Advanced High-Temperature Reactor for Hydrogen and Electricity Production

(Joint ORNL–Sandia Activity)

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Advisory Committee on Reactor Safety

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OAK RIDGE NATIONAL LABORATORY
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UT-BATTELLE

Outline

- **Is a nuclear-based hydrogen economy in our future?**
- **The Advanced High-Temperature Reactor (AHTR)**
  - **An option for hydrogen production**
  - **An option for electric production**
- **Regulatory implications**

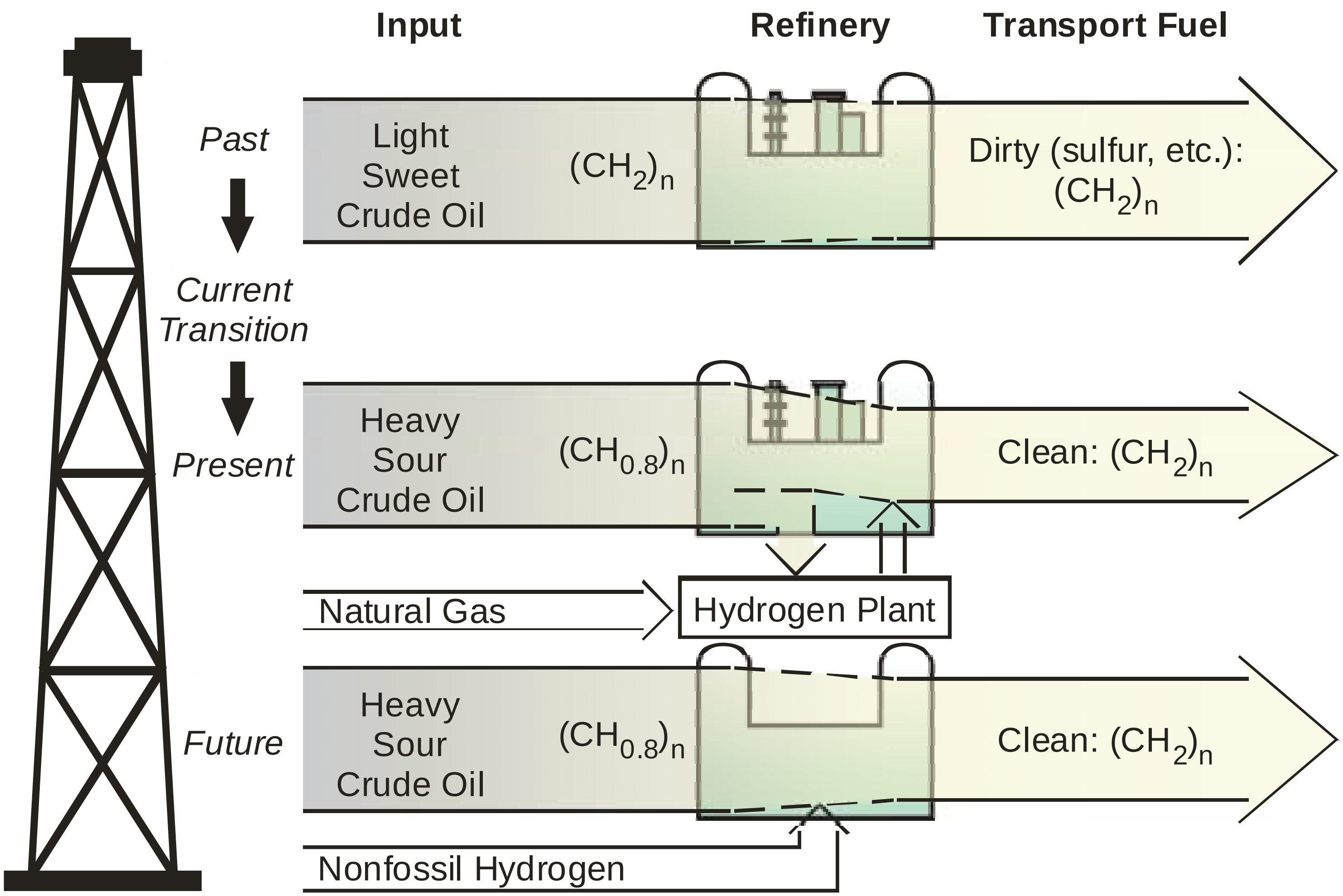
Is a Hydrogen Economy in our Future?

(It may already be here)

Rapid Growth Is Expected in Industrial Hydrogen (H_2) Demand

- **Rapidly growing H_2 demand**
  - **Production uses 5% of U.S. natural gas plus refinery by-products**
  - **If projected rapid growth in H_2 consumption continues, the energy value of fuel used to produce H_2 will exceed the energy output of all nuclear power plants after 2010**
- **The chemical industry (NH_3 & CH_3OH) is a large consumer**
- **Changing refinery conditions are driving up the H_2 demand**
  - **More heavy crude oils (limited supplies of high-quality crude)**
  - **Demand for clean fuels (low sulfur, low nitrogen, non-toxic fuels)**
  - **Changing product demand (less heating oil and more gasoline)**
- **If nonfossil sources of hydrogen are used, lower-value refinery streams can be used to make gasoline rather than hydrogen—reduced oil imports**

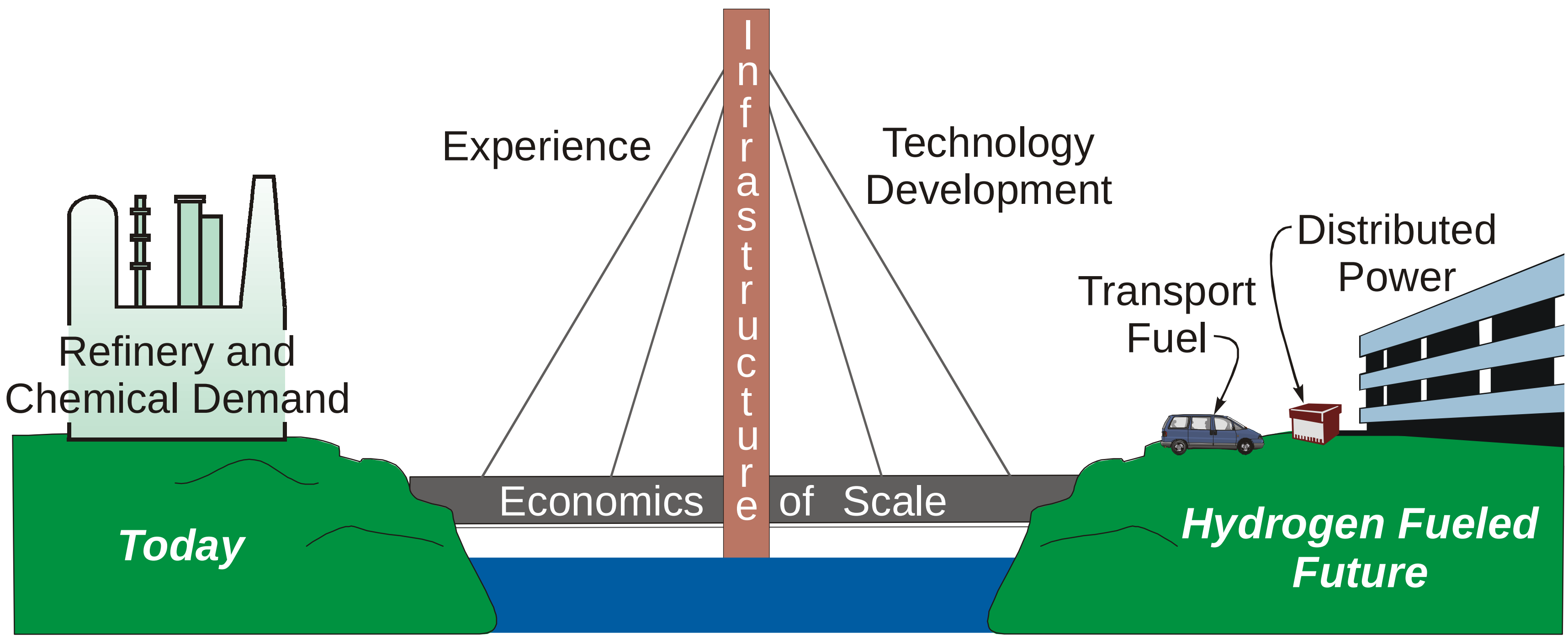
Increased Use of More Abundant Heavy Crude Oils Reduces Refinery Yields, Unless Nonfossil Hydrogen Is Used



Multiple Benefits with Economic Nonfossil Sources of Hydrogen

- **Increased transport fuel yields per barrel**
  - **Lower-value oil components converted to transport fuel rather than to hydrogen (current practice)**
  - **Reduced imports of crude oil and natural gas**
- **Greater use of heavy crude oils**
  - **More abundant with lower costs**
  - **Western Hemisphere suppliers (Venezuela, Canada, and the United States)**
- **Competitive chemical and refinery industry**
  - **Natural gas price increases are increasing H_2 costs**
  - **Risk of parts of the industry moving offshore**
- **Lower carbon dioxide emissions**

The Growing Industrial Demand for Hydrogen Creates a Bridge to the Hydrogen Economy

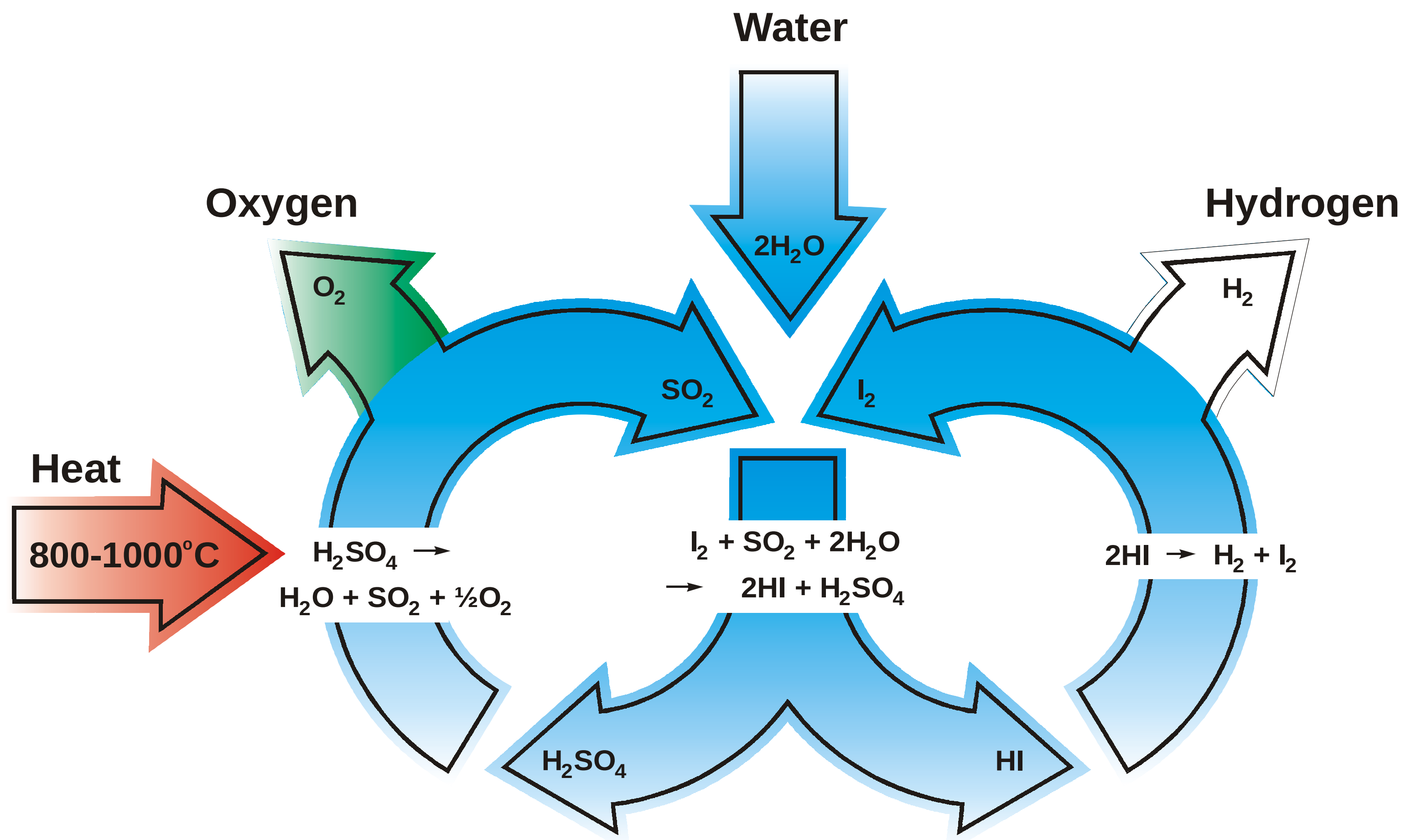


Hydrogen Can Be Produced with Heat from a Nuclear Reactor

- **Heat + water ⋗ hydrogen (H_2) + oxygen (O_2)**
- **Nuclear energy would compete with natural gas for H_2 production**
  - **Rising natural gas prices**
  - **Constant (level load) H_2 demand matches nuclear output**
- **Characteristics of hydrogen from water**
  - **Projected efficiencies of >50%**
  - **High-temperature heat is required: 800 to 1000ºC**
  - **Existing commercial reactors can not produce heat at these high temperatures**
  - **An alternative reactor concept is required**

Chemical Processes Convert High-Temperature Heat and Water to Hydrogen and Oxygen

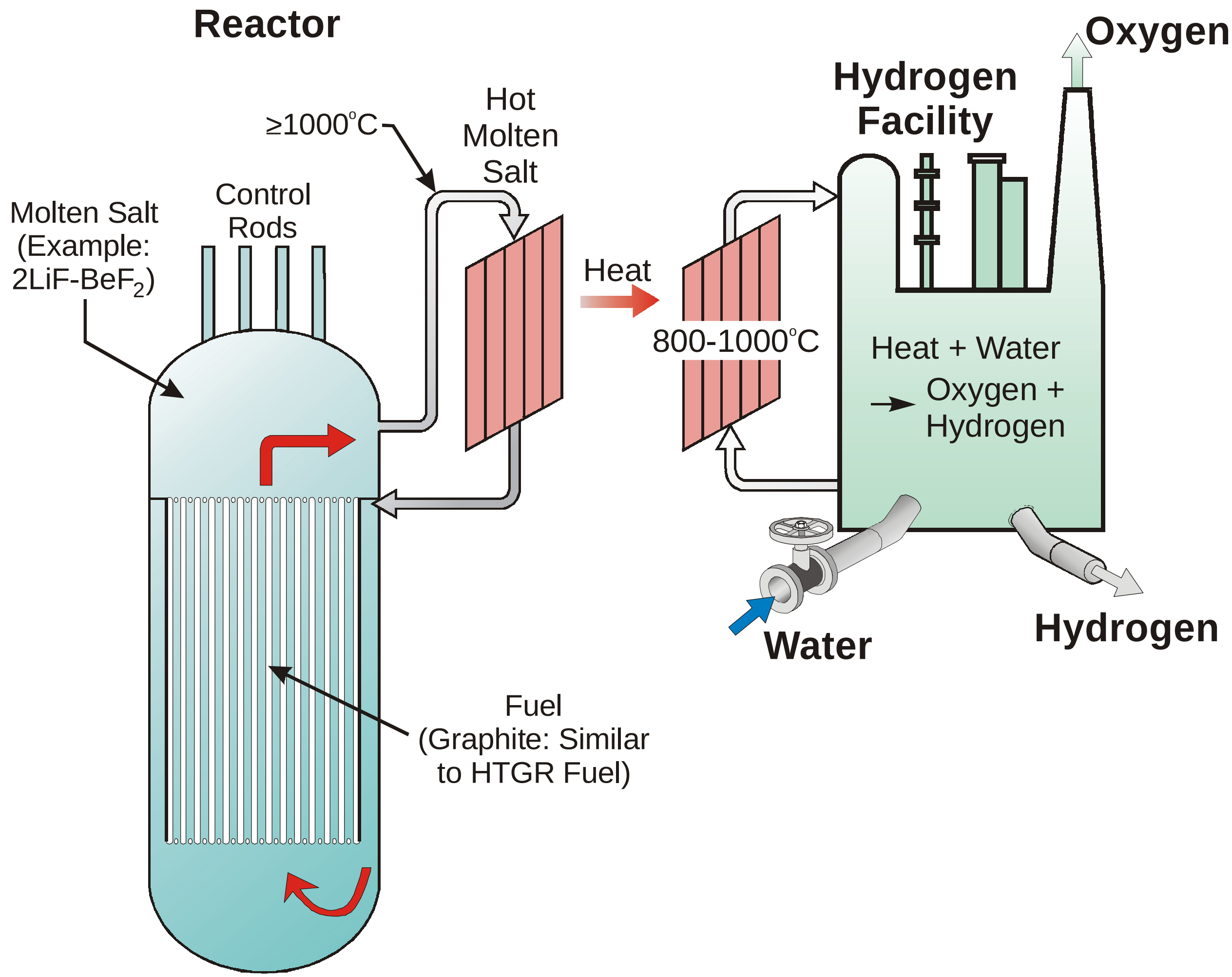
(Example: Iodine–Sulfur Process)



An Advanced High-Temperature Reactor (AHTR)—A Reactor Concept for Hydrogen Production

(Different products may require different reactors)

Advanced High Temperature Reactor Coupled to a Hydrogen Production Facility



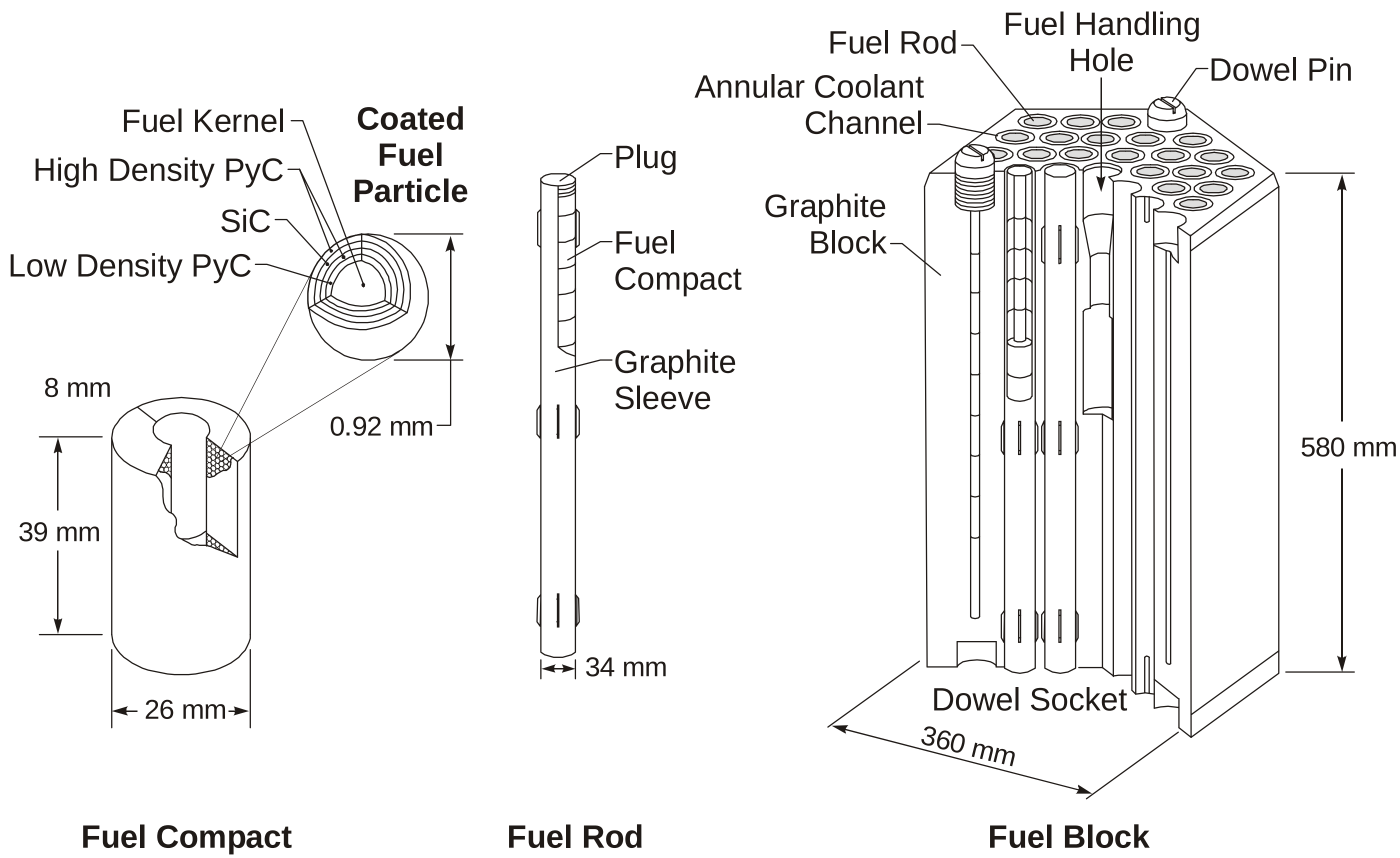
Desired Reactor Characteristics to Produce High-Temperature Heat

- **Low-pressure system (atmospheric)**
  - **Metals become weaker at higher temperatures**
  - **Low pressures minimize strength requirements**
  - **Match chemical plant pressures (atmospheric)**
- **Efficient heat transfer**
  - **Need to minimize temperature drops between the nuclear fuel and application to deliver the highest-temperature heat**
  - **Liquid coolant**

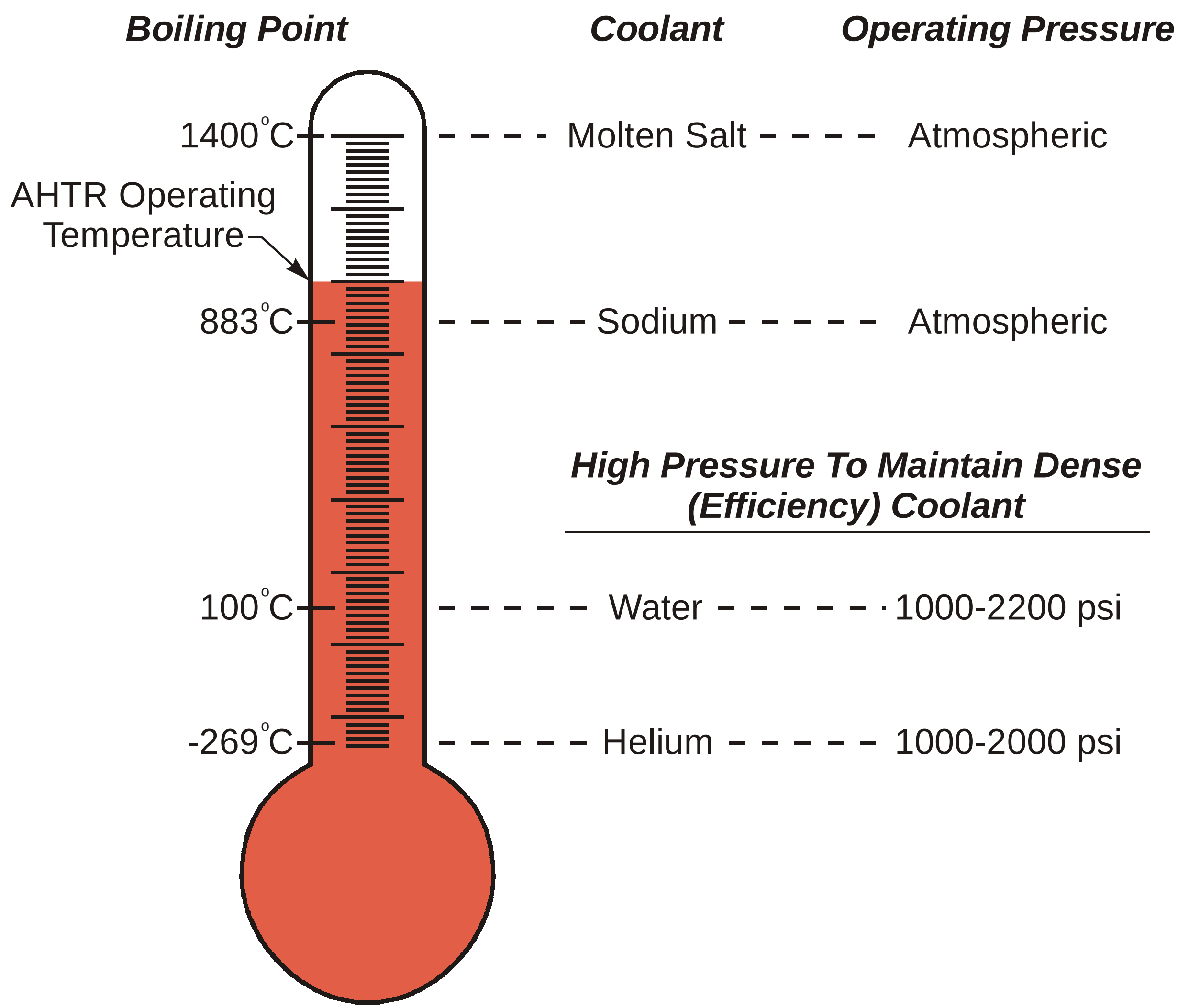
The AHTR Combines Two Different Technologies To Create an Advanced High-Temperature Reactor Option

- **Graphite-matrix fuel**
  - **Demonstrated operation at an operating limit of ~1200ºC**
  - **Same fuel technology planned for modular high-temperature gas-cooled reactors**
  - **Fuel geometry/dimensions would be different for molten salt**
- **Molten salt coolant (2LiF-BeF_2)**
  - **Very low pressure (boils at ~1400ºC)**
  - **Efficient heat transfer (similar to that of water, except it works at high temperatures)**
  - **Proposed for fusion energy machines**
  - **Family of molten salt coolant options**

Japanese High-Temperature Engineering Test Reactor Fuel for 950ºC Helium Exit Temperatures



Molten Salt Coolants Allow Low-Pressure Operations at High Temperatures Compared With Traditional Reactor Coolants



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The Safety Case for the AHTR

- **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**
  - **Minimize chemical plant pressurization issues**
- **Passive decay-heat-removal system similar to that proposed for other advanced reactors**
  - **Heat conducts outward from fuel to pressure vessel to passive vessel-cooling system**
  - **Power limited to ~600 MW(t)**
- **Good coolant characteristics provide added safety margins for many upset conditions**

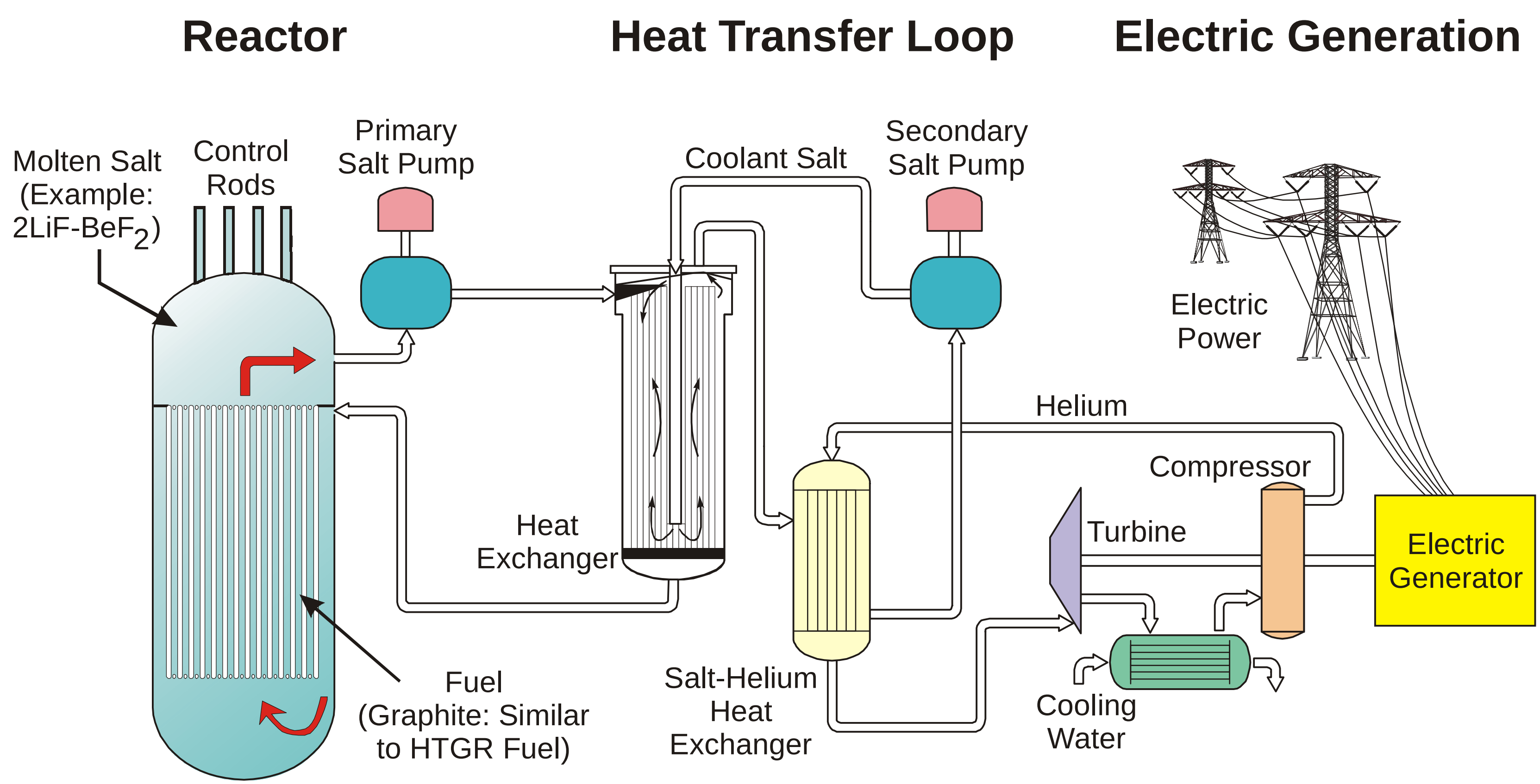
Characteristics of Molten Salts Assist Safety Performance

- **Large (~400ºC) temperature margin from the reactor operating temperature to the boiling point**
- **Natural circulation liquid coolant**
- **Salt acts as a secondary barrier to fission product and actinide release from the reactor**
  - **Fluoride salts dissolve most fission products and actinides (ionic liquid with high solubility at high temperatures)**
  - **Molten salt fueled reactor (alternative concept) based on dissolution of uranium and fission products in salt)**
- **Large industrial experience with other fluoride salts (aluminum metal production)**
- **Other considerations**
  - **Freeze point is ~457ºC**
  - **Family of fluoride salts that allow modification of properties if desired (Example: FLiNaK: 46.5 mole % LiF, 11.5 mol % NaF, 42 mol % KF)**

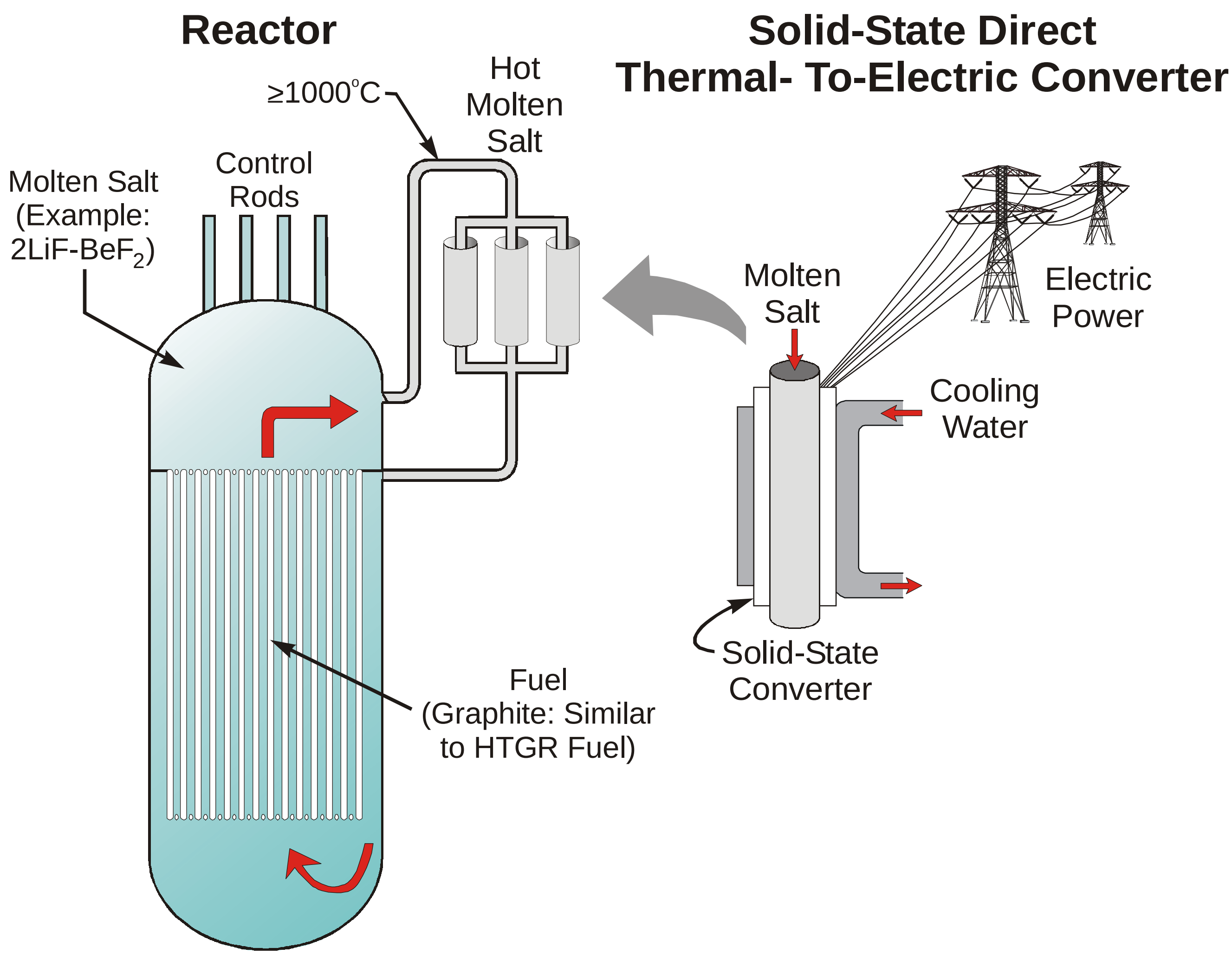
High Temperatures Also Create New Options For Production of Electricity

- **High-efficiency helium gas-turbine cycles**
  - **Conversion efficiency >50% at 1000ºC**
  - **Provide isolation of power cycle from the reactor using low-temperature-drop heat exchangers**
  - **Use advanced gas-turbine technology**
- **Direct thermal to electric production**
  - **No moving parts (solid-state) methods to produce electricity from high-temperature heat**
  - **Radically simplified power plant**
  - **Potential for major cost reductions**
  - **Longer-term option—solid-state technology is in an earlier stage of development**

Advanced High Temperature Reactor With Brayton Cycle For Electricity Production



The AHTR May Enable the Longer-Term Option of Direct Conversion of Thermal Energy to Electricity



High Temperatures Create Development Challenges

- **AHTR uses some demonstrated technologies**
  - **Fuels (modified HTGR fuel)**
  - **Coolant**
- **AHTR requires advanced technology**
  - **High-temperature materials of construction**
  - **Optimized system design**
  - **Heat exchangers**
  - **Hydrogen and energy conversion systems**

Regulatory Implications of Hydrogen Production

- **Different owners: oil & chemical companies**
  - **Larger than traditional utilities**
  - **Different perspectives**
- **Both chemical and nuclear safety must be considered (it is not clear where the primary hazard is)**
  - **Chemical plant must not impact nuclear plant**
  - **Nuclear plant must not impact chemical plant**
- **Non traditional (non-water, non-liquid-metal, non-gas) reactors may be preferred**

Conclusions

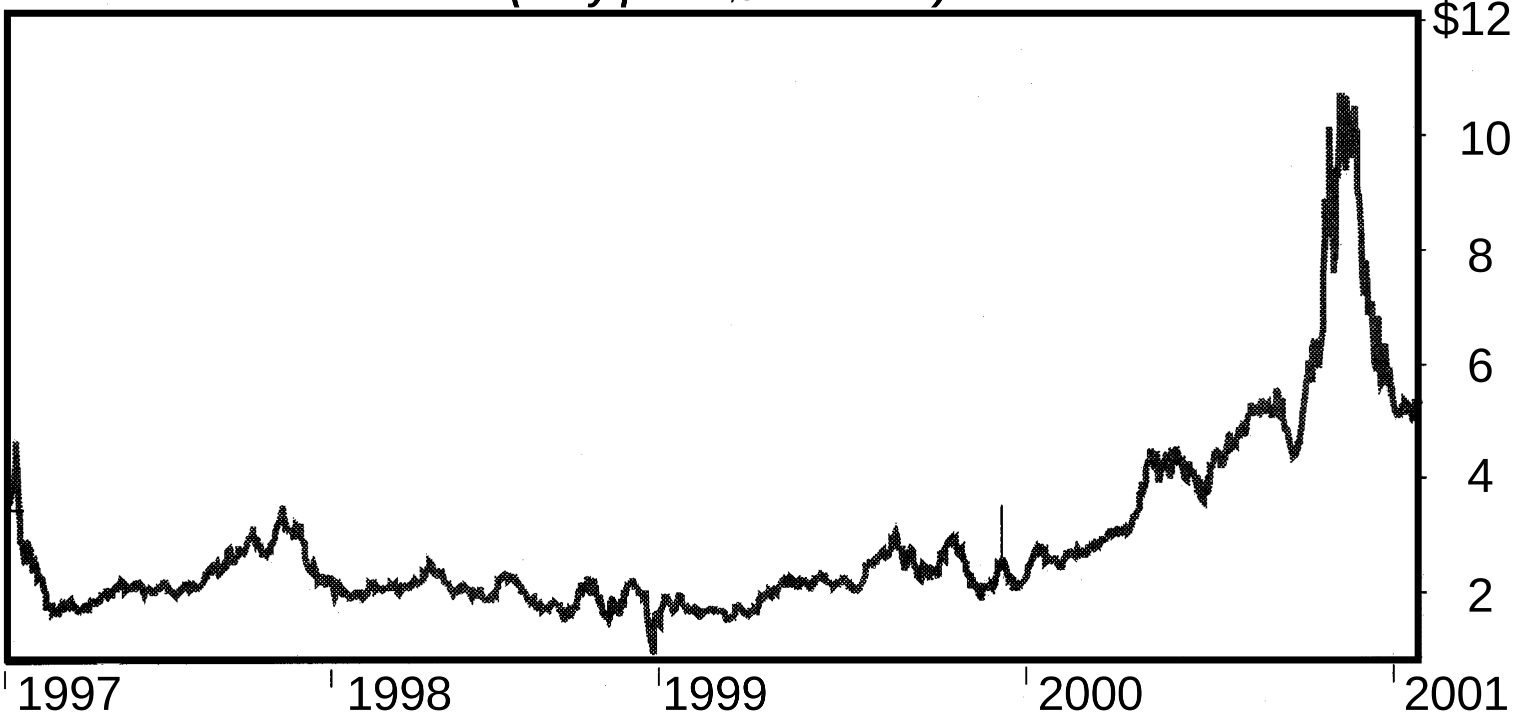
- **Economic methods to produce hydrogen from nuclear power may provide multiple benefits**
  - **Increased gasoline and diesel fuel yields per barrel of crude oil with reduced dependence on foreign oil**
  - **Long-term pathway to a hydrogen economy**
- **High-temperature heat allows for new, more-efficient methods to produce electricity**
- **Reactors with different characteristics may be preferred for such different uses**
  - **Very high temperatures**
  - **Low pressures**

Added Information

Hydrogen is Made From Natural Gas—If Gas Prices Remain High, a Significant Fraction of the Chemical and Refinery Industry May Move Offshore

U.S. Natural Gas Prices are Rising

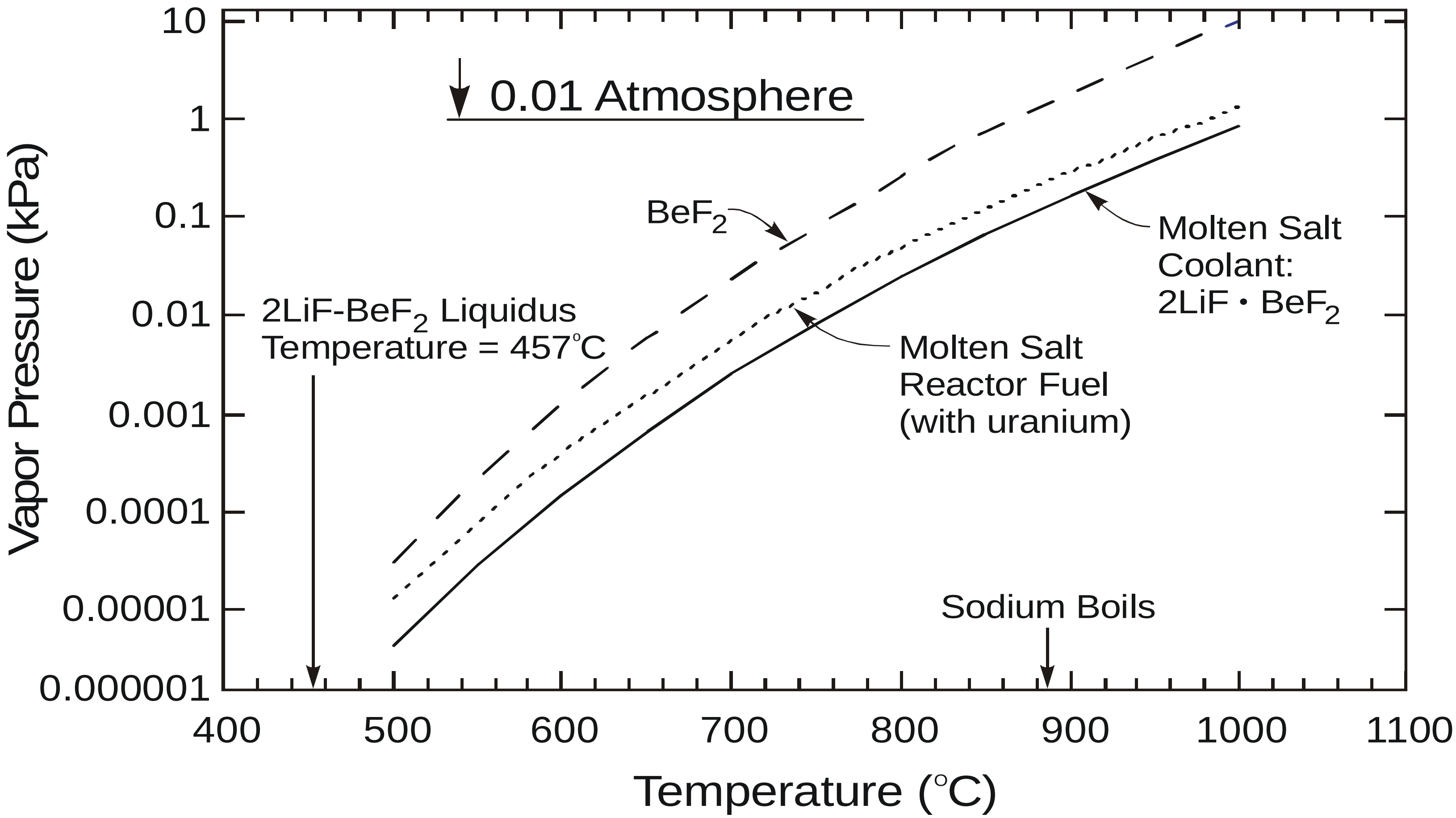
(daily price $/1000 cu ft)



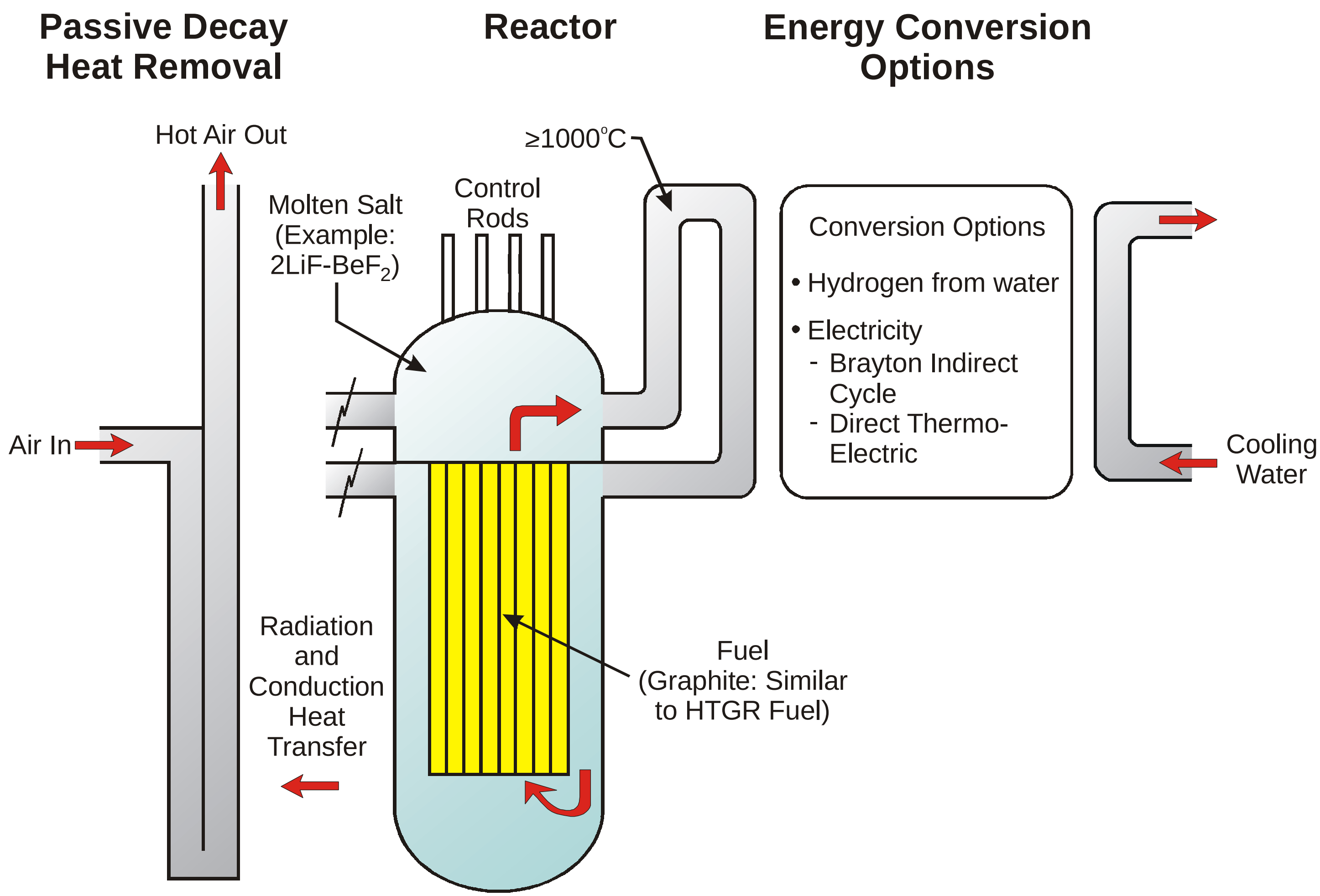
There Has Been Extensive Development of Molten Salt Technologies For High-Temperature Nuclear Applications

- **Initial development was for the Aircraft Nuclear Propulsion Program**
  - **Heat transferred from the solid-fueled reactor to the heat exchanger in the aircraft jet engine**
  - **Molten salts were chosen based on physical (pressure <1 atm.) and nuclear properties**
- **Molten salts are being considered for cooling fusion reactors (both types)**
- **Russian studies on molten-salt-cooled reactors**

Vapor Pressure of $2LiF-BeF_2$ Is Low Compared To Other Reactor Coolants



Advanced High-Temperature Reactor



Summary

Advanced High-Temperature Reactor for Hydrogen and Electricity Production

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Historically, the production of electricity has been assumed to be the primary application of nuclear energy. That may change. The production of hydrogen (H_2) may become a significant application. The technology to produce H_2 using nuclear energy imposes different requirements on the reactor, which, in turn, may require development of new types of reactors. This alternative application of nuclear energy may necessitate changes in the regulatory structure.

Alternative Applications of Nuclear Energy—H_2 Production

World consumption of H_2 for the production of chemicals (e.g., CH_3OH and NH_3) and the refining of crude oil into transport fuels is growing rapidly. Hydrogen is added to heavy crude oils to (1) produce lighter fuels such as gasoline and (2) remove impurities such as sulfur. As resources of high-quality light crude oils are exhausted, more H_2 is required to produce an equivalent amount of gasoline per barrel of lower-grade crude oil. Because much of the H_2 is produced from lower-value refinery streams, an economical outside source of H_2 would allow the conversion of these hydrocarbons into gasoline rather than require their use for H_2 production. As a result, the output of liquid fuel per barrel of crude oil could significantly increase, thereby reducing crude oil imports. Nonfossil H_2 would also substantially decrease the quantity of natural gas that is used to produce H_2, thus reducing carbon dioxide emissions.

Currently it is estimated that 5% of natural gas is used to manufacture H_2 for chemical and refinery use. Hydrogen consumption is increasing rapidly, and some projections indicate that by 2010 the energy value of the hydrocarbons used to manufacture H_2 will exceed the energy output of all nuclear reactors in the United States. Hydrogen has also been proposed as a future transport and distributed-power fuel. These advanced applications would increase the H_2 demand by one to two orders of magnitude. The development of economic nonfossil H_2 would also protect the domestic chemical and refinery from high natural gas prices that could increase H_2 costs sufficiently to cause parts of these industries to move offshore for lower cost sources of natural gas.

Hydrogen and electricity represent the only large potential markets for nuclear energy. Therefore, if the uses of nuclear power are to expand, reactors must be designed to efficiently produce H_2. Many direct thermochemical methods are possible for producing H_2 with the input of heat and water. High temperatures (800 to 1000EC) are required to ensure rapid chemical kinetics (small plant size with low capital costs) and high conversion efficiencies (- 50% thermal energy converted to H_2). A low-pressure reactor coolant is desired to couple to the low-pressure chemical plant. The development of such a reactor would also make possible better methods of electricity production: indirect Brayton cycles and direct thermal-to-electric conversion techniques. Efficient solid-state technologies for the latter process do not exist at present.

Advanced High-Temperature Reactor (AHTR)

If nuclear energy is to be used for production of H_2 or similar applications, reactors that can meet the unique high-temperature requirements (800 to 1000EC) are required. One such reactor—the AHTR—is described herein. The high-temperature operations also create the potential for very-high efficiency methods for the production of electricity.

The AHTR would generate up to 600 MW(t) with an outlet temperatures of >1000EC. The reactor core contains a graphite-matrix fuel and core that has the same general characteristics as that developed for modular high-temperature gas cooled reactors (MHTGRs). Such fuels have been demonstrated at temperatures up to 1200EC. The AHTR fuel cycle would be similar to that for the MHTGR. The liquid coolant would be a molten fluoride salt ($2LiF\text{-}BeF_2$) developed for molten-salt-fueled fission reactors and proposed as a coolant for fusion reactors. The coolant would transfer heat from the coated-particle graphite fuel to the H_2 chemical plant. This particular salt has a boiling point of -1400EC. Several other candidate salts exist such as FLiNaK (a eutectic mixture of 46.5 mol % LiF, 11.5 mol % NaF, and 42 mol % KF). Fluoride salts are fully compatible with graphite (the aluminum industry has electrolyzed aluminum fluoride salts in graphite furnaces for over a century to produce aluminum metal).

The combination of the graphite fuel form and the molten salt coolant makes possible the very high temperatures. The low-pressure coolant reduces the need for high-temperature, *high-strength* materials in the external heat exchangers, compared with those required in reactors that use high-pressure helium or other high-pressure fluids to transfer heat. The maximum salt outlet temperature can be significantly higher than that for a gas-cooled reactor with the same graphite fuel and same peak fuel-temperature limits. This is a consequence of the heat-transfer properties of molten salt (similar to water) compared to helium. The improved heat transfer lowers temperature drops between (1) fuel and coolant and (2) coolant and the H_2 plant.

The AHTR reactor has some safety systems in common with other reactors, as well as some unique features. Reactor power is limited by the high-temperature Doppler effect within the fuel. Because the molten salt expands upon heating, an additional negative moderator temperature coefficient is associated with coolant expansion. The reactor physics are similar to those of the MHTGR. In an accident, the decay heat would be conducted directly from the reactor core, through the reactor vessel, and then to the environment. This is similar to the emergency decay-heat-removal system in an MHTGR.

The liquid coolant lowers the potential for radionuclide release by several mechanisms: (1) atmospheric pressure eliminates a primary driving force for radionuclide releases, reduces the forces that can destroy the containment or confinement system, and simplifies isolation of the reactor from the environment, (2) the difference (at least 400EC) between the operating temperature and boiling point of the salt provides a large margin before boiling occurs, (3) the physical properties of the coolant allow natural circulation of the coolant to provide decay-heat cooling, and (4) most fission products and actinides dissolve into the coolant. Significant work is required before the full safety implications of this type of reactor are understood and before such a reactor could be built.

Regulatory Implications

The production of alternative products using nuclear energy encompasses different safety considerations involving both the reactor and the energy conversion facility. The impacts of the reactor on the chemical plant and the impacts of the chemical plant on the reactor must both be considered. It implies ownership—and possibly operation—by non-utility corporations. The different products (H_2) may require reactors with non-traditional coolants such as molten salts.