Hydrogen Production Process Requirements and Nuclear Reactor Options

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Objectives

Define Methodology to Evaluate Reactor Options for Hydrogen Production

Identify Viable Reactor Options for Large-Scale Use by 2025

(Significant Deployment To Match Hydrogen Economy)

Four Requirements For Nuclear-Hydrogen Deployment Within Decades

- Hydrogen chemical plant requirements
  - Match reactor size with commercial-size H_2 production facilities (economics)
  - Match reactor with hydrogen process requirements (temperature, etc.)
- Nuclear reactor requirements
  - Available within twenty years
  - Viable near-term fuel cycle

Five Potentially Viable Reactor Concepts Were Identified

Reactor Option	*Fuel*	*Coolant*
Advanced High Temperature Reactor	Coated Particle	Molten Salt
Very-High Temperature Reactor	Coated Particle	Helium
Molten Salt Reactor	Fuel Dissolved in Coolant	Molten Salt
Lead-Cooled Fast Reactor	Uranium Nitride Other	Molten Lead
Gas-Cooled Fast Reactor	Undefined	Helium

Hydrogen Chemical Plant Requirements

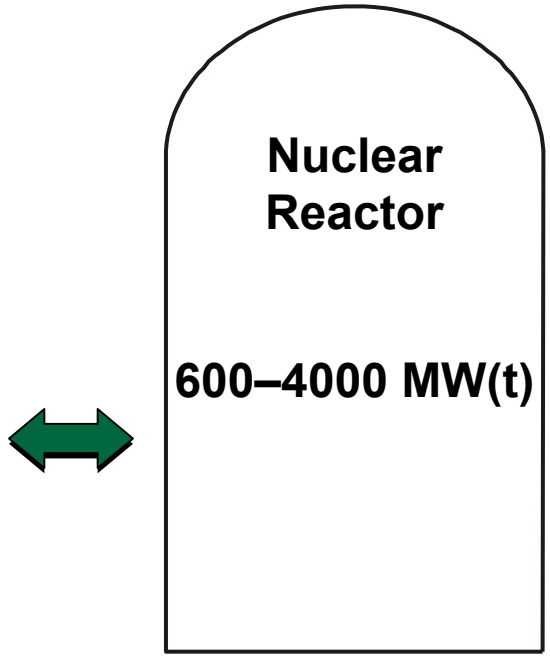
Match reactor size with commercial-size H_2 production facilities (economics)

The Scale of Hydrogen Production Is Beginning to Match Large Reactors

Plant Size

H_2 Plants	Energy to Produce H_2 (50% Efficient)
200×10^6 scf/d (Existing)	1600 MW(t)
300×10^6 scf/d (Future)	2400 MW(t)

Time



Hydrogen Chemical Plant Requirements:

Rating: Match Reactor Size With Commercial-Size Hydrogen Production Facilities

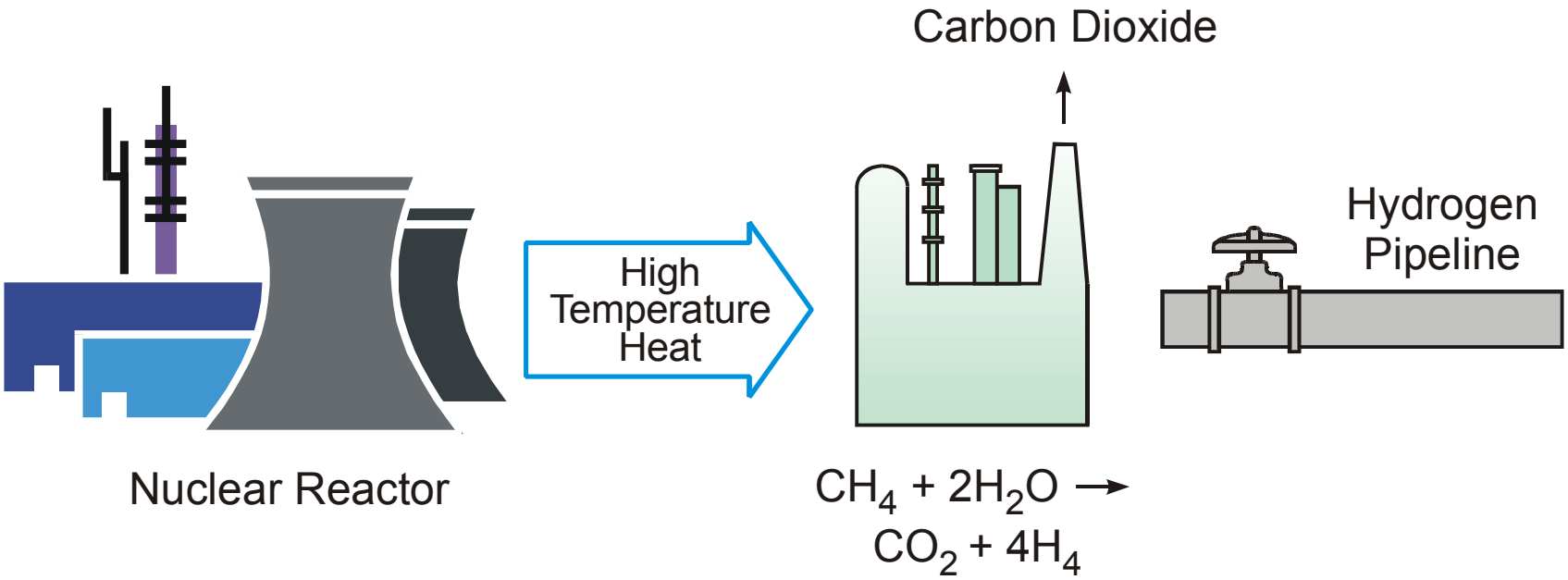
Reactor Option	*Rating*
Advanced High Temperature Reactor	High
Very-High Temperature Reactor (Modular: ~600 MWt)	Low
Molten Salt Reactor	High
Lead-Cooled Fast Reactor	High
Gas-Cooled Fast Reactor (Modular: ~600 MWt)	Low

Hydrogen Chemical Plant Requirements

Match reactor with hydrogen process requirements (temperature, etc.)

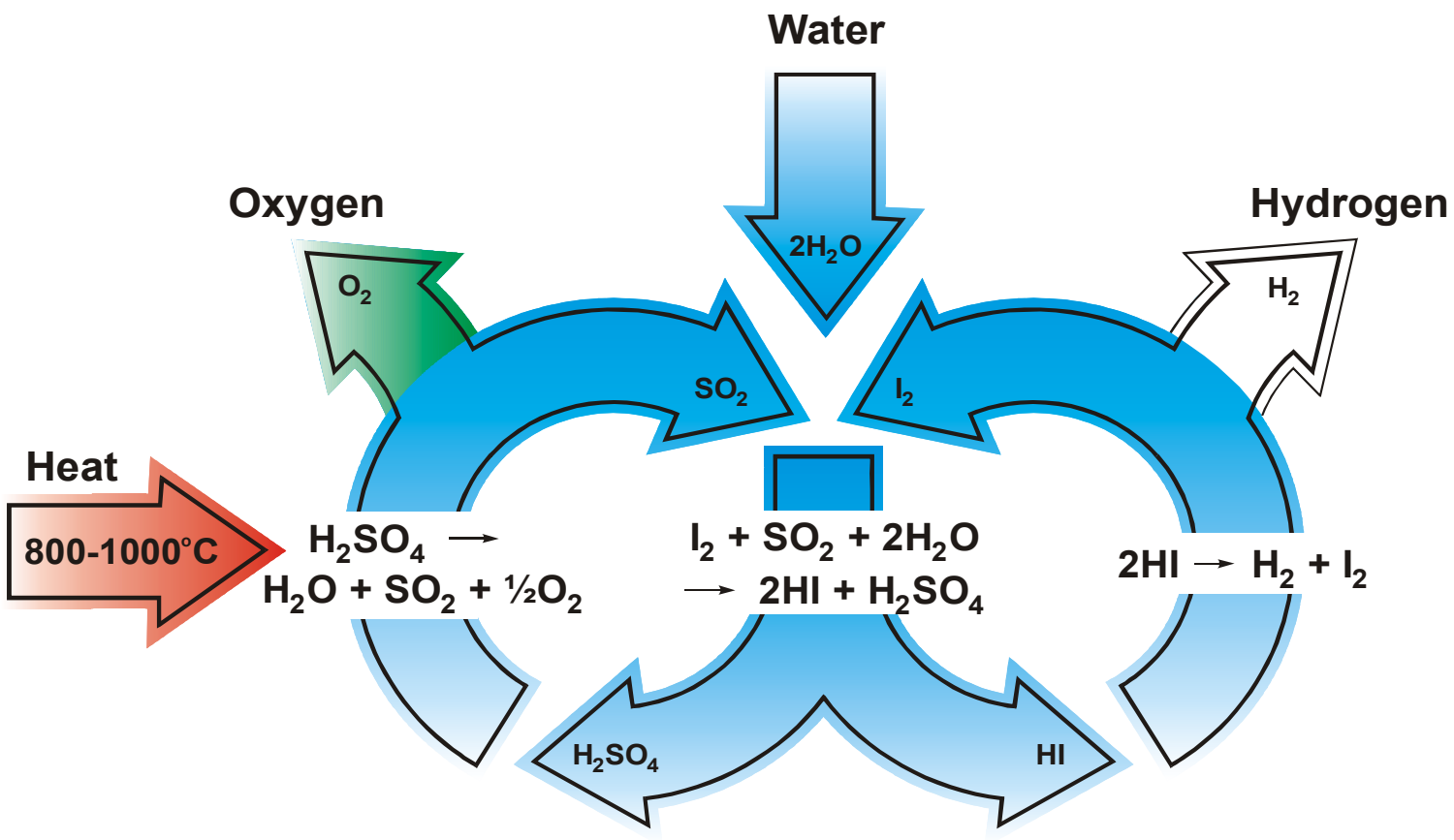
Nuclear-Assisted Steam Reforming of Natural Gas Uses Nuclear High-Temperature Heat (~800°C) to Reduce the Energy Requirements for Hydrogen Production

(Development Programs in Japan: Couple to High Temperature Test Reactor)



Thermochemical Processes Use Nuclear High-Temperature Heat and Water to Produce H_2

(Cost Estimated at 60% of Electrolysis; Iodine-Sulfur Process Is the Leading Candidate with a Potential for Lower Peak Temperatures)

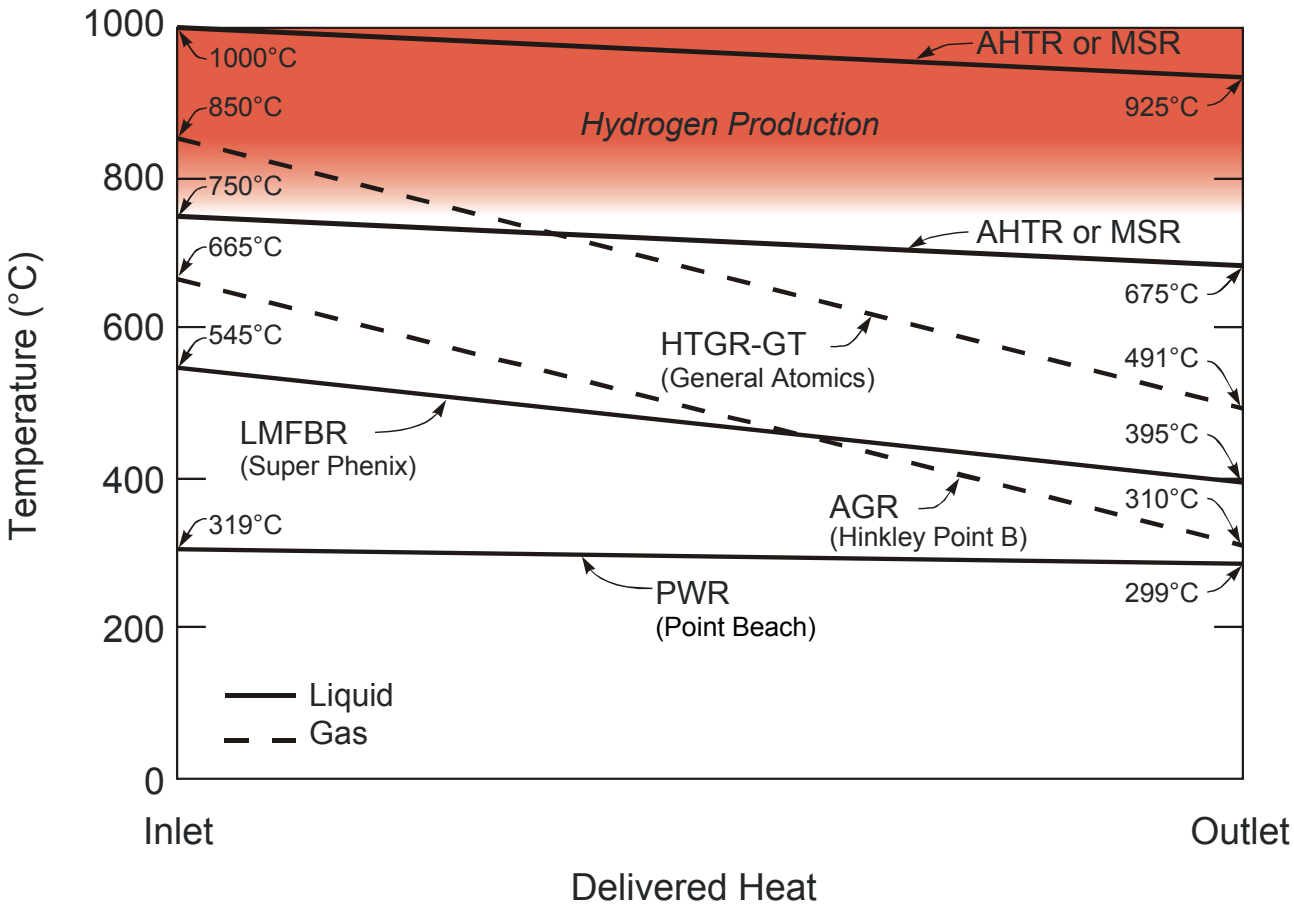


Hydrogen Production Processes Impose Tough Requirements on the Reactor

- High temperatures (750 to 1000°C)
- Heat delivered at constant temperature
- Low pressure to hydrogen facility
  - Match process requirements
  - Minimize potential accidental releases of toxic chemicals (off-site public safety)
- Separation of hydrogen chemical plant from the reactor (plant safety)
  - Corrosive and hazardous chemicals

Power Reactor Experience Shows That Liquid Coolants Minimize Peak Reactor Temperatures

(Minimize Peak Reactor Temperatures)



Liquid-Cooled Reactors Best Match Hydrogen Production Process Requirements

(Relative Rankings: High Is Best)

	AHTR	VHTR	MSR	LFR	GFR
Temp.	High	High	High	Low	Low
Temp. Range	High	Low	High	High	Low
Pressure	High	Low	High	High	Low
Isolation	High	Low	Medium	High	Low

Nuclear Reactor Requirements

Available Within Twenty Years

Nuclear Reactor Requirements:

Rating: Available Within Twenty Years

Reactor Option	*Rating*	*Limiting Factor*
Advanced High Temperature Reactor	High	
Very-High Temperature Reactor	High	
Molten Salt Reactor	Low	Multiple Uncertainties
Lead-Cooled Fast Reactor	Low	Corrosion at High Temp.
Gas-Cooled Fast Reactor	Low	Fuels

Nuclear Reactor Requirements

Viable Near-Term Fuel Cycle

Nuclear Reactor Requirements:

Rating: Viable Near-Term Fuel Cycle

Reactor Option	*Rating*	*Limiting Factor*
Advanced High Temperature Reactor	High	
Very-High Temperature Reactor	High	
Molten Salt Reactor	Medium	Partial Fuel Processing
Lead-Cooled Fast Reactor	Low	Fuel Recycle Required
Gas-Cooled Fast Reactor	Low	Fuel Recycle Required

Conclusions: There Are Two Nuclear Reactor Options For Hydrogen Production Within the Next 20 Years

Very-High-Temperature Reactor

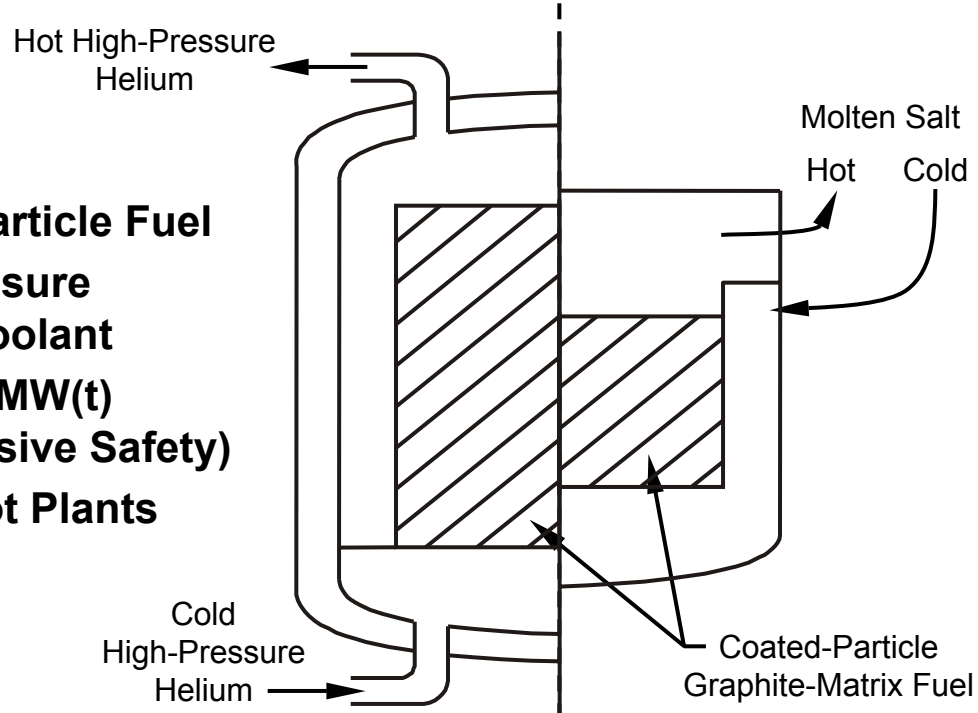
(Developed Originally for Electric Production)

- **Coated-Particle Fuel**
- **High-Pressure Helium Coolant**
- **Size: 600 MW(t) (With Passive Safety)**
- **Small Pilot Plants**

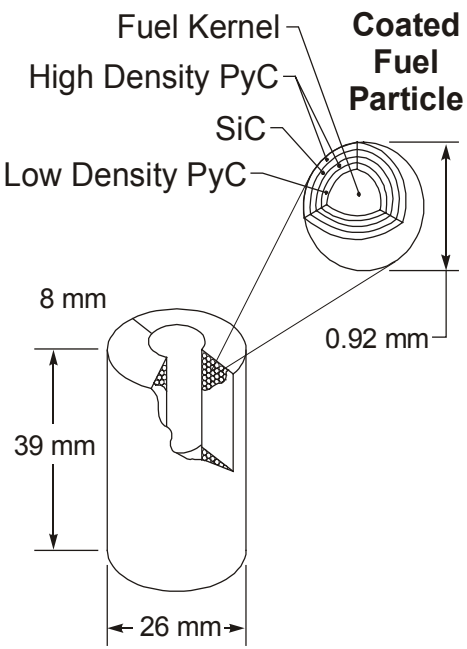
Advanced High-Temperature Reactor

(Designed for Hydrogen Production)

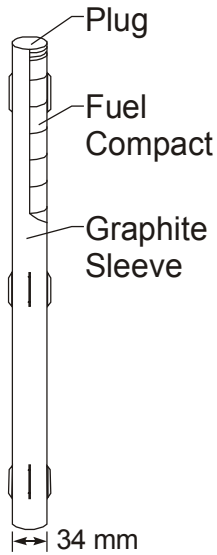
- **Coated-Particle Fuel**
- **Atmospheric-Pressure Molten Salt Coolant**
- **Size: To 2400 MW(t) (With Passive Safety)**
- **New Concept**



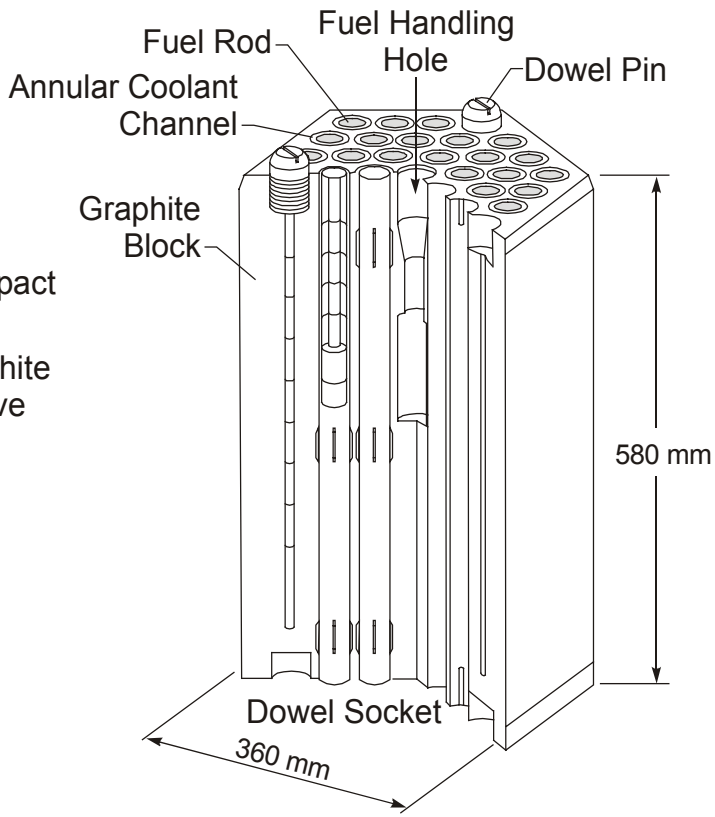
Coated-Particle Fuels Are the Only Proven Fuels at Required Temperatures for H_2 Production



Fuel Compact



Fuel Rod



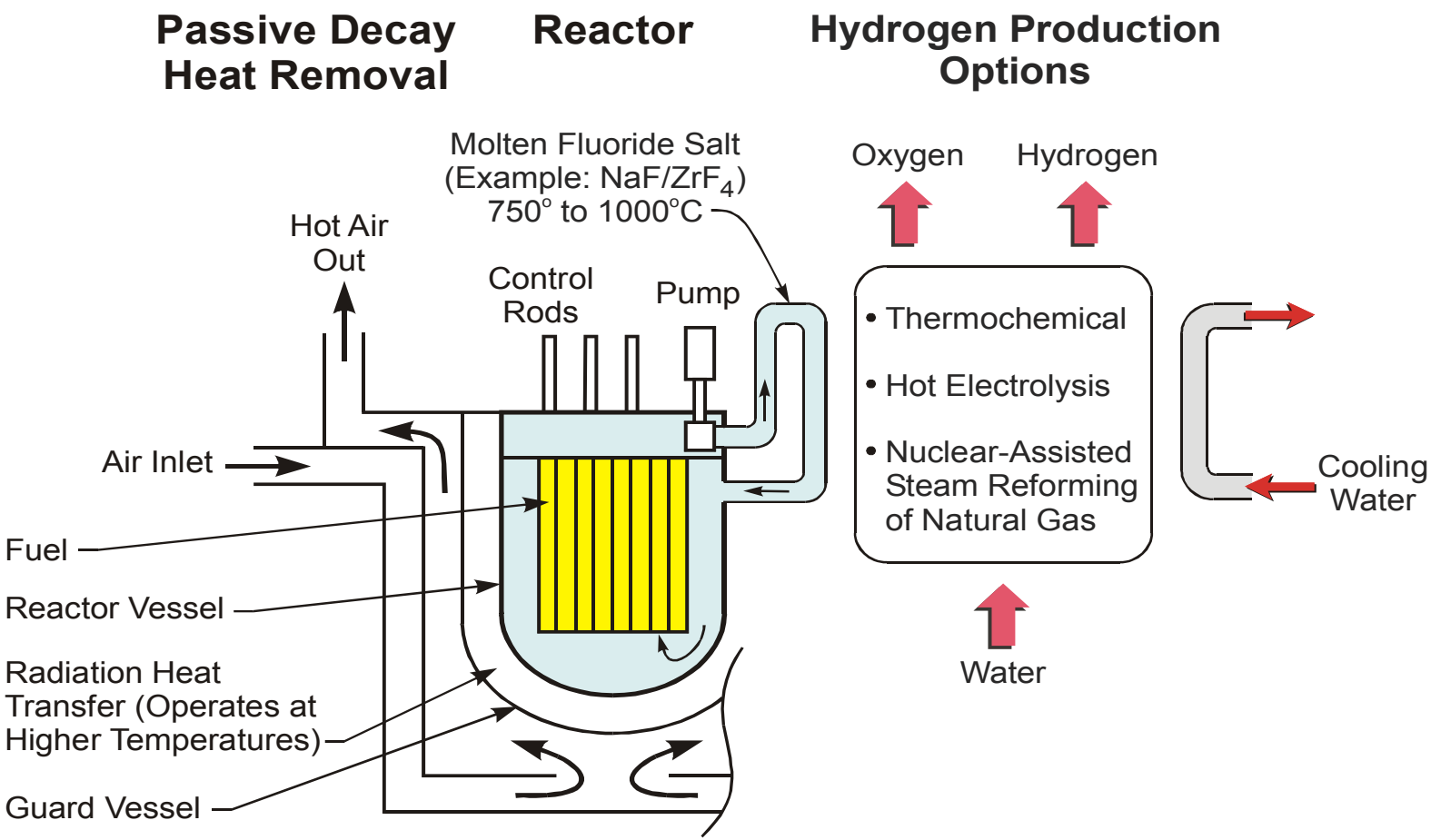
Fuel Block

Conclusions

- Making hydrogen is tough
- Only 5 reactors are possible candidates
- Only 2 reactors are near-term candidates
- Other options are longer term because of one or more limitations
  - Undeveloped fuels (GFR)
  - Corrosion at high temperatures (LFR)
  - Conceptually different (MSR)
  - Requires recycle fuel with long deployment times (GFR, LFR)

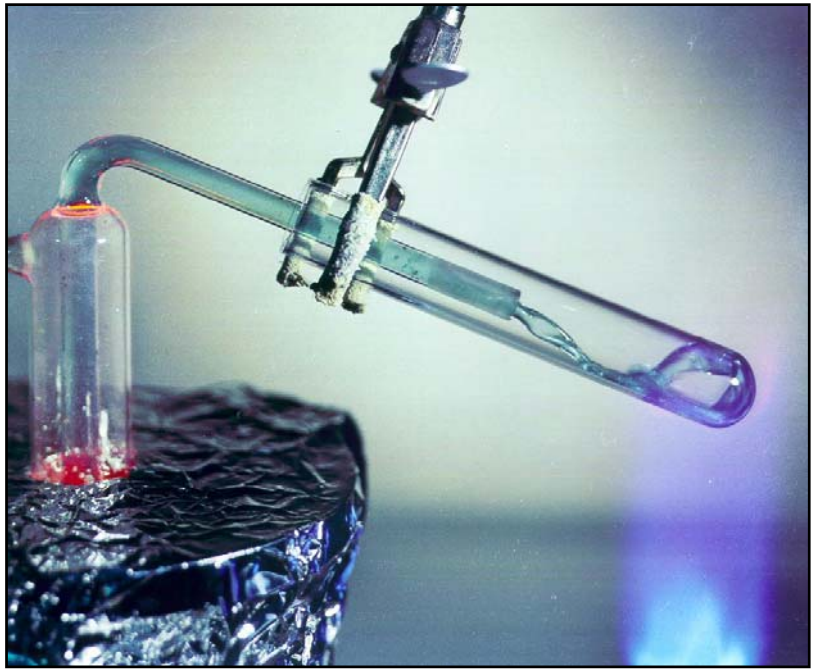
Backup Slides

Advanced High-Temperature Reactor



Molten-Salt-Coolant Technology Was Developed in the Aircraft Nuclear Propulsion Program

(Test Reactor Short-Term Peak Temperatures at 860°C; Aircraft Nuclear Propulsion Program Was a Molten-Salt Fueled (Not Cooled) Reactor; Large Coolant Test Loops Operated; Salts Being Considered for Fusion Reactor Cooling)



Molten Fluoride Salts Are Compatible With Graphite-Based Fuels

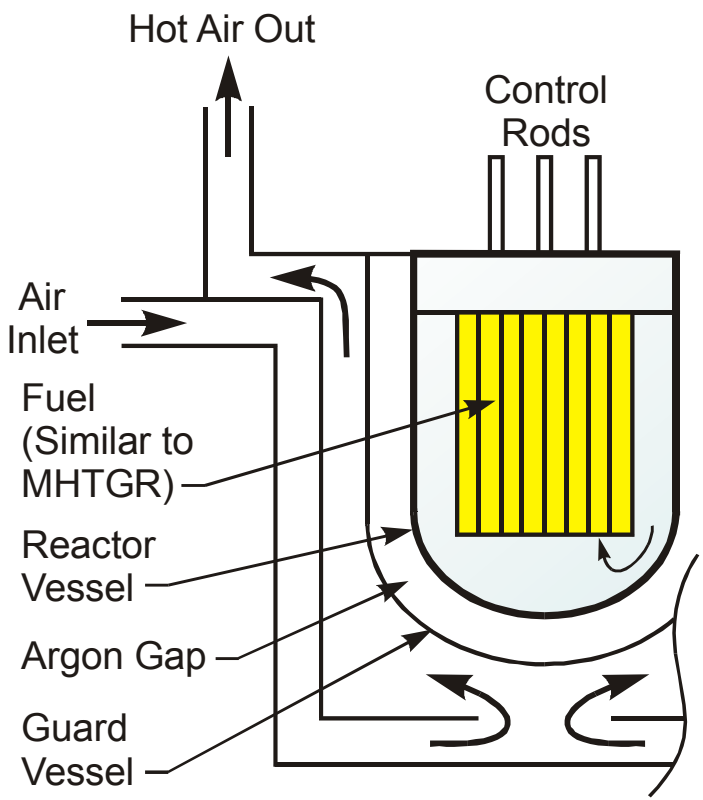
- Molten Salt Reactor Experiment showed that salt and graphite are compatible
- Industrial experience
  - Hall aluminum production since 1890s
  - Graphite baths
  - AlF_3/NaF_3 salt
  - 1000°C

The High-Temperature, Low-Pressure Liquid Coolant Enables Passive Decay Heat Removal in Large Reactors

(One Example: Several Other Decay-Heat Cooling Options Exist)

Passive Decay Heat Removal

Reactor



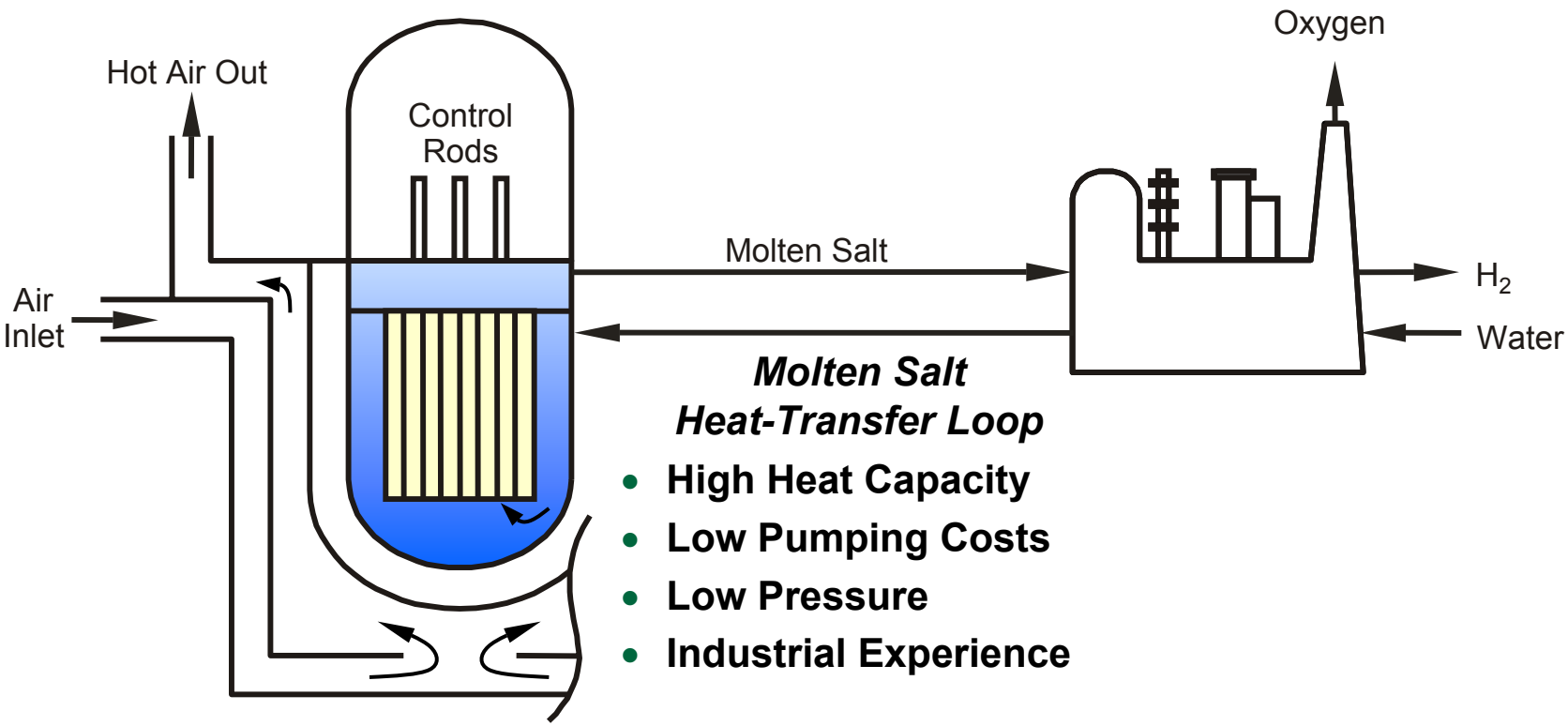
Decay-Heat Cooling System Characteristics

- Similar to GE S-PRISM (LMR)
- Argon Gap
  - Heat Transfer ~T^4
  - Thermal Switch Mechanism
- Heat Rejection: Temperature Dependent
  - LMR: 500-550°C [~1000 Mw(t)]
  - AHTR: 750-1000°C [>2000 Mw(t)]

The Reactor and Hydrogen Production Facility Will Be Physically Separated to Ensure Safety

Nuclear Safety by Isolation

Hydrogen Safety by Dilution

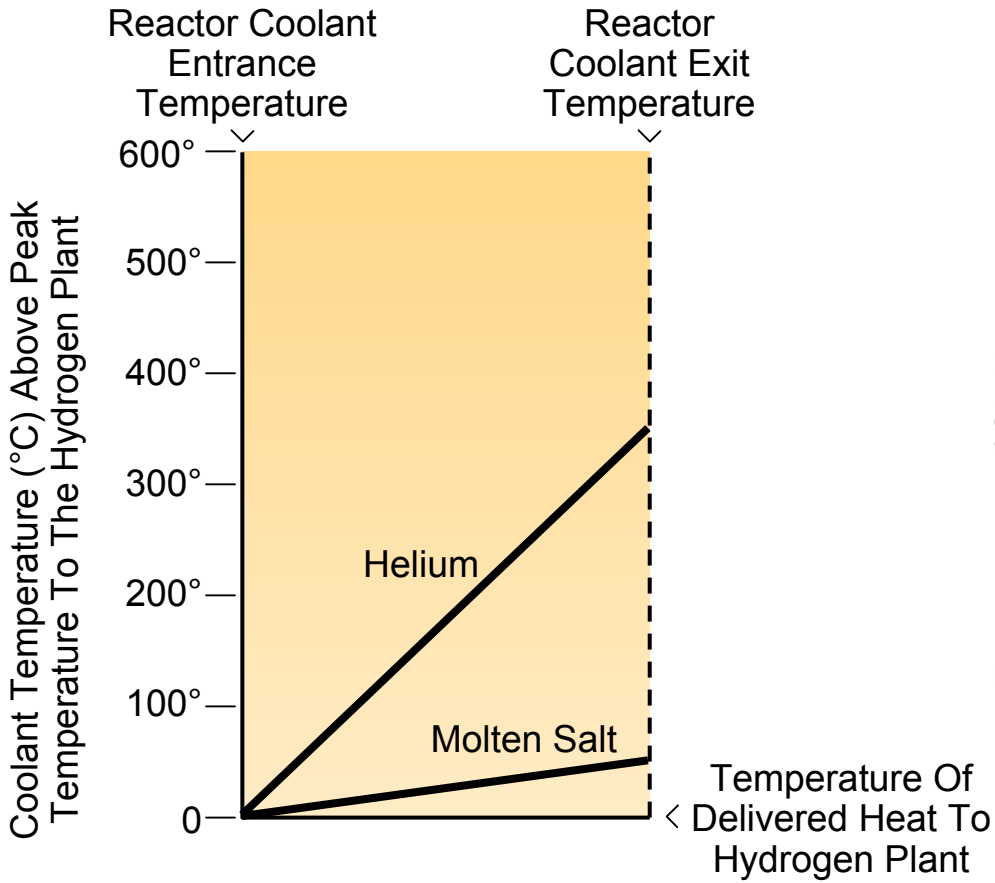


Molten Salt Heat-Transfer Loop

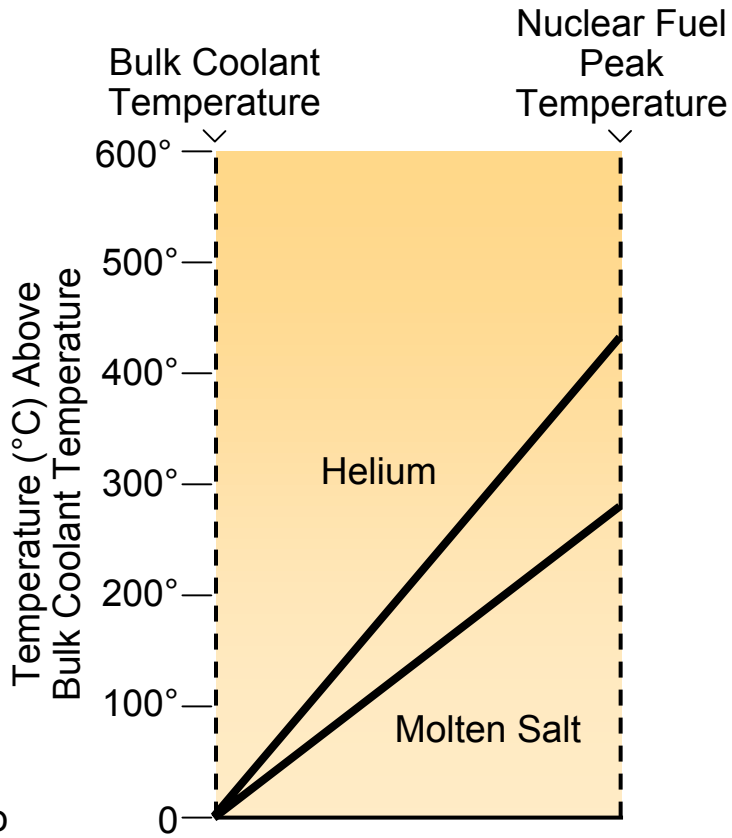
- **High Heat Capacity**
- **Low Pumping Costs**
- **Low Pressure**
- **Industrial Experience**

The AHTR Reduces Reactor And Fuel Temperatures Compared to Gas-Cooled Reactors

Bulk Coolant Temperature Rise Across Reactor

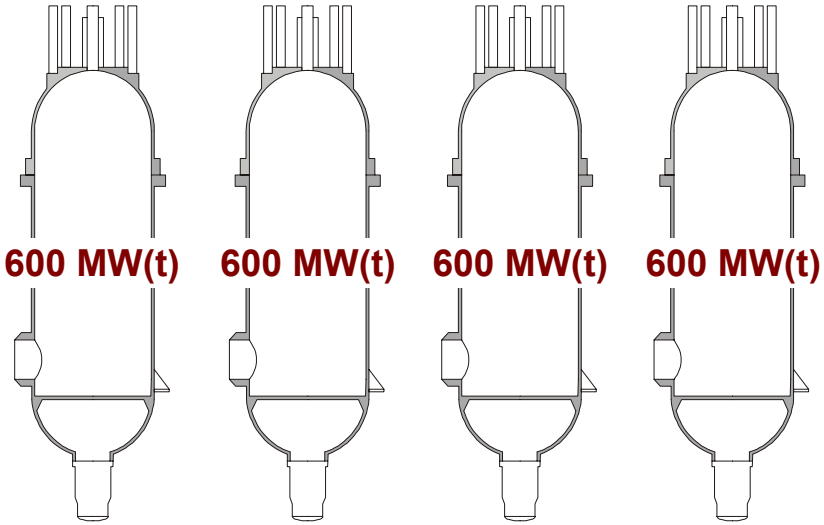


Temperature Rise From Coolant To Fuel Centerline

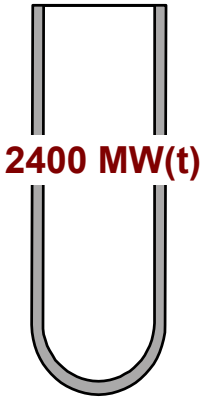


The Economics of High-Temperature Liquid-Cooled Reactors may be Superior to Gas-Cooled Reactors for Systems with the Same Safety Goals

Pressure Vessels For 2400 MW(t) of HTGRs

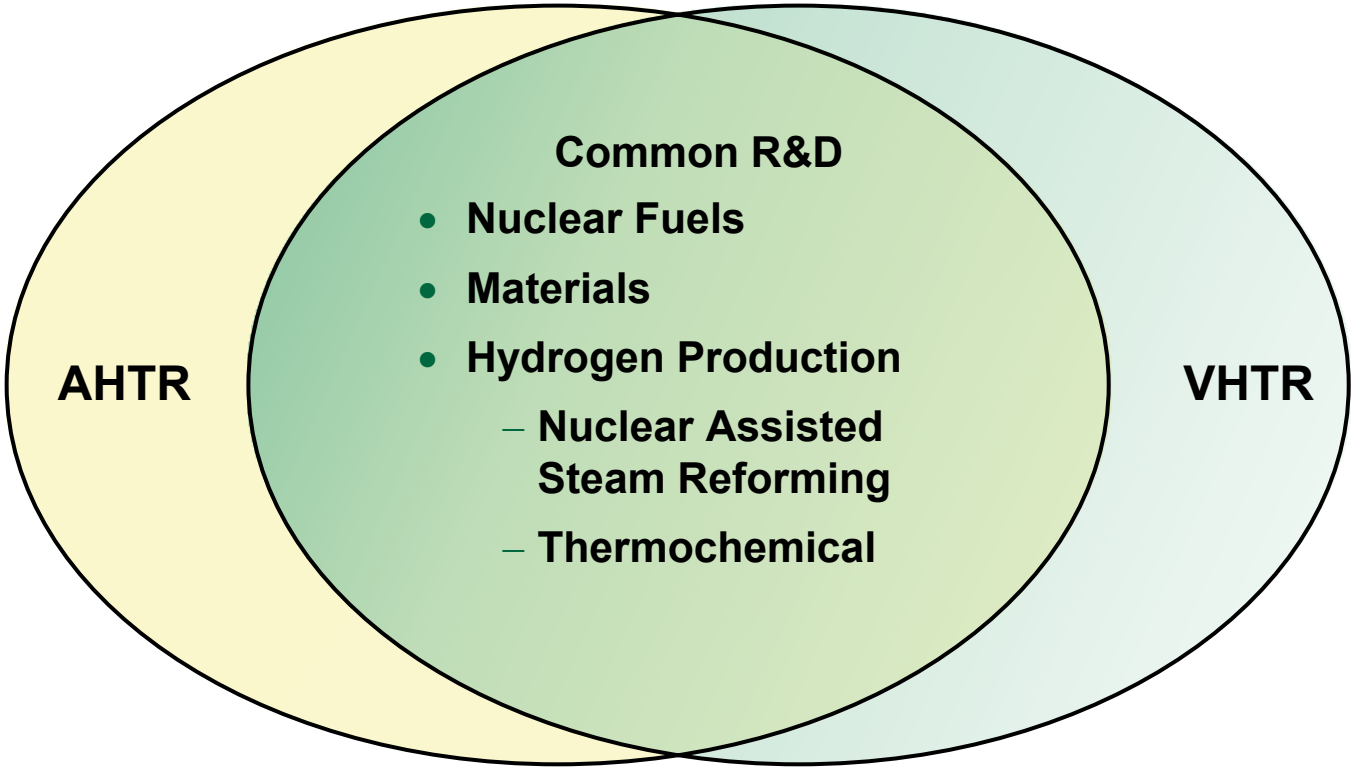


Low-Pressure Vessel For 2400 MW(t) of AHTR



Five Reactor Concepts Have the Potential for Hydrogen Production

(However Existing Nuclear Fuels Technology Implies Only Two Viable Candidates for Deployment Before 2020)

Reactor Option	Demonstrated Temperature	Developed Fuel
Advanced High-Temperature Reactor	Yes	Yes
Very-High-Temperature Reactor	Yes	Yes
Molten Salt Reactor	Yes	No
Lead-Cooled Fast Reactor	No	No
Gas-Cooled Fast Reactor	No	No

The R&D Requirements For the AHTR and VHTR Have Much In Common