Hydrogen Production Using The Advanced High-Temperature Reactor

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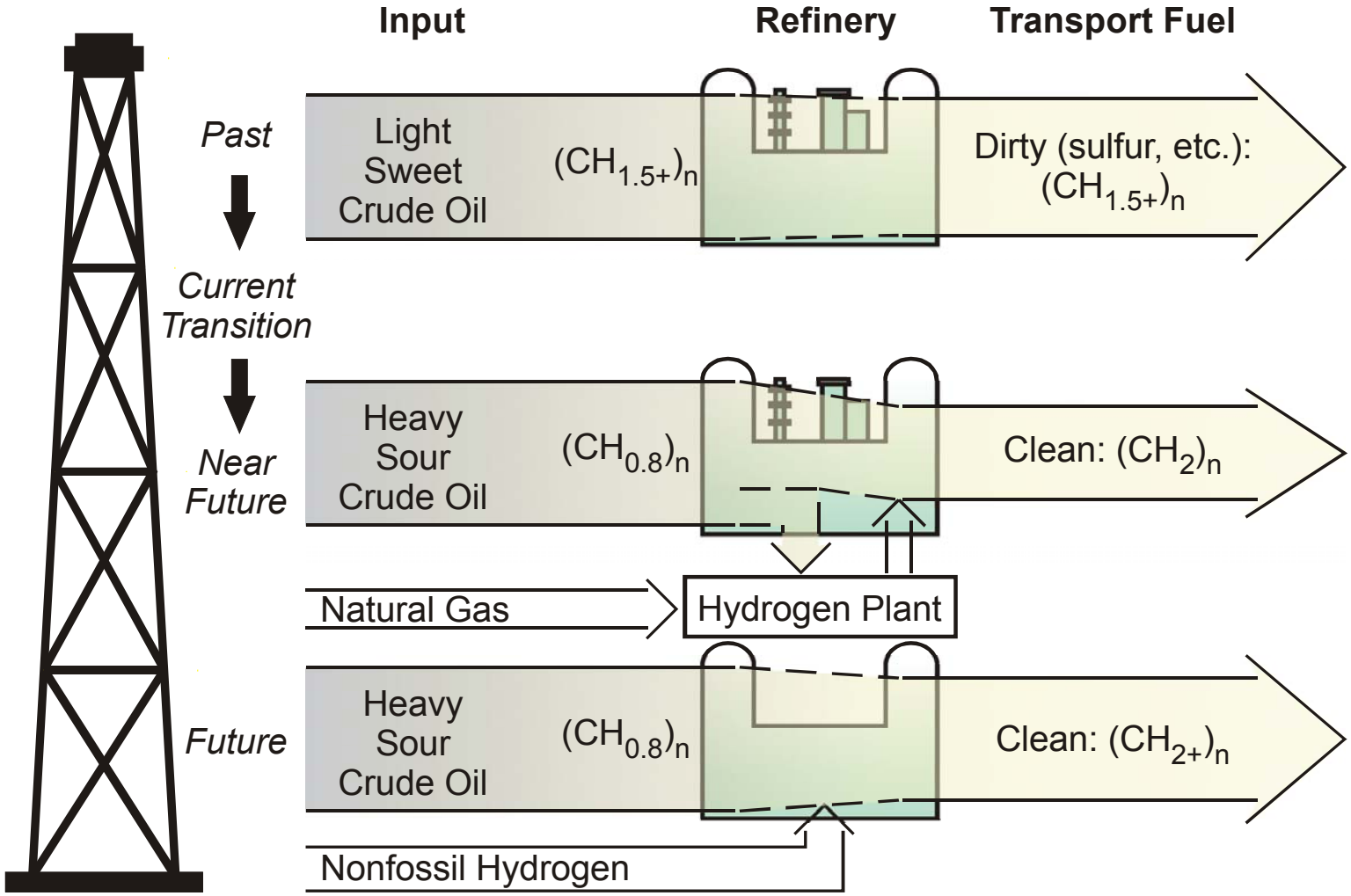
Hydrogen Demand and Nuclear Energy

The size of individual hydrogen production plants and the total market demand for hydrogen are sufficient to justify development and use of nuclear reactors for hydrogen production

Liquid Fuels Production Is Rapidly Becoming the Major Market for Hydrogen



Nuclear Energy Is Now Compatible with Hydrogen Production Because of the Growth in the Size of Hydrogen Production Facilities

Plant Size

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

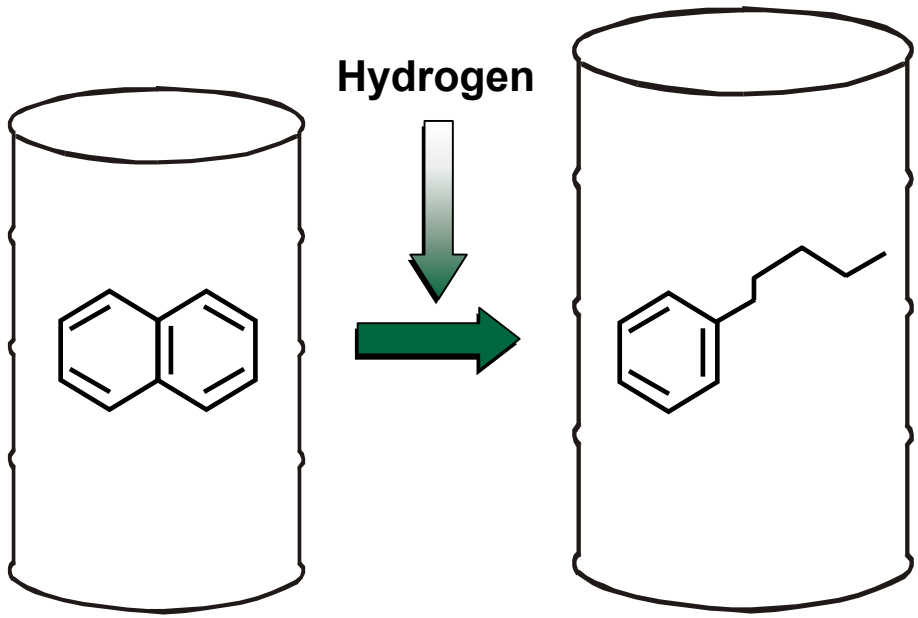
Time

Nuclear Reactor

600–4000 MW(t)

Addition of Hydrogen Can Increase Liquid Fuel Yields per Barrel of Oil by Up to 15%

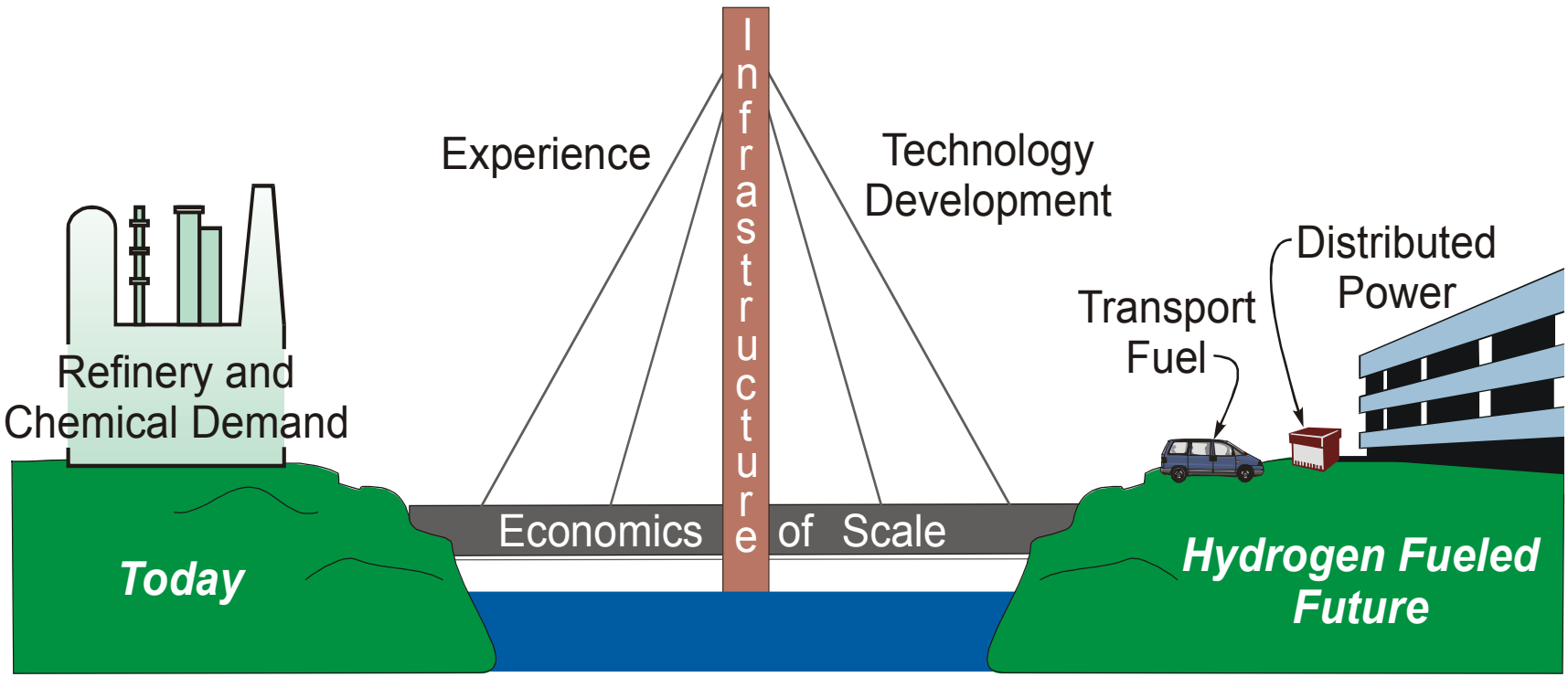
(Potential Nuclear-Hydrogen Midterm Market with a Hydrogen Source Not Coupled to Oil Prices)



Benefits

- Lower imports
- Reduced CO_2
- Reduced NO_X
- Reduced sulfur
- Reduced diesel particulate

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



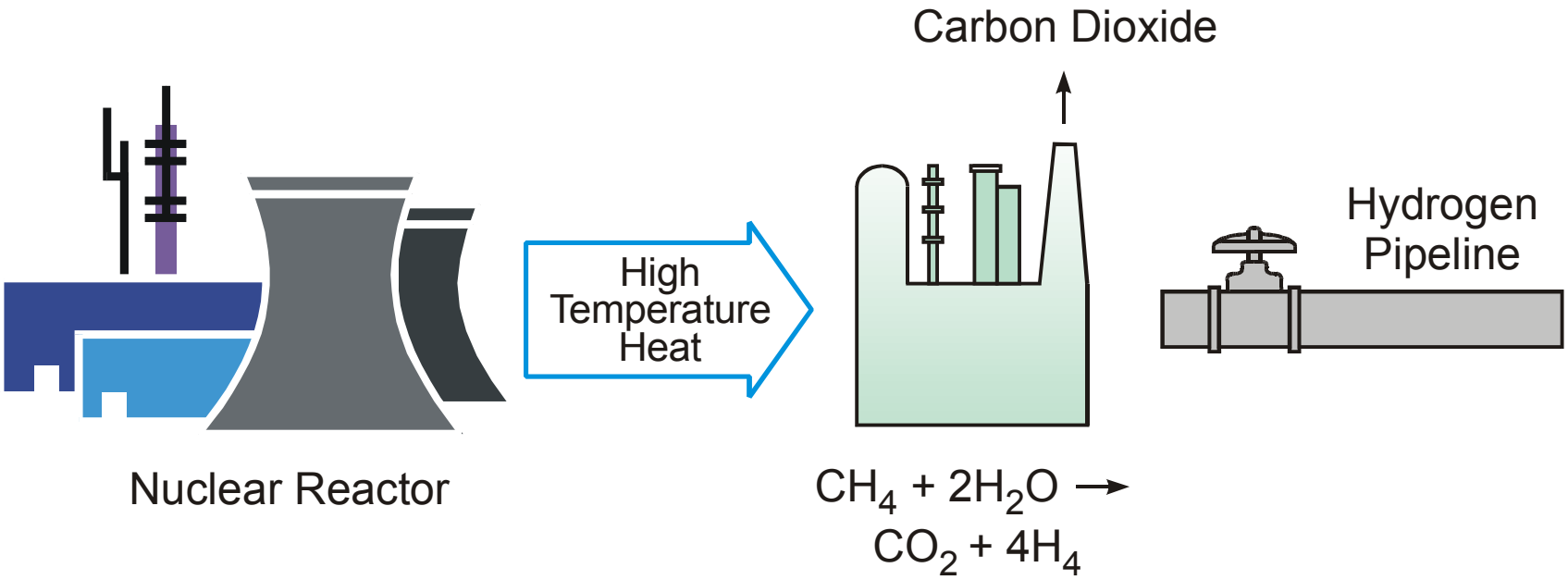
Methods to Make Hydrogen Using Nuclear Energy
(Reactor Provides High-Temperature Heat)

Nuclear-assisted steam reforming of natural gas

Thermochemical cycles

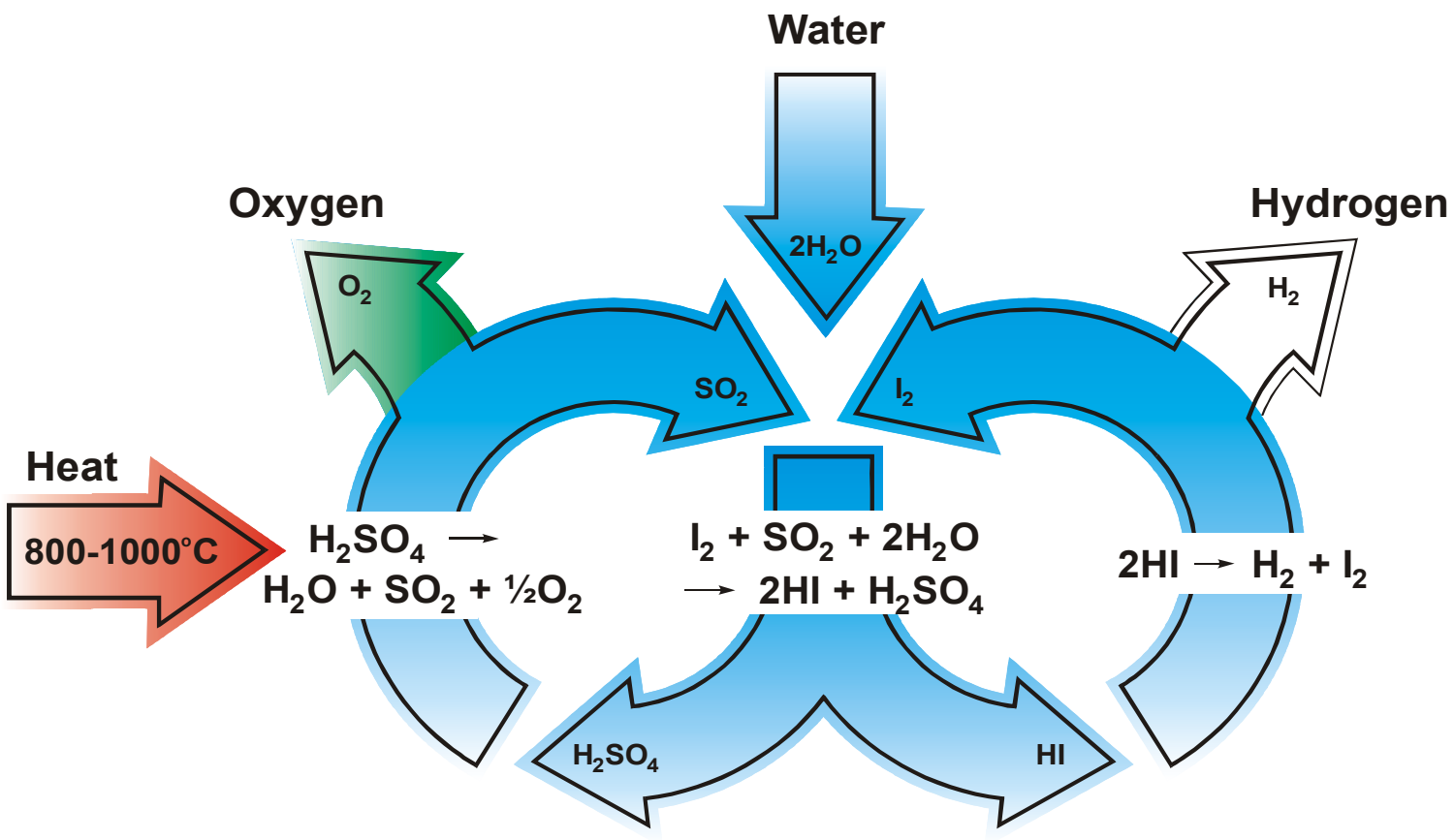
Nuclear-Assisted Steam Reforming of Natural Gas Uses Nuclear High-Temperature Heat (~800°C) to Reduce the Energy Requirements for Hydrogen Production

(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)



Efficient Hydrogen Production Imposes Tough Requirements on the Reactor

- Economics: match expected H_2 plant size
  - Largest H_2 plants on order: 300 million ft^3/d
  - Required nuclear heat (50% efficiency): 2400 MW(t)
- 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

Advanced High Temperature Reactor

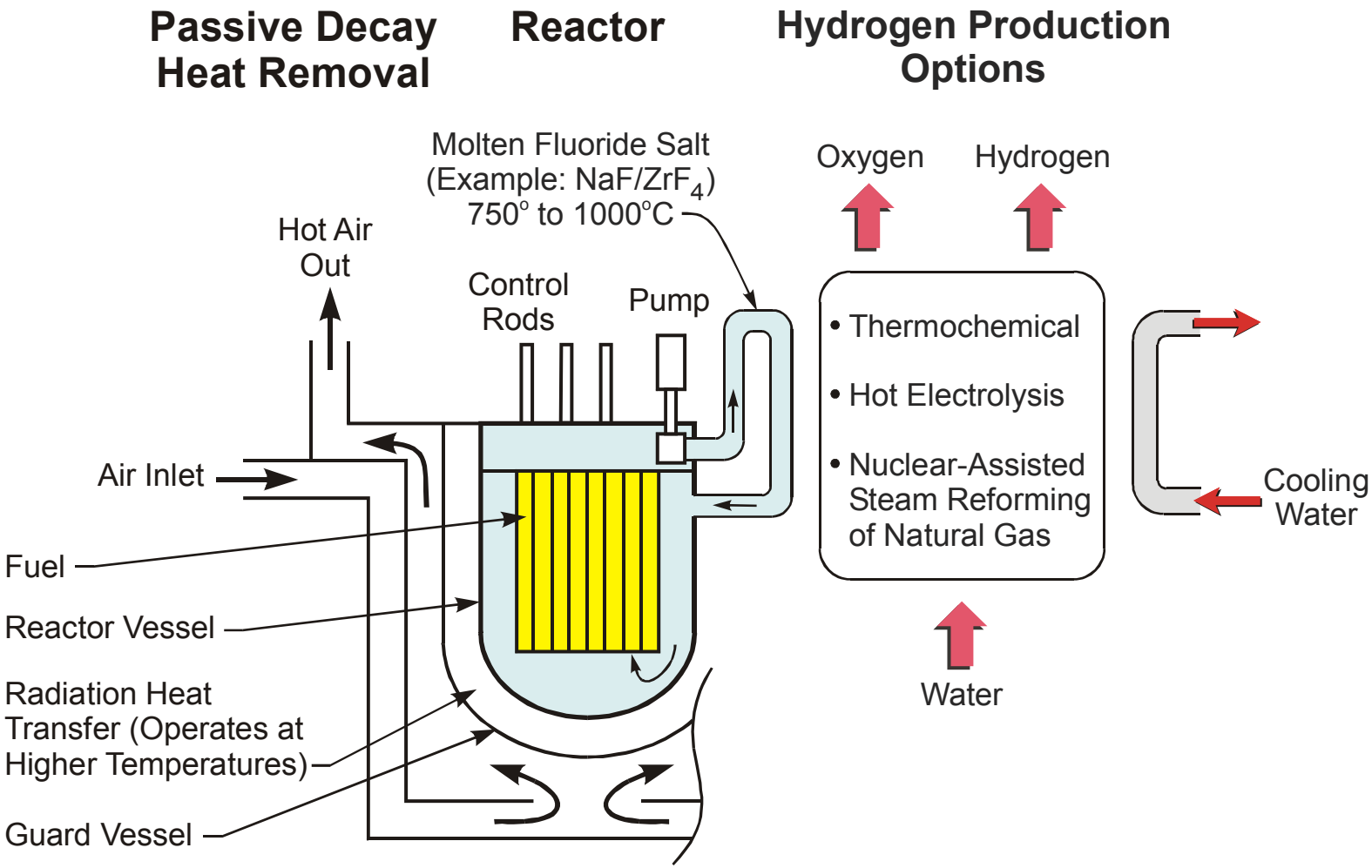
Hydrogen Production Requirements

Define Reactor Requirements, Which, in Turn, Define Viable Reactor Options

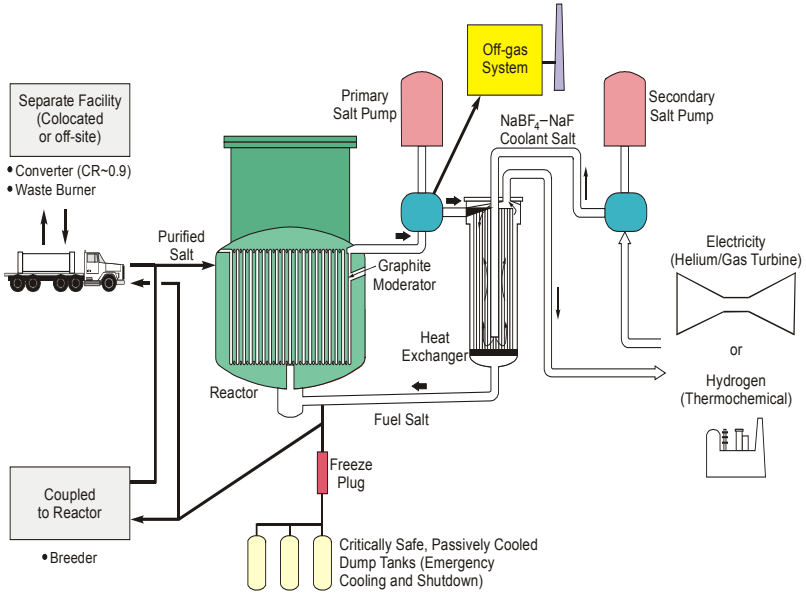
Status of Advanced High-Temperature Reactor

- New reactor concept
  - Concept ~2 years old
  - Limited work
  - Large uncertainties
- Working with:
  - U. of California (Berkeley): Per Peterson
  - Sandia National Laboratory: Paul Pickard

Advanced High-Temperature Reactor

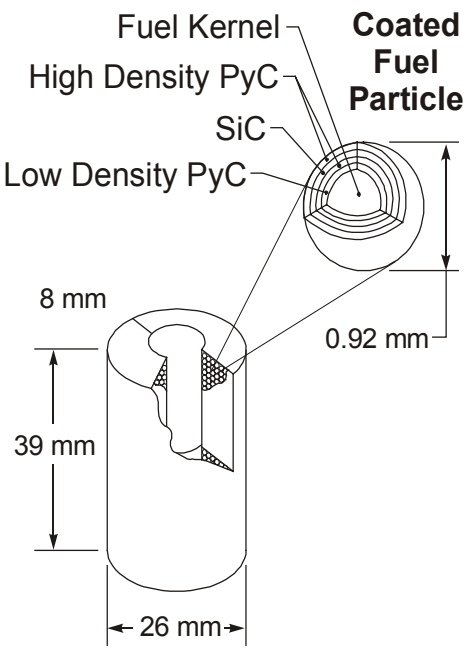


The AHTR Is NOT a Molten Salt Reactor (MSR)

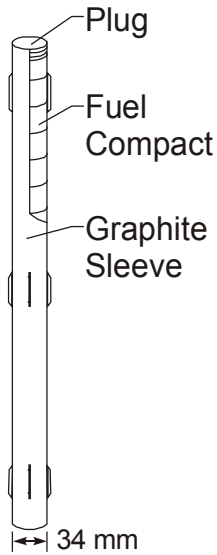


- **MSR**
  - **Fuel dissolved in the molten salt**
  - **Aircraft Reactor Experiment operated at 815 °C**
- **AHTR**
  - **Solid fuel**
  - **Molten salt coolant**
  - **Uses MSR experience**

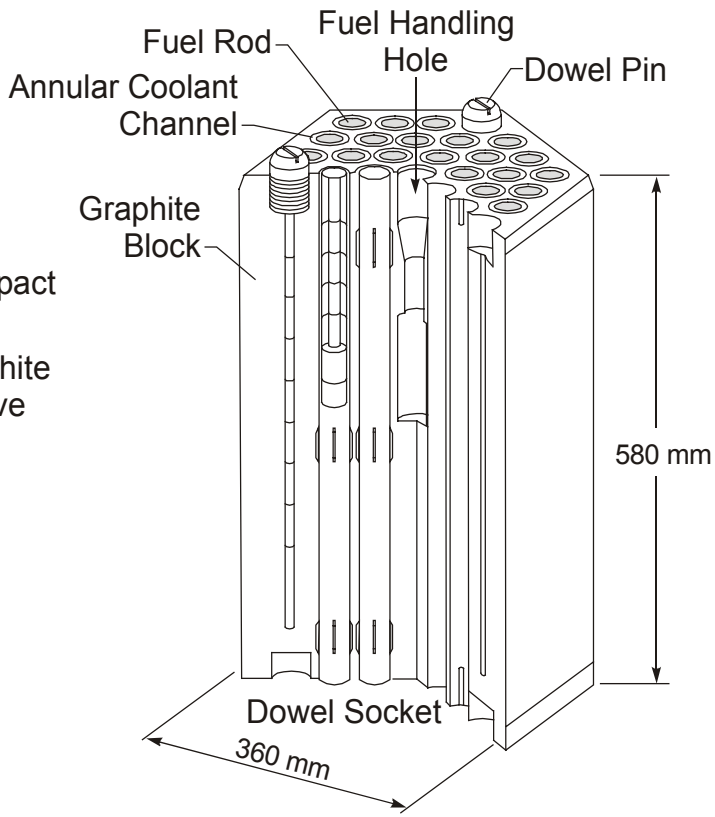
The AHTR Uses Graphite-Matrix Coated-Particle Fuels: Only Proven Fuel That Operates at Required Temperatures for Hydrogen Production



Fuel Compact



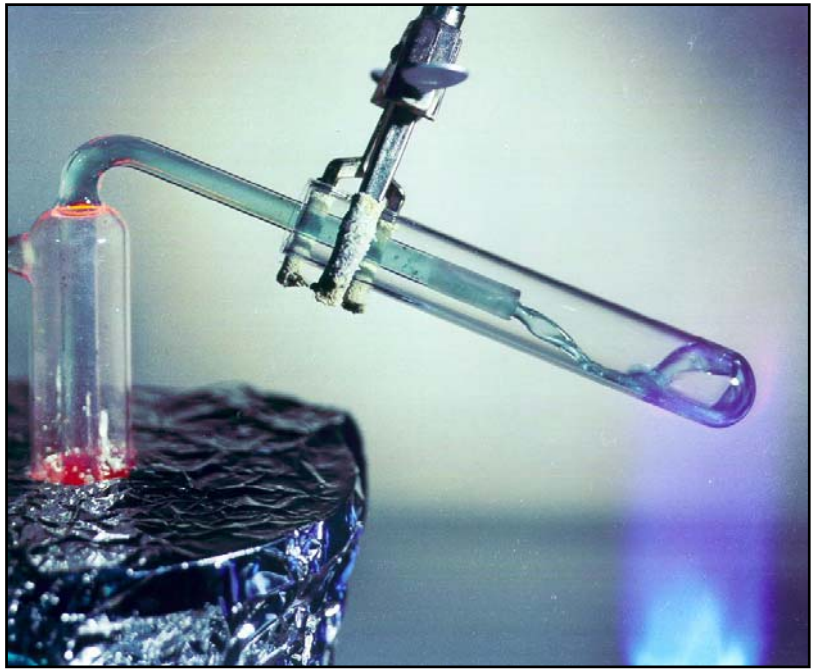
Fuel Rod



Fuel Block

AHTR Molten Salt Reactor Technology Was Developed in the Aircraft Nuclear Propulsion Program with Test Reactor Operations at 860°C

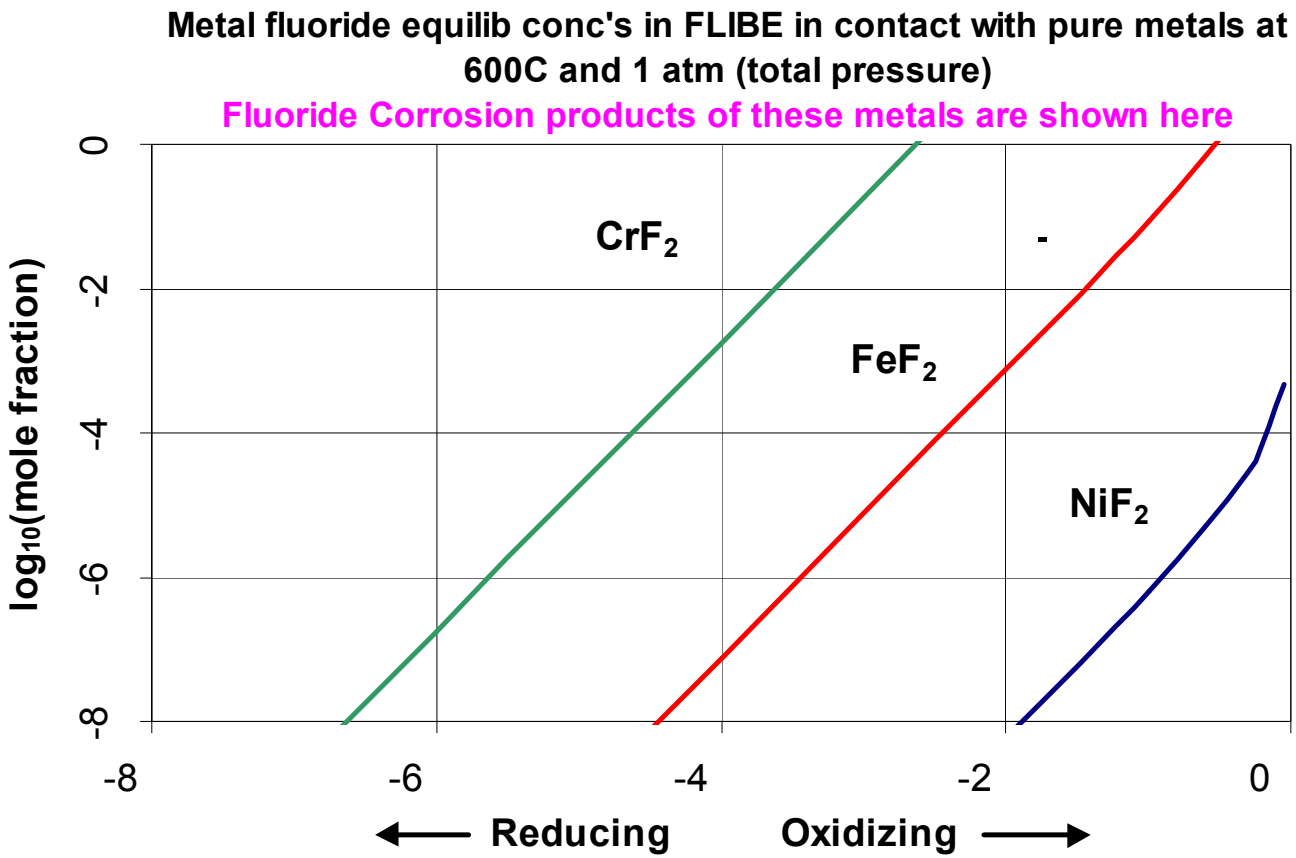
(Aircraft and Hydrogen Reactor Requirements Similar : High Temperature and Low Pressure; Current Molten Salt Coolant Interests: AHTR and Fusion Reactor Cooling)



Molten Fluoride Salts Are Compatible With Graphite-Based Fuels

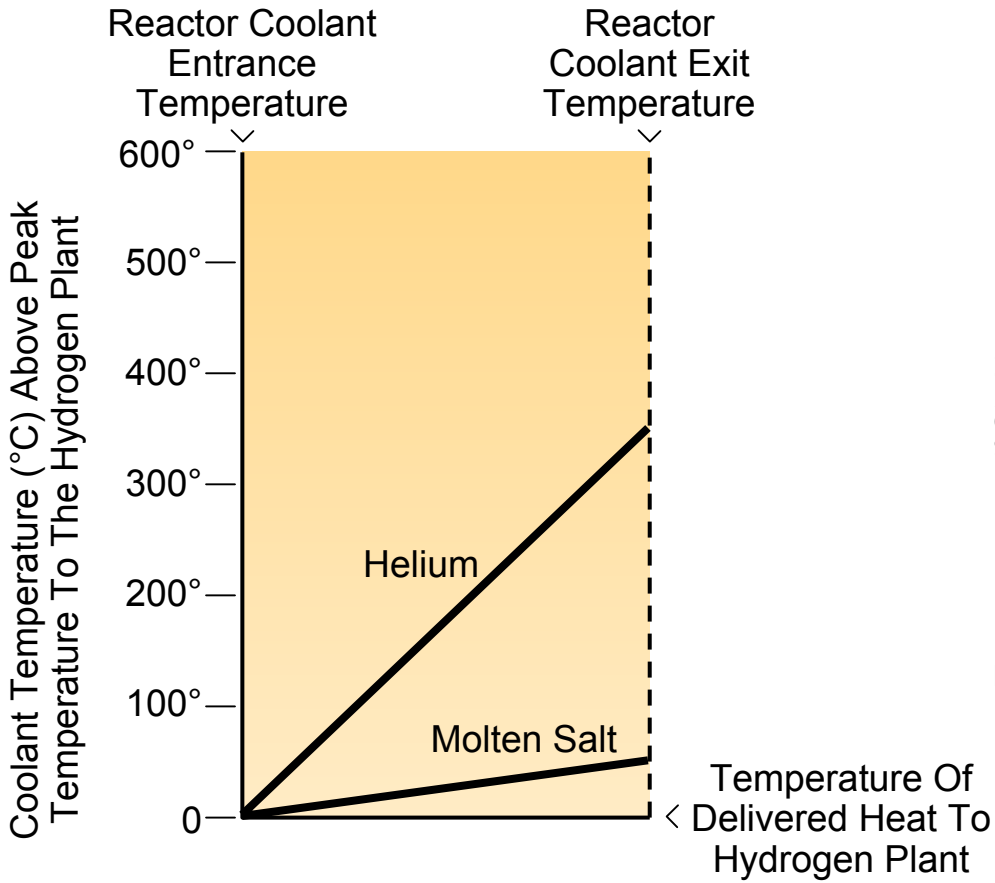
- Molten Salt Reactor Experiment showed that salt and graphite are compatible
- Industrial experience
  - Hall aluminum production since 1890s
  - Graphite baths
  - AlF_3/NaF_3 salt
  - 1000°C

The Reactor Metals of Construction Are Noble With Respect to Metal Corrosion by Control of the Molten Salt Redox Potential

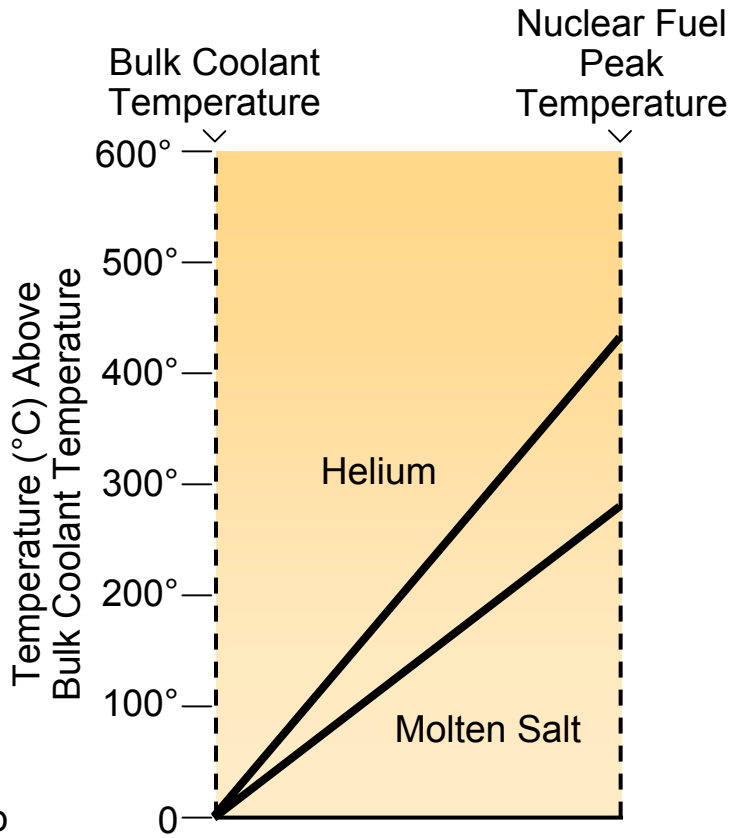


The AHTR Reduces Reactor Temperatures Compared to Gas-Cooled Reactors For Heat Delivered at the Same Temperatures

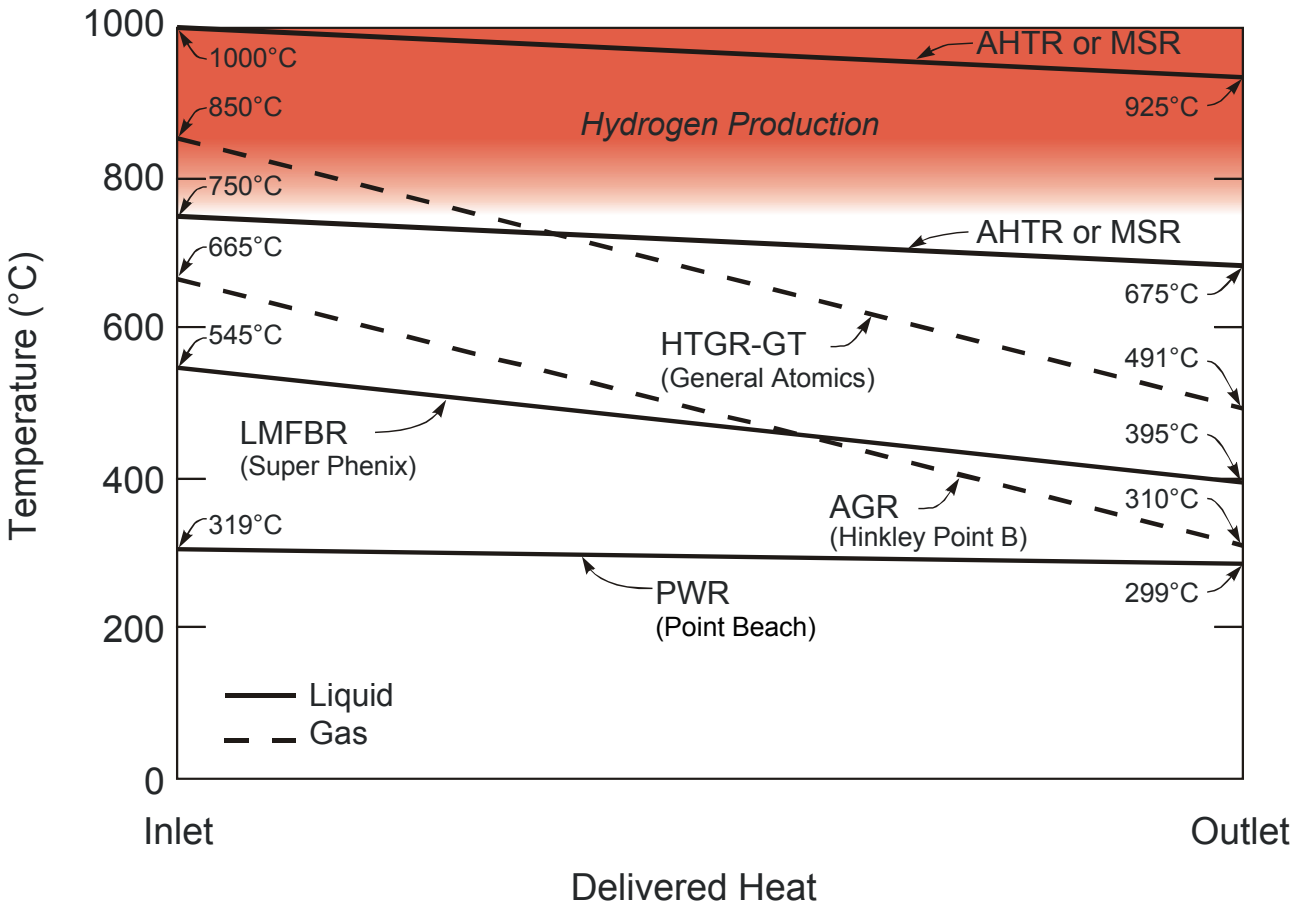
Bulk Coolant Temperature Rise Across Reactor



Temperature Rise From Coolant To Fuel Centerline



Power Reactor Experience Shows That Liquid Coolants Minimize Peak Reactor Temperatures

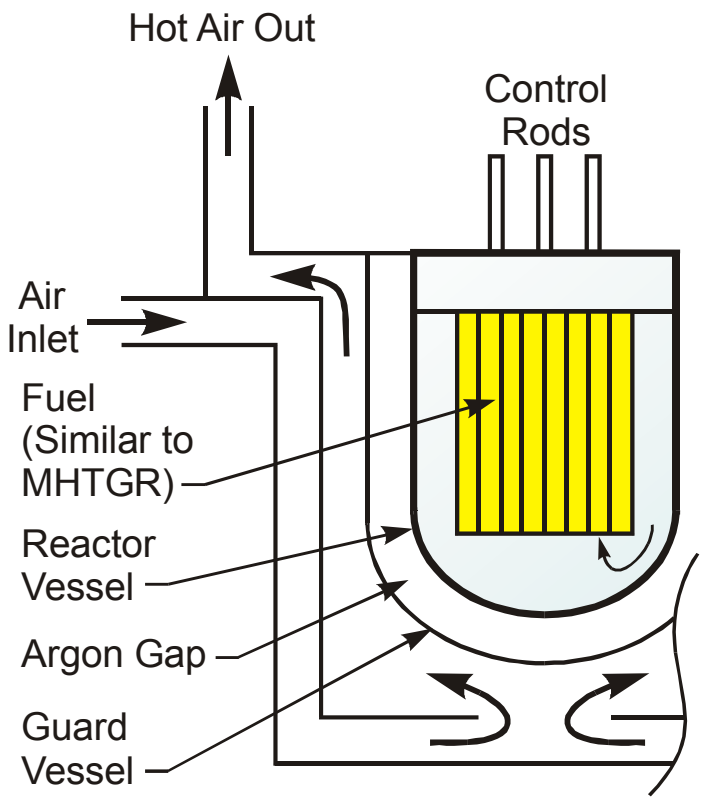


The High-Temperature, Low-Pressure Liquid Coolant Enables Passive Decay Heat Removal in Large Reactors

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

Passive Decay Heat Removal

Reactor

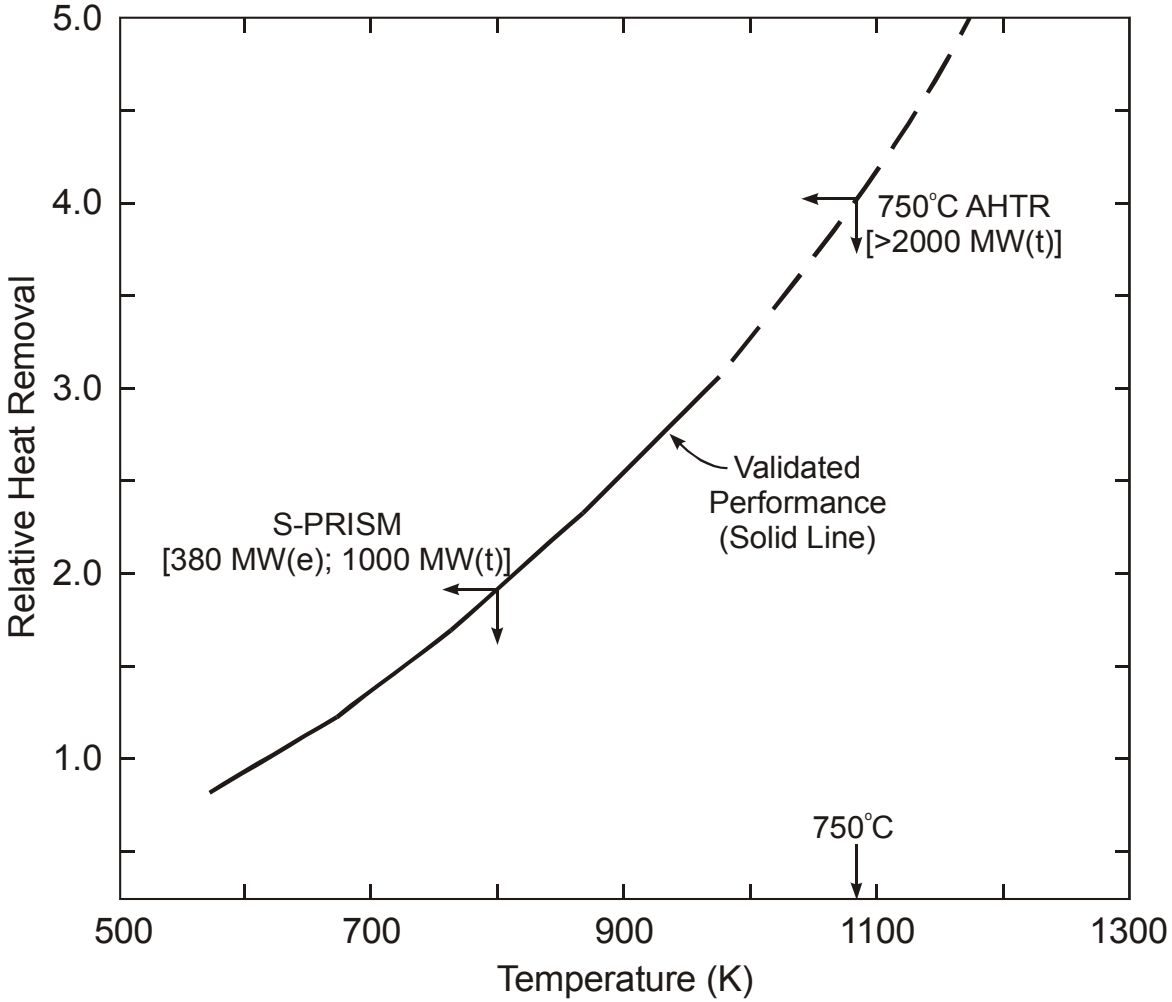


Decay-Heat Cooling System Characteristics

- 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)]

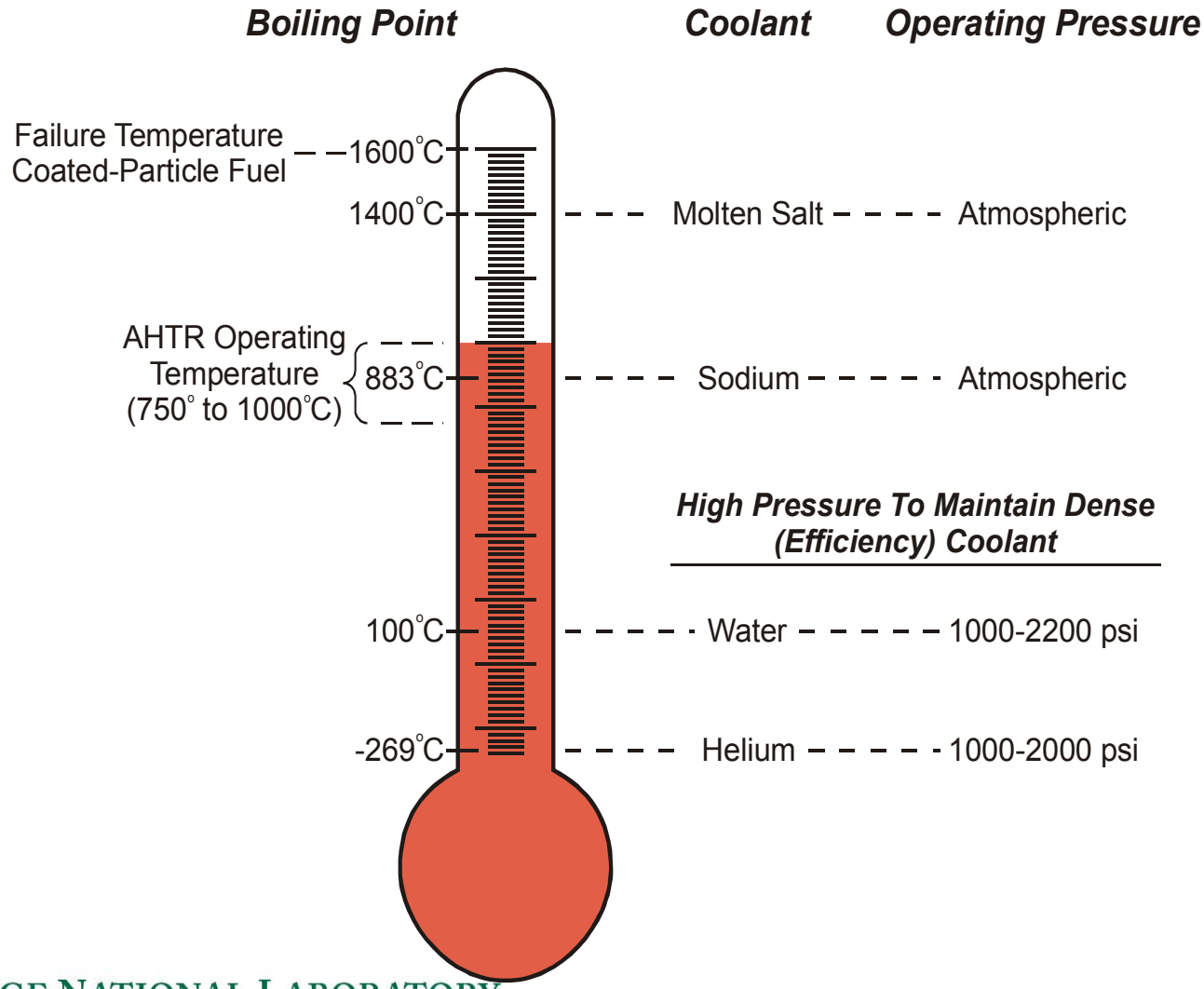
Higher Temperatures of the AHTR Allow Much Larger Reactors with the Same Size Systems

(S-PRISM and AHTR with Identical 9-m Vessels)

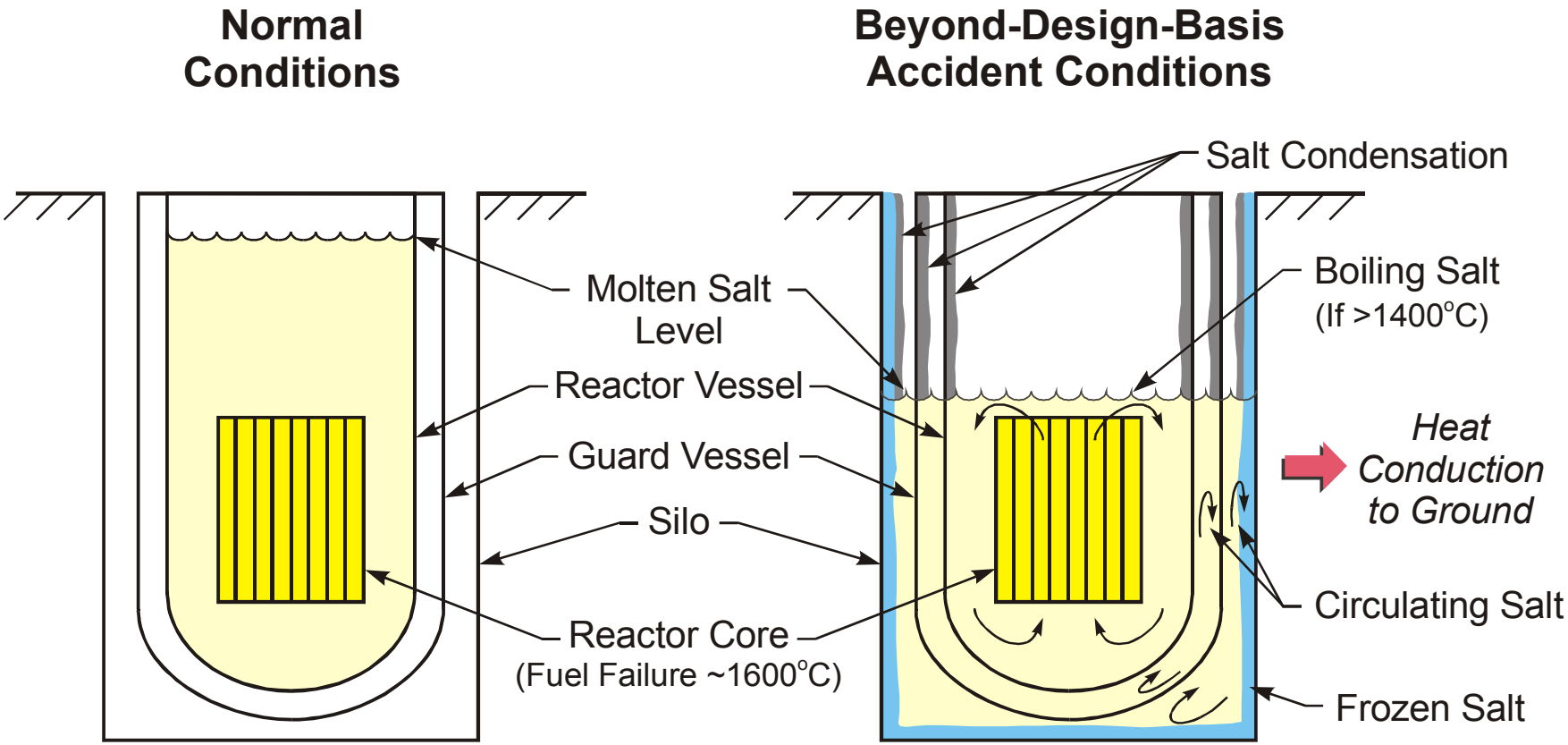


Safety Strategy for Beyond Design-Basis Accidents

Molten Salts Have Large Margins to the Boiling Point and Boil-Off Before Major Fuel Failure



Beyond-Design-Basis Accident Avoids Radionuclide Release By Decay Heat Conduction-To-Ground

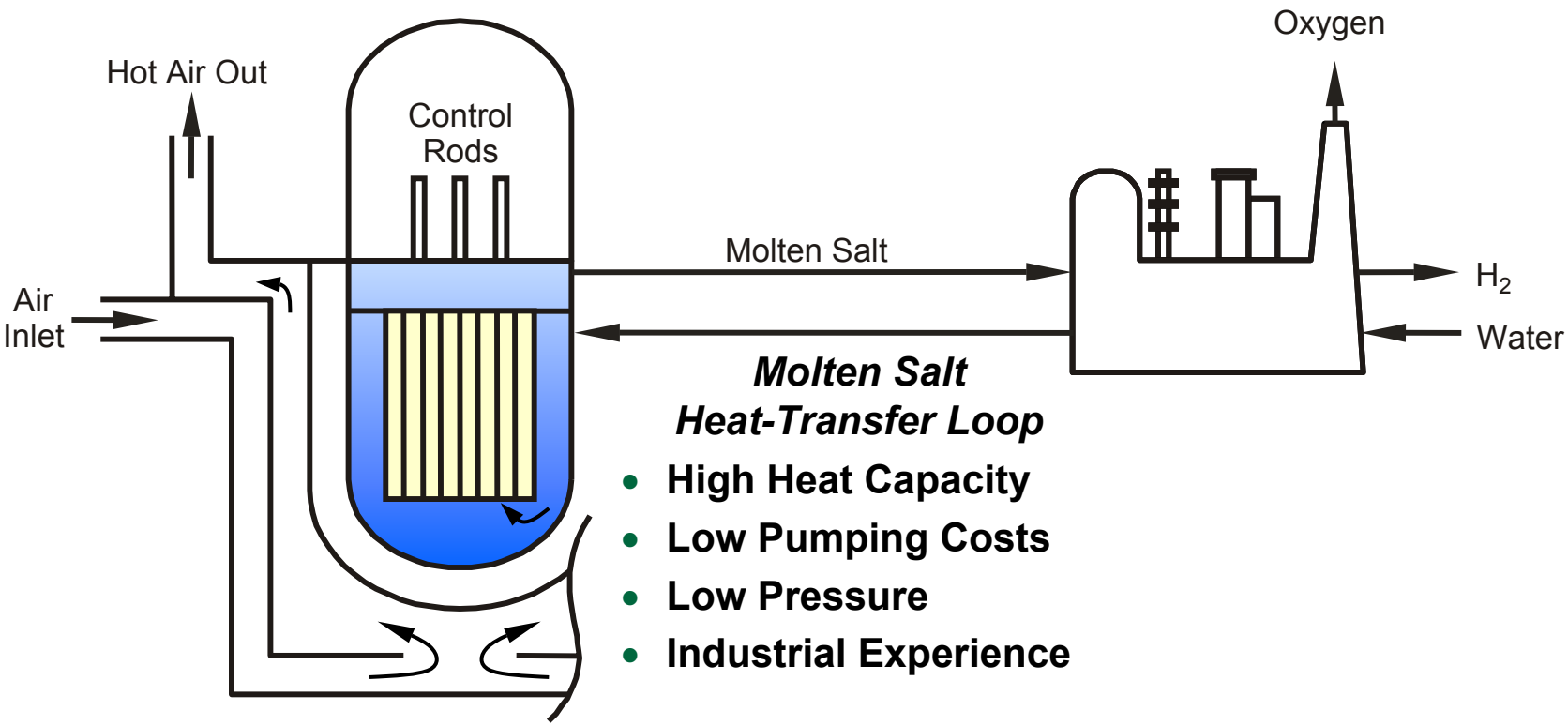


AHTR Hydrogen and Electricity Interfaces

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

Nuclear Safety by Isolation

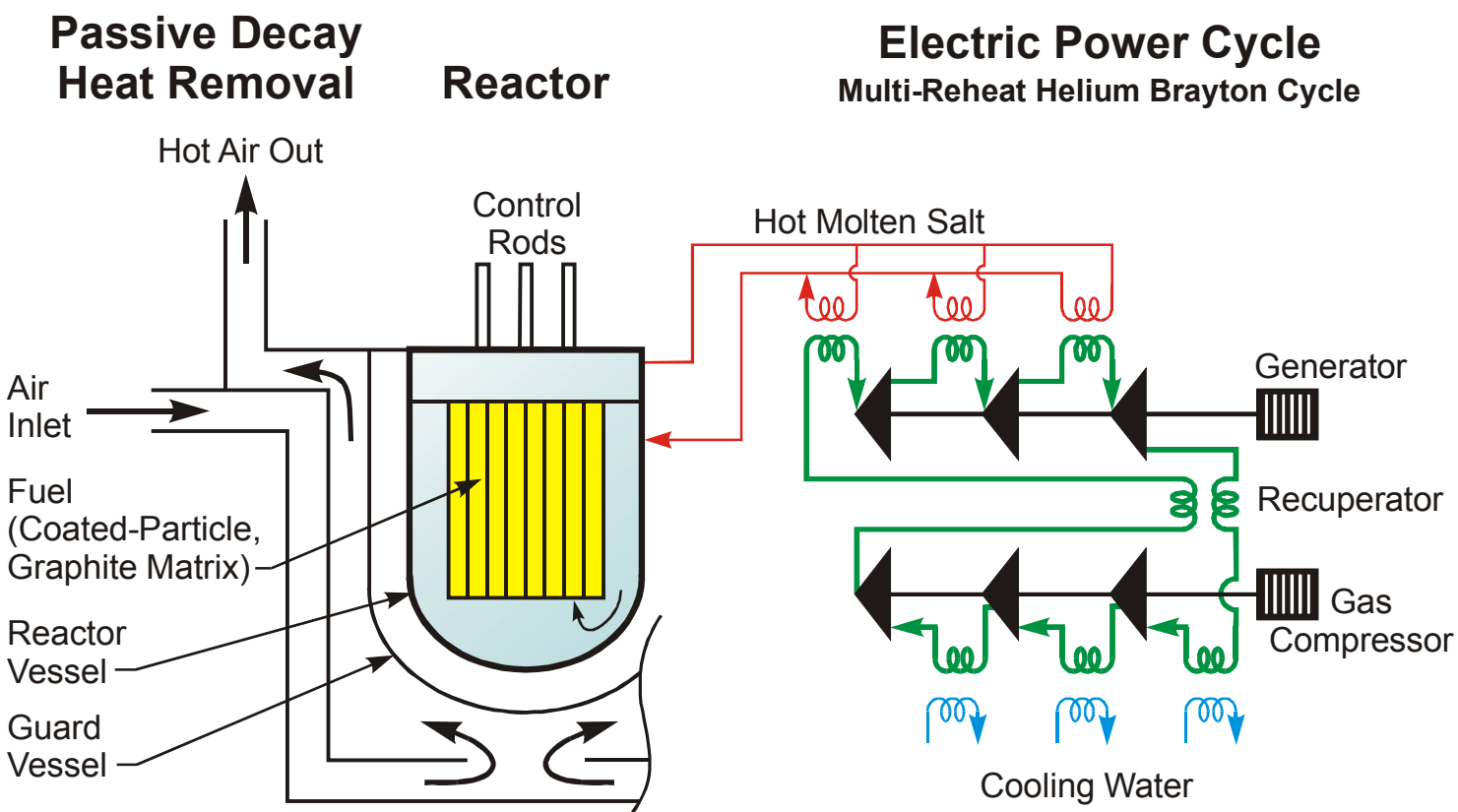
Hydrogen Safety by Dilution



Molten Salt Heat-Transfer Loop

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

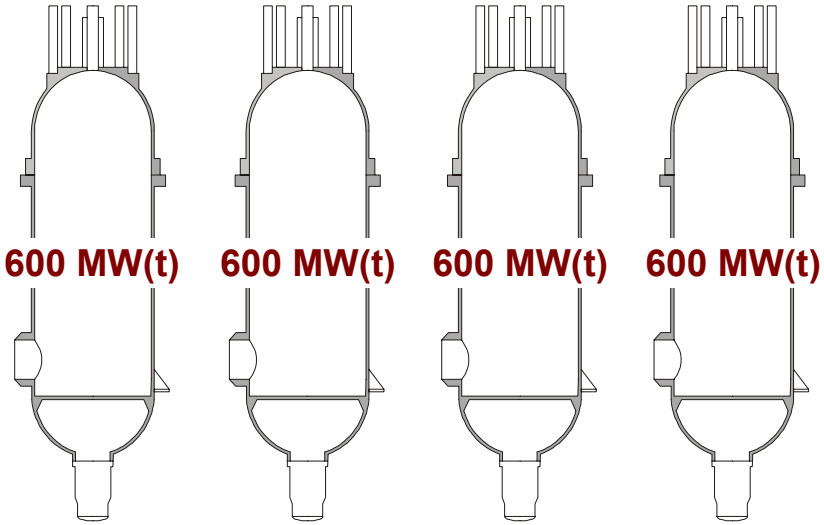
The AHTR Uses a Multi-Reheat Brayton Cycle for High-Efficiency Electricity Production



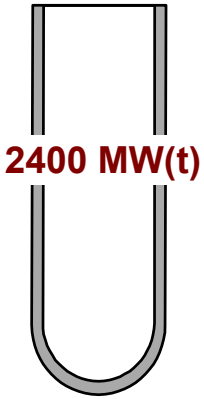
Efficiency
- 48% at 750° C
- 56% at 750° C
- 59% at 1000° C

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

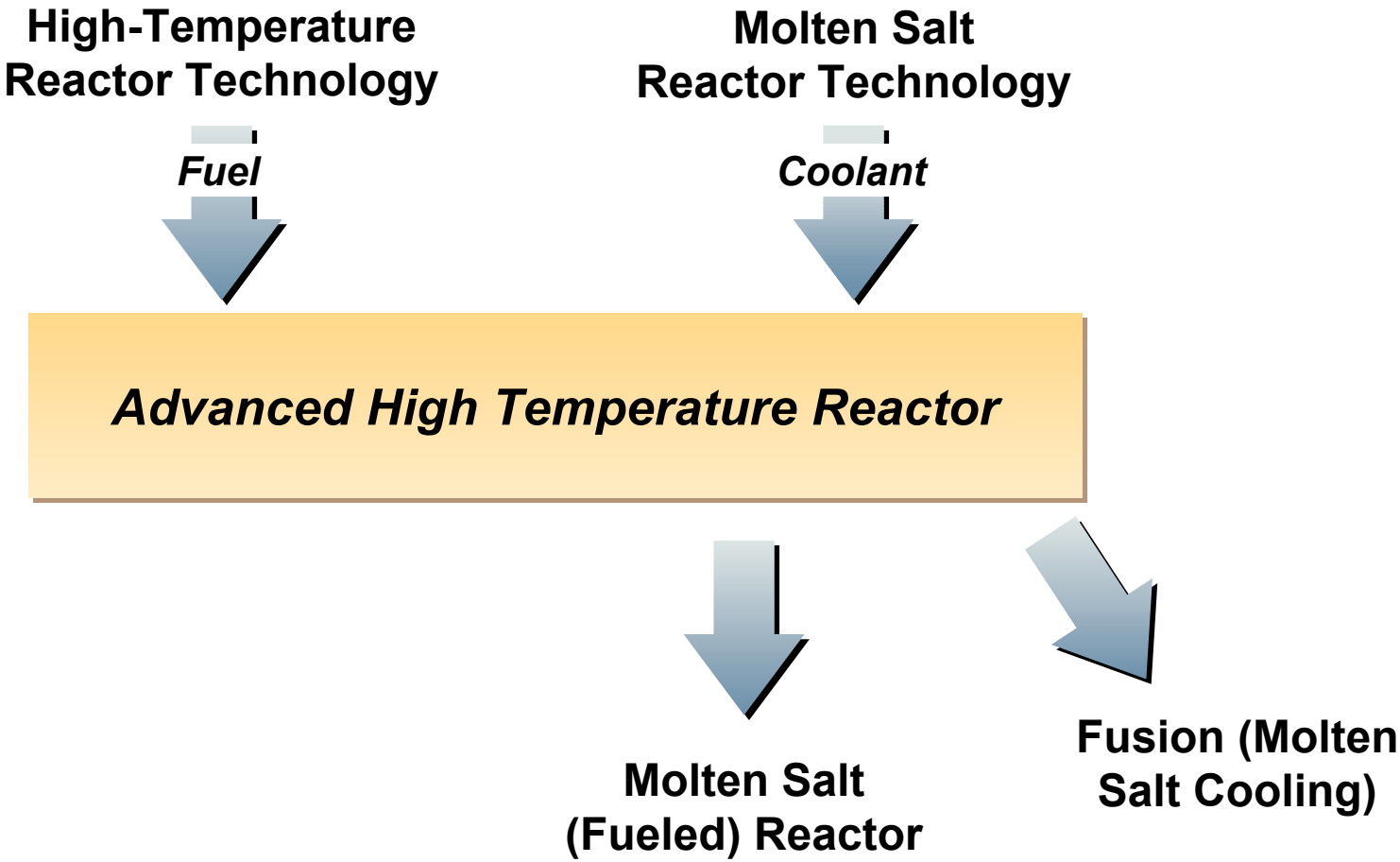


Low-Pressure Vessel For 2400 MW(t) of AHTR

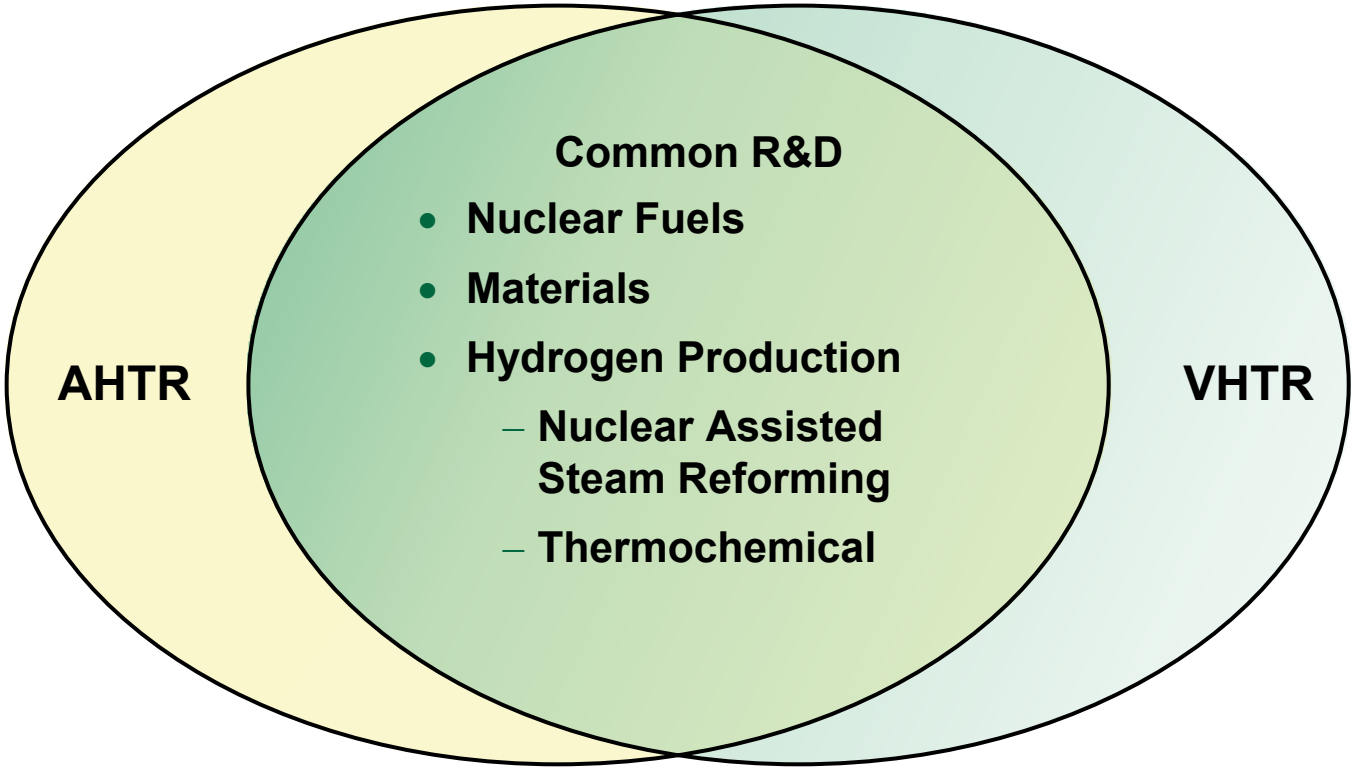


Programmatic Considerations

The AHTR Combines Existing Technologies While Supporting Future Technical Options



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



Conclusions

- Growth in hydrogen demand and plant size makes nuclear hydrogen a realistic possibility
- Making hydrogen is tough
- Reactor design should match requirements
- The AHTR is a potentially competitive option
  - New concept (~2 years)
  - Potentially attractive economics
  - Many design variants not evaluated
  - Major uncertainties
- Characteristics of an AHTR program
  - Based on coated particle (gas-cooled reactor) fuel
  - Develops technology for MSR

Molten Salt Options

- Choice of molten fluoride salt is dependent upon multiple factors
  - Neutronics
  - Economics
  - Melting points (mixtures lower melting points)
- Different fluoride salts have somewhat similar properties
- Leading candidates
  - $NaF\text{-}ZrF_4$ (50%/50%): used in Aircraft Reactor Experiment—experimental test reactor
  - $NaF\text{-}RbF\text{-}ZrF_4$ (8%/50%/42%)
  - $^{7}Li_2BeF_4$