Hydrogen Production And The Advanced High-Temperature Reactor

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Outline

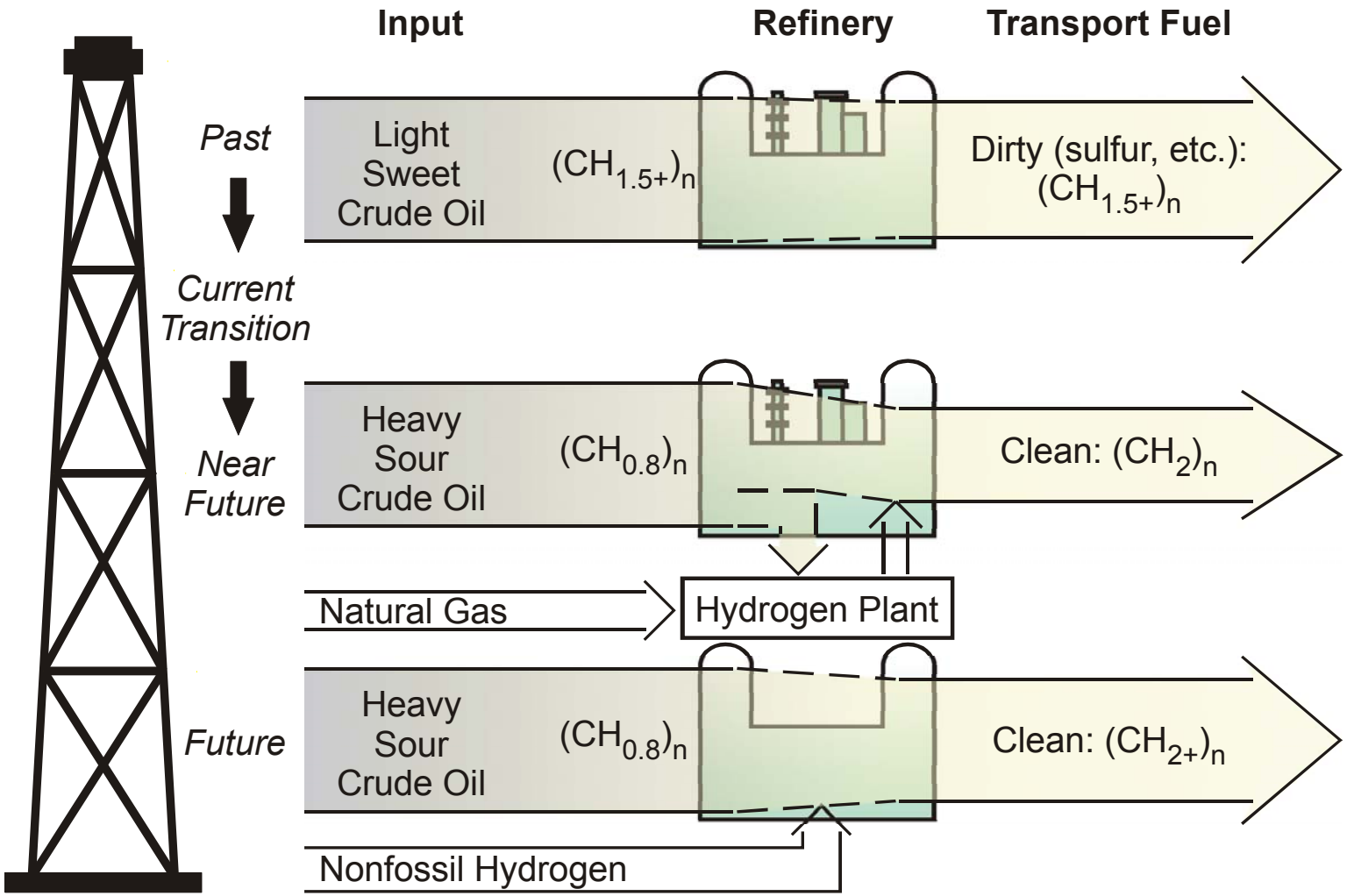
- Hydrogen (H_2) futures
- Compatibility of nuclear energy for hydrogen production
- Hydrogen production using nuclear energy
- The Advanced High-Temperature Reactor
- Electricity Production
- Conclusions

Hydrogen Futures

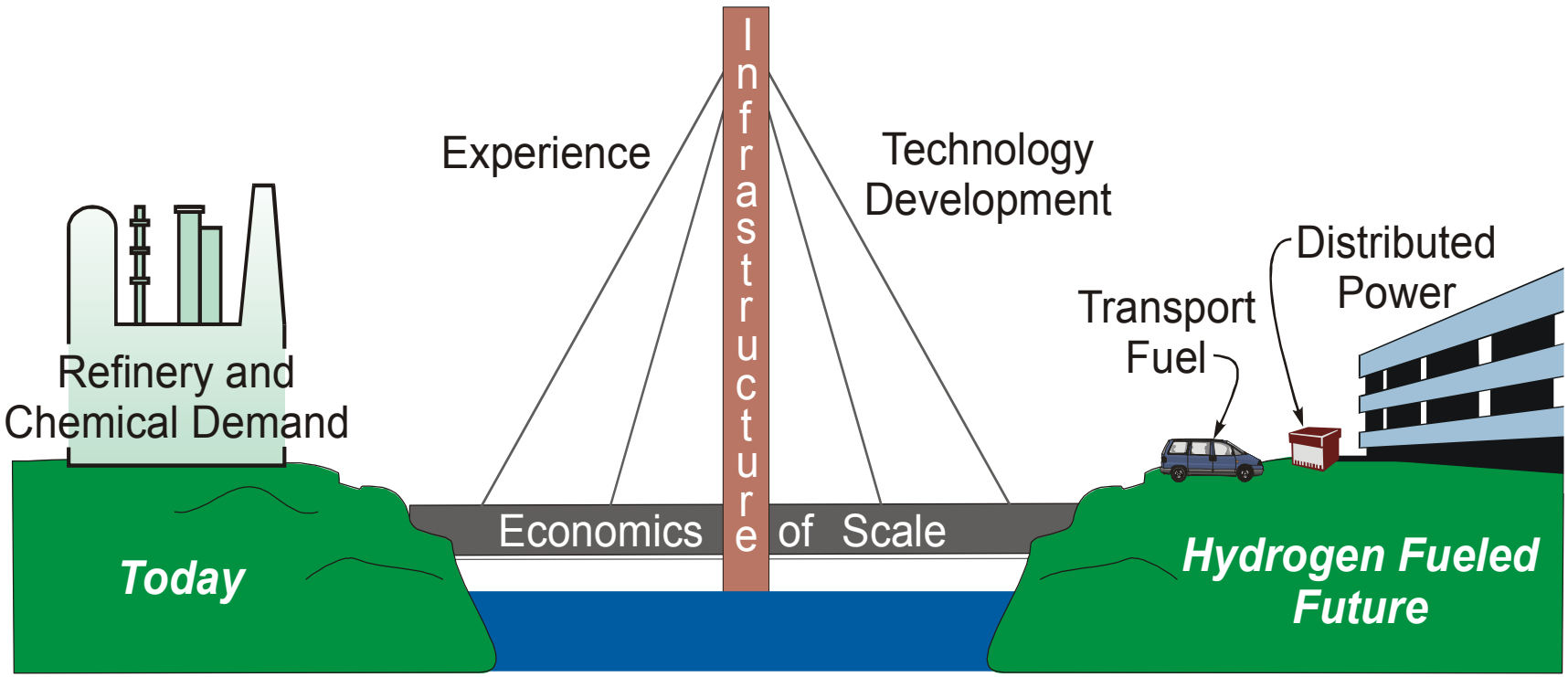
Hydrogen Demand Is Large and Growing Rapidly

- World consumes 50 million tons of H_2/year
  - ~80% intentionally produced; remainder, by-product H_2
  - 200 GW(th) if the H_2 is burned
  - 4 to 10% growth per year
- Within 10 to 20 years, the energy to produce H_2 in the U.S. may exceed current energy production from nuclear power
- Rapid hydrogen-demand growth to produce clean fuels from lower-grade crude oils

Liquid Fuels Production Is Rapidly Becoming the Major Market for Hydrogen



The Growing Hydrogen Demand Creates a Bridge to the Hydrogen Economy—With a Future Hydrogen Energy Demand That May Exceed That for Electricity



Hydrogen Could Exceed Electricity As An Energy Carrier By 2050

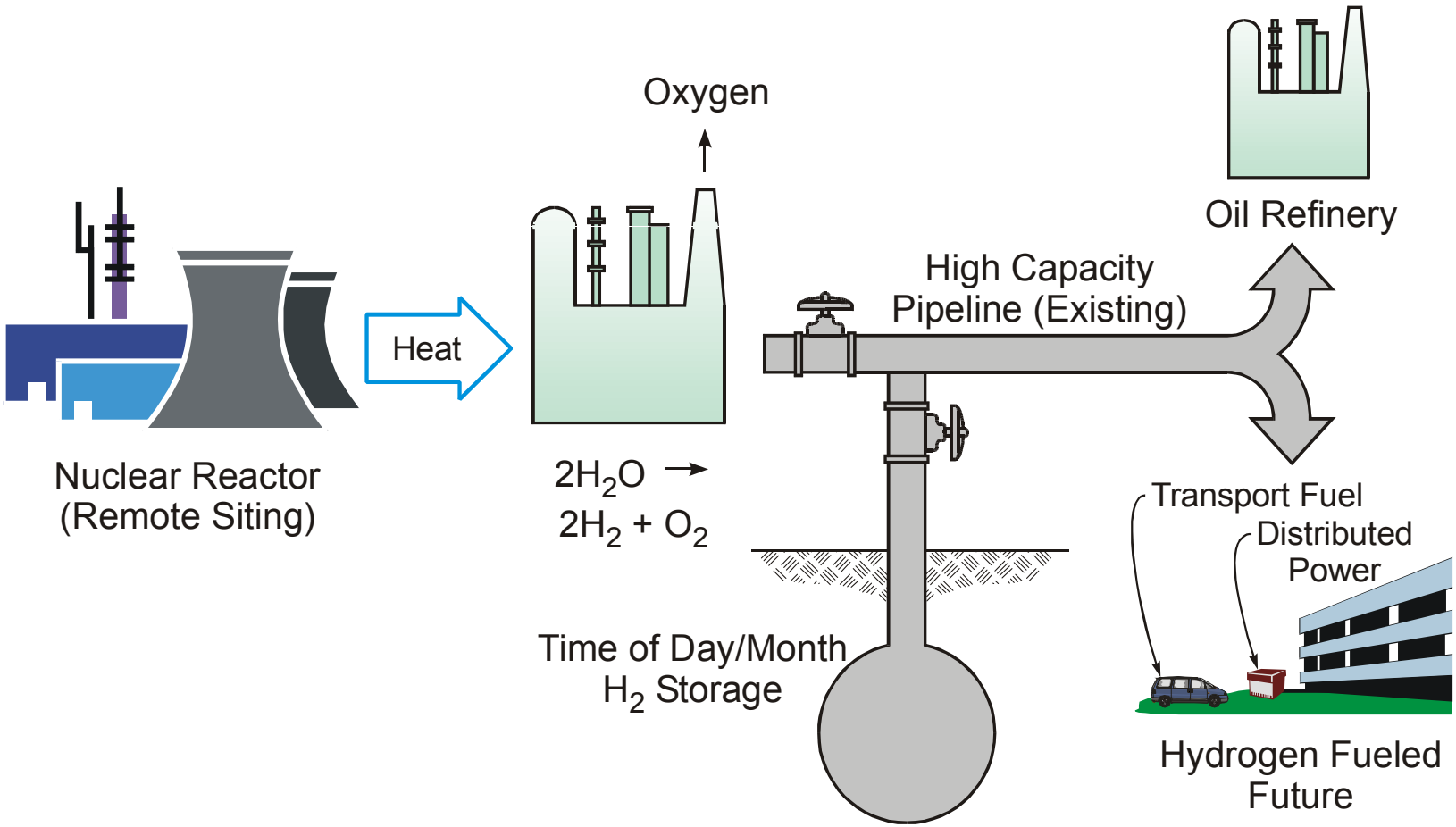
- Auto companies and Presidential initiate to develop fuel cells for cars within 10 y
- Fuel cells require H_2
- If H_2 replaces liquid fuels, H_2 demand may exceed electricity demand
- Technological transitions typically take several decades
  - 20 years for France to move from oil to nuclear
  - 40 years for electricity
  - 30 years for horses to cars

Compatibility of Nuclear Energy for Hydrogen Production

Intrinsic Characteristics of Different Technologies Determine the Viability of Combining Technologies

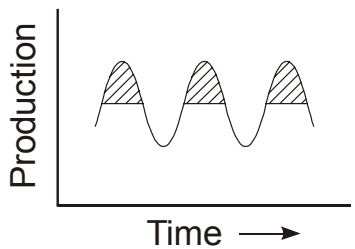
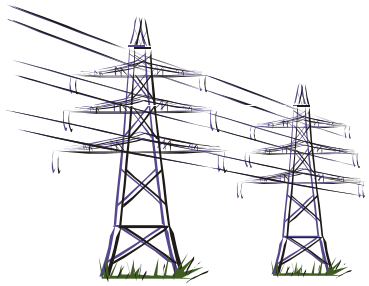
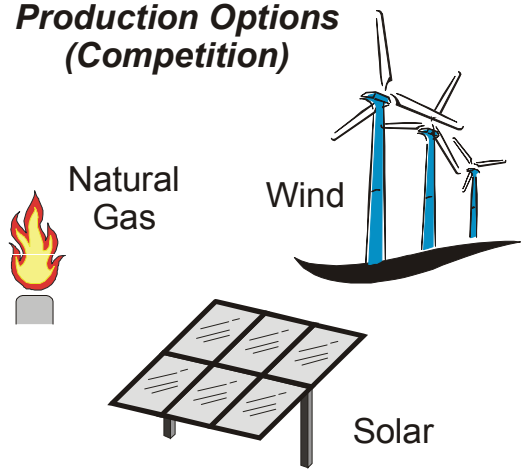
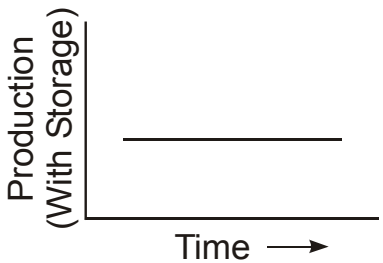
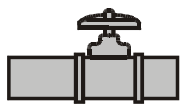
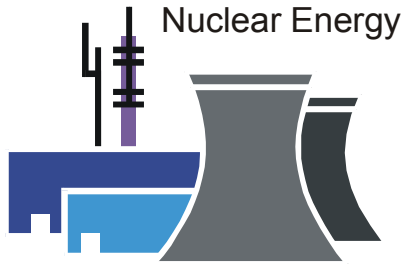
The Intrinsic Characteristics of Nuclear Power Are Compatible with Hydrogen Production

(Remote Siting, Scale of Operations, and Full-Load Operations)



By 2050, Hydrogen Production May Be the Primary Application of Nuclear Energy

(Assuming Fuel Cells Power Vehicles)

Energy Source	*Production Requirement vs Time (High Capital, Low Operating)*	*Long-Distance Transmission (Remote Siting)*	*Production Options (Competition)*
Electricity			
	Fuel Cell (Hydrogen to Electricity)	**~2 GW**	**Many**
Hydrogen			
		~25 GW	**Few**

Hydrogen Production Using Nuclear Energy

Temperatures >750°C

Low Pressures (Highly Desirable)

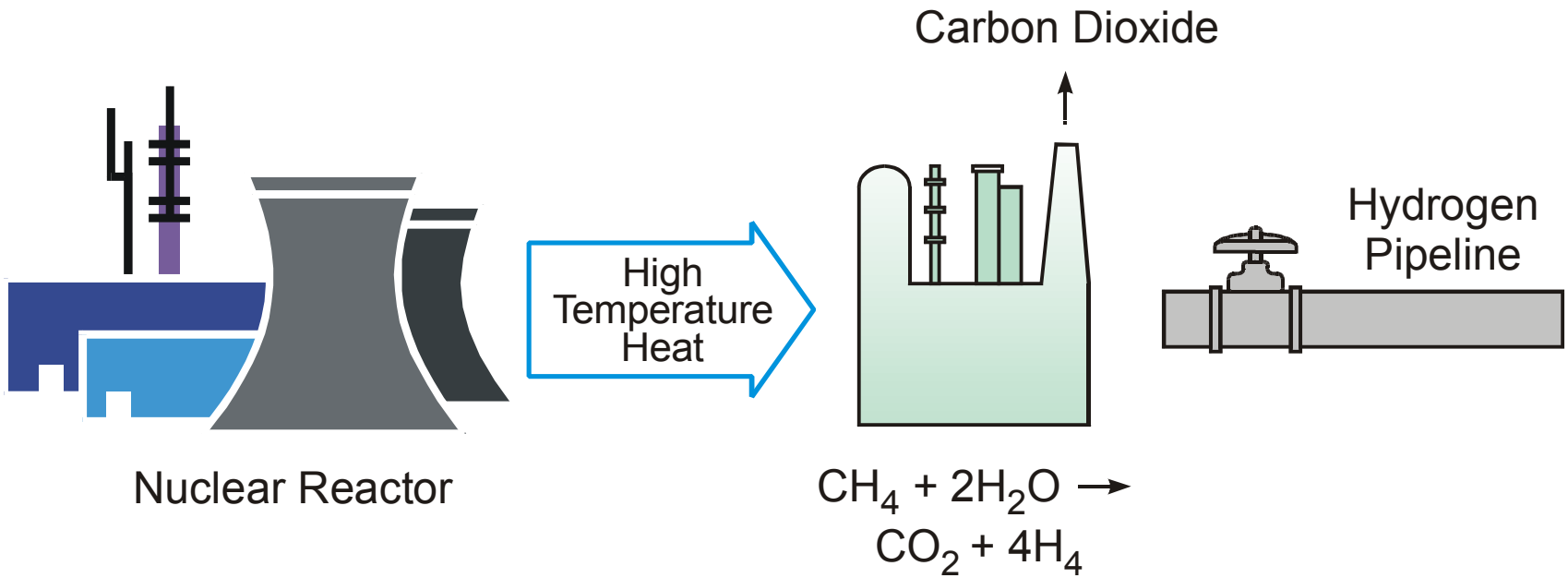
Isolation

Characteristics of Current Hydrogen Production Techniques

- Most H_2 is made from natural gas
  - Heat + methane (CH_4) + water (H_2O) ☑ hydrogen (H_2) + carbon dioxide (CO_2)
  - Endothermic process with heat input to 900°C
- Water electrolysis is used to produce small quantities of H_2
  - Inefficient: heat to electricity to chemical energy (H_2)
  - Viable where electricity is cheap (night time)

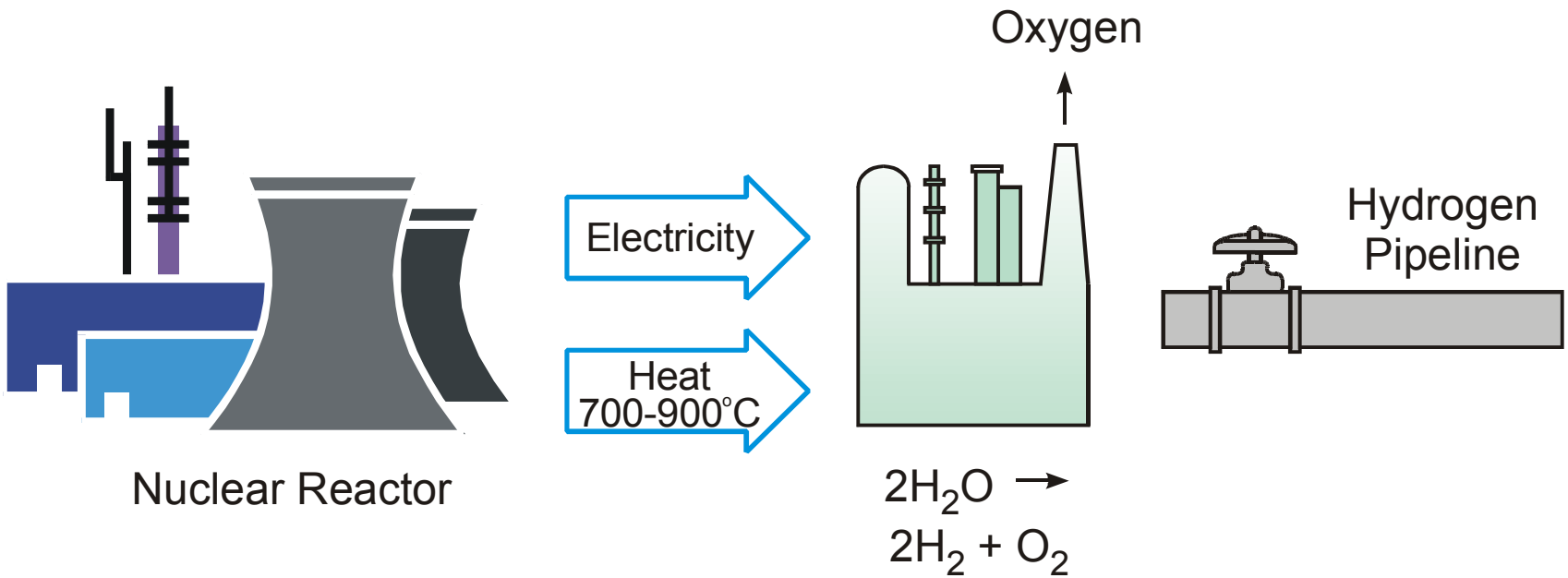
Nuclear-Assisted Hydrogen Production Uses High Temperature Heat (to 900°C) To Reduce Energy Requirements For Steam Reforming of Natural Gas

(Development Program in Japan)



Hot Electrolysis Hydrogen Production Requires High-Temperature Heat (700-900°C) and Electricity

(Current Technology Expensive)

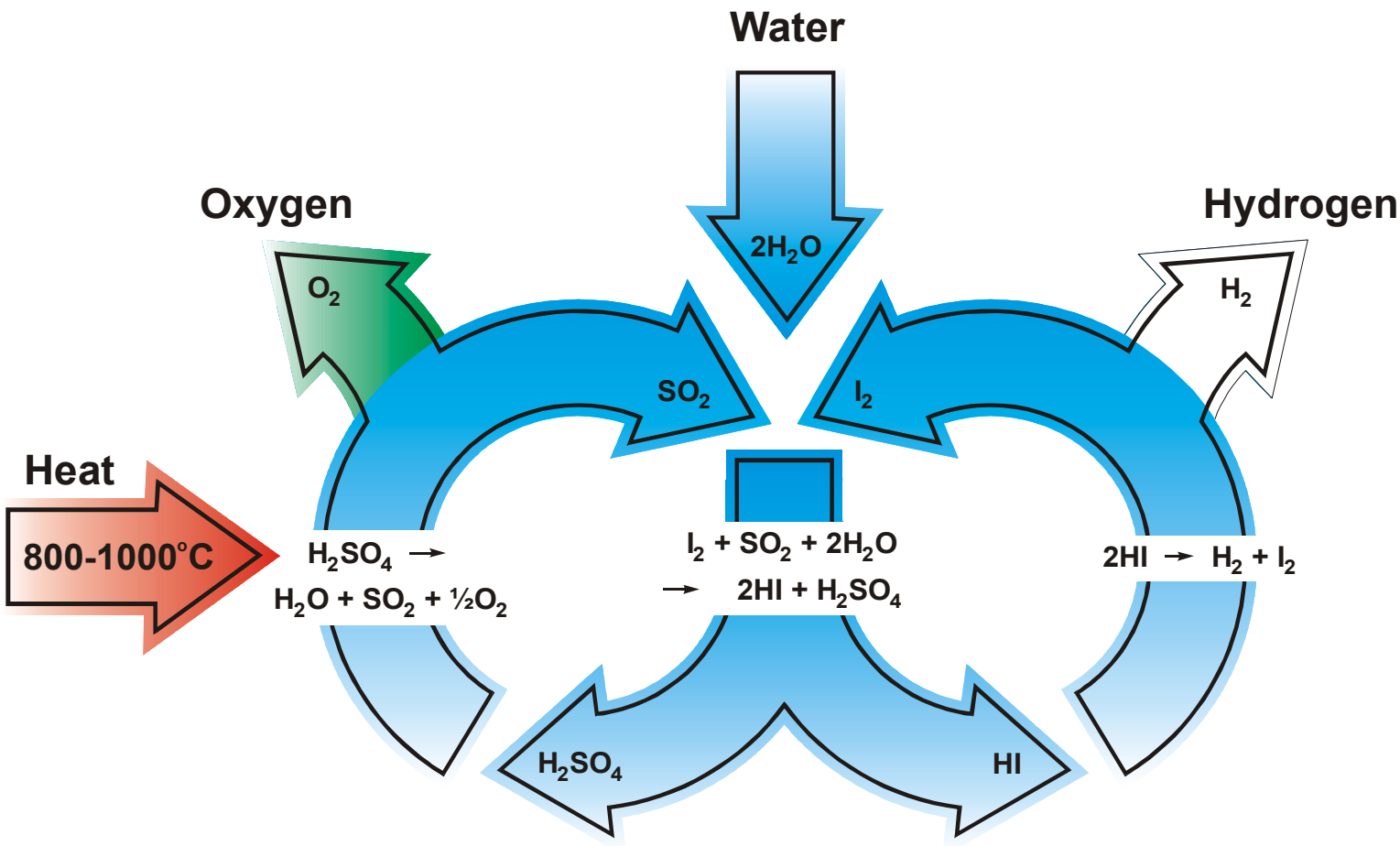


Thermochemical Production of H_2 Is The Leading Technology

- Heat + water ☑ hydrogen (H_2) + oxygen (O_2)
- Heat input >750°C
- Low pressure
  - Drive chemical reactions
  - Minimize materials requirements
- Lowest potential costs
  - Projected efficiencies of >50%
  - Projected best long-term economics (60% of cold electrolysis)

Thermochemical Processes Convert High-Temperature Heat and Water to H_2 and Oxygen

(Example [leading candidate]: Iodine–Sulfur Process)



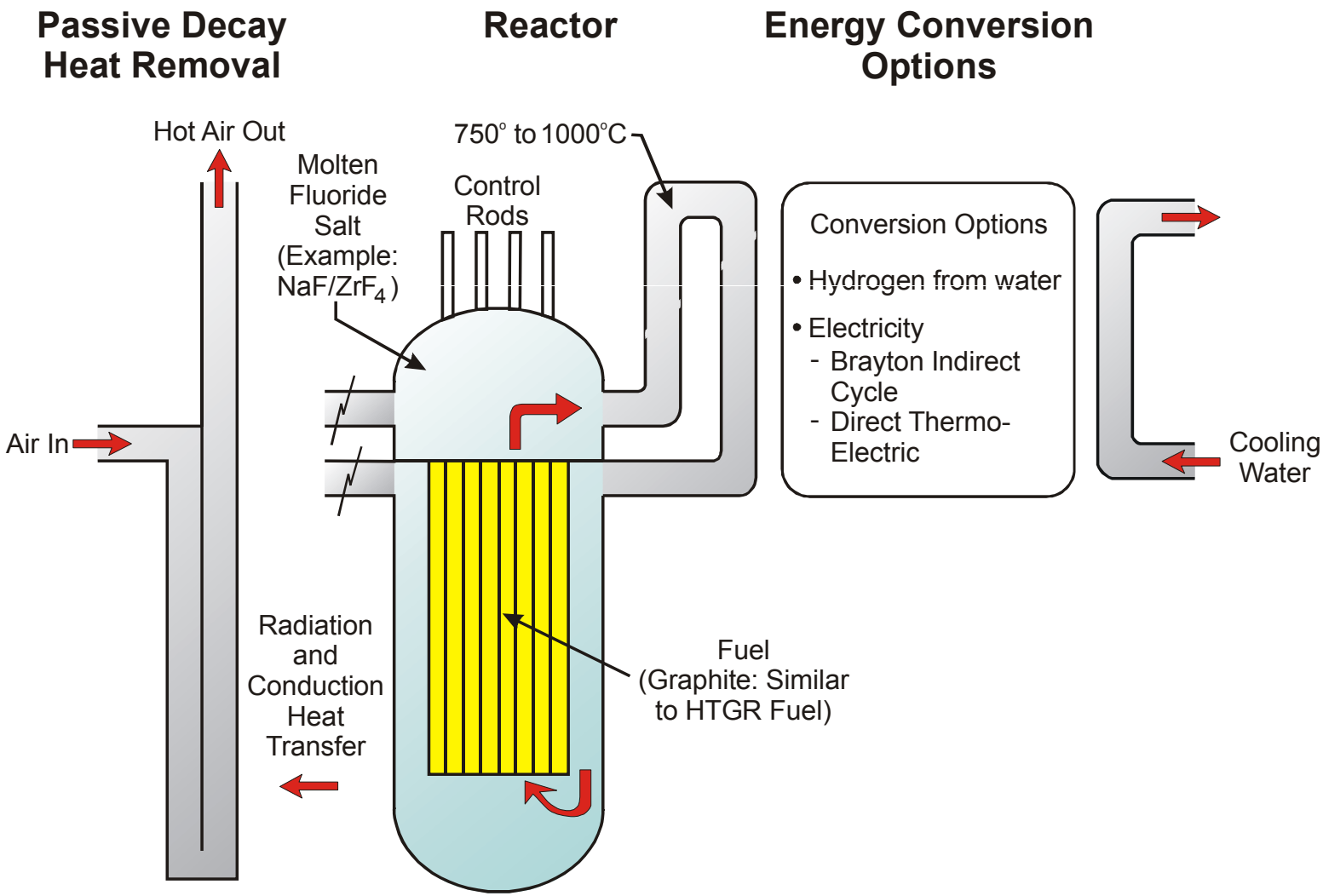
High-Temperature, Low-Pressure Heat Required For Nuclear Hydrogen Production

Production Method	Temperature (°C)
Hot Electrolysis	700-900
Assisted Steam Reforming	To 900
Thermochemical	>750

The Advanced High-Temperature Reactor (AHTR)

Designing a Reactor for Hydrogen Production (High Temperature and Low Pressure) and Electricity Production

Advanced High-Temperature Reactor



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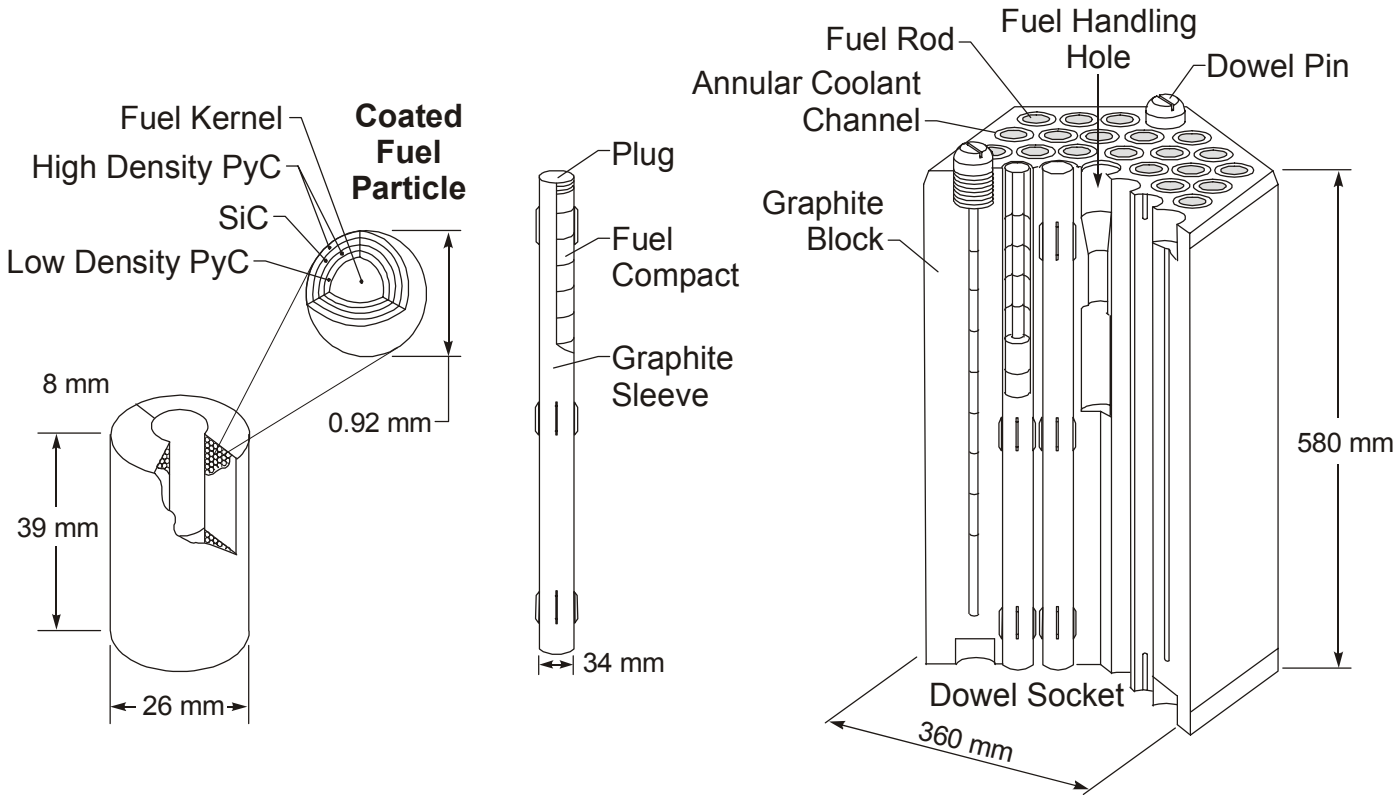
The AHTR Combines Two Technologies To Produce High-Temperature Heat

- Coated-particle, graphite-matrix fuel
  - Demonstrated temperature limit of ~1200ºC
  - Same fuel technology planned for modular high-temperature gas-cooled reactors
  - Compatible with molten fluoride salts
- Molten fluoride salt coolant (examples: (NaF/ZrF_4, $^7LiF/BeF_2$)
  - Very low pressure (boils at ~1400ºC)
  - Efficient heat transfer
    - Similar to that of water
    - Significantly higher reactor coolant exit temperatures for the same fuel temperature limits compared with helium
  - Coolant for proposed fusion energy plants
  - Developed for the Aircraft Nuclear Propulsion Program

The AHTR Uses Coated-Particle Fuel: Same Fuel As High-Temperature Gas-Cooled Reactors

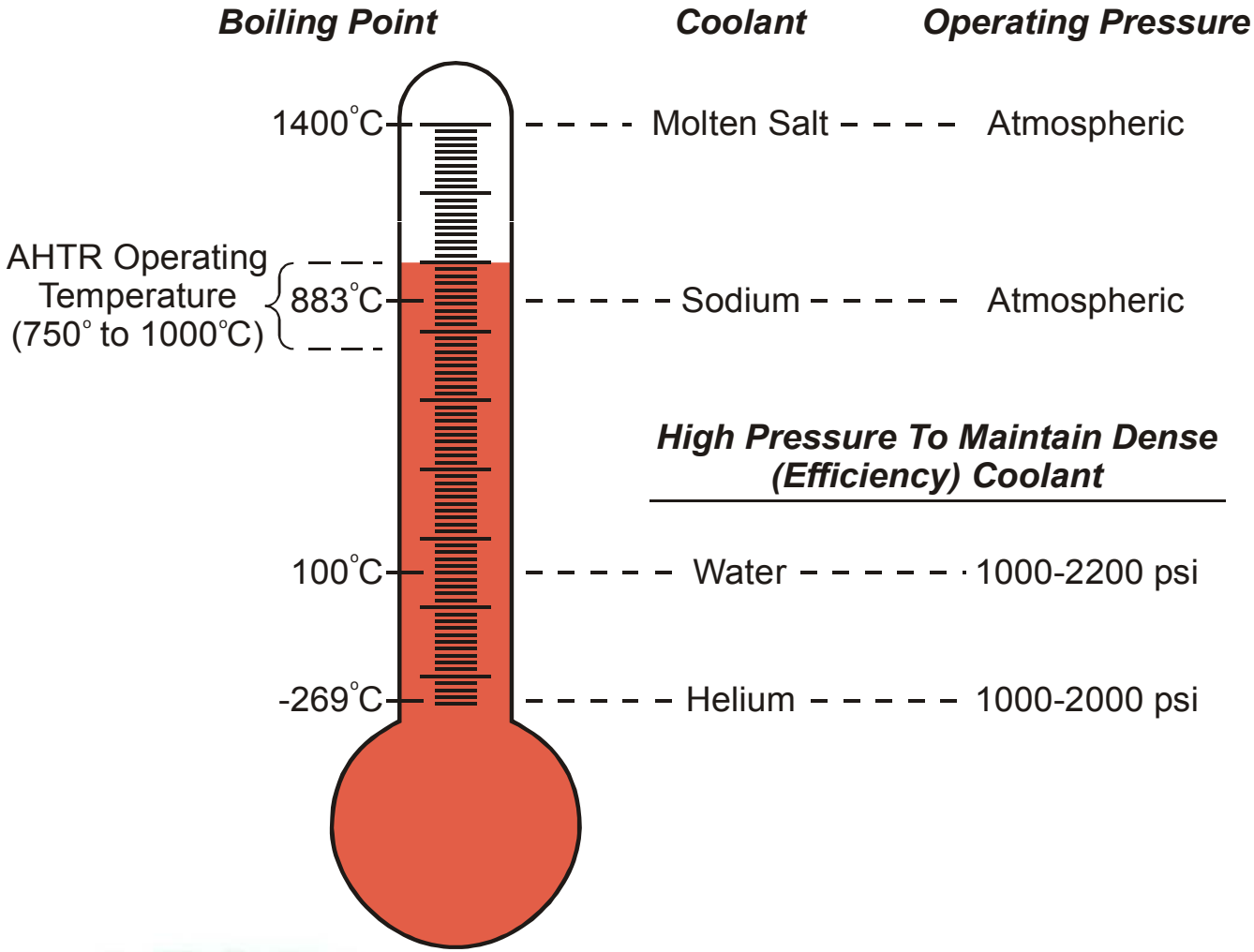
(Example: High-Temperature Engineering Test Reactor, 950ºC Helium Exit Temperatures; Japan)



Fuel Compact **Fuel Rod** **Fuel Block**

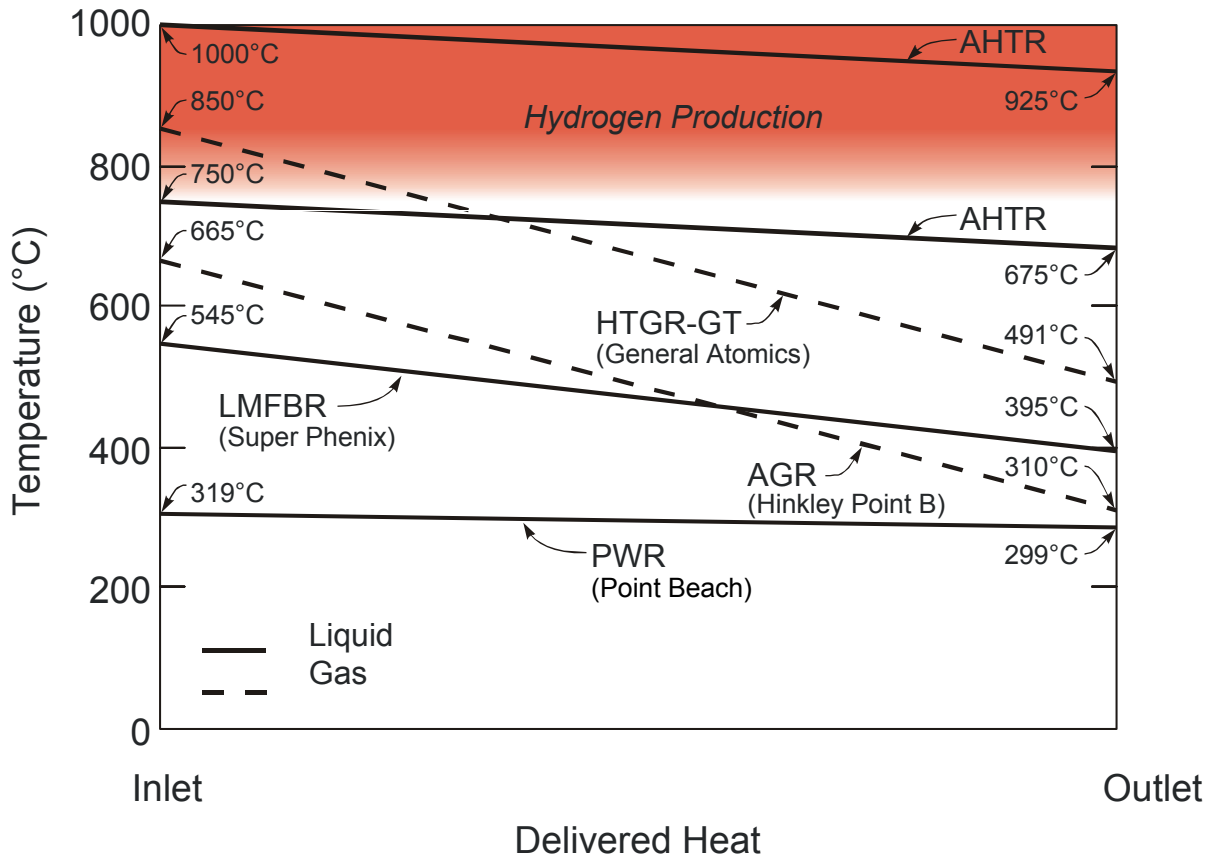
The AHTR Uses Molten Fluoride Salt Coolants: High-Temperature, Low-Pressure Coolants

(Developed for the 1950s Aircraft Nuclear Propulsion Program)



Liquid Coolants Deliver All The Heat At High Temperatures To Match H_2 Plant Requirements

(Pumping Losses Restrict the Capability of Gas Coolants)



The Safety Case for the AHTR: Accident Control

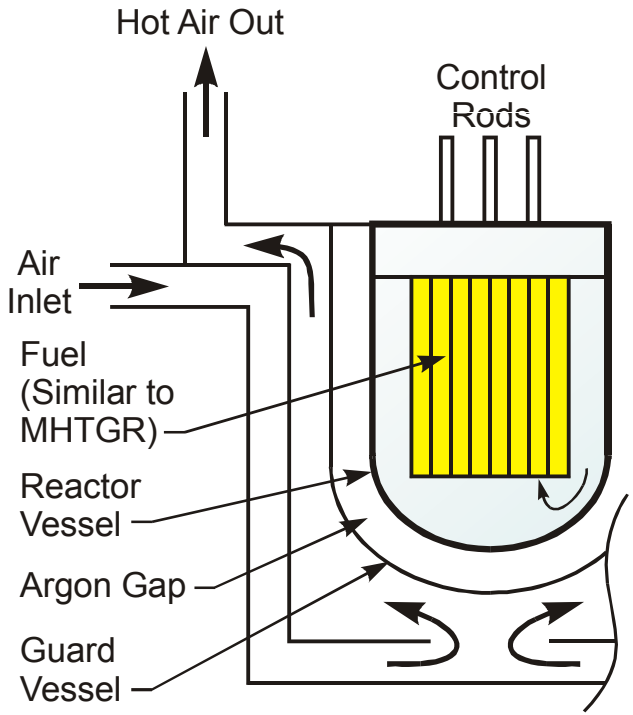
- Low-pressure (subatmospheric) coolant
  - Escaping pressurized fluids provide a mechanism for radioactivity to escape from a reactor during an accident
  - Low-pressure (<1-atm) salt coolant minimizes accident potential for radioactivity transport to the environment
- Molten salt is a secondary barrier to prevent radionuclide releases to the environment (fission products and actinides dissolved in salt)
- Passive decay-heat-removal systems similar to those of proposed modular liquid-metal reactors

The High-Temperature, Low-Pressure, Liquid Coolants Enable Passive Decay Heat Removal In Large Reactors

(AHTR Using Modular Liquid-Metal Reactor Decay-Heat System)

Passive Decay Heat Removal

Reactor



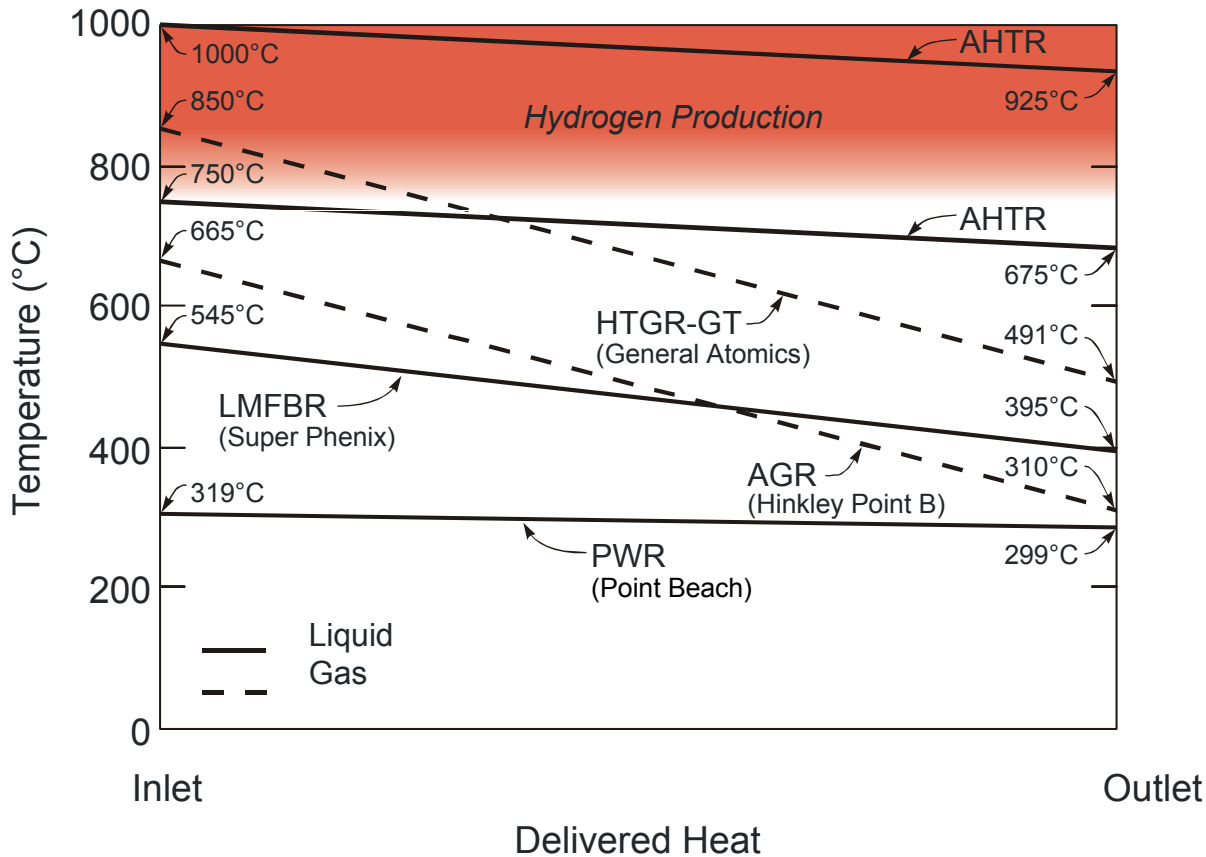
Decay-Heat Cooling System Characteristics

- 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(th))
  - AHTR: 750-1000°C (>2000 Mw(th))

Electricity Production

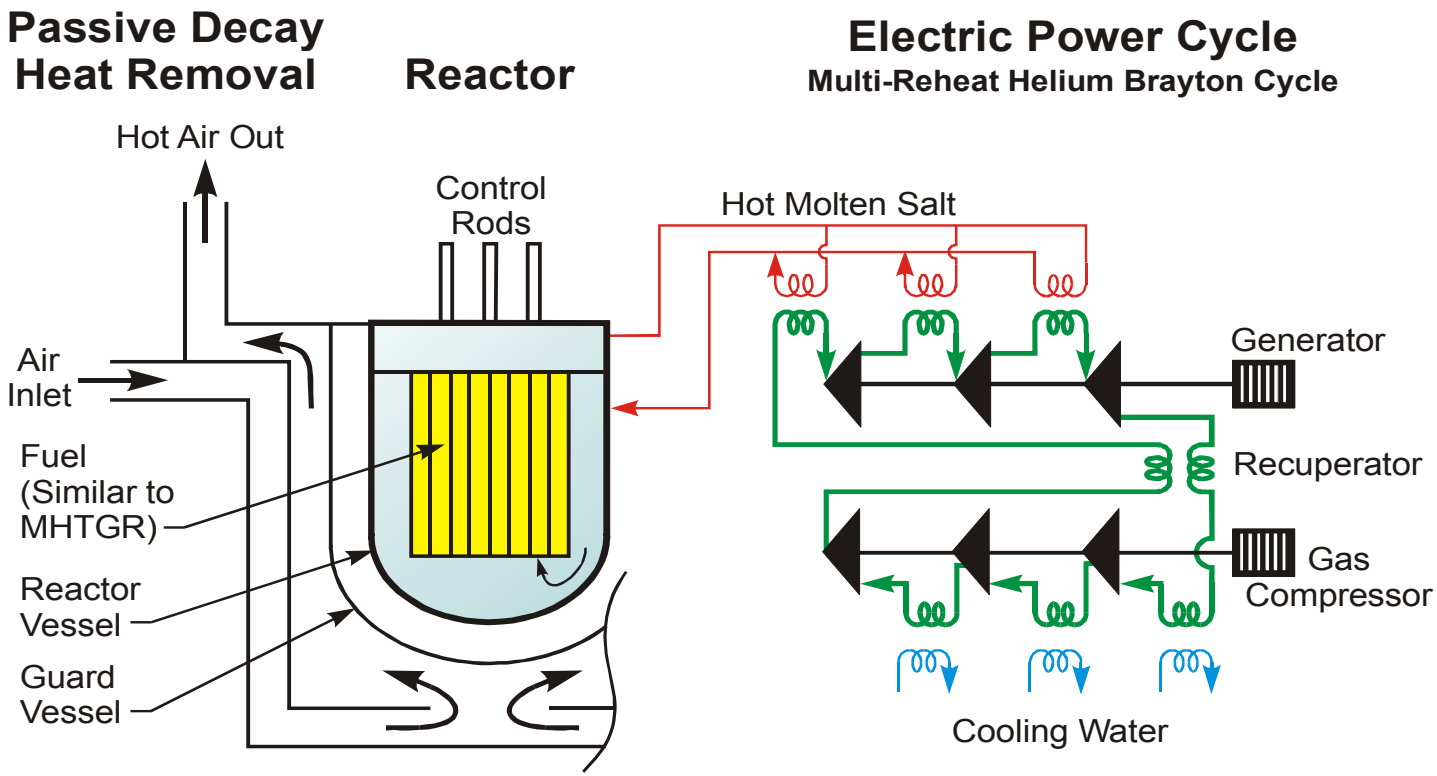
Efficient Hydrogen Production Implies Efficient Electricity Production

The Temperatures At Which Nuclear Heat Is Supplied Determines Electrical Plant Efficiency



AHTR High-Temperature Heat Enables Use of a Multi-Reheat Brayton Cycle With Efficient Electric Production

(48% at 750°C, 59% at 1000°C)



The AHTR Has the *Potential* for Excellent Economics Because It Is a Liquid-Cooled, Low-Pressure, High-Temperature Reactor

- Characteristics of AHTR for comparison
  - 1000 MW(e) [2000 MW(th)]
  - Passive decay-heat cooling
  - Gas-turbine power cycle
- Concept is new so no bottoms-up estimate is available
- Use relative comparisons
  - GT-MHR (General Atomics)
  - S-PRISM (General Electric)
  - LWR (Existing Technology)

Relative Comparison of the AHTR With the Gas-Turbine Modular Helium Reactor

- **GT-MHR**
  - 600 MW(th)
  - Size limited by passive decay heat cooling system
- **Common Components**
  - Fuel and fuel cycle
  - Gas-turbine power cycle
- **AHTR specific capital cost 70% of GT-MHR**
  - Larger size (2000 MW[th)) because of S-PRISM decay heat removal system (Liquid, low-pressure coolant)
  - Economics of scale using 0.7 scaling factor

Relative Comparison of the AHTR With the S-PRISM Liquid-Metal Fast Reactor

- S-PRISM
  - 380 MW(e) [1000 MW[th]) with 9 m vessel diameter
  - Size limited by passive decay heat cooling system
- Common Components
  - Low pressure liquid systems
  - Same basic passive decay-heat removal system
- Plant size of a 1000 MW(e) AHTR similar to a 380 MW(e) S-PRISM
  - S-PRISM vessel includes core and heat exchangers; AHTR includes only the core (no intermediate loop)
  - Higher temperatures allows same size decay-heat cooling system (controls vessel size)
  - Liquid coolant allows AHTR power density between gas-cooled and liquid-metal-cooled reactor

Relative Economic Comparison of the AHTR With A Light Water Reactor

- **LWR**
  - 1000 MW(e) [3000 MW[th])
  - Steam cycle
- **AHTR Areas of improved economics**
  - Passive decay heat removal
  - Higher efficiency (smaller power cycle, smaller decay heat cooling system, smaller cooling towers, etc.)
  - Lower cost gas-turbine cycle (higher power density with much smaller equipment)

Conclusions

- Large, growing hydrogen demand
- Hydrogen may be the biggest use of nuclear energy by mid-to-late century (depends upon vehicle fuel cells)
- Efficient H_2 production places major demands on the reactor
- The AHTR is designed to match H_2 production requirements
- AHTR characteristics derive from use of a *high-temperature, low-pressure coolant*