Advanced High-Temperature Reactor:
Molten Salt Coolant and Graphite Fuel

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Outline

- Why is a nuclear reactor needed to produce high-temperature heat?
- The Advanced High-Temperature Reactor (AHTR)
- Conclusions

There Are Strong Incentives To Develop Higher Temperature Reactors

- Growing hydrogen demand (50 million tons/year)
  - Large demand for fertilizer and chemical production
  - Increasing hydrogen demand by refineries to make transport fuels
    - Economic hydrogen could allow production of 15% more gasoline, diesel, and jet fuel per barrel of oil
      - Less dependence on foreign oil
      - Address balance-of-trade issues
      - Lower carbon dioxide emissions
    - Hydrogen rich fuels are clean fuels
    - Future hydrogen economy
- High-efficiency electric production

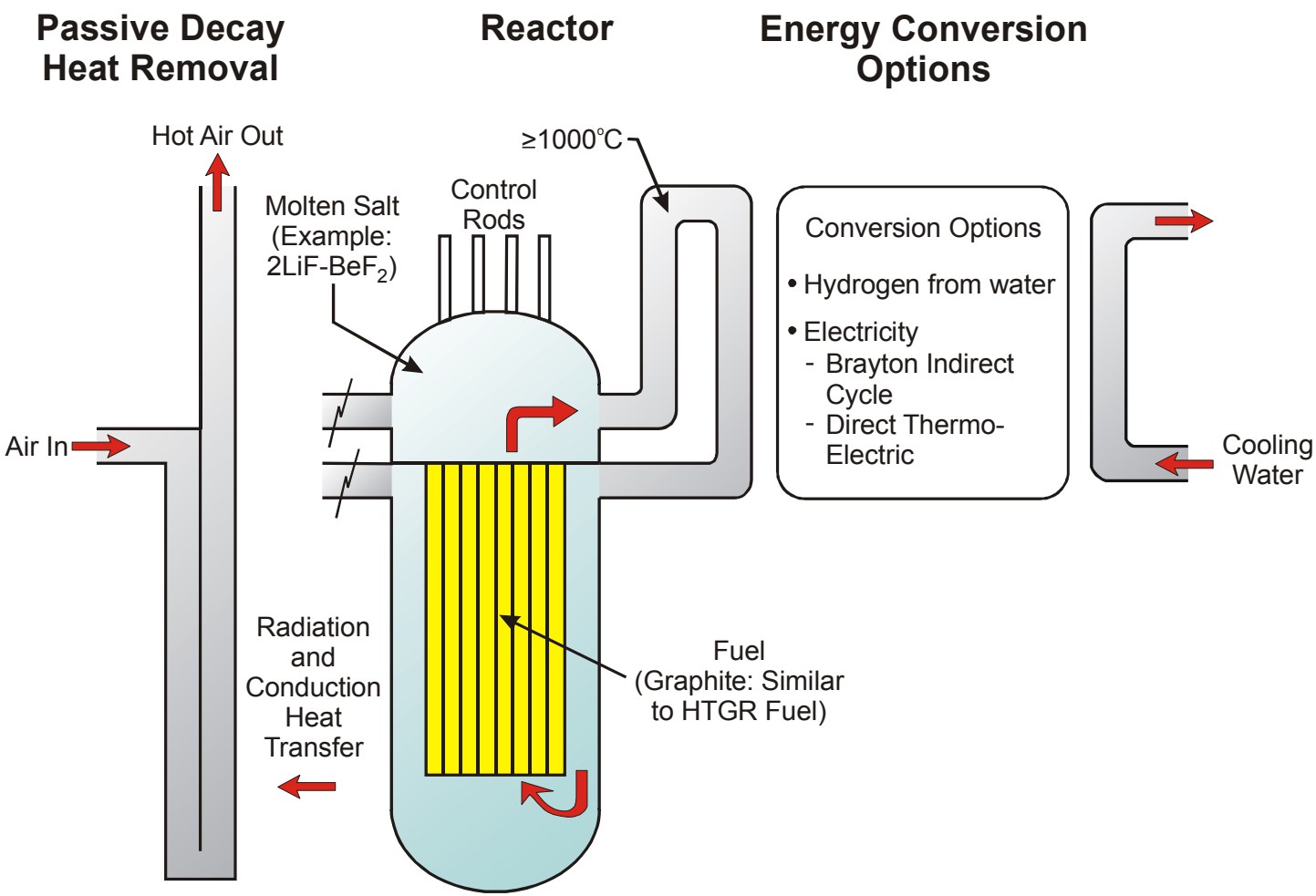
Hydrogen Production And High-Efficiency Electric Production Place Requirements on the Reactor

- Hydrogen production requirements
  - High-temperatures (800 to 1000ºC)
  - Low pressure (highly desirable)
    - Minimize material strength requirements
    - Match H_2 plant conditions
- Electric production
  - Efficiency increases with temperature
  - Lower environmental impacts (less reject heat, reduced fuel consumption)

Advanced High Temperature Reactor

Coated Particle Fuel (Similar to HTGR)
Molten Salt Coolant

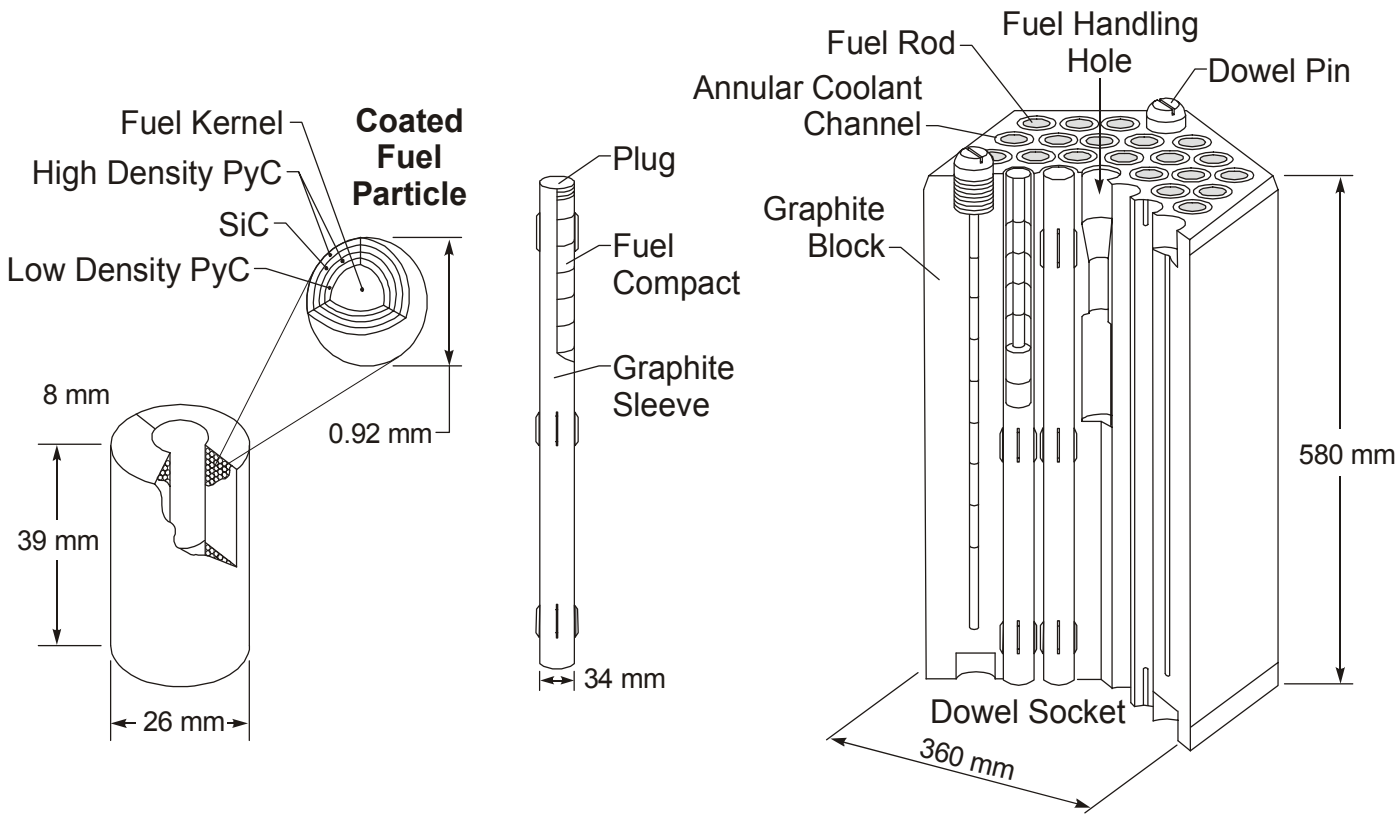
Advanced High-Temperature Reactor



The AHTR Combines Two Technologies To Produce High-Temperature Heat

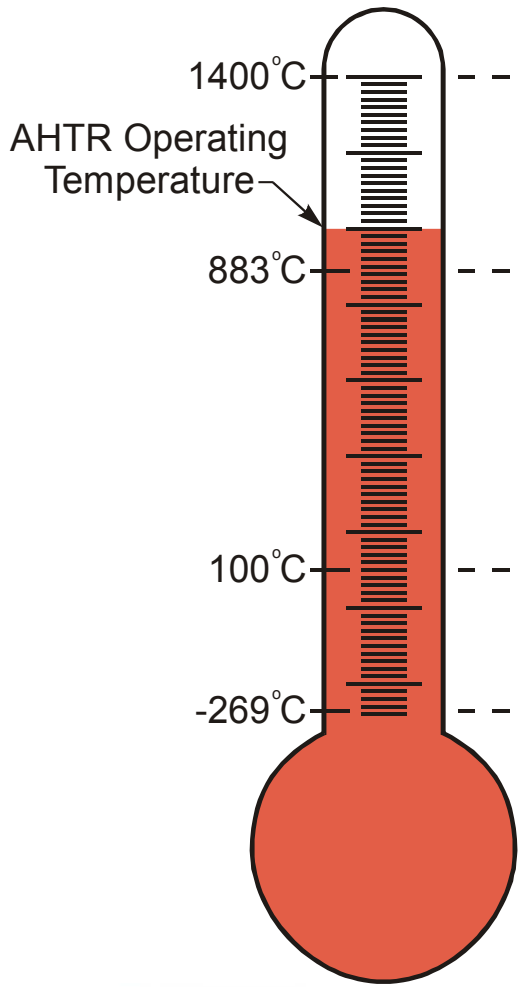
- **Coated-particle, graphite-matrix fuel**
  - Demonstrated temperature limit of ~1200ºC
  - Same fuel technology planned for modular high-temperature gas-cooled reactors
- **Molten salt coolant (Example: $2LiF\text{-}BeF_2$)**
  - Very low pressure (boils at ~1400ºC)
  - Efficient heat transfer
    - Similar to that of water
    - Significantly higher reactor coolant exit temperatures for the same fuel temperature limits compared to helium
  - Coolant for proposed fusion energy plants
  - Developed for aircraft nuclear propulsion program

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



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

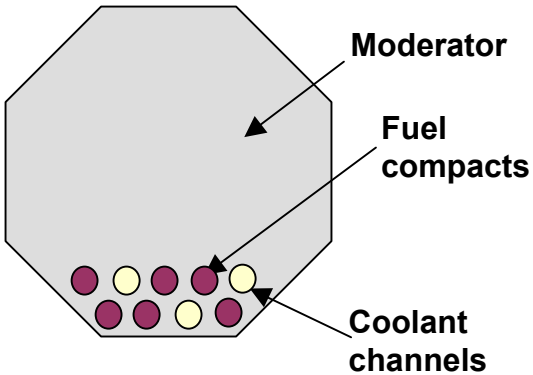
Molten Salt Coolants Allow Low-Pressure Operations at High Temperatures Compared With Traditional Reactor Coolants



Boiling Point	*Coolant*	*Operating Pressure*
1400°C	Molten Salt	Atmospheric
883°C	Sodium	Atmospheric
	High Pressure To Maintain Dense (Efficiency) Coolant	
100°C	Water	1000-2200 psi
-269°C	Helium	1000-2000 psi

Fuel Element / Moderator Configurations Determine Fuel Coolant Temperature Differentials

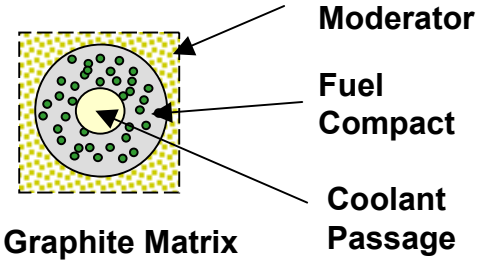
Cooling channels in moderator



Graphite Matrix with Coolant Channels and Fuel Rods

2 cm diameter coolant channel
2cm spacing to fuel rod
4 cm diameter rod

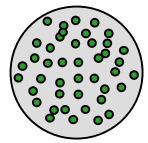
Central Cooling Channels



Graphite Matrix with Fuel Particles

2 cm diameter coolant channel
~10% Coolant Volume
6.3 cm diameter compact

Pebble Bed



Graphite Pebble with Fuel Particles

6 cm diameter
~40% Coolant Volume

Temperature Drops (Loses) From Fuel To Coolant Are Smaller For Molten Salt Coolants Than For Helium

(Higher Delivered Temperatures For Identical Fuel Limits)

Fuel Element Configuration (Power Density 5 W/cm^3)	Delta T (°C) Molten Salt	Delta T (°C) Helium
Cooling Channels in Moderator	280	415
Central Cooling Channel	170	305
Pebble Bed	65	105

Parallel Improvements In Heat Exchangers With Molten Salts Compared To Helium

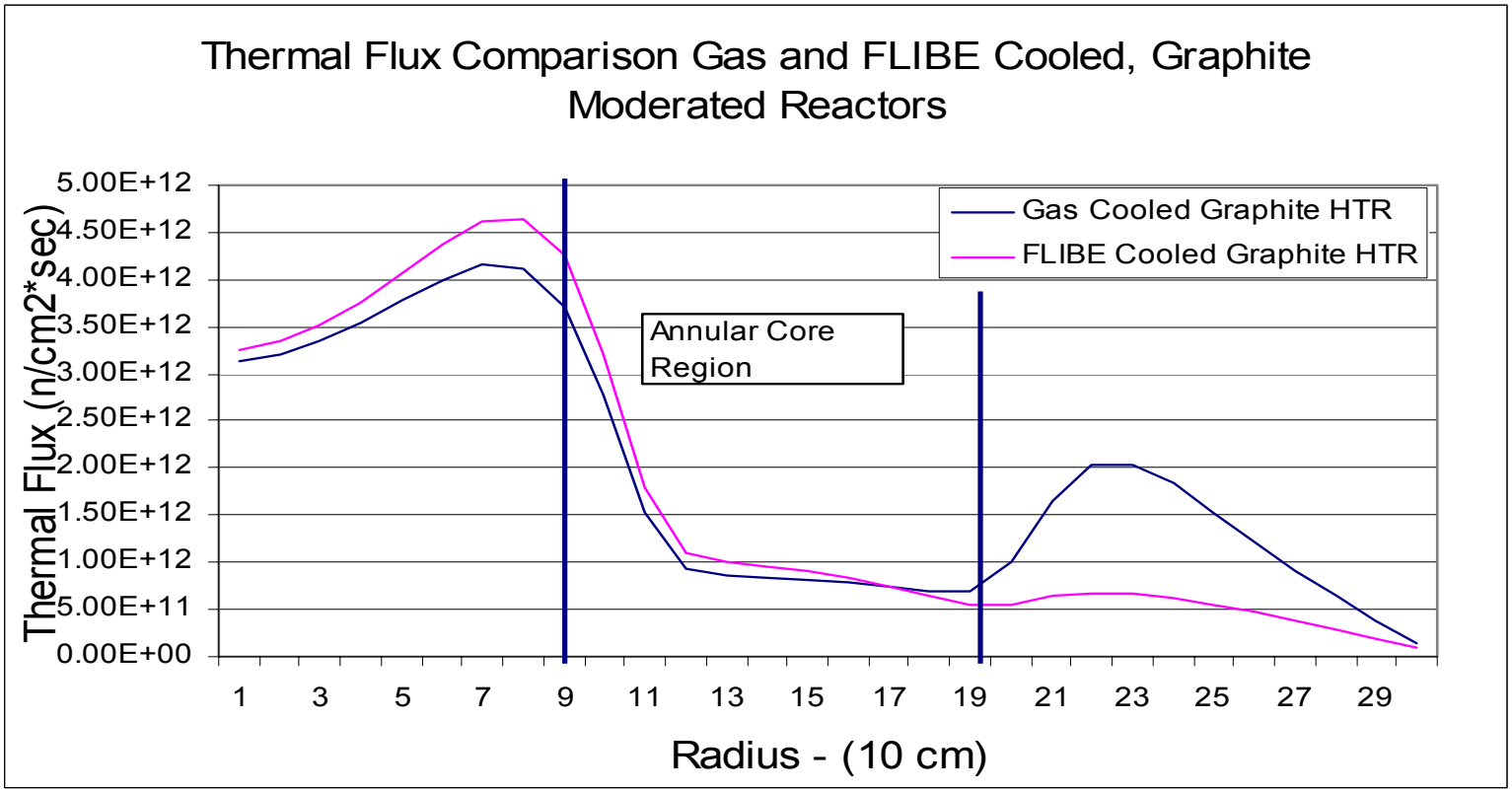
The Safety Case for the AHTR: Accident Prevention

- Power levels limited by inherent design of the reactor
  - Negative void coefficient reduces power transients
  - Negative fuel Doppler coefficient
- Coolant properties increase safety margins
  - Natural circulation of coolant removes radioactive decay heat from the reactor core to heat sinks
  - Efficient heat transfer minimizes the temperature rise of the fuel during off-normal conditions
  - High heat capacity reduces the rate of reactor core heat up during off normal conditions
  - Large temperature margin (~400 ºC) between coolant operating temperature and boiling point

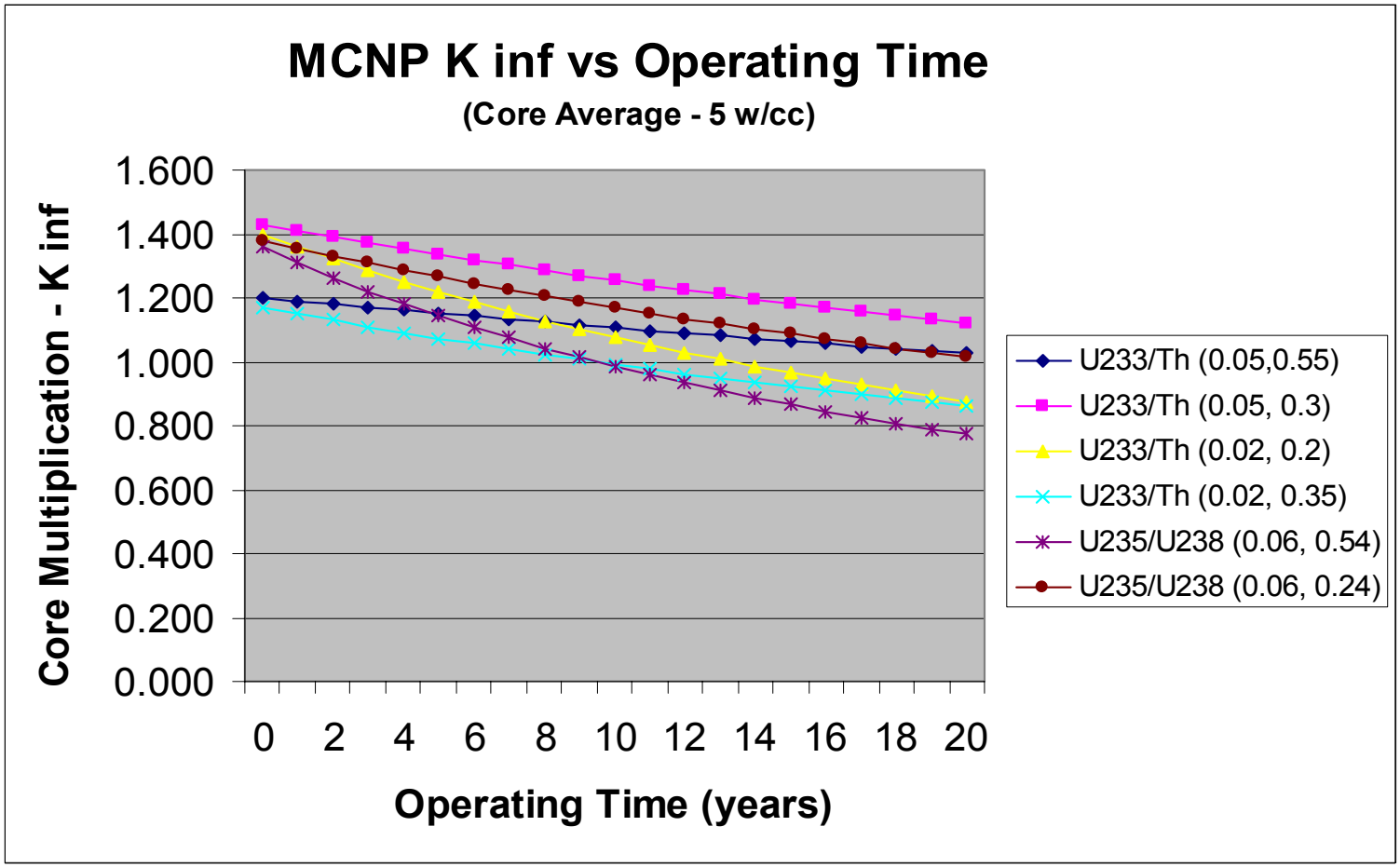
The Safety Case for the AHTR Accident Control

- 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 proposed gas-cooled reactors

AHTR Neutron Flux Characteristics Are Similar To A Gas-Cooled Reactor



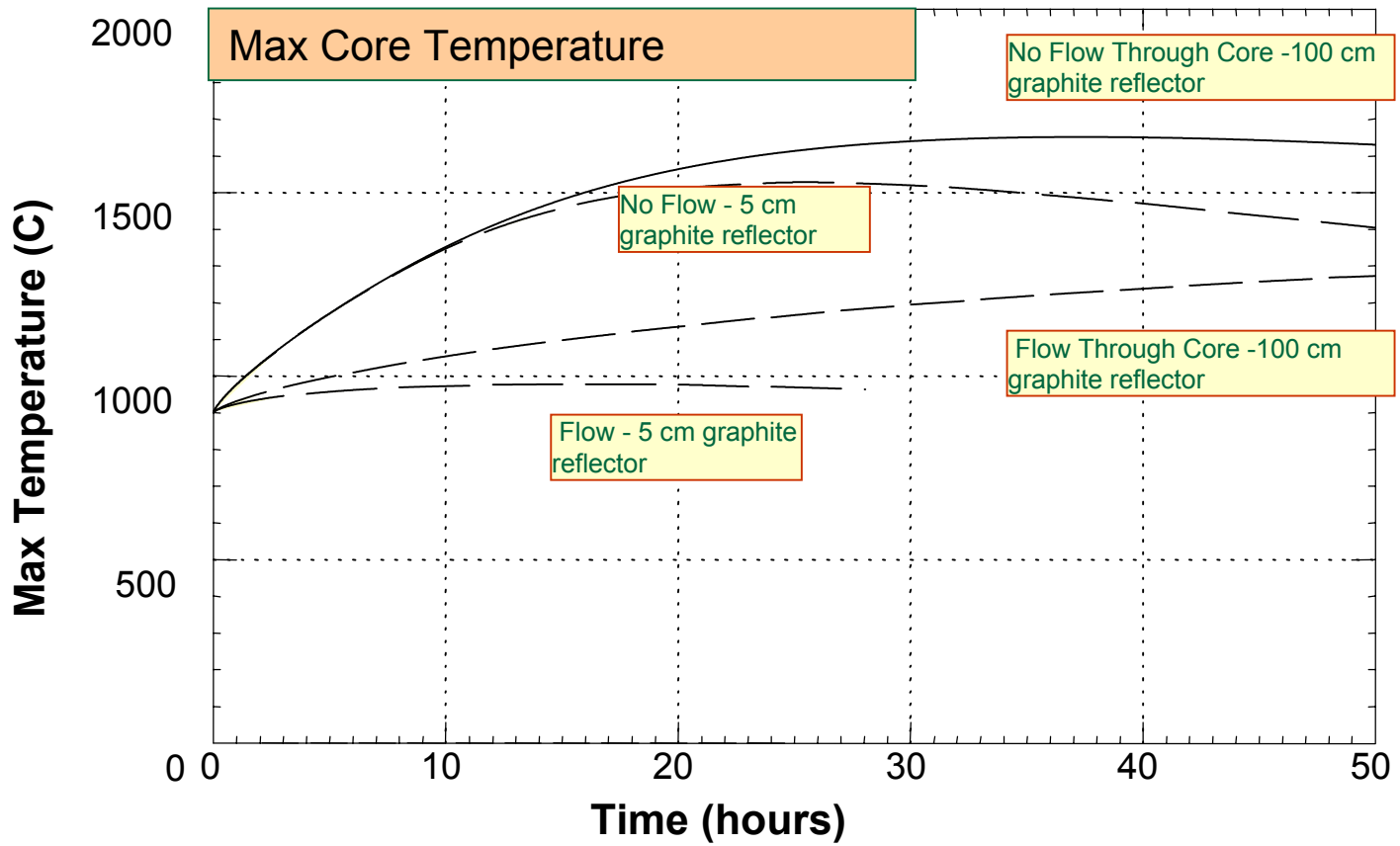
AHTR Fuel And Fuel Lifetime Characteristics Are Similar To A Gas-Cooled Reactor



Molten Salt Coolant Heat Transfer Enhanced Passive Safety Characteristics May Allow Larger Reactors With Passive Cooling

- Parametric Analyses
  - 5 W/cc -10 yr Operating History Core
  - Core Radius - 300 cm
  - Molten Salt Region - 100 cm
  - Graphite Reflector - 100 cm or 5 cm
  - Hastelloy-N Vessel
  - Air Convection
- Low pressure, high heat capacity, pool type vessel configuration
- FLIBE cooled low power density core -natural circulation facilitates decay heat transfer from core to vessel
- Vessel and pool diameter, vessel heat transfer characteristics, can be designed to optimize passive safety characteristics

Maximum Core Temperatures for 850 MWth Pool Reactor



Conclusions

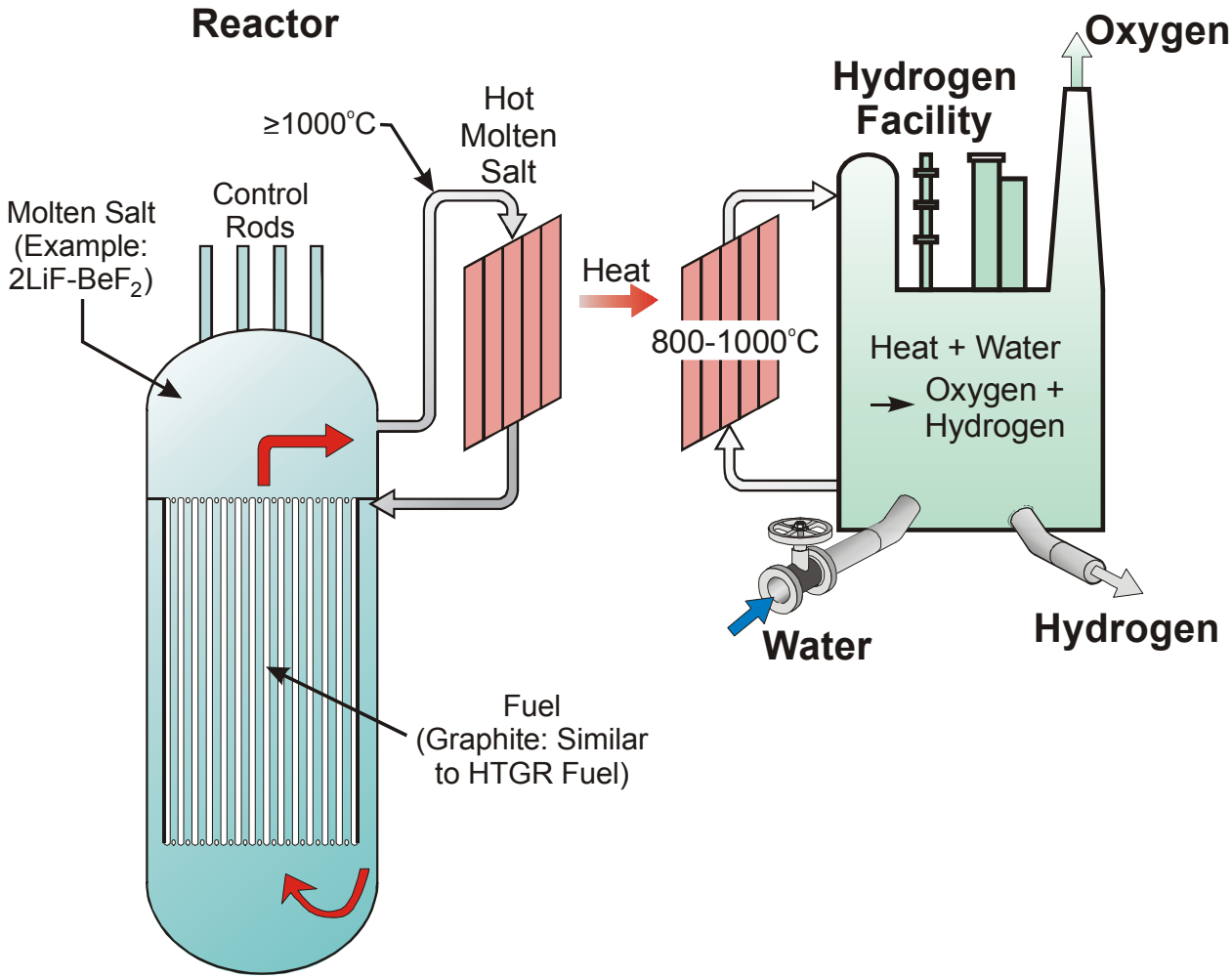
- There is a demand for very-high temperature reactors for hydrogen and efficient electric production
- The AHTR is proposed to meet these requirements
  - Coated particle fuel for high temperatures
  - Molten salt coolant
    - Efficient heat transfer to minimize fuel and system temperatures
    - Low pressure operation to maximize safety and minimize materials requirements
- New concept with many options

Backup Viewgraphs

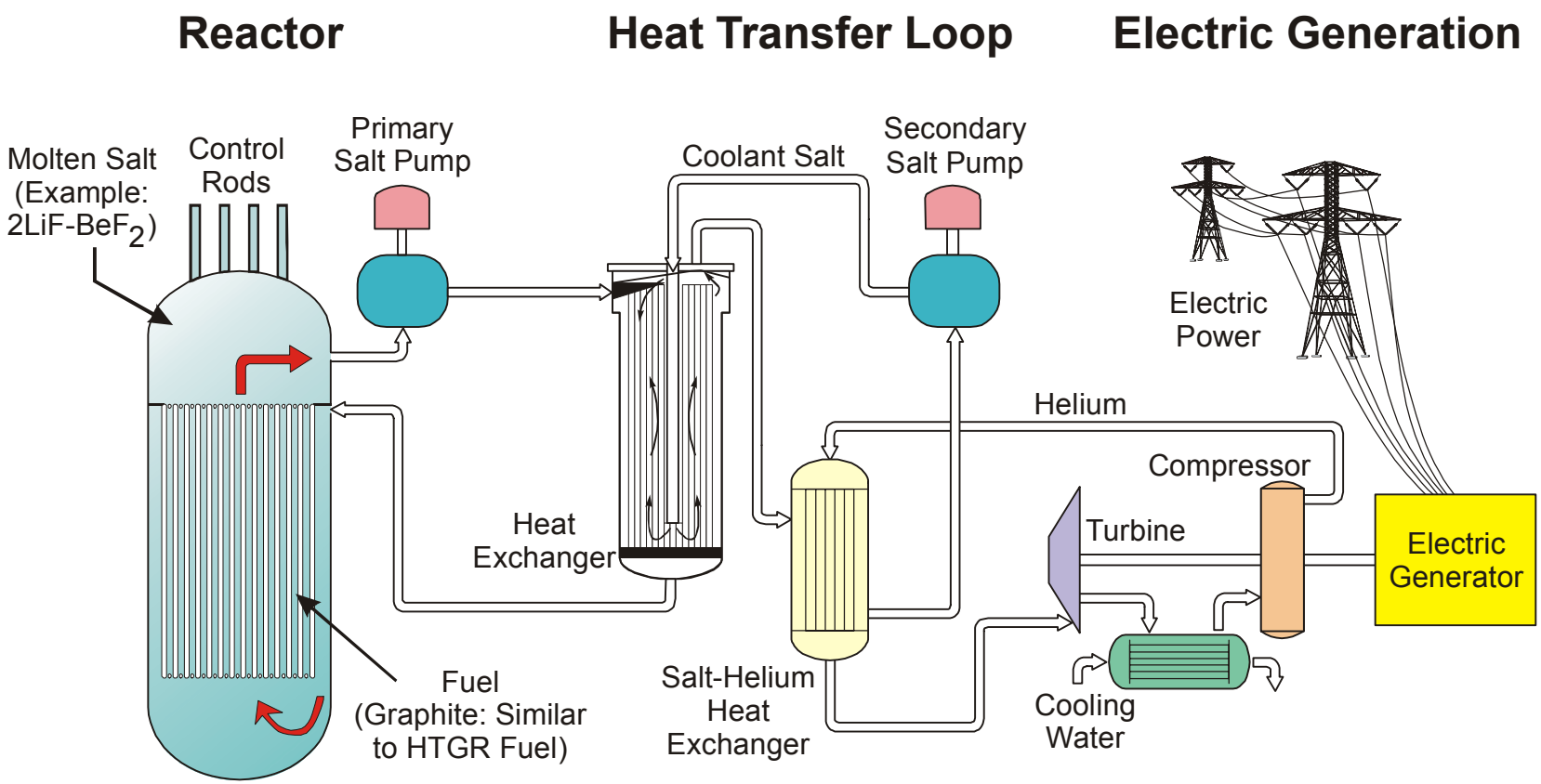
High Temperatures Create New Options For Production of Electricity

- **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

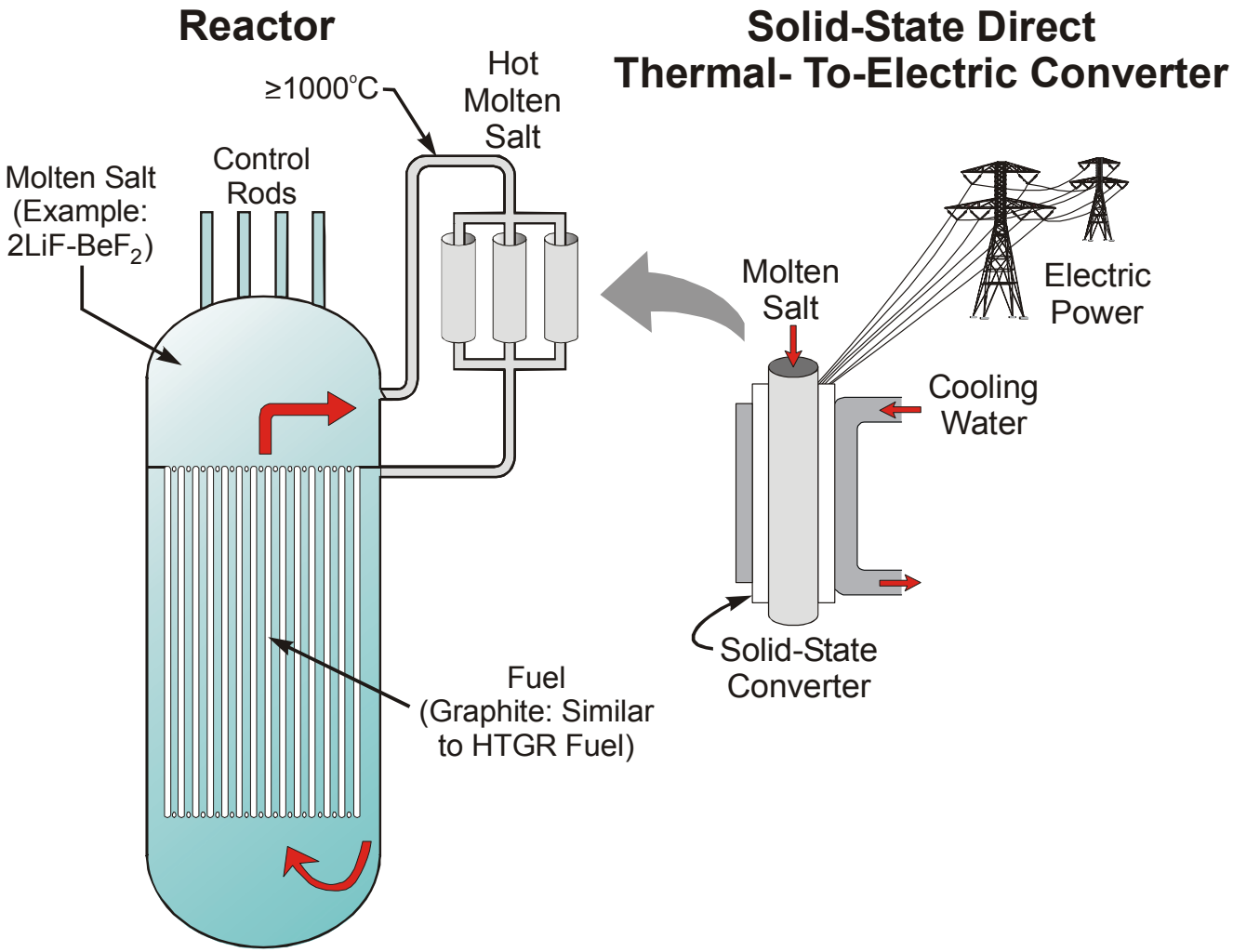
Advanced High-Temperature Reactor Coupled to a Hydrogen Production Facility



Application: Advanced High Temperature Reactor With Brayton Cycle For Electricity Production



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



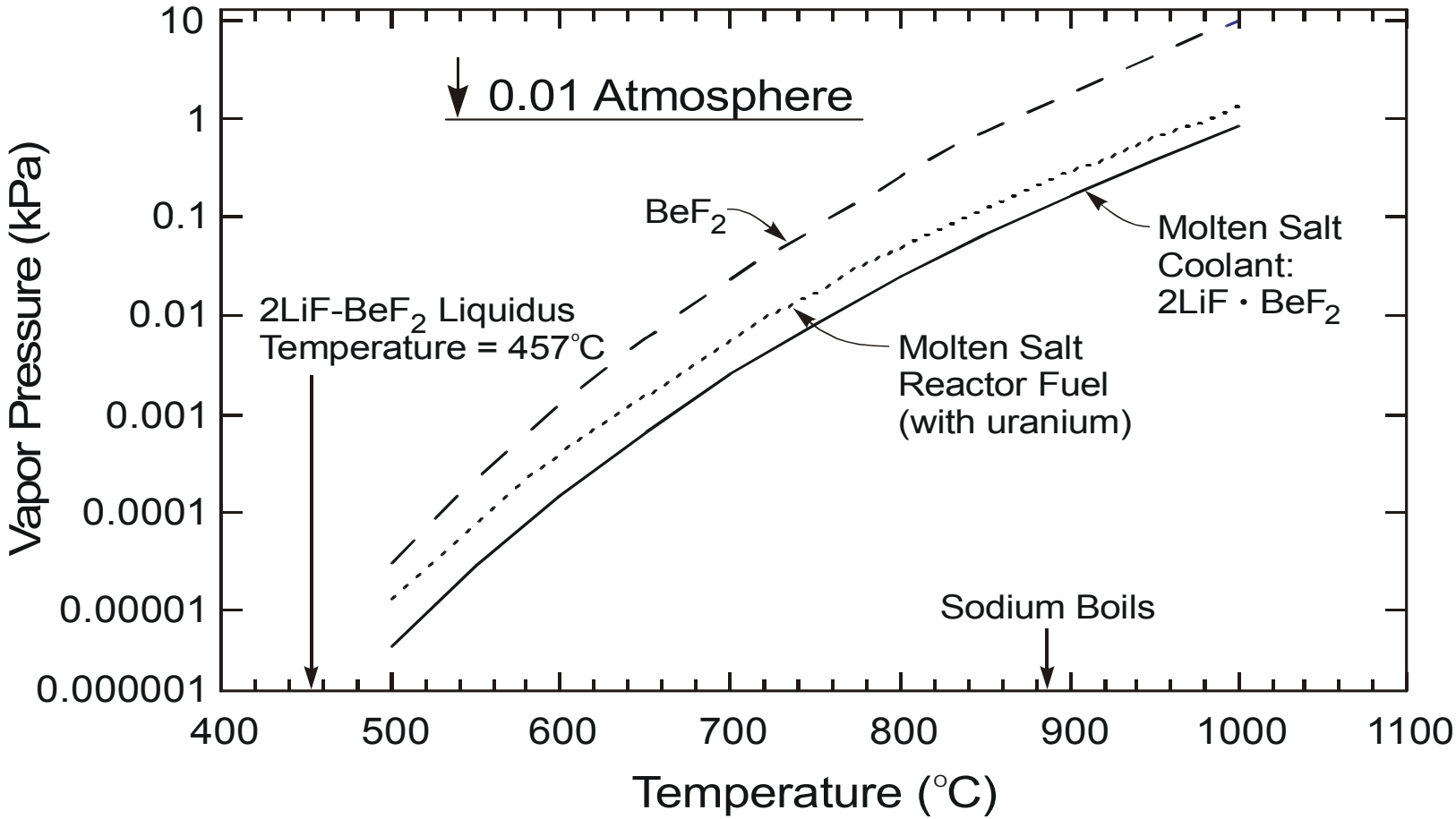
Desired Reactor Characteristics to Produce High-Temperature Heat

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

Development Challenges for the AHTR

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

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



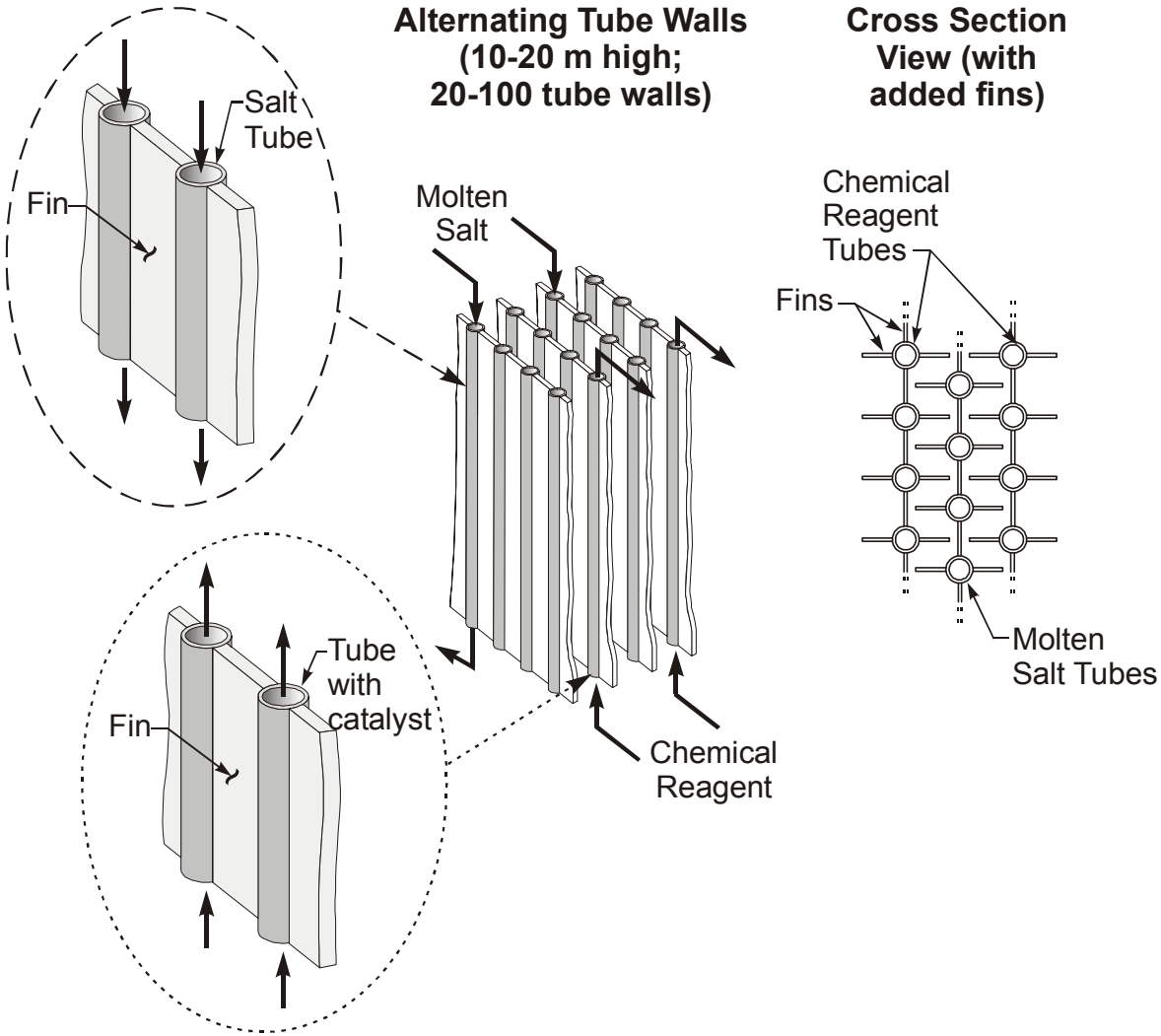
There Has Been Extensive Development of Molten Salt Technologies For High-Temperature Nuclear Applications

- 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 (first wall)
- French, Russian, and Japanese studies on molten salt reactors

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)

Thermal-Radiation Heat Exchanger Option for AHTR-Hydrogen Production Facility



Comparison of AHTR and MHTGR

AHTR

- Low pressure
  - Couple to H_2 plant
  - No direct gas-turbine cycle
  - Safety advantage
- Salt coolant
- Very high temperatures
  - Excellent coolant heat-transfer
  - Higher exit coolant temperatures because of low temperature drops

MHTGR

- High pressure
  - Issues with H_2 coupling
  - Direct gas-turbine cycle
  - Safety concern
- Helium coolant (inert)
- High temperatures
  - Poor coolant heat-transfer
  - Lower exit coolant temperatures because of high temperature drops

Outline for Discussions on AHTR

1. - Motivation for High temp reactor: H_2, electricity, safety, fuel, etc
2. - Concept description - AHTR basics
3. - Fuel coolant, moderator, core (temps), neutronics
4. - Neutronics - run time, power density, etc fuel cycle options
5. - Systems options -- schematics
6. - Safety, proliferation
7. - Issues

Options for Nuclear Hydrogen Production

Electrolysis and Thermo-chemical Cycles

Electrolysis

- established technology
- scaling and economics issues for large systems
- 80 to 90 % efficient (electricity to Hydrogen)
- overall efficiency = thermal X electrolysis = 25 to 35%

Thermo- chemical cycles

- Numerous cycle options examined (>115)
- Most promising cycles demonstrated at Lab scale only
- All require very high temperature stages (>750 C)
- Projected efficiency for Sulfur-Iodine cycle > 50%
- ~50 % of energy required in high temperature stage

Nuclear System Options for Efficient Hydrogen Production

• Efficient Hydrogen production requires some fraction of energy at elevated temperatures (~ 900 C)

• Advanced nuclear system required to meet temperature requirements

•Nuclear system should also address passive safety, proliferation, minimum waste and cost/efficiency goals

• Systems with potential to meet Hydrogen production requirements

- **High temperature gas cooled** (GTMHR, PBMR) - current design concepts meet temperature minimum, high pressure system

- **Metal cooled(Pb, Pb/Bi, Li)** - potential to meet temperature requirements if materials compatibility is satisfactory

- **Molten salt cooled** (MSRE type, or MS cooled Graphite) - alternative approach - low pressure system

• Molten salt cooled reactor may have significant advantages for Hydrogen production

Advanced High Temperature Reactor (AHTR)

Fuel -- Coated particle, graphite matrix fuel

Moderator -- Graphite moderator blocks (prismatic)

Fuel Element -- Annular or rod geometry graphite fuel compact

Coolant -- Molten salt coolant (LiF/BeF, 70/30), BP - 1400 C

Neutronics -- 2.6e13 n/cm2*sec @2 w/cc, negative void, temperature coefficients, generation time 1 msec

Power density -- 5 - 10 w/cc

Vessel -- Loop or pool type vessel configurations

Fuel Cycle -- Core loading, refueling, burnup, and fuel cycle similar to other graphite fueled, gas cooled systems

Advanced High Temperature Reactor (AHTR)

Description: …….. Molten salt cooled, prismatic graphite moderator, coated particle fuel, passive decay heat removal

Application…….. H2 production (HX) and indirect cycle electric

Configuration ……. Pool type, graphite moderated/reflected, axial flow

Fuel Material: …… UO2 or UO2/ThO2 kernel, SiC coating, particles in graphite compact

Fuel Element …. Annular fuel compact id=1 cm, od=3 cm, 10 - 20v/o particles in alternating 3 cm holes in graphite prismatic blocks

Max Fuel Temp …. 1250 C (operational), 1600 (extended transient)

Coolant …… LiF/BeF salt (FLIBE), molten salt BP ~ 1400 C,

Fuel-Coolant dT .. 200 to 250 C

Coolant Outlet T .. 1000 C

System Pressure .. Near ambient (<50 psi),

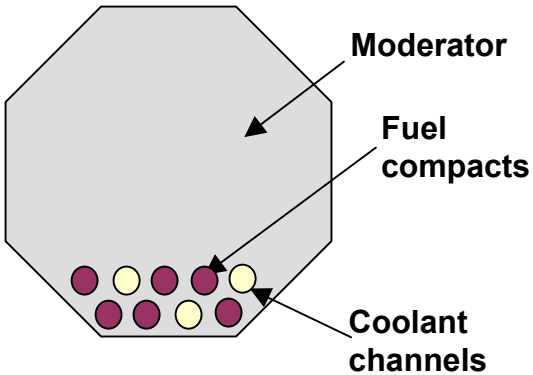
Power (size) ……. 500 to 2000 MWth, passive decay heat removal

Est Efficiency …… 55 %, indirect recuperated Brayton cycle, 900 C available at HX for H2 production

Refueling …… 2 year partial core refuel, 6 year cycle

Fuel Element / Moderator Configurations Determine Fuel Coolant Temperature Differentials

Cooling channels in moderator



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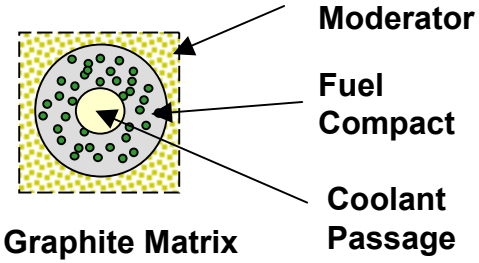
2 cm diameter coolant channel
2cm spacing to fuel rod
4 cm diameter rod

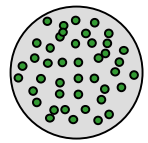
Central Cooling Channels



Graphite Matrix with Fuel Particles

2 cm diameter coolant channel
~10% Coolant Volume
6.3 cm diameter compact

Pebble Bed



Graphite Pebble with Fuel Particles

6 cm diameter
~40% Coolant Volume

Fuel Element Configuration 5 W/cc Core Avg. Power Density	Delta T -- Fuel Compact and Coolant (C) –Molten Salt Coolant	Delta T -- Fuel Compact and Coolant (C) – Helium Gas Coolant
Cooling Channels in Moderator	280	415
Central Channel Cooling of Fuel Compact	170	305
Fuel Pebble	65	105

Fuel Element / Moderator Configurations Determine Fuel Coolant Temperature Differentials

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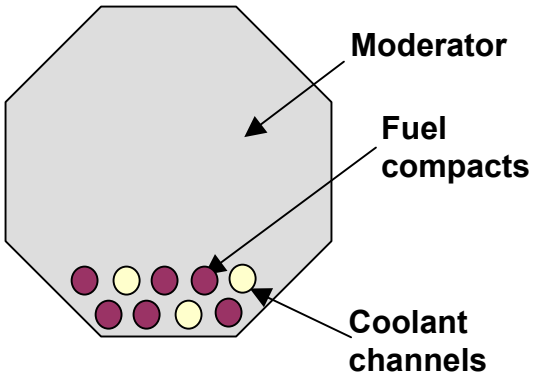

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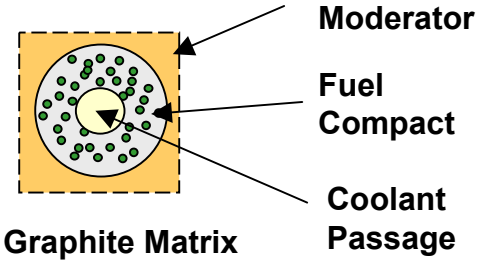
2cm spacing to fuel rod
2cm diameter rod

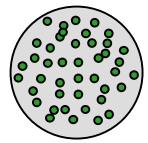
Central Cooling Channels



Graphite Matrix with Fuel Particles

1 cm diameter coolant channel
~10% Coolant Volume
3.2 cm diameter compact

Pebble Bed



Graphite Pebble with Fuel Particles

6 cm diameter
~40% Coolant Volume

Fuel Element Configuration 5 W/cc Core Avg. Power Density	Delta T -- Fuel Compact and Coolant (C) –Molten Salt Coolant	Delta T -- Fuel Compact and Coolant (C) – Helium Gas Coolant
Cooling Channels in Moderator	220	355
Central Channel Cooling of Fuel Compact	80	135
Fuel Pebble	65	105

Molten Salt Coolant Heat Transfer Enhance Passive Safety Characteristics

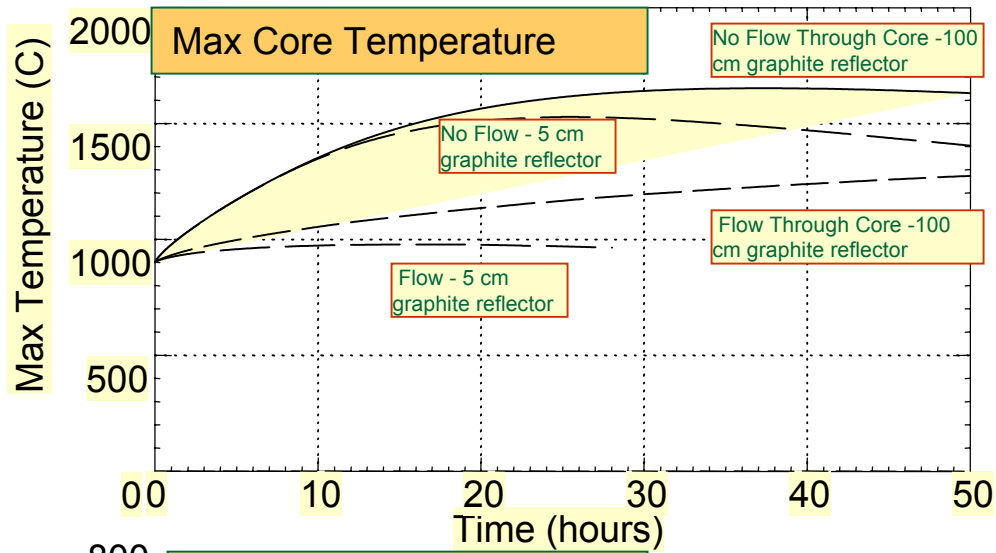
Parametric Analyses

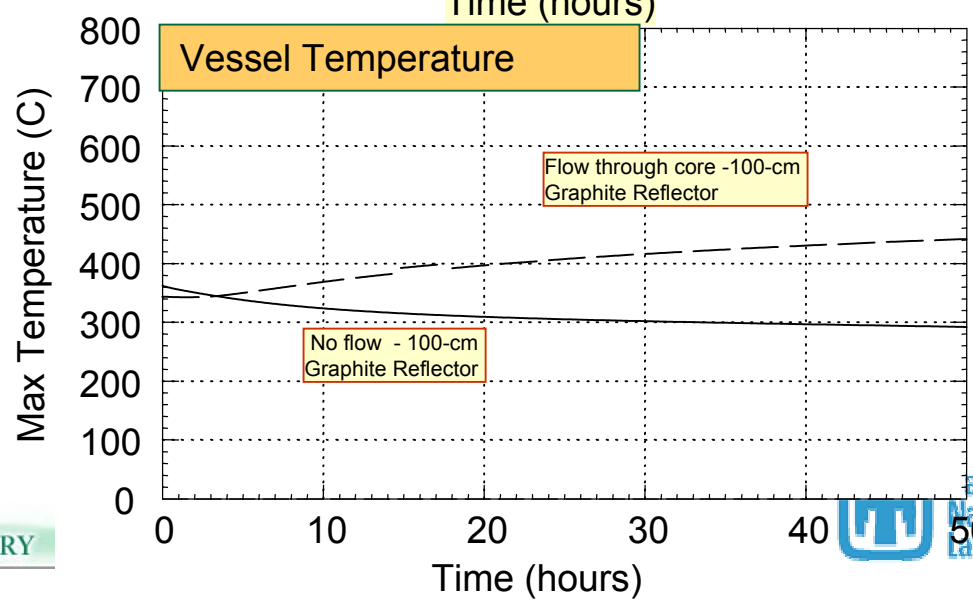
- 5 W/cc -10 yr Operating History Core
- Core Radius - 300 cm
- Molten Salt Region - 100 cm
- Graphite Reflector - 100 cm or 5 cm
- Hastelloy-N Vessel
- Air Convection

Low pressure, high heat capacity, pool type vessel configuration

FLIBE cooled low power density core -natural circulation facilitates decay heat transfer from core to vessel

Vessel and pool diameter, vessel heat transfer characteristics, can be designed to optimize passive safety characteristics

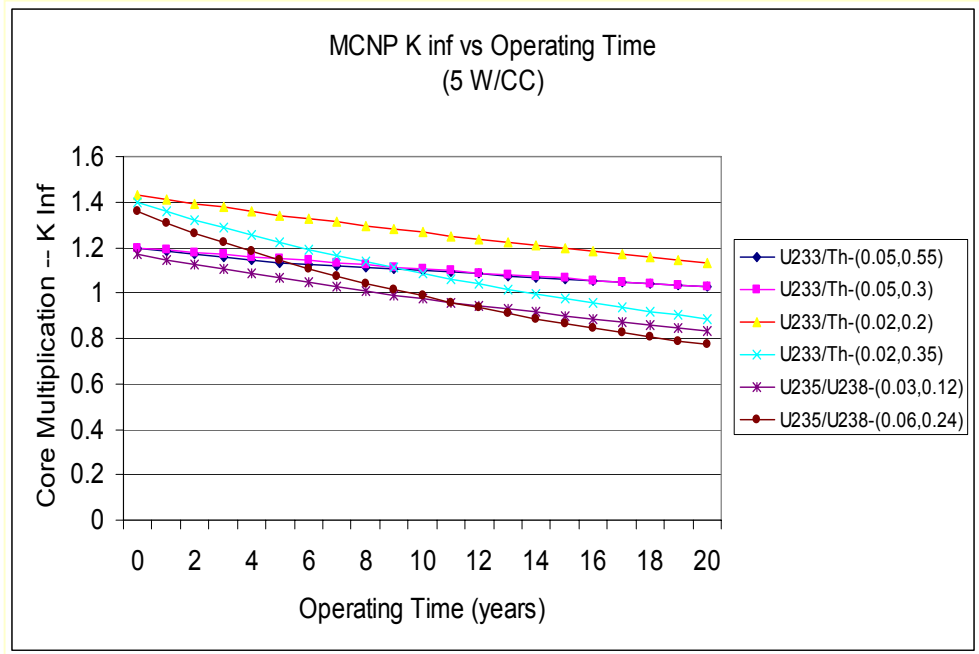
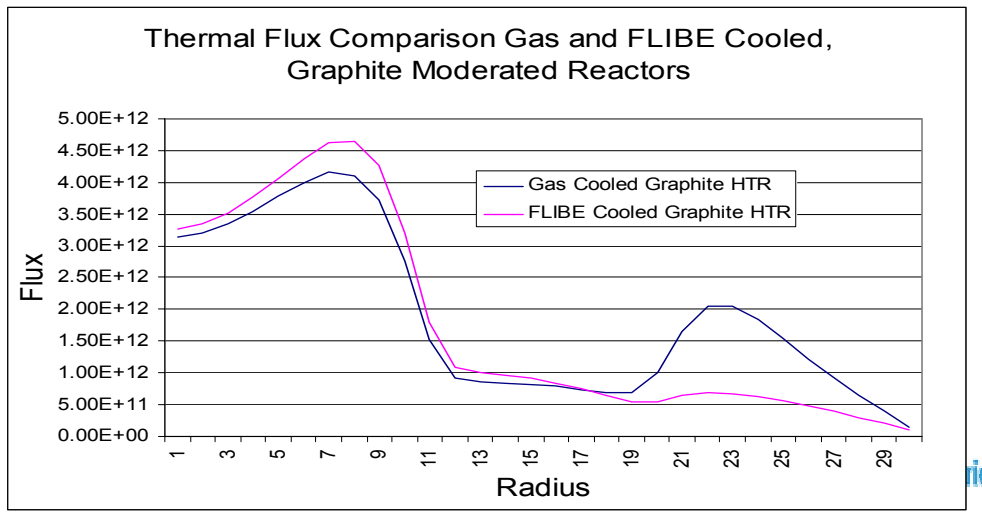




AHTR Neutronic Characteristics

Parametric analyses - annular core, graphite moderator, graphite or FLIBE reflector

- Core id/od/h -- 1m,2m,6m,
- 10 w% UO_2 in Graphite
- 10 volume% coolant
- ($LiF-BeF_2$) 66 m% LiF

Neutronic characteristics of molten salt and gas cooled systems similar - criticality, burnup, kinetics, dK FLIBE reflector = 0.038 ~$5.47, negative void, temperature coefficients

Fissile loading, burnup options similar to PBMR,GTMHR