Advanced High-Temperature Reactor for Hydrogen and Electricity Production

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Outline

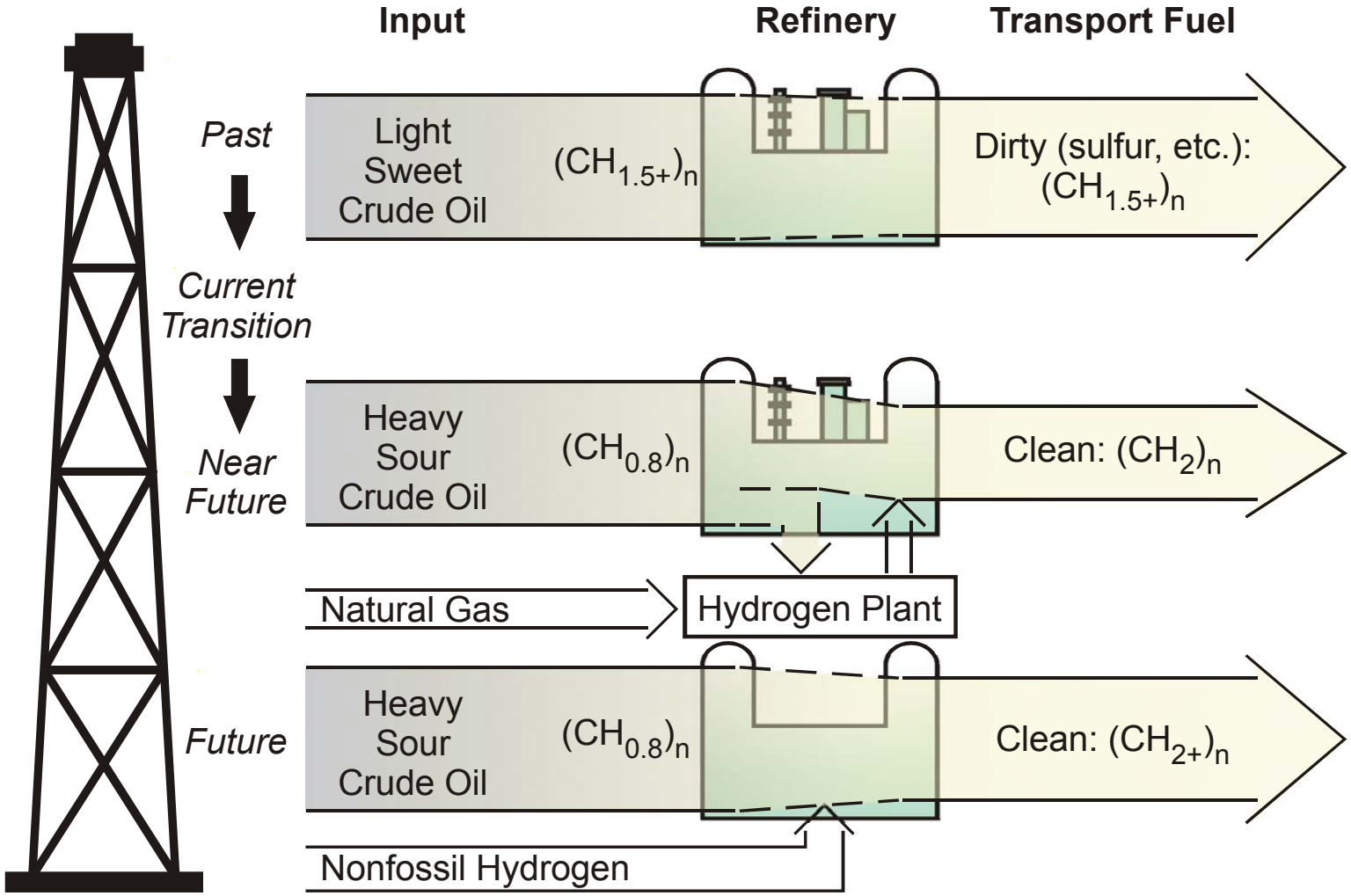
- Hydrogen production may be the future of nuclear energy
- Methods to make hydrogen using nuclear energy are required; however, making hydrogen is tough
- Advanced High-Temperature Reactor (AHTR)
- Design issues
- Conclusions

Advanced High-Temperature Reactor

- New concept: 2 years old
- Designed for hydrogen production
- Capable of efficient electricity production
- Based on two other technologies
  - High-temperature gas-cooled reactors (HTGRs)
  - Molten salt reactors
- Cooperative effort with Sandia National Laboratories and Univ. of California (Berkeley)

Hydrogen Production May Be the Future of Nuclear Energy

Liquid Fuels Production Is Rapidly Becoming the Major Market for Hydrogen

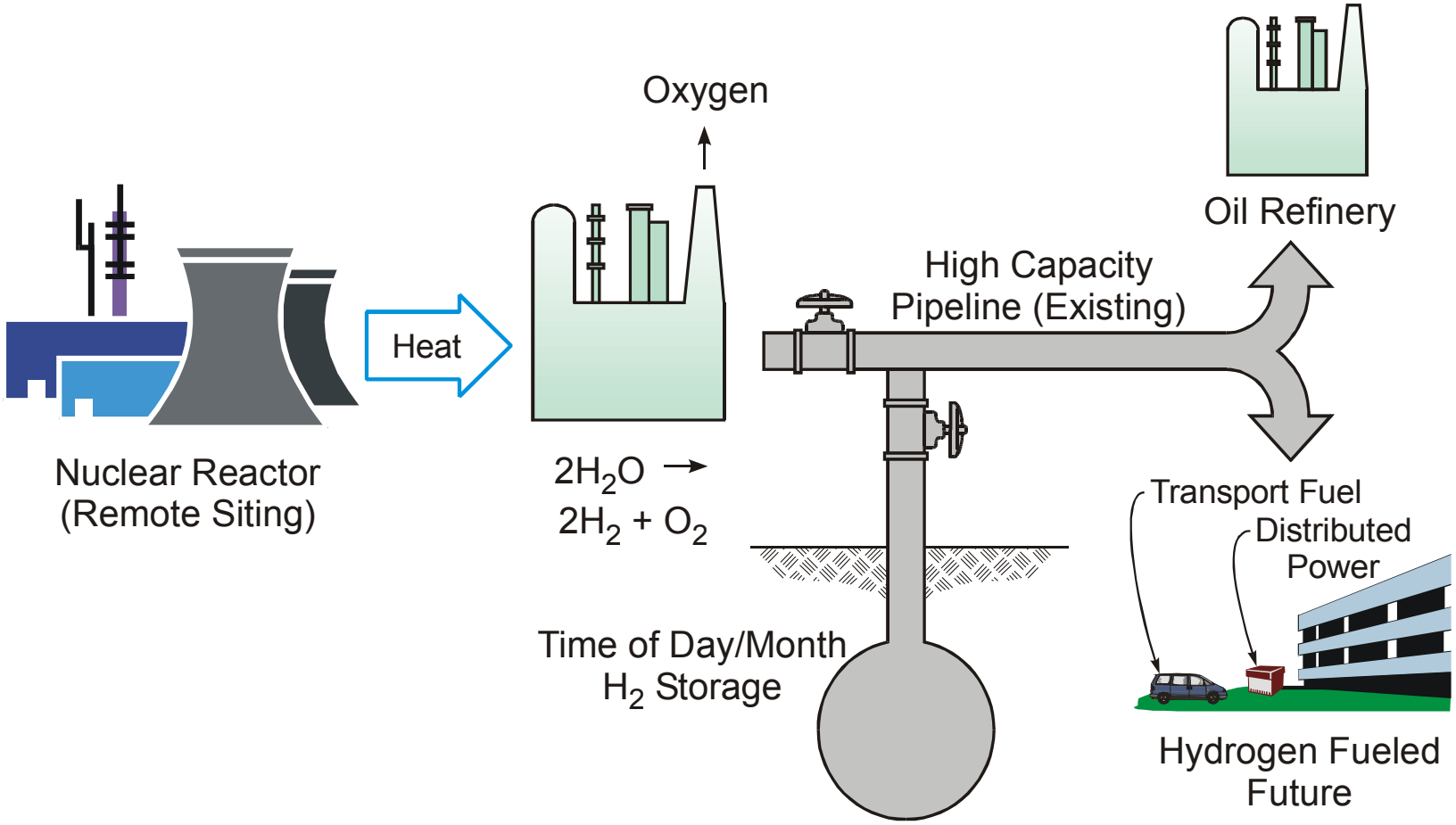


Hydrogen Demand Is Large and Growing Rapidly

- World consumes 50 million tons of H_2/year
  - ~80% intentionally produced; remainder, by-product H_2
  - 200 GW(t) if the H_2 is burned
  - 4 to 10% growth per year
  - Applications: fertilizer, chemical industry, liquid fuels
- Within decades, the energy to produce H_2 in the U.S. may exceed current energy production from nuclear power
- If H_2 replaces liquid fuels, H_2 demand may exceed electricity demand

The Intrinsic Characteristics of Nuclear Power Are Compatible with Hydrogen Production

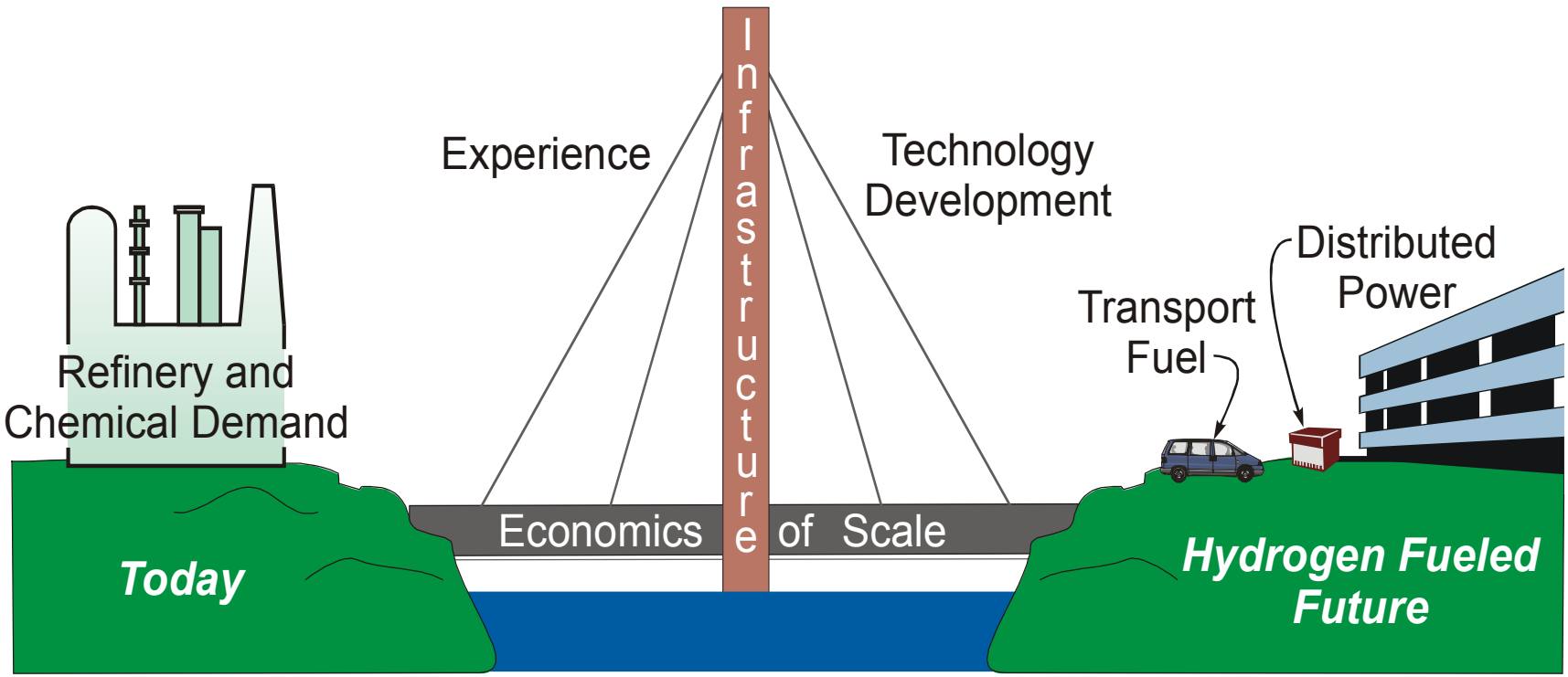
(Remote Siting, Scale of Operations, and Full-Load Operations)



Scale of Hydrogen Production Matches Nuclear Energy

- The economics of nuclear reactors implies energy outputs of 600 to 4500 MW(t)
- Newest world-class H_2 plants (natural gas fuel) under construction will produce 300 million ft^3/day
- Equivalent to 2400-MW(t) reactor (Assuming 50% thermal to H_2 conversion efficiency)
- No size mismatch

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 initiative to develop fuel cells for cars within 10 years
- Technological transitions typically take several decades
  - 40 years from whale oil lamps to electricity
  - 30 years from horses to cars
- If H_2 replaces liquid fuels, H_2 demand may exceed electricity demand
  - Y in energy projections
  - One future, electricity; the other future, H_2 and electricity
  - No solid basis to predict which future will occur

Methods to Make Hydrogen Using Nuclear Energy Are Required; However,

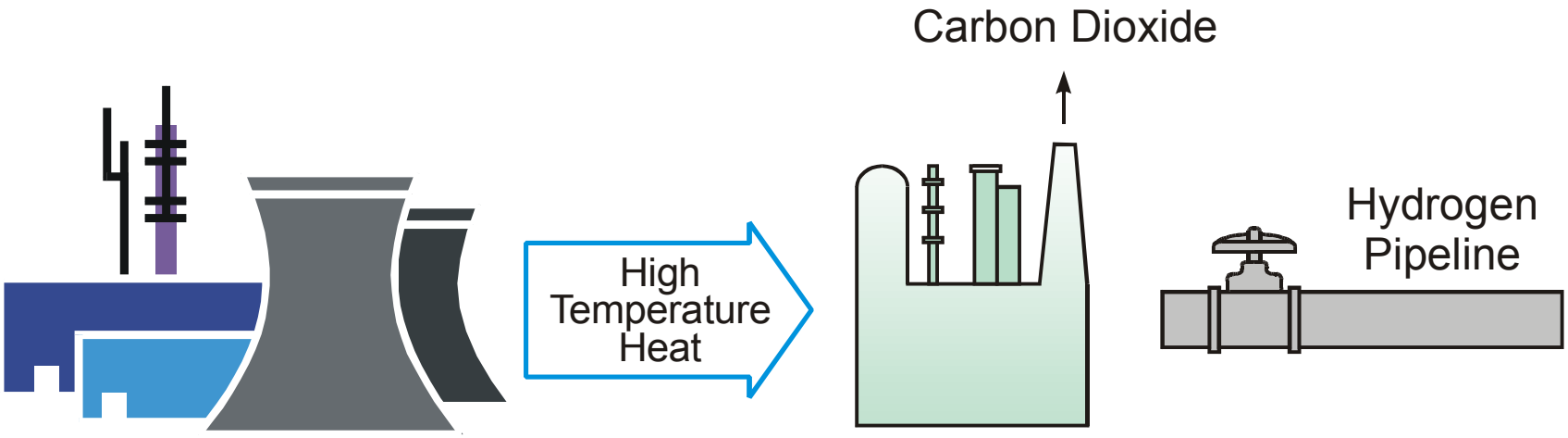
Making Hydrogen Is Tough!

Characteristics of Current Hydrogen Production Techniques

- Most H_2 is made from natural gas
  - Heat + methane (CH_4) + water (H_2O) $\Rightarrow$ hydrogen (H_2) + carbon dioxide (CO_2)
  - Endothermic process with heat input at ~800°C
- Water electrolysis is used to produce small quantities of H_2
  - Inefficient: heat to electricity to H_2
  - Viable when electricity is cheap (e.g., night time)

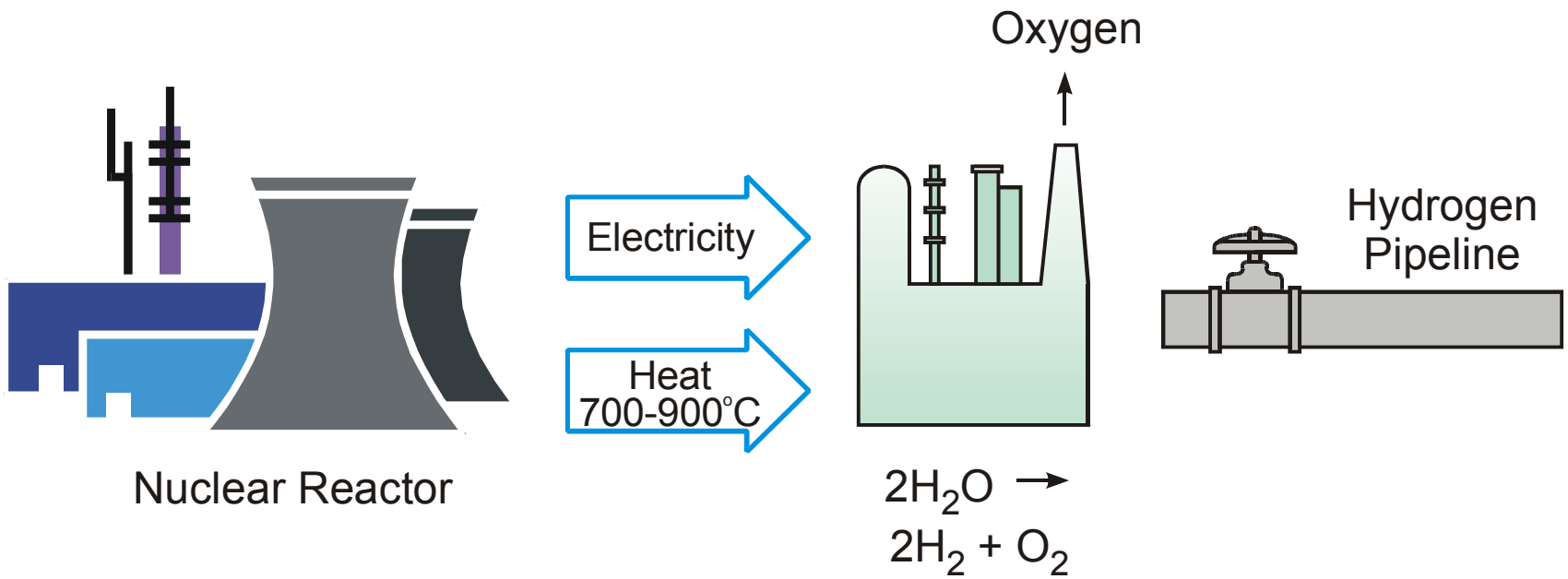
Nuclear-Assisted Hydrogen Production Uses High-Temperature Heat (to 900°C) to Reduce Energy Requirements for Steam Reforming of Natural Gas

(Development Program in Japan)



$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_4$$

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

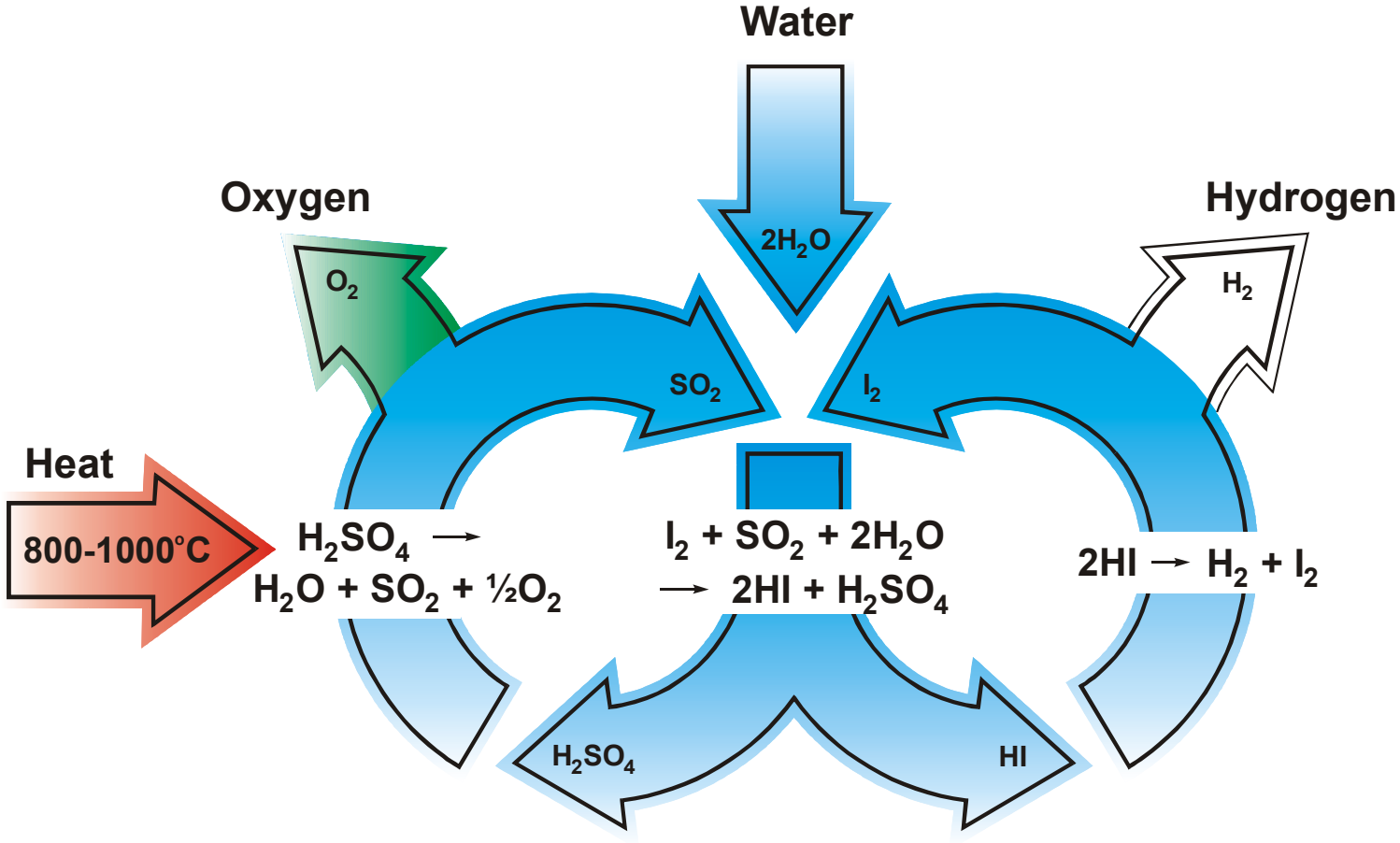


Hydrogen from Hot Electrolysis

- Heat + water (H_2O) + electricity $\Rightarrow$ hydrogen (H_2) + oxygen (O_2)
- Heat replaces some of the electric demand
- Heat input at 700 to 900°C
- High-temperature operation may also reduce other losses in the electrolysis process

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

(Leading candidate: Iodine-Sulfur Process)



Thermochemical Production of H_2 Is the Leading Technology

- Heat + water $\Rightarrow$ hydrogen (H_2) + oxygen (O_2)
- Heat input >750°C
- Low pressure
  - Chemical reactions favored at low pressures
  - Materials requirements minimized
- Lowest potential costs
  - Projected efficiencies of >50%
  - Projected best long-term economics (60% of cold electrolysis)

Efficient Hydrogen Production Imposes Tough Requirements on the Reactor

- Economics: match large H_2 plants
- 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

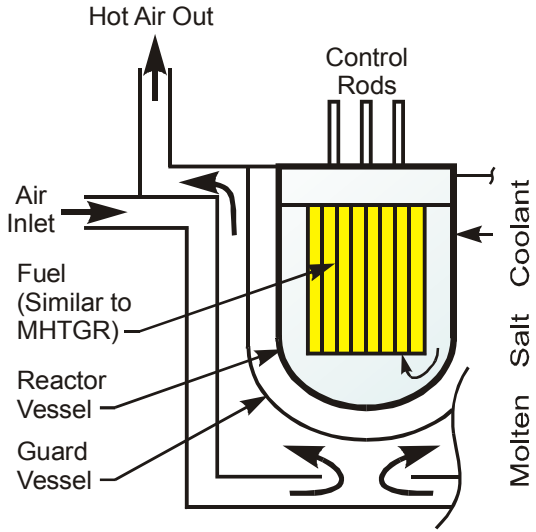
Advanced High-Temperature Reactor —A New Reactor Concept—

Reactor Design Based on Hydrogen Production Requirements

The Advanced High-Temperature Reactor for Hydrogen and Electricity Production Uses a Molten Salt Coolant and Graphite-Matrix Coated-Particle (HTGR) Fuel

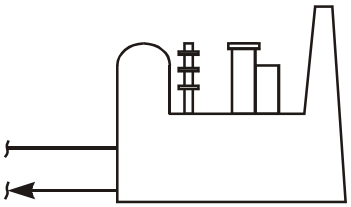
Reactor System

Passive Decay Heat Removal *Reactor*



Applications

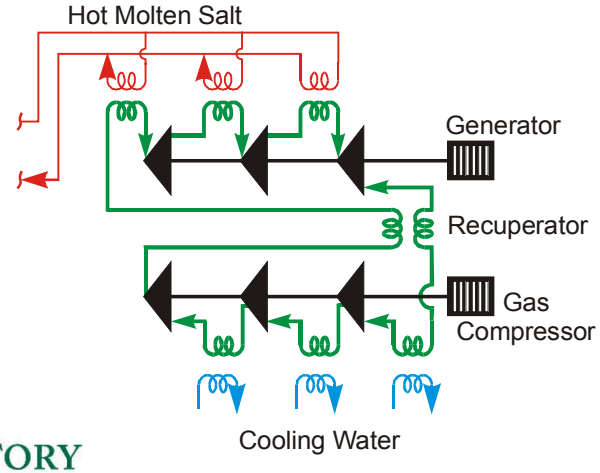
Hydrogen (Thermochemical)



Match H_2 Requirements

- High temperatures
- Heat delivered over small temperature range
- Low tritium (non Li/Be salts)
- Low pressure

Electricity: Multi-Reheat Helium Brayton Cycle



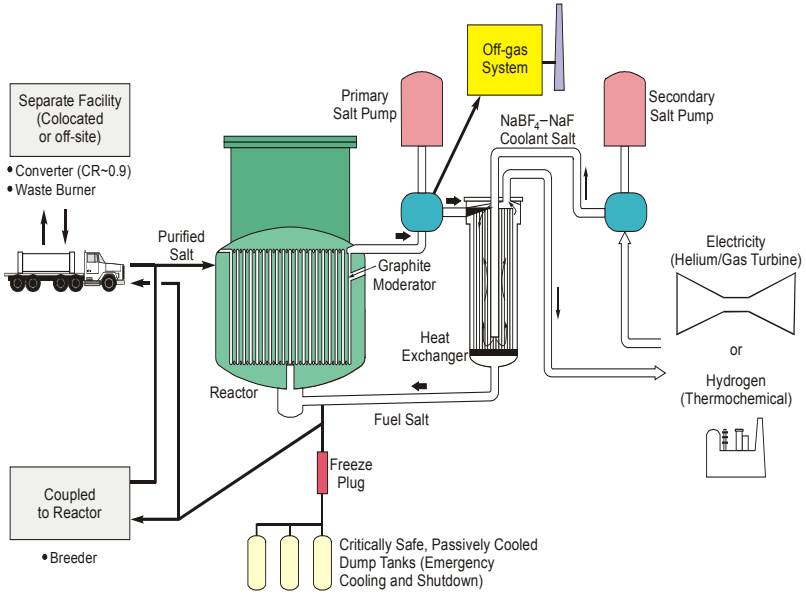
High Efficiency Electricity

- 48% at 750°C
- 56% at 850°C
- 59% at 1000°C

The AHTR Combines Two Technologies to Produce High-Temperature Heat

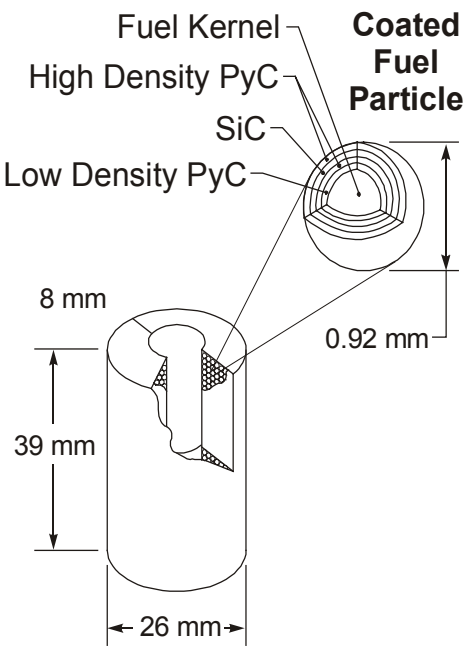
- **Coated-particle graphite-matrix fuel**
  - Demonstrated temperature limit of ~1200ºC
  - Same fuel technology used for high-temperature gas-cooled reactors
  - Compatible with molten fluoride salts
- **Molten fluoride salt coolant (NaF/ZrF_4, etc.)**
  - Very low pressure (boils at ~1400ºC)
  - Efficient heat transfer: Similar to that of water
  - Coolant for proposed fusion energy plants
  - Developed for the Aircraft Nuclear Propulsion Program
    - Aircraft Reactor Experiment operated at 815°C

The AHTR Is NOT a Molten Salt Reactor (MSR)

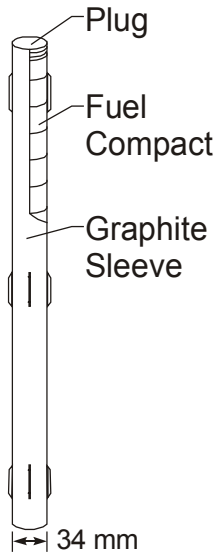


- **MSR**
  - **Fuel dissolved in the molten salt**
  - **Aircraft Reactor Experiment operated at 815 °C**
- **AHTR**
  - **Solid fuel**
  - **Molten salt coolant**
  - **Uses MSR experience**

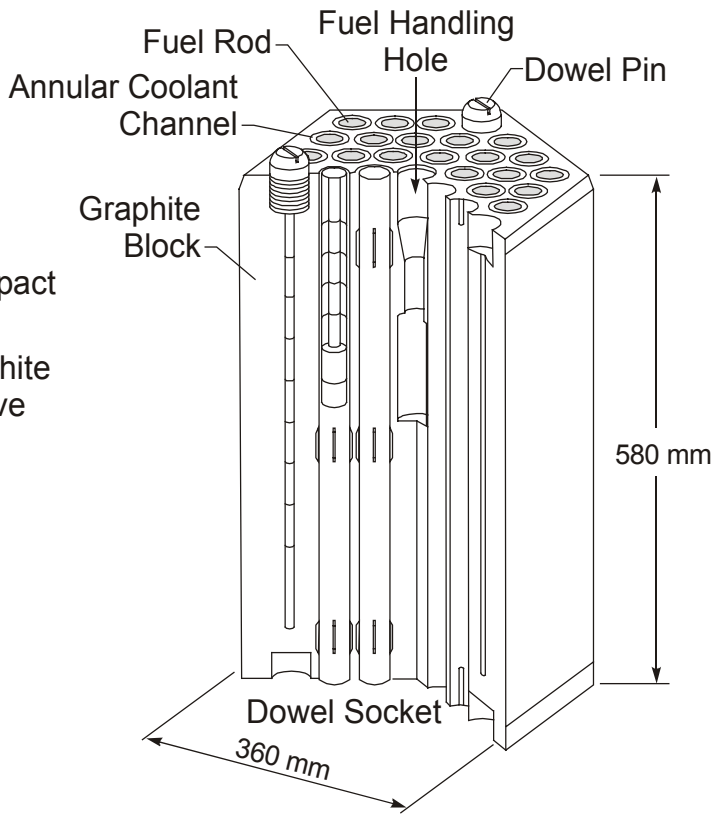
Graphite-Matrix Coated-Particle Fuels Are the Only Proven Fuels That Operate at Required Temperatures for Hydrogen Production



Fuel Compact

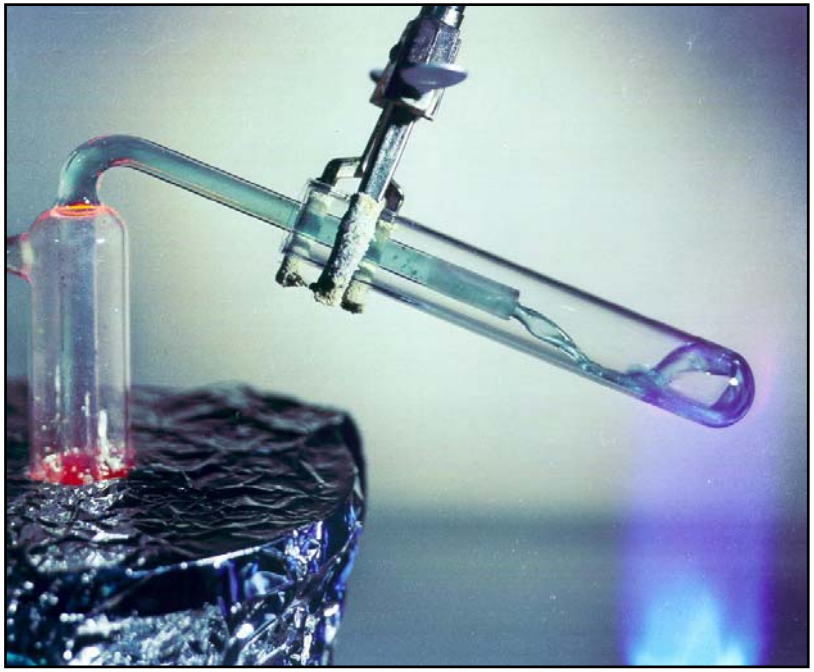


Fuel Rod



Fuel Block

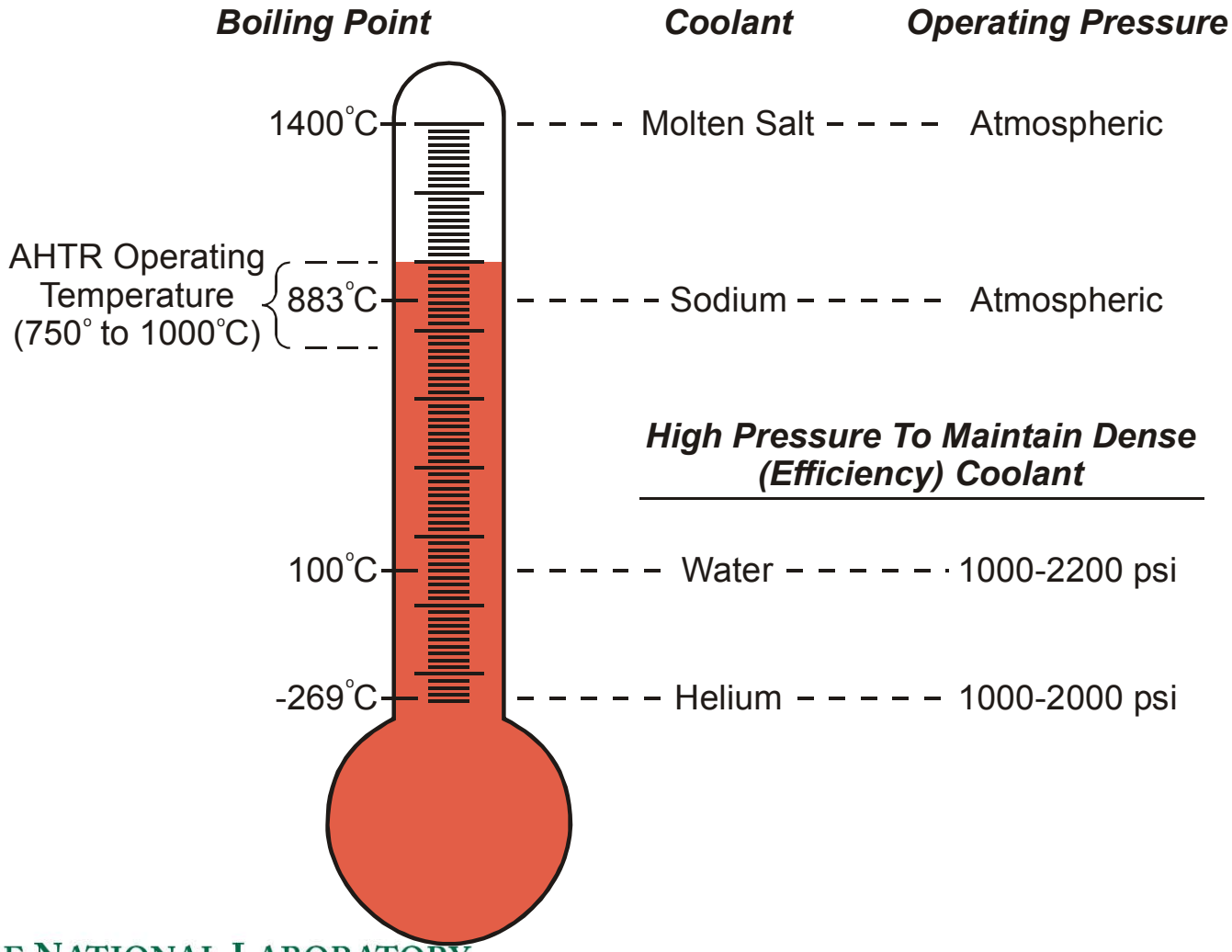
Fluoride Molten Salts Have Heat Transfer Properties Similar to Water (Transfer in Air at 600°C)



- Transparent
- High heat capacity
  - 4X better than sodium
- No rapid chemical reactions
- Low pressure
- Fluoride salt options
  - Salt mixtures
  - Candidate fluorides (Na, Zr, Rb, Be, etc.)

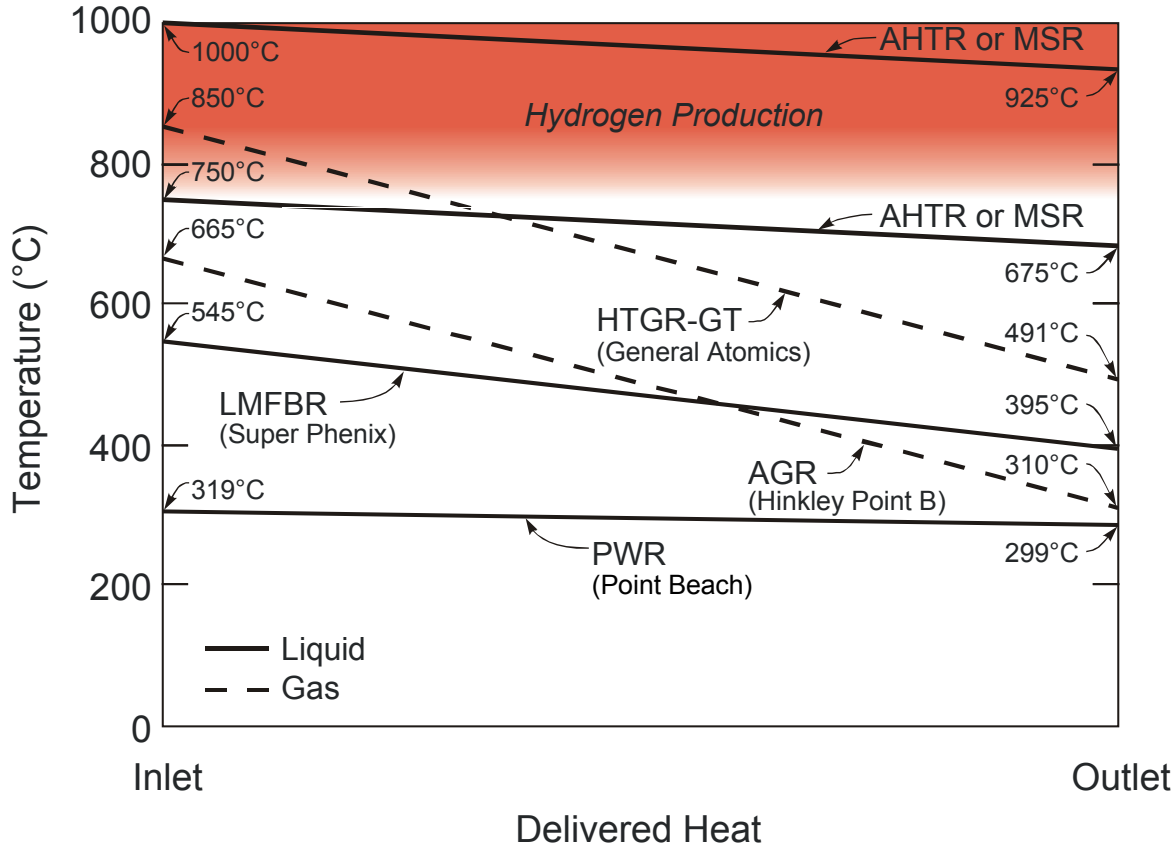
Molten Salts Are a Low-Pressure Reactor Coolant

(Avoid Pressurization Risk at Chemical Plant; Minimum Stress on Materials)

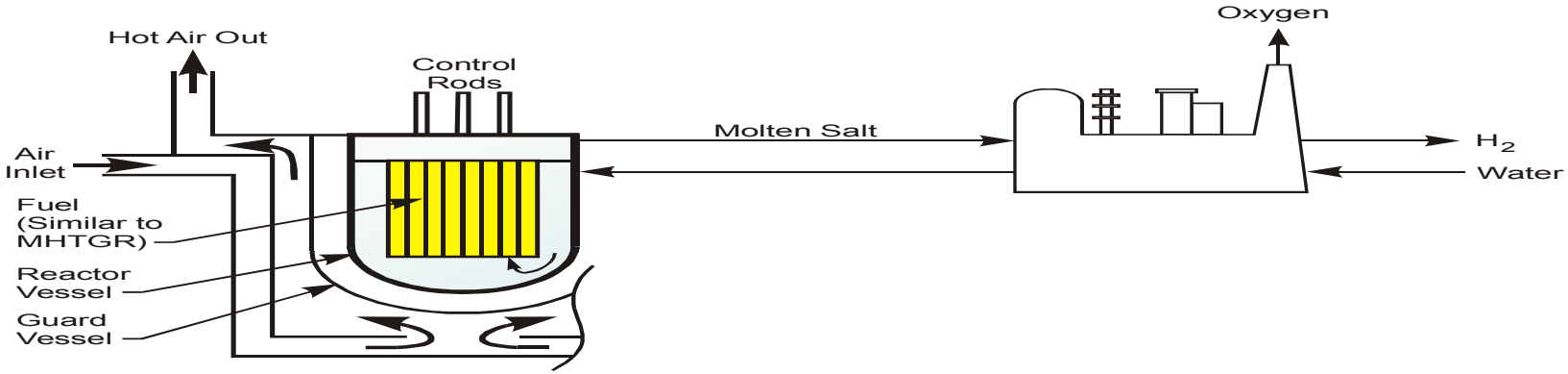


Liquid Coolants Can Deliver All the Heat Over a Small Temperature Range

(Matches Requirements for Hydrogen Production While Minimizing the Reactor Core and Heat-Exchanger Temperatures)



Molten Salts Are an Efficient Method for Transporting High-Temperature Heat from Reactor to Hydrogen Production Plant



- The chemical industry traditionally uses low-pressure molten salts for high-temperature heat transport
- AHTR interfaces efficiently with molten-salt heat transport systems
- Efficient heat transfer (high heat capacity, low pumping power, etc.)

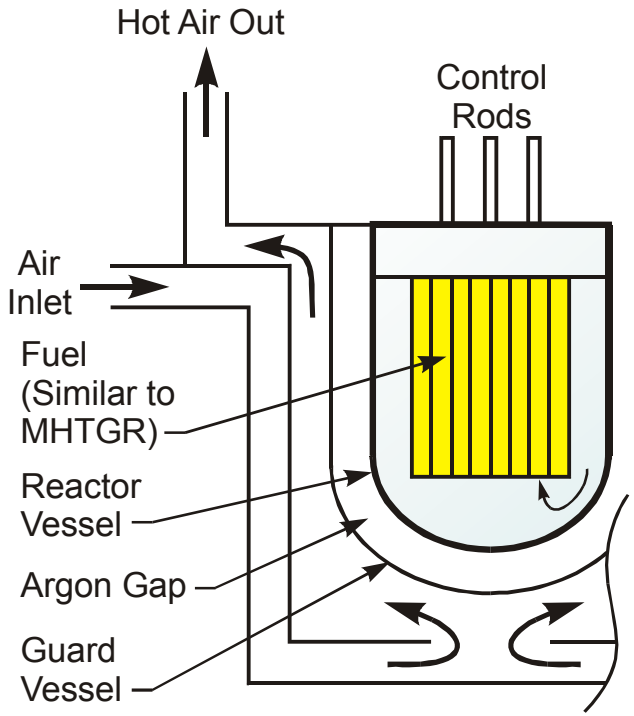
Molten Salts Are a Preferred Interface Fluid Between Nuclear and Chemical Plants

- Chemical plant hazards may require that the reactor be located some distance away
- Molten salts minimize safety issues
  - Low pressure minimizes stress on high-temperature equipment
  - Low chemical reactivity
- Molten salts are the traditional heat-transfer fluids used in chemical plants
  - Low pumping costs
  - Efficient heat transfer
  - High heat capacity (4X of sodium)

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

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

Passive Decay Heat Removal **Reactor**

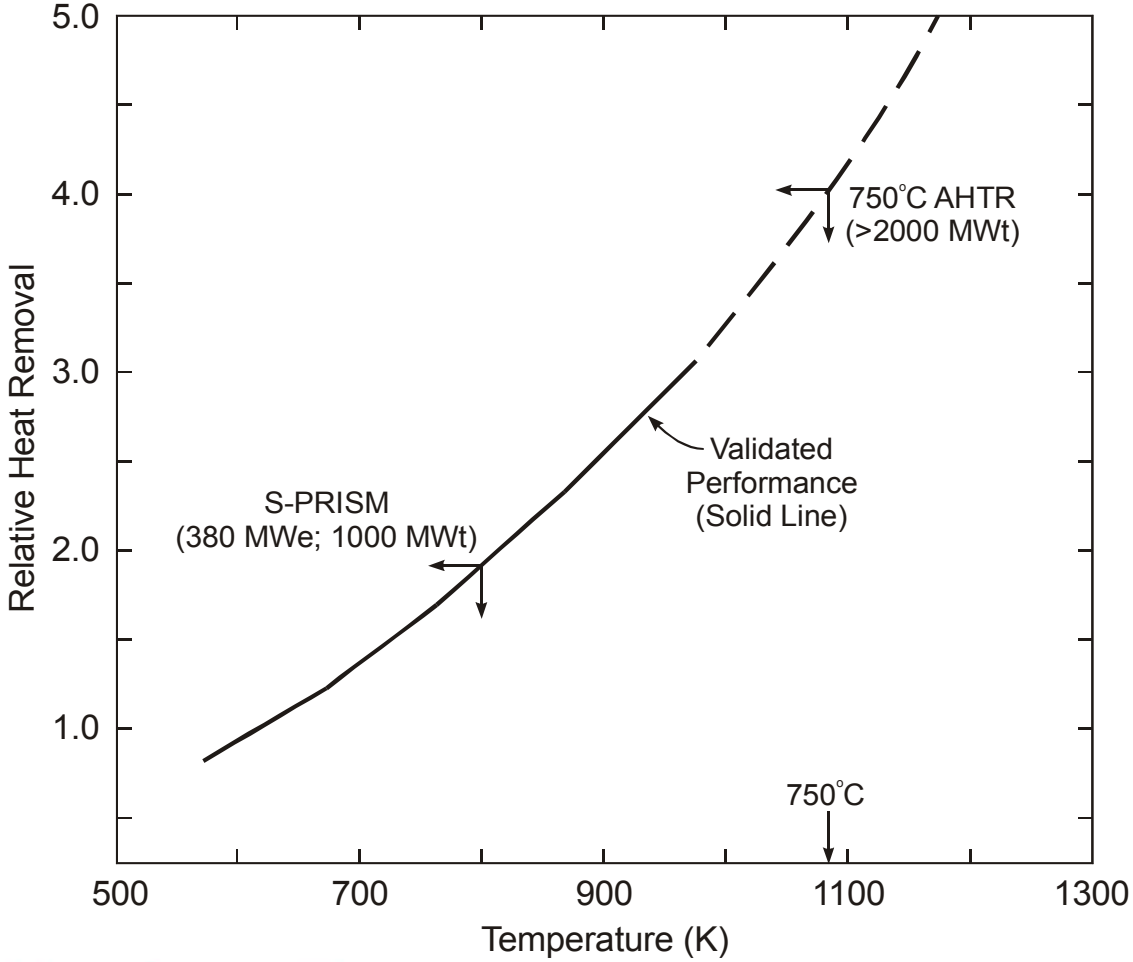


Decay-Heat Cooling System Characteristics

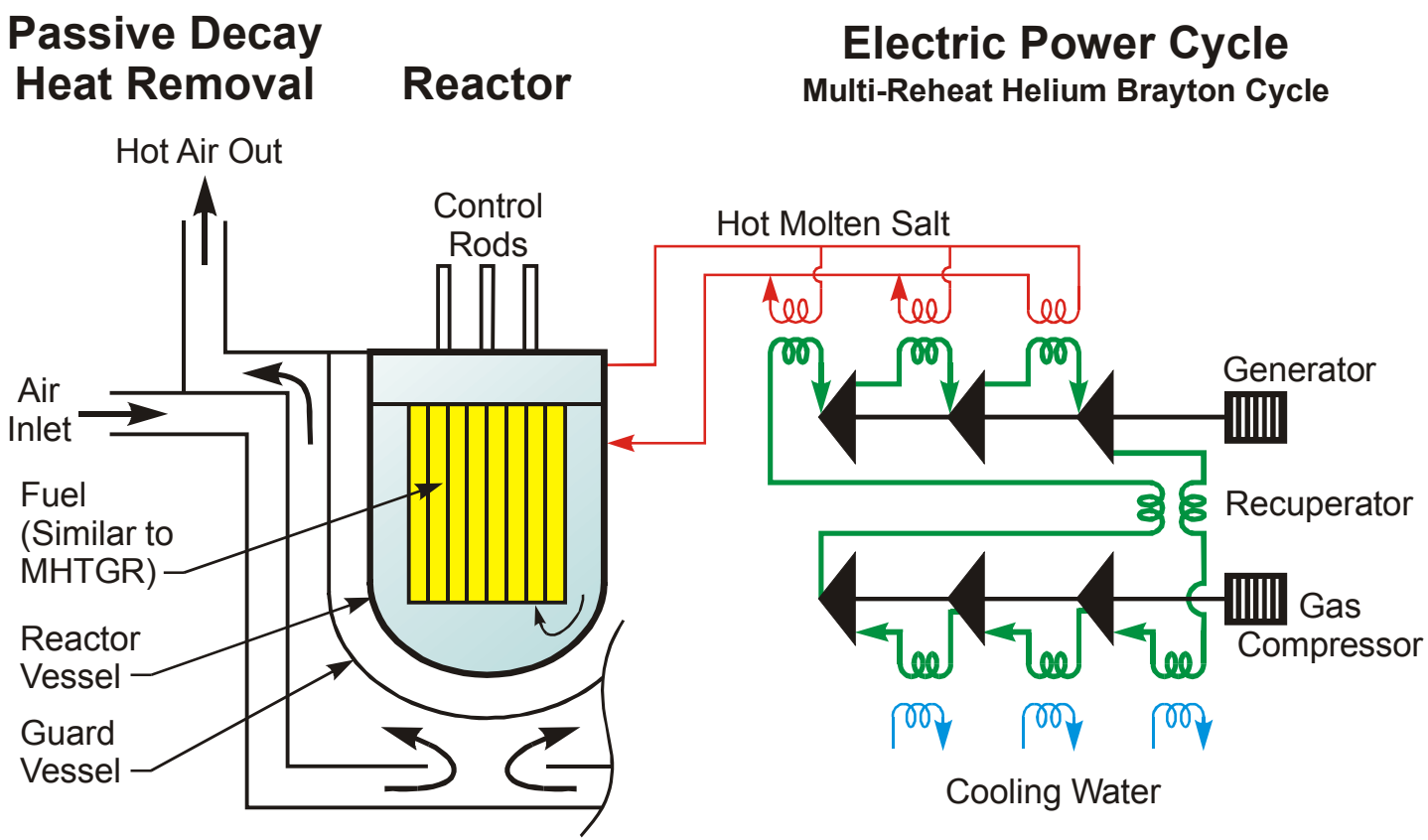
- Similar to GE S-PRISM (LMR)
- Argon Gap
  - Heat Transfer ~T^4
  - Thermal Switch Mechanism
- Heat Rejection Temperature Dependent
  - LMR: 500-550°C (~1000 Mw(th))
  - AHTR: 750-1000°C (>2000 Mw(th))

AHTR Higher Temperatures Allow Much Larger Reactors With The Same Size Systems

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



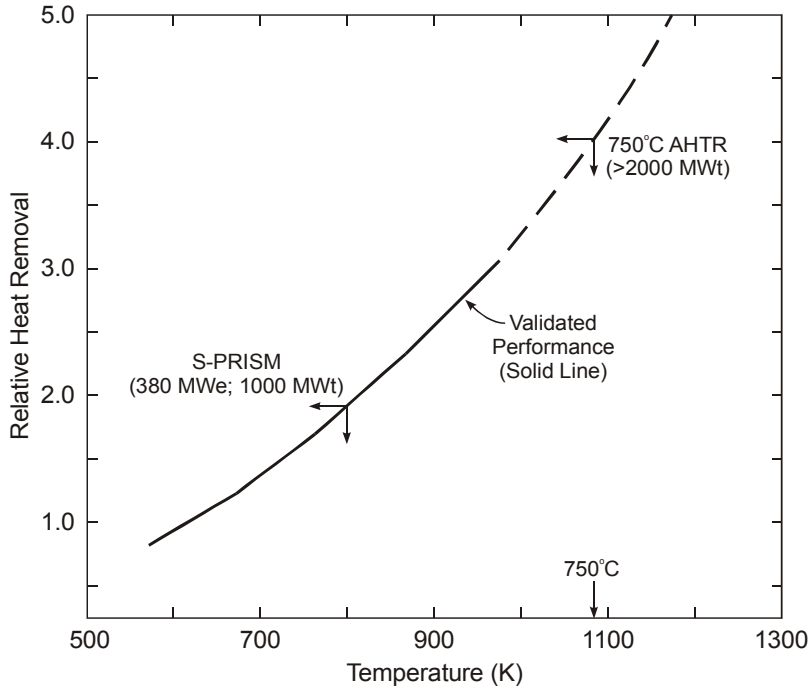
The AHTR Uses a Multi-Reheat Brayton Cycle for High-Efficiency Electricity Production



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

- Brayton cycle equivalent to multi-reheat steam cycle used in fossil power plants
- Electrical efficiency
  - 48% at 750°C
  - 56% at 850°C
  - 59% at 1000°C
- Efficiency dependent upon how heat is delivered to the power cycle
  - 48% at 750°C for AHTR with heat delivered at a nearly constant temperature
  - 48% at 850°C for direct-cycle helium-cooled reactor with heat delivered over 300+°C

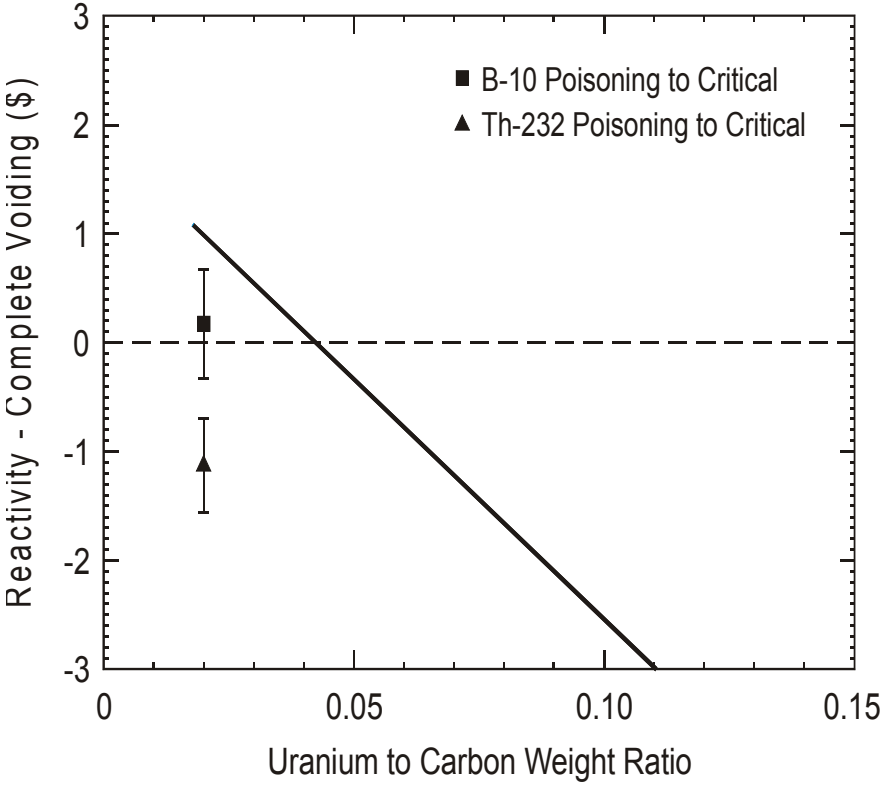
The Potential Exists for Excellent Economics Because of the High Temperatures and Low Pressures



- 1000-MW(e) [2000-MW(t)] AHTR in the reactor vessel of a 380-MW(e) [1000-MW(t)] PRISM reactor
- Higher-efficiency power cycle
- Smaller, lower-cost multi-reheat power cycle

Design Issues

Neutronic Analysis Indicates Stable AHTRs Can Be Built

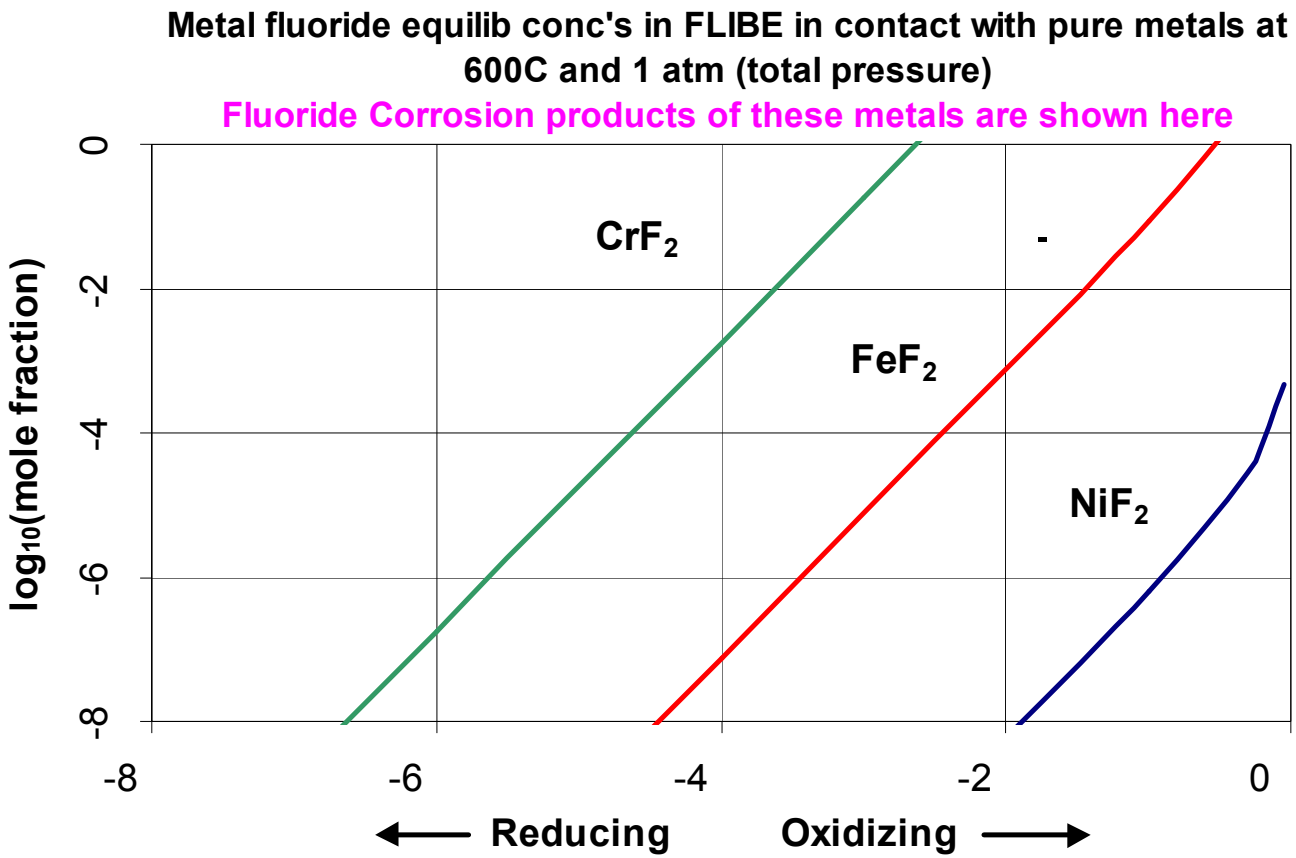


- Low pressure allows choice of reactor height-to-width ratio
- Efficient liquid coolant allows variable fuel, moderator, and coolant ratios
- Choice of burnable absorber locations
  - Fuel
  - Graphite
  - Coolant

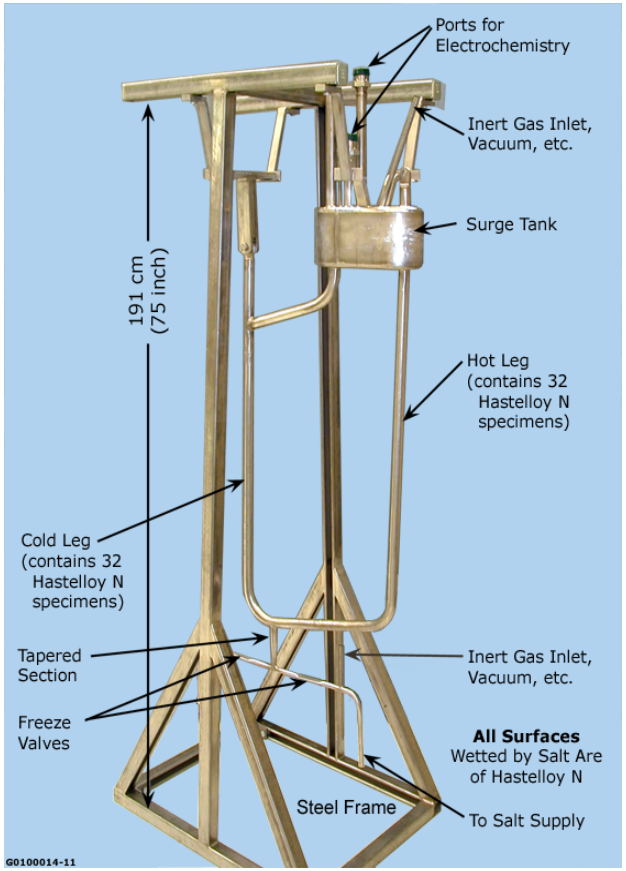
Molten Fluoride Salts Are Compatible With Graphite-Based Fuels

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

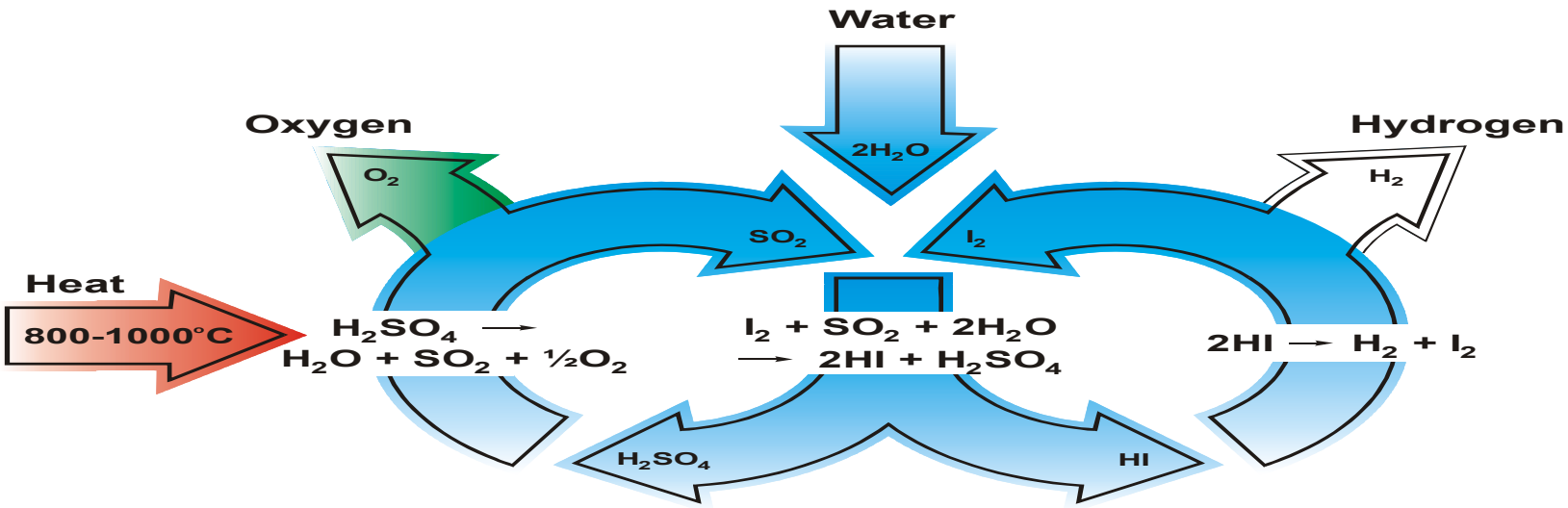


Materials Development Is Required Because of Other Temperature Limitations
(ORNL Test Loop for Molten Salts)



- **High-temperature issues**
  - Transport of metals by temperature differences
  - Strength of materials
  - Lifetimes
- **Temperature limits**
  - Current limit of materials near ~850°C
  - Significant development for higher temperatures

There Are Major Materials Issues with Hydrogen Production



- Highly oxidizing conditions in parts of the thermochemical cycles
- Other corrosion issues

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%)
  - $NaF\text{-}RbF\text{-}ZrF_4$ (8%/50%/42%)
  - $^{7}Li_2BeF_4$

AHTR Beyond-Design-Basis-Accident Systems

- Fission products dissolve in molten salts
- High temperatures aid heat removal
- Molten salt boil-off can remove decay heat
  - Salt boiling point: ~1400°C
  - Coated-particle fuel limit: ~1600°C
  - Potential for frozen-wall cooling system
    - Salt creates frozen wall around reactor
    - Reflux of salt to provide cooling

Conclusions

- Making hydrogen is demanding
- Economics and safety suggest that chemical plant requirements should drive reactor design requirements
- The Advanced High-Temperature Reactor is an initial effort to develop a reactor to match hydrogen production requirements
- Reactors that can make hydrogen have a high potential for making electricity

Backup Information

Relative Rankings of Reactors for Hydrogen Production

(Qualitative: Best, + ; Worst, =)

	AHTR	HTGR	MSR	Pb-Fast	Fast-Gas
Temperature	+	+	+	-	-
Small Delta T	+	-	+	+	-
Low Pressure	+	-	+	+	-
Technology Status					
Nuclear	0	+	-	-	=
Chemical	+	-	-	-	-
Metallurgy	+	+	0	-	+
Fuel Cycle					
Technology	+	+	-	0	=
Deployable	+	+	+	-	-
Development Effort	+	+	-	-	-
Size	+	-	+	0	-

Reactor Definitions

- AHTR: Advanced high-temperature reactor
- HTGR: High-temperature gas-cooled reactor
- MSR: Molten salt reactor
- Pb-Fast: Lead-cooled fast reactor
- Fast-Gas: Fast neutron spectrum gas-cooled reactor

Explanation of Parameters: I

- Demonstrated Maximum Temperature
  - HTGR and MSRs have operated above 800°C
  - AHTR uses molten salts similar to MSR
- Small Temperature Drop
  - Liquid-cooled reactors (AHTR, MSR, Pb-fast) deliver heat over small temperature ranges
  - Gas-cooled reactors deliver heat over larger temperature ranges
- Low Pressure
  - Low pressure desired for H_2
  - Molten salts and lead have high boiling points

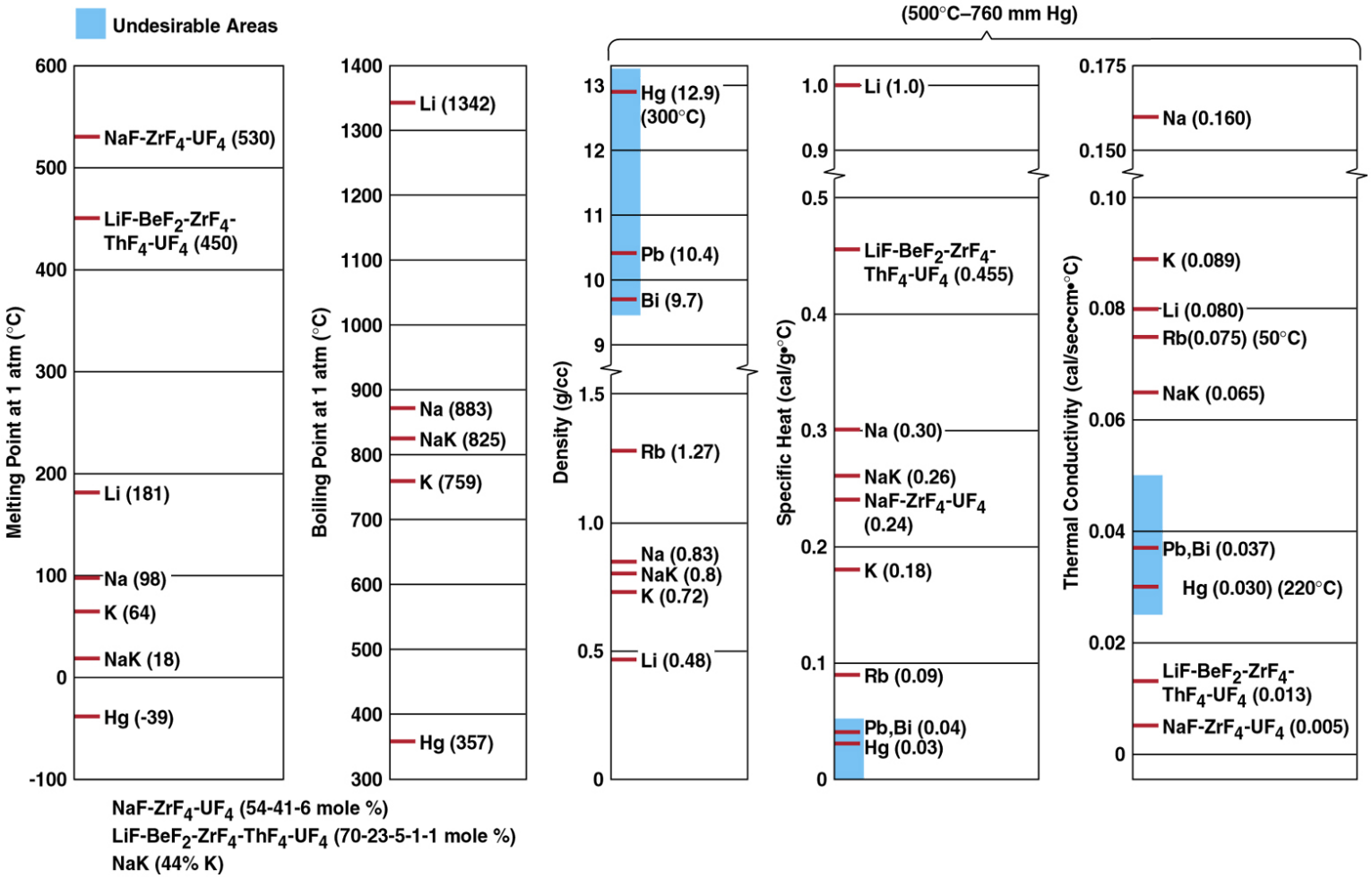
Explanation of Parameters: II

- Technology status
  - Nuclear
    - AHTR and HTGR have demonstrated fuels
    - Pb-fast and fast-gas fuels have not been demonstrated for required temperatures
  - Chemical
    - AHTR compatible with molten-salt heat-transfer loop and long-distance heat transfer
    - High-pressure gas coolant more difficult to interface with chemical plant
  - Metallurgical
    - Helium and molten salts used at high temperatures

Explanation of Parameters: III

- Fuel Cycle
  - Technology
    - Fuel cycle demonstrated for AHTR and HTGR
    - Development work required for MSR
    - High-temperature Pb-fast and fast-gas fuel cycles not demonstrated
  - Deployable
    - Low fissile inventory for AHTR, HTGR, and MSR
    - Large-scale recycle of SNF must be initiated to deploy Pb-fast and fast-gas
- Size
  - AHTR and MSR deployable as large passively safe reactors
  - HTGR, Pb-fast, and fast-gas use smaller modular reactor concepts

Comparison of Molten Salt/Fuel/Coolant Properties

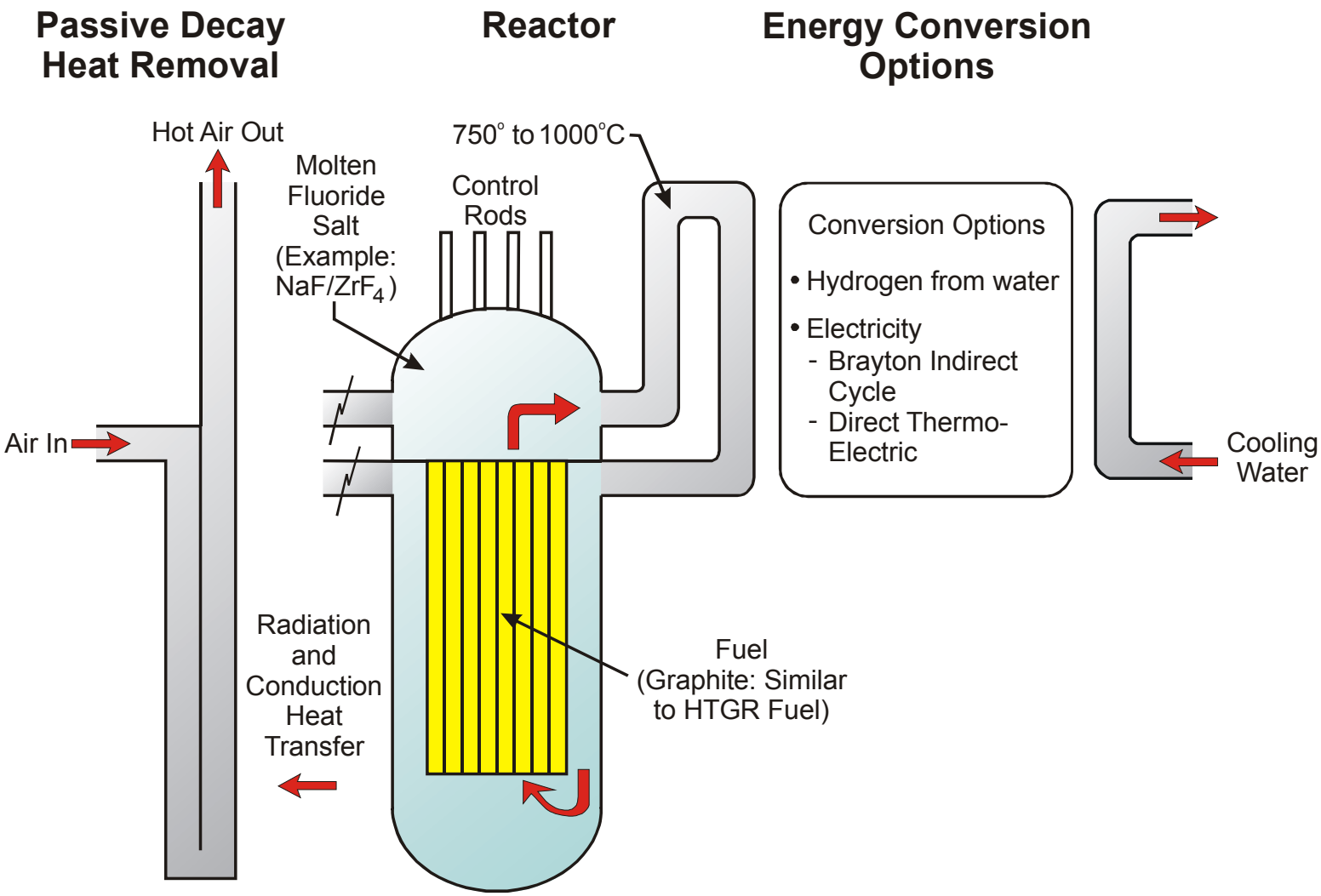


$NaF-ZrF_4-UF_4$ (54-41-6 mole %)
$LiF-BeF_2-ZrF_4-ThF_4-UF_4$ (70-23-5-1-1 mole %)
NaK (44% K)

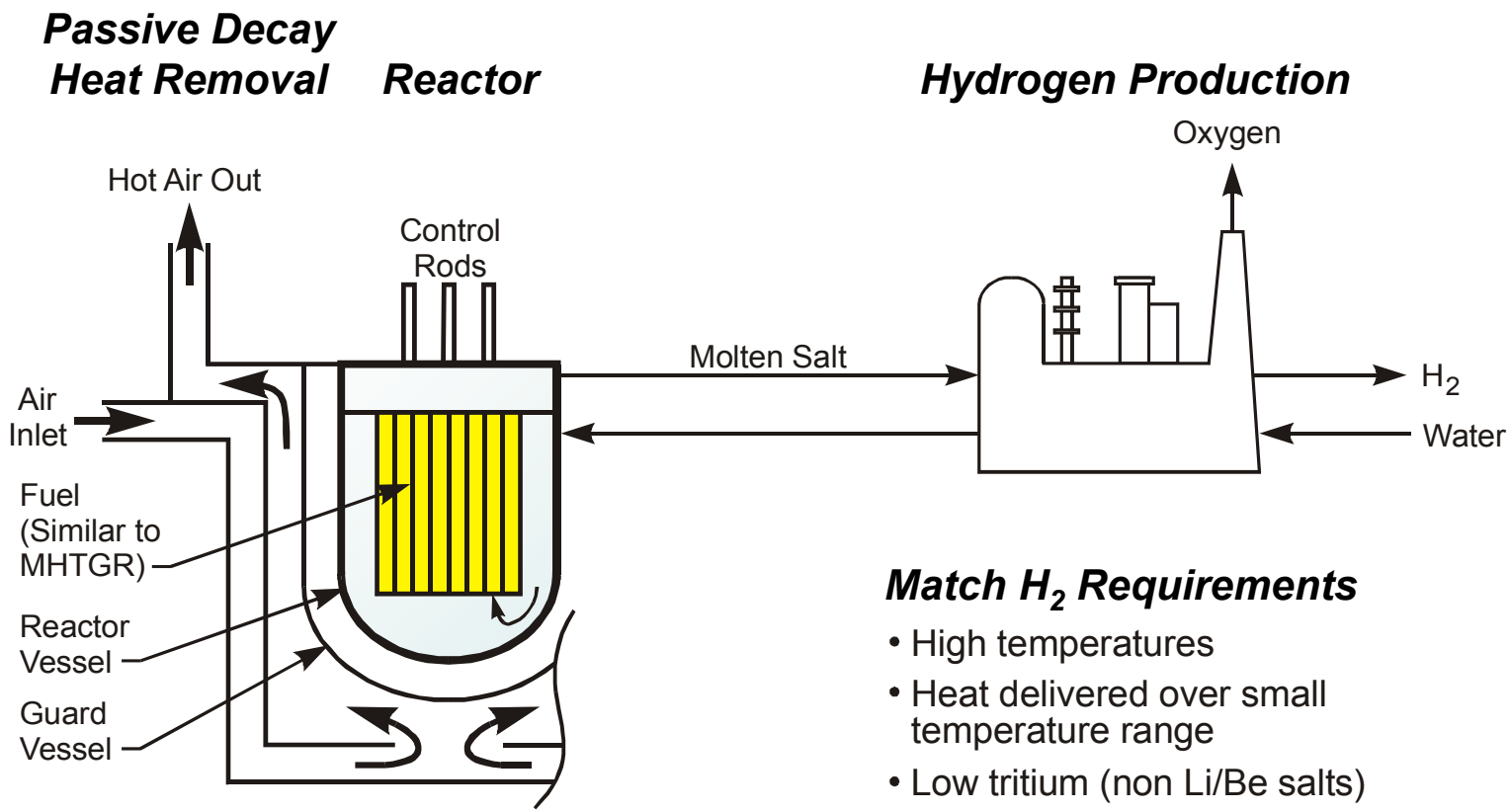
The Safety Case for the AHTR: Accident Control

- Low-pressure (subatmospheric) coolant
  - Escaping pressurized fluids provide a mechanism for radioactivity to escape from the 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

Advanced High-Temperature Reactor



The Advanced High-Temperature Reactor (AHTR) Uses a Molten Salt Coolant and a Graphite-Matrix Coated-Particle (HTGR) Fuel



Match H_2 Requirements

- High temperatures
- Heat delivered over small temperature range
- Low tritium (non Li/Be salts)
- Low pressure (< 0.1 psia)