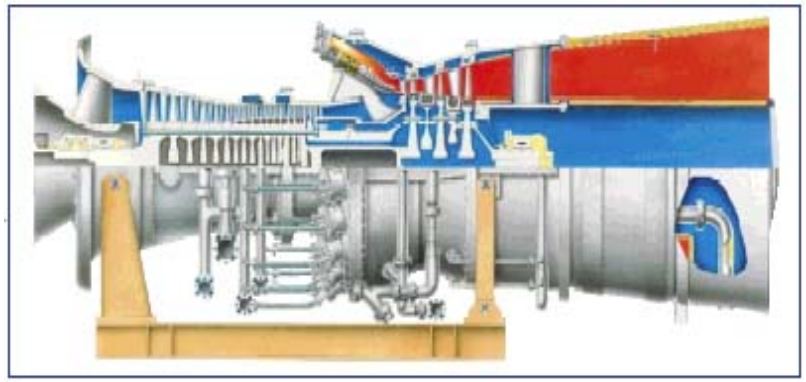


Decay Heat from Vessel to Environment

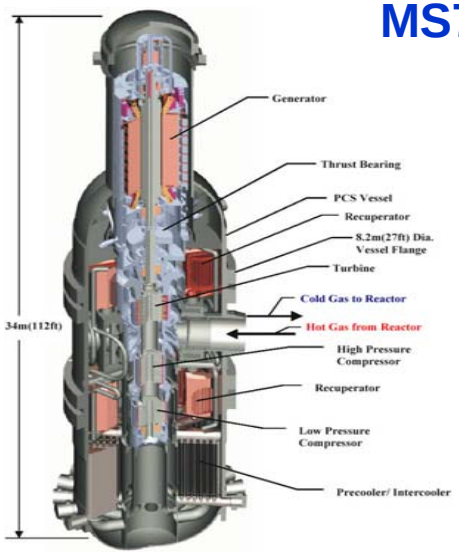
- Similar to GE S-PRISM (LMR)
- Liquid transfers heat from fuel to wall with small temperature drop (~50ºC)
- Argon gap: Reactor to guard vessel
  - Heat transfer: ~T^4
  - Thermal switch mechanism
- Heat rejection: Vessel temperature dependent
  - LMR: 500-550ºC [~1000 MW(t)]
  - AHTR: 750ºC [~2400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

Closed Nitrogen or Helium Brayton Cycle for Electricity Production

- **Same turbine technology as existing natural-gas-fired turbines (but closed cycle, not open cycle)**
  - **Lower temperatures than current commercial units**
  - **For 2400 MW(t) AHTR**
    - **1145 MW(e) if peak molten salt temperature 800ºC**
    - **1300 MW(e) if peak molten salt temperature 1000ºC**
- **Choice of horizontal or vertical (GT-MHR) systems**
- **Helium Brayton Cycle is a longer term option**

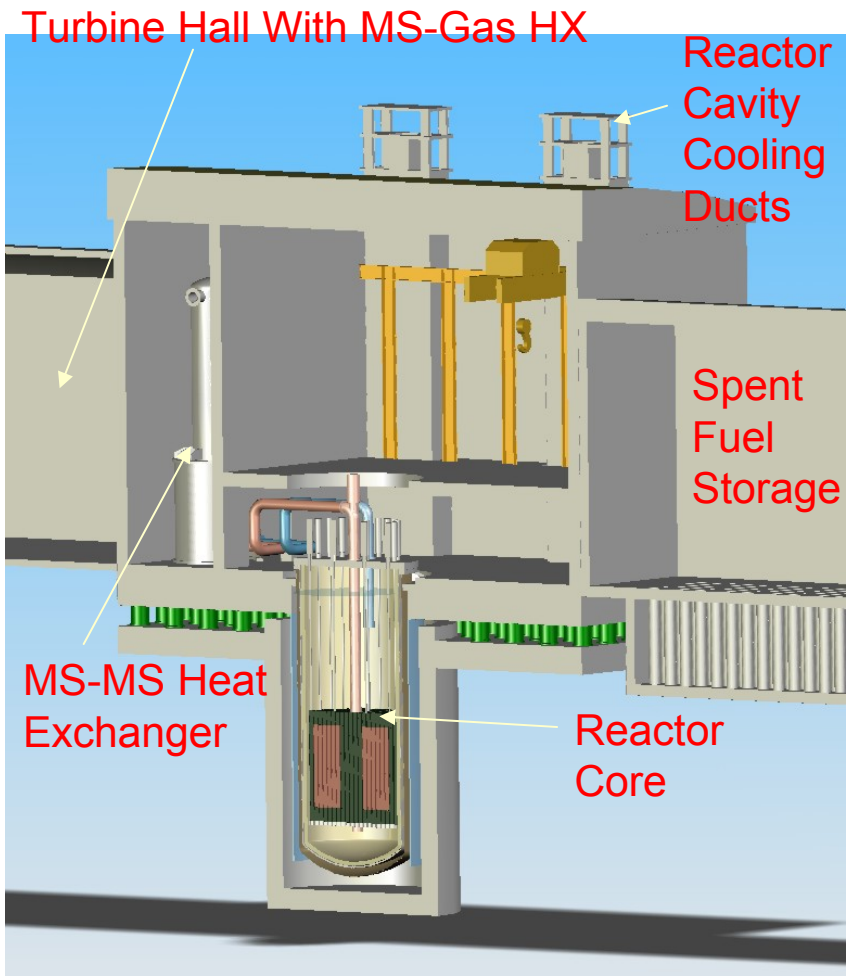


GE Power Systems MS7001FB



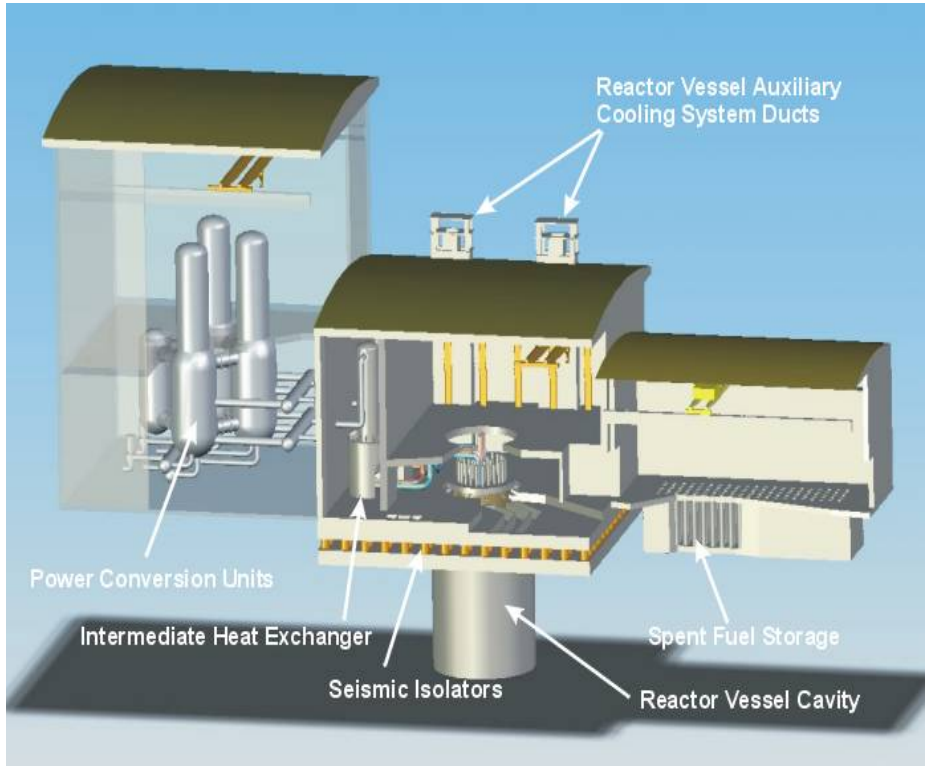
General Atomics GT-MHR Power Conversion Unit (Russian Design)

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



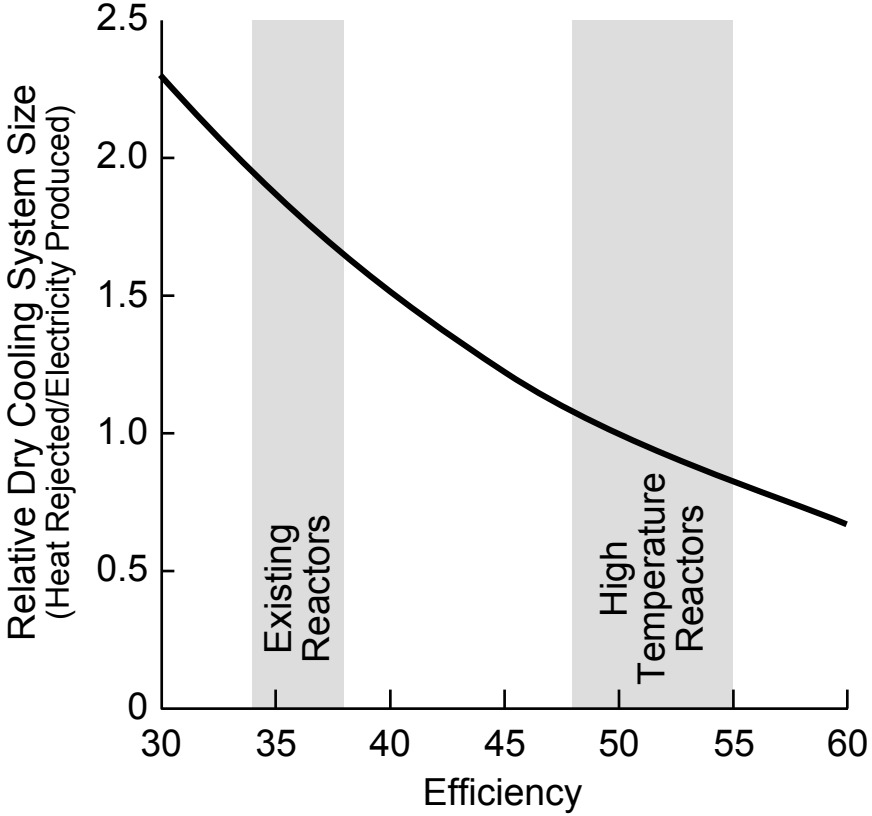
- **Differences from S-PRISM facility layout:**
  - **No SNF storage in vessel**
  - **No heat exchanger inside vessel**
  - **Molten salt-to-gas heat exchanger in turbine hall**
- **Same vessel size (low pressure)**
  - **Space for 2400-MW(t) AHTR core with low power density**
- **Similar equipment size**
  - **Molten salt volumetric heat capacity greater 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

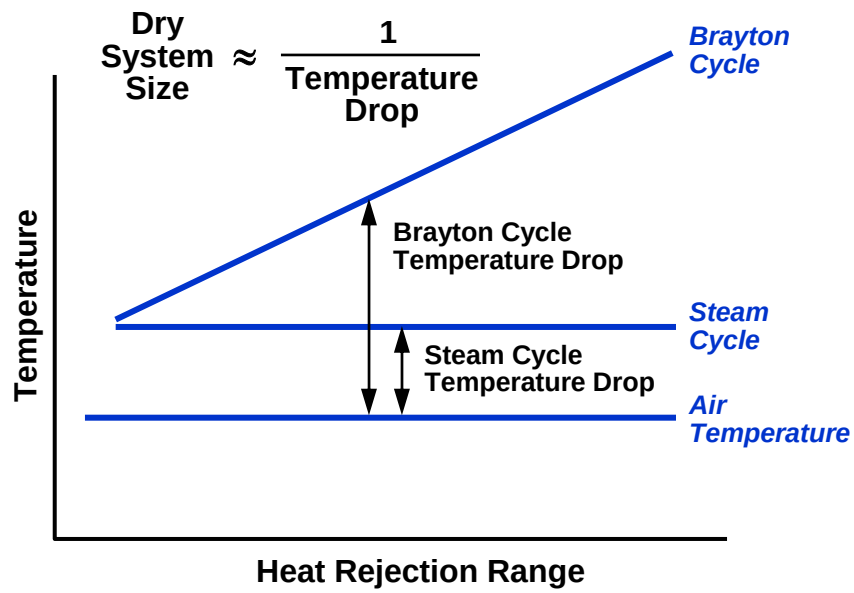


- **Economics of scale**
  - **2400 MW(t) vs 600 to 1000 MW(t)**
  - **1300 MW(e) vs 300 to 380 MW(e)**
- **Passive safety in a large reactor**
  - **Liquid heat transport inside reactor vessel**
  - **Higher temperature (750ºC) vessel increases heat rejection**
- **Higher efficiency multi-reheat Brayton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

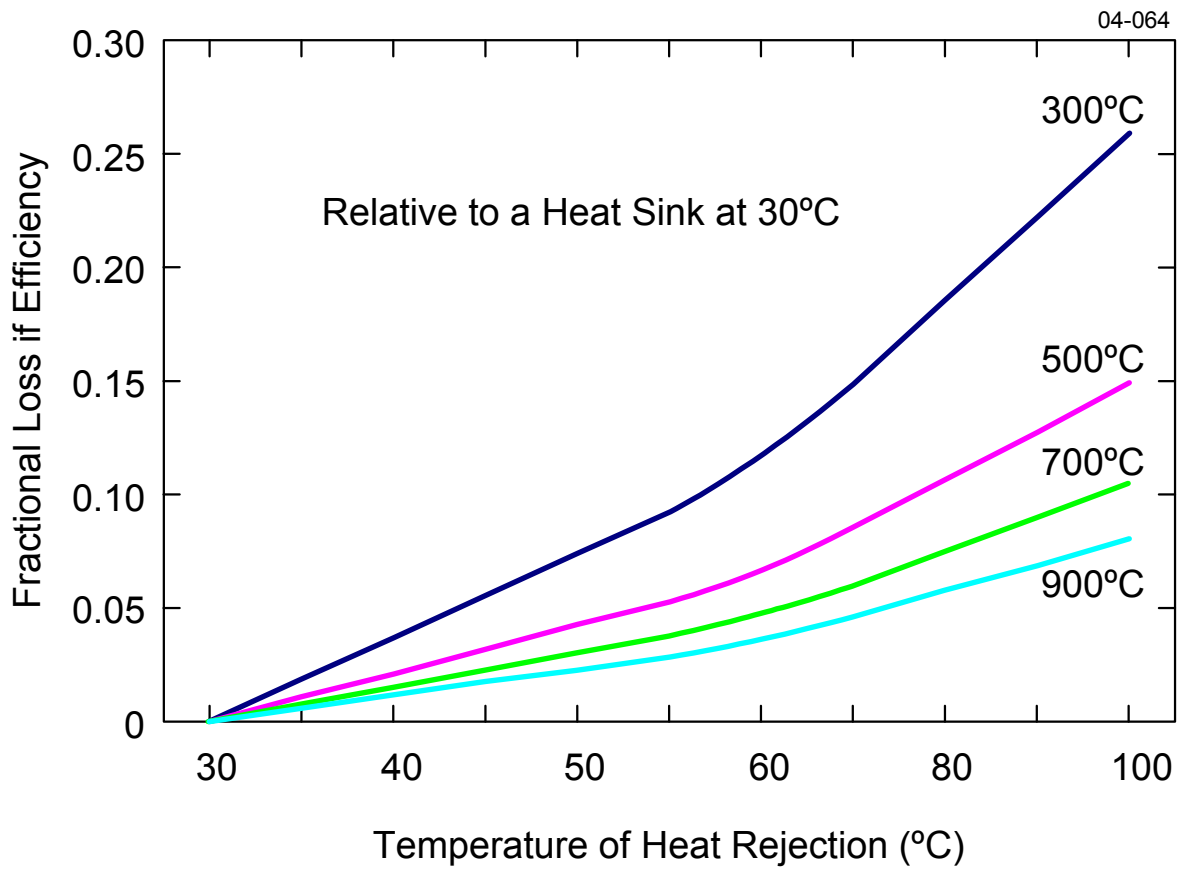
High-Temperature Reactors with Brayton Cycles Reduce Dry Cooling System Costs



**Cost Reduction by Efficiency Increase*



Less Heat Rejection

Smaller System Per Unit of Heat Rejected

Efficiency Loses Depend Upon Reactor and Heat Sink Temperature