The Advanced High-Temperature Reactor

Back to the Future With Liquid and Molten Salt

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Rotary
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ORNL Reactor History

Molten Salt Reactors

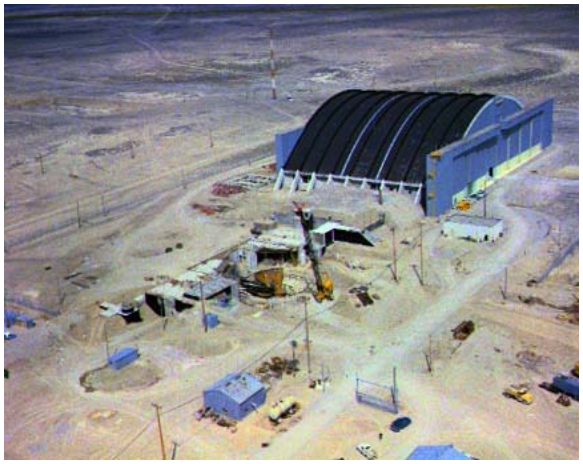
High-Temperature Reactors

ORNL Developed Molten Salt Reactors from the 1950s to the Mid 1970s

Aircraft Nuclear Propulsion Program

← ORNL Aircraft Reactor Experiment: 2.5 MW; 882ºC

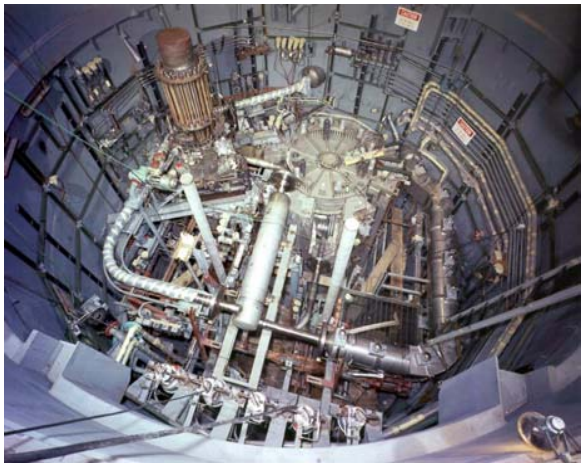
INEL Shielded Aircraft Hanger →



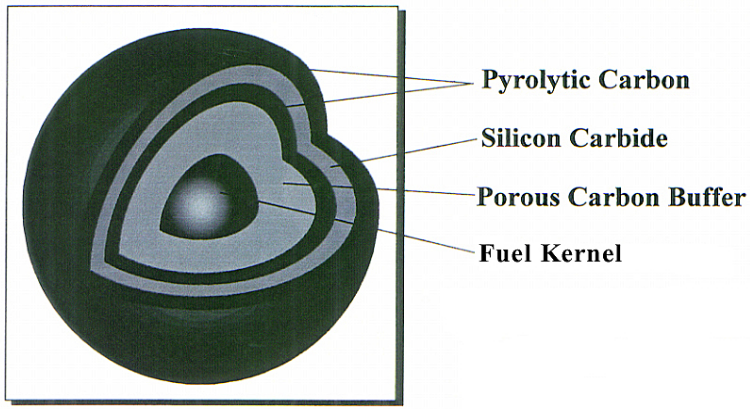
Molten Salt Breeder Reactor Program

← ORNL Molten Salt Reactor Experiment Power level: 8 MW(t)

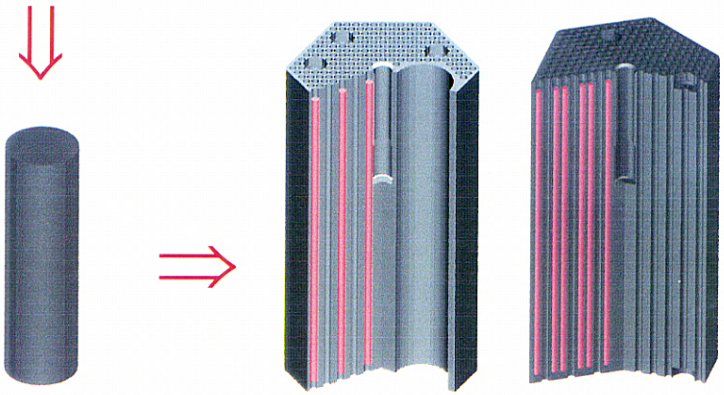
Inside the MSRE containment →



ORNL Developed High-Temperature Reactor Technologies in the 1970s



FUEL PARTICLE



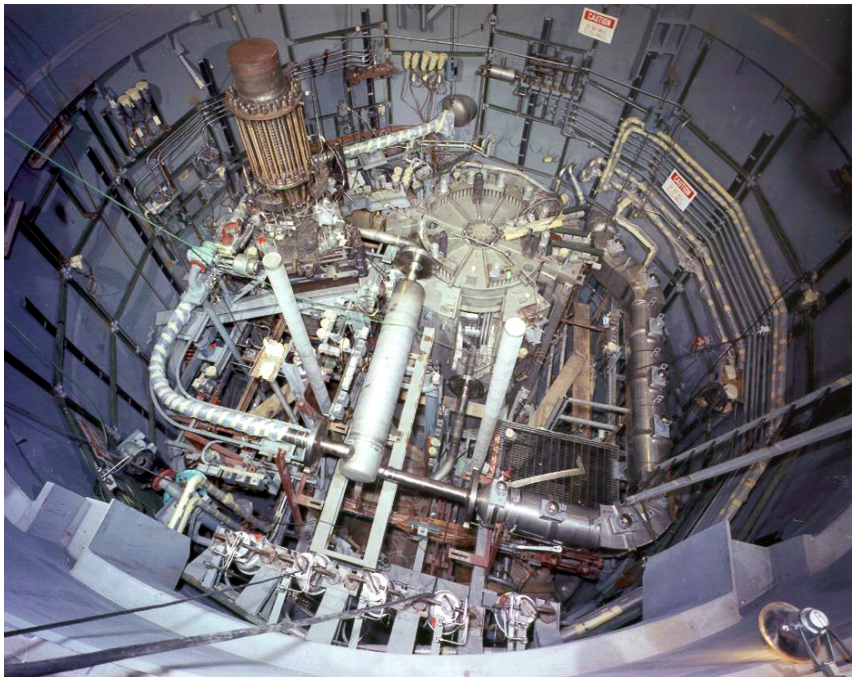
FUEL COMPACT

FUEL ASSEMBLIES

PEACH BOTTOM 1: 1967–1974

FORT ST. VRAIN: 1976–1989

The Reactor Technologies Were Developed



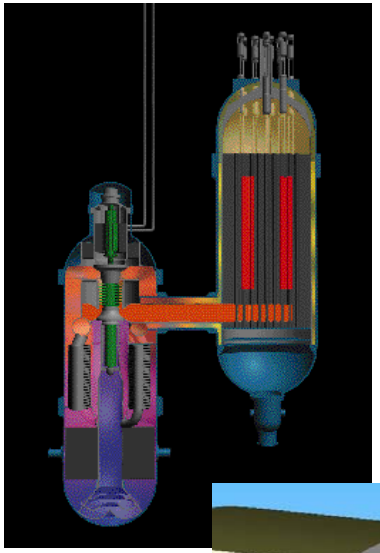
Molten Salt Reactors

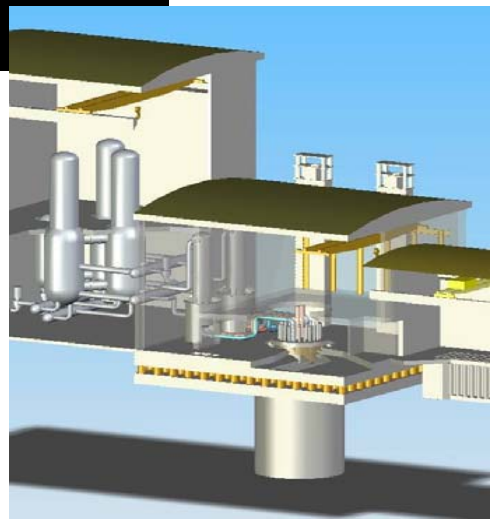
High-Temperature Reactors

And Then They Were Abandoned....

Back to the Future

Rebirth of High-Temperature Reactors and the Birth of the Advanced High Temperature Reactor (AHTR)





- **New needs and new technologies resurrect old technologies**
- **AHTR combines four technologies to create a new reactor concept**
  - **Liquid salt coolants (ORNL)**
  - **High-temperature fuel (ORNL)**
  - **Brayton power cycles**
  - **Sodium reactor plant design**

What Has Changed?

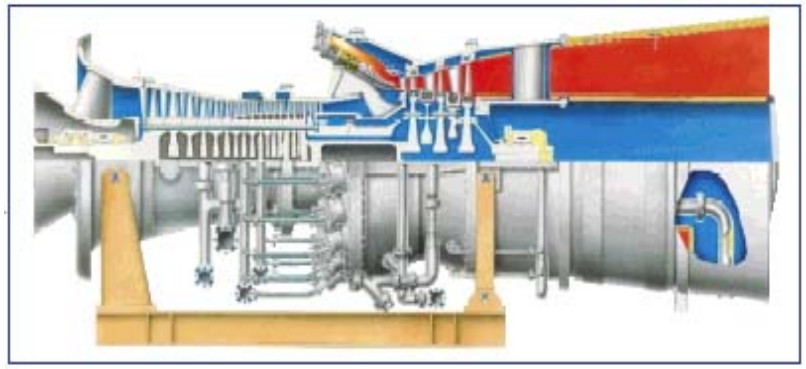
Electricity Production

A New Technology Makes an Old Technology Useful by More Efficiently Converting High-Temperature Heat to Electricity

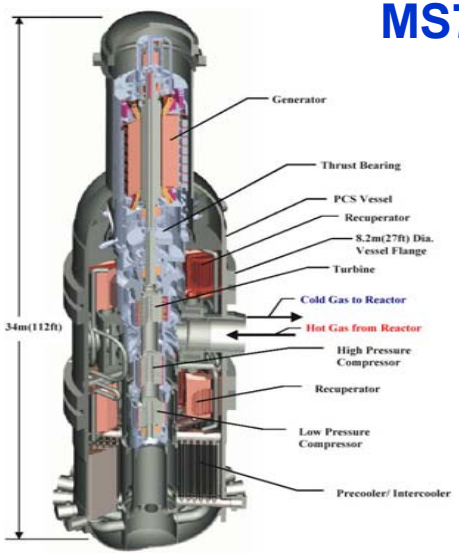
Brayton Power (Jet Engine) Cycles may Make High-Temperature Reactors Viable

(Helium or Nitrogen Brayton Power Cycles)

- High-temperature heat is only useful if it can be converted to electricity
- Steam turbines, the traditional heat-to-electricity technology, have historically had a temperature limit of ~ 550ºC
- New Brayton cycles can efficiently convert high-temperature heat to electricity and make high-temperature reactors more useful
- Boost heat-to-electricity efficiency from 40% to 50%



GE Power Systems MS7001FB



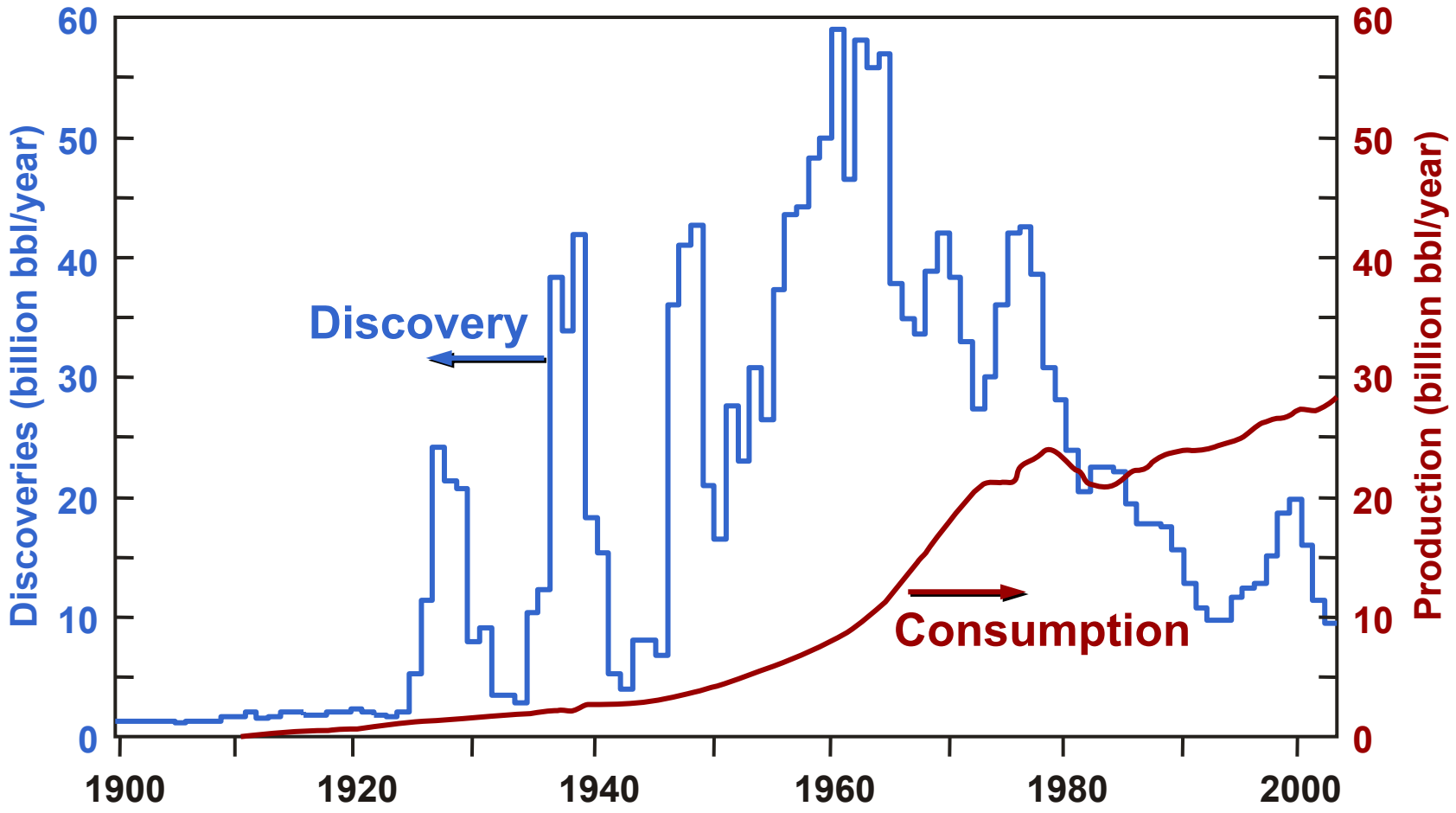
General Atomics GT-MHR Power Conversion Unit (Russian Design)

What Has Changed II

Liquid Transport Fuels

(New Need for Alternative Fuel Sources)

The Age of Oil for Fuels is Closing



Oil and Gas J.; Feb. 21, 2005

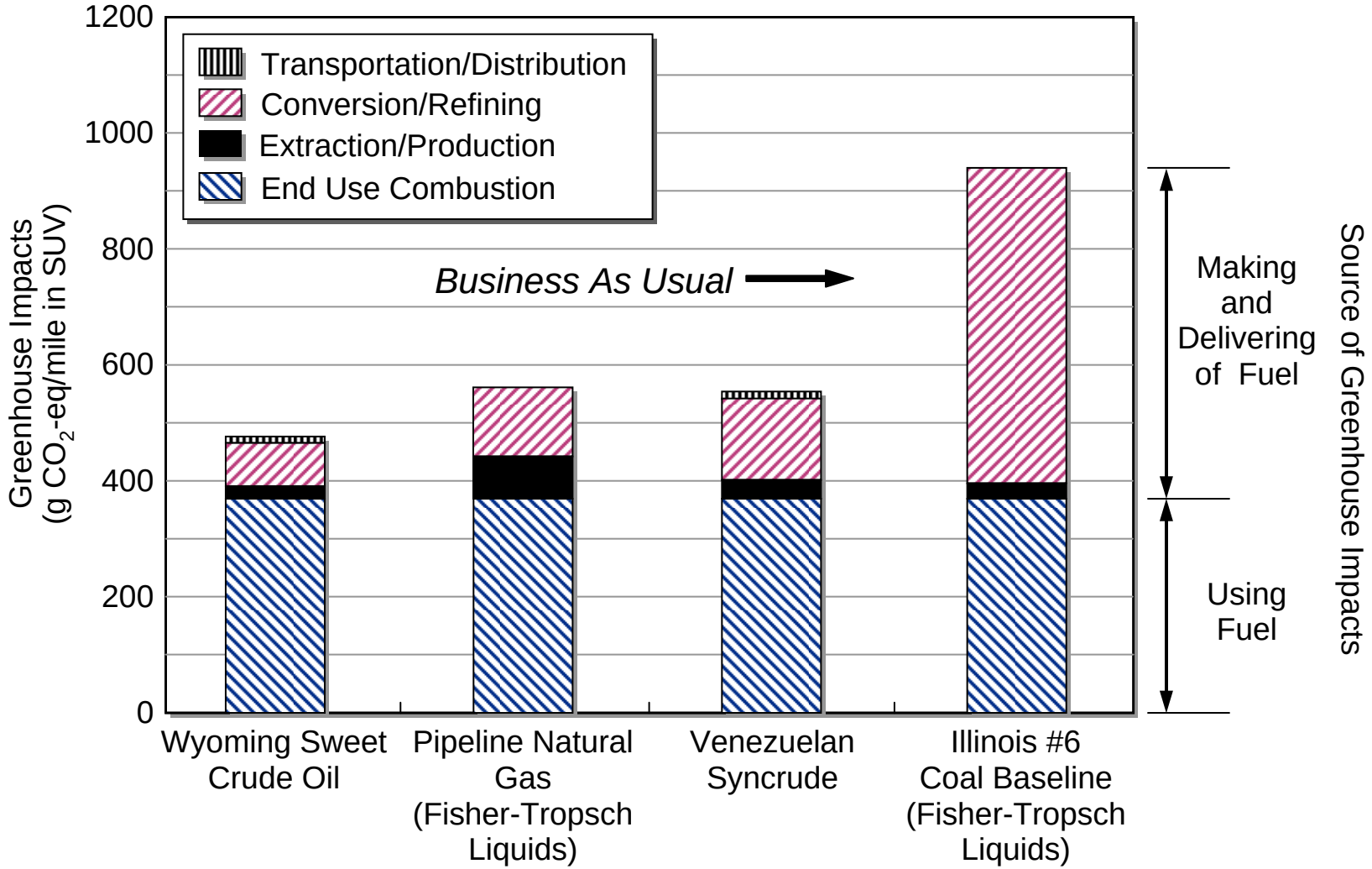
Conventional Futures: Liquid Fuels will be Made from Heavy Oils and Tar Sands

(Lower Hydrogen-to-Carbon Ratios)

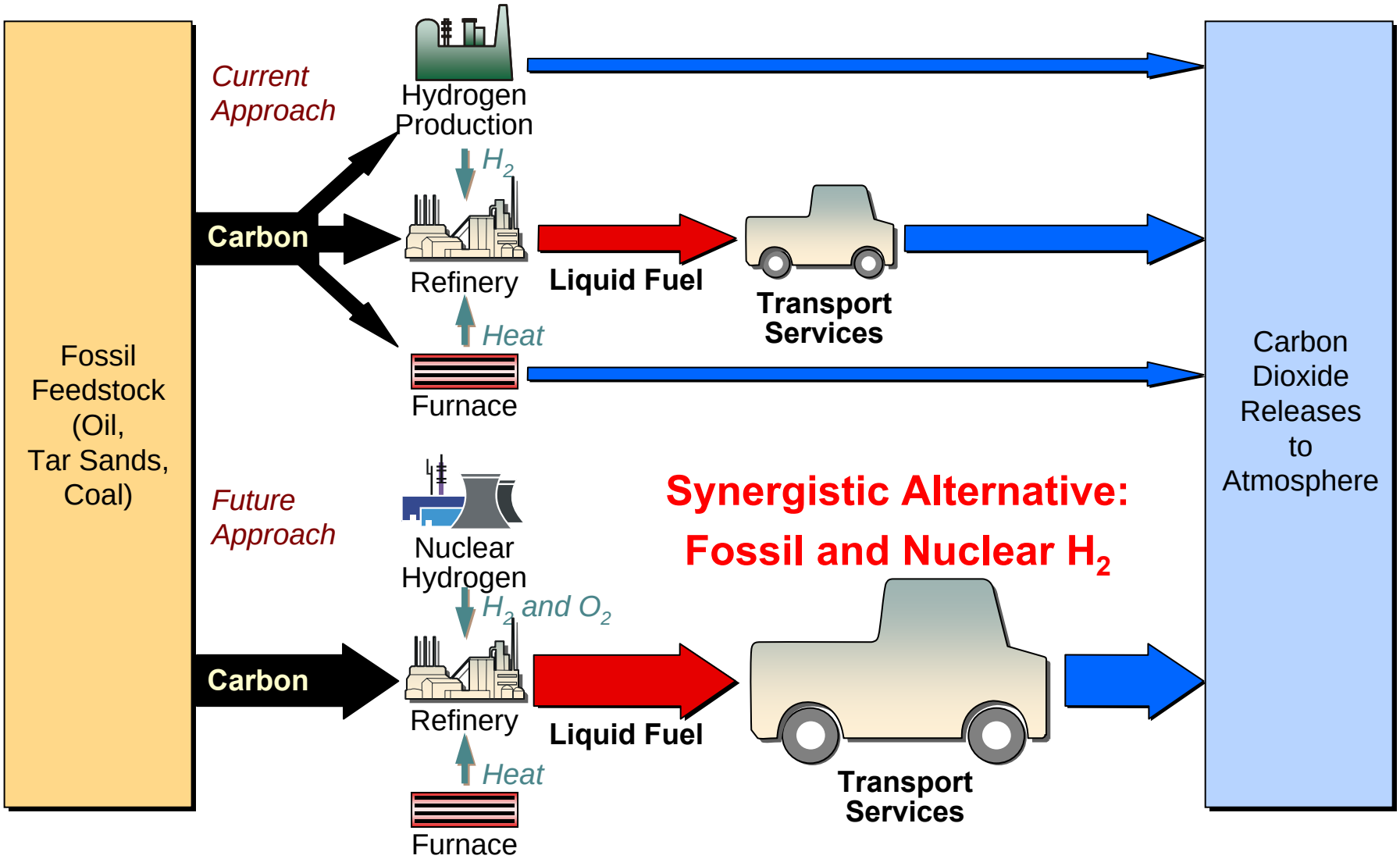
Syncrude Canada Ltd.
Tar Sands Operations

- Tar sands and heavy oils are converted to liquid fuels by:
  - Addition of hydrogen
  - Removal of carbon (usually with CO_2 to atmosphere)
- Implies massive increase in H_2 demand
- Imply major increases in CO_2 releases per vehicle mile (greenhouse-gas concern)

Conventional Futures Imply Increasing Greenhouse Emissions per Mile Traveled



Nuclear Hydrogen can Increase Liquid Fuel per Unit of Feedstock and Reduce Emissions



Hydrogen sources: nuclear, renewables, and coal with carbon dioxide sequestration

High-Temperature Heat is Needed for Nuclear Hydrogen Production

Today

Input: Electricity

Future

Input: Lower Cost High-Temperature Heat

Electrolysis

Electricity + $2H_20 \rightarrow 2H_2 + O_2$

High-Temperature Electrolysis

Electricity + $2H_20$ (Steam) $\rightarrow 2H_2 + O_2$

Hybrid Cycles

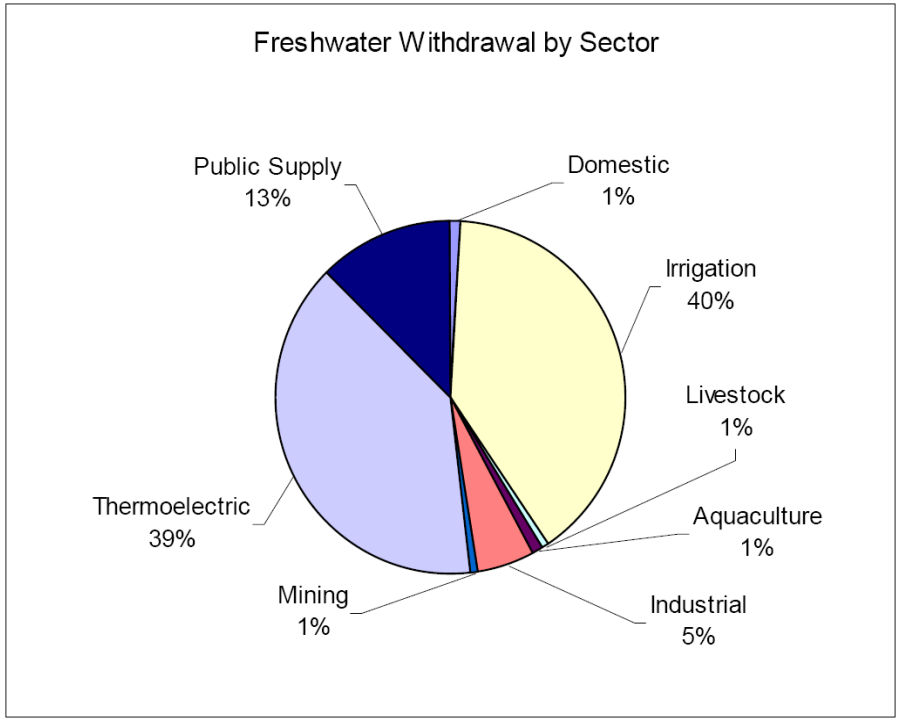
Heat + Electricity + $2H_20 \rightarrow 2H_2 + O_2$

Thermochemical Cycles

Heat + $2H_20 \rightarrow 2H_2 + O_2$

Water-Energy Conflicts
(Growing Demands for Water)

Electric Power Plants are Major Consumers of Water



Proposed New Nuclear Reactor at North Anna Plant in "Water-Rich" Virginia Requires $\$200 \cdot 10^6$ for Added Dry Cooling Towers

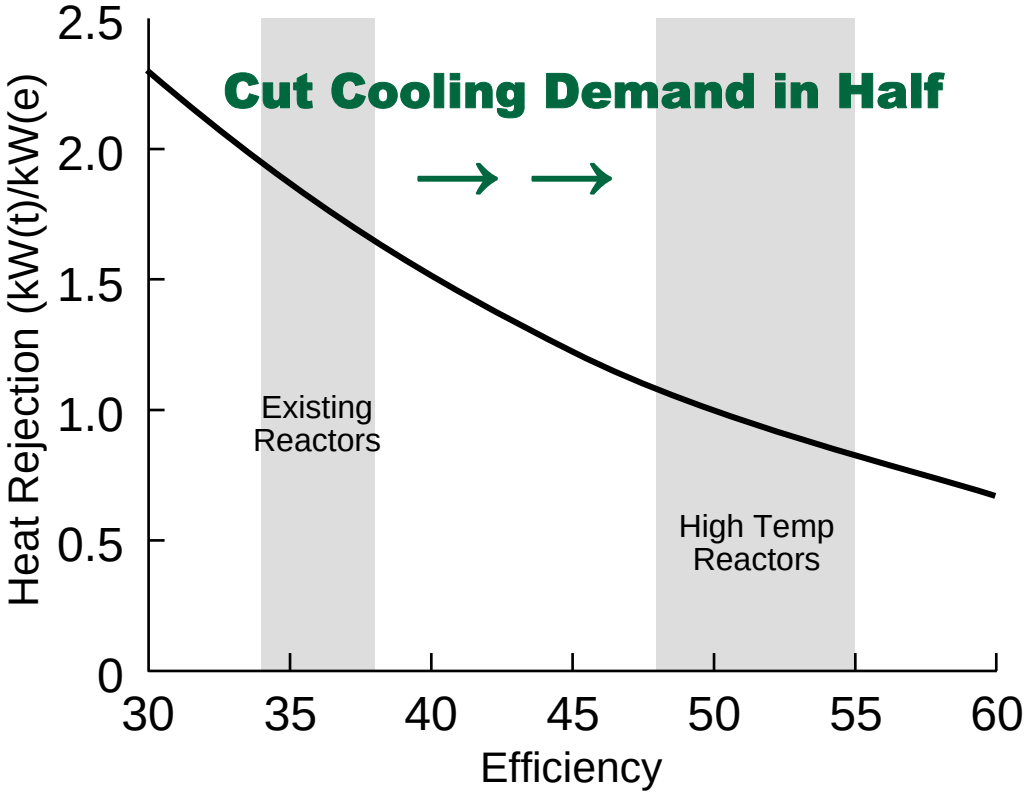
High-Temperature Reactors Reduce Water Requirements and Enable Dry Cooling

(New Nuclear Sites Away from Water [and People])

Thermal Power Plant Dry Cooling

(ACC at PacifiCorp's Wyodak Power Plant (Courtesy of R. Garan)

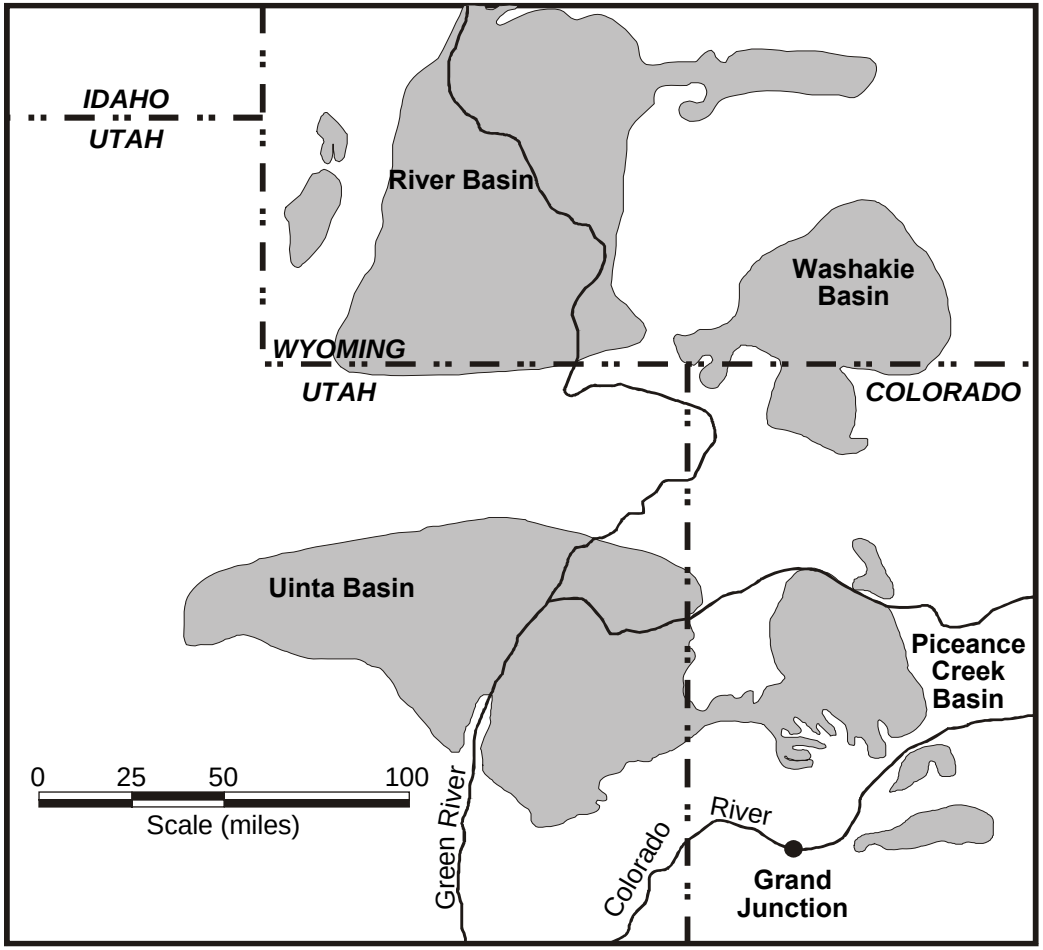
Dry Cooling for Electricity Generation



Shale Oil

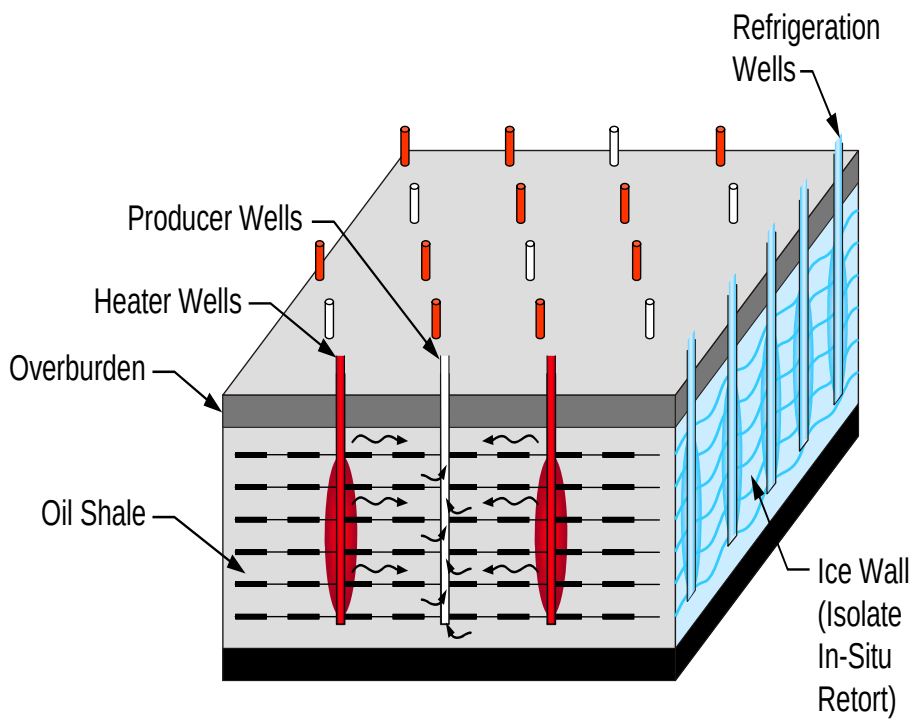
Shale Oil is a Massive United States Resource for High-Quality Crude Oil

- ~800 billion barrels of oil
- Oil resources 3 times those of Saudi Arabia
- ~100-year oil supply for the United States



The Shell In Situ Conversion Process:
Heat Oil Shale Electrically to Release Liquid Fuel

- **Heat oil shale with electric heat**
  - **Slow heating**
  - **High temperature**
- **Incentives for high-temperature nuclear-heat option**
  - **No greenhouse gases from electricity generation**
  - **Avoid heat → electricity → heat conversion loses**
  - **Reduce water need**

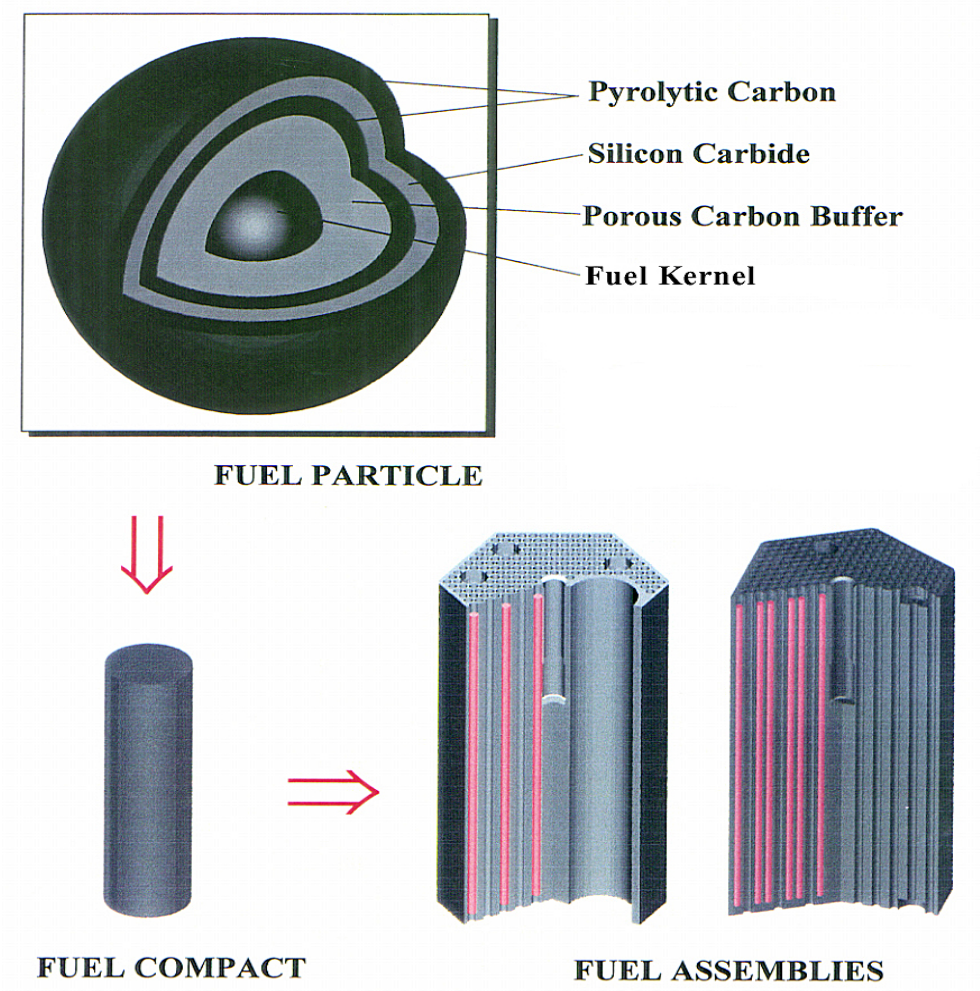


C. W. Forsberg, "High-Temperature Nuclear Reactors for In-Situ Recovery of Oil from Oil Shale," Proc. International Congress on Advances in Nuclear Power Plants, American Nuclear Society, Reno, Nevada, June 4-8, 2006

High Temperature Reactors

Back to the Future

There is One Demonstrated High-Temperature Reactor Fuel



- No choice on high-temperature fuel
- Coated particles of uranium oxides or carbides
- Graphite matrix fuel
- Multiple fuel geometries
  - Block
  - Pebbles

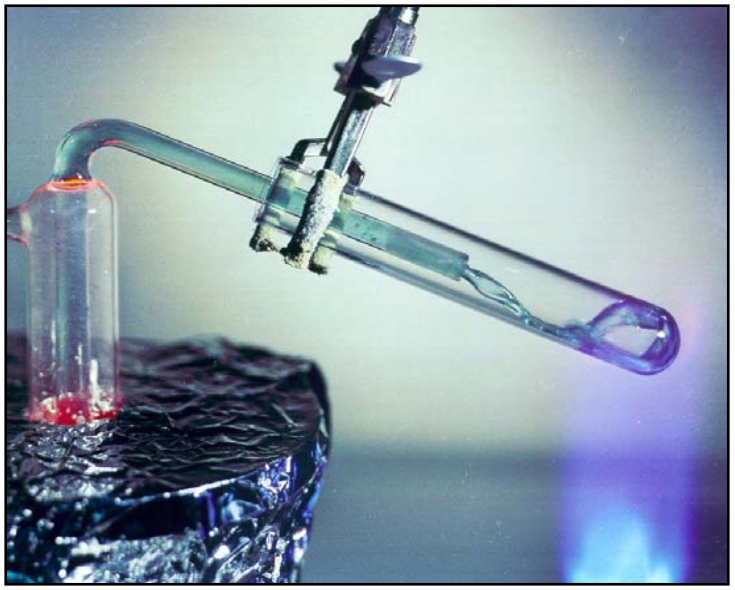
Two Reactor Coolants are Chemically Compatible with Graphite-Matrix Fuel

Modular High-Temperature Gas-Cooled Reactor

Helium

(High Pressure/Transparent)

Advanced High-Temperature Reactor



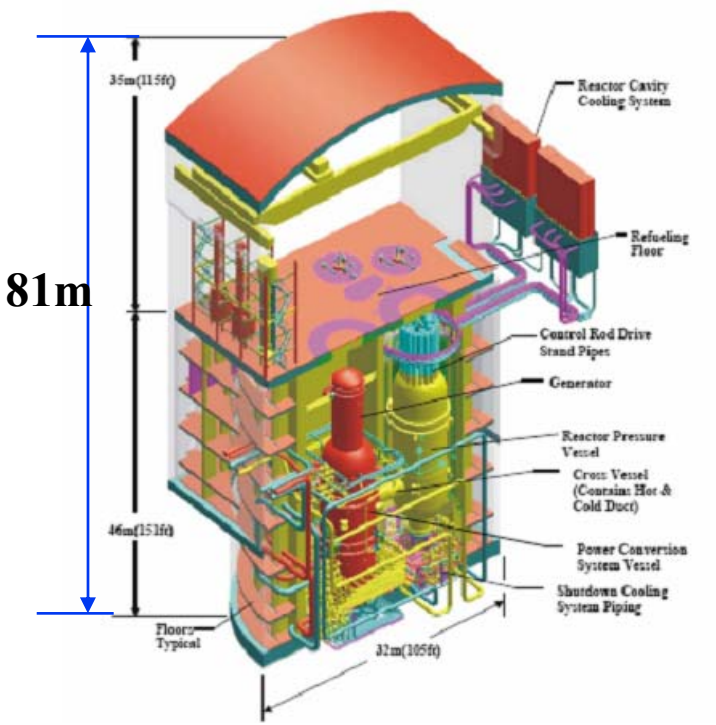
Liquid Fluoride Salts

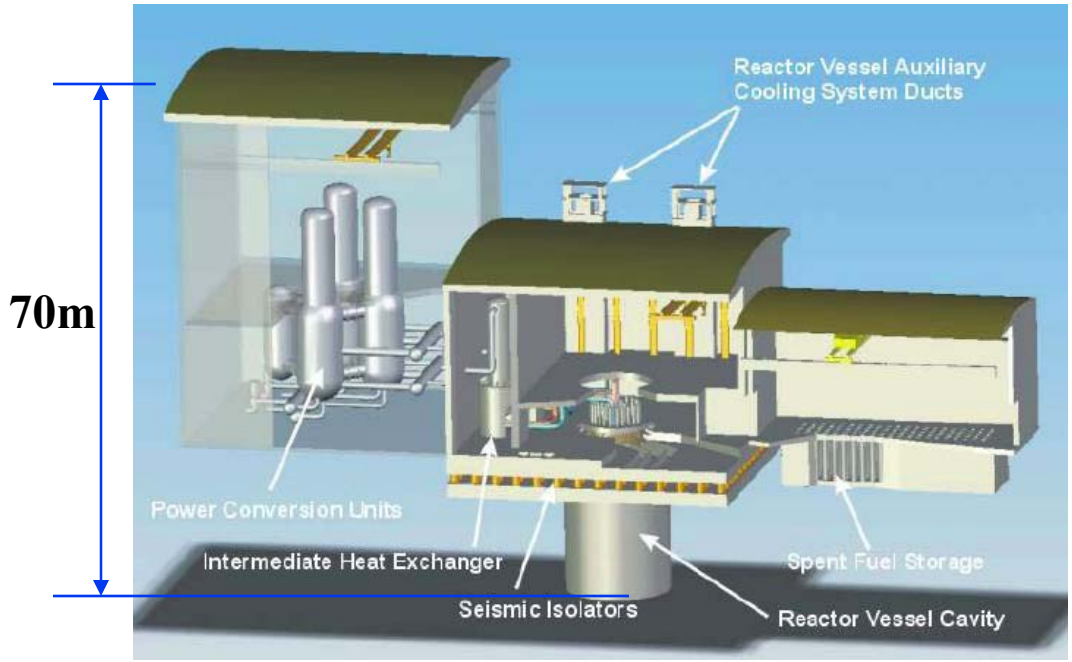
(Low Pressure/Transparent)

Two Reactor Options Based on Choice of Coolant

Two Types of High-Temperature Reactors are being Developed

(MHTGR Near-term; AHTR Midterm)





Modular High-Temperature Gas-Cooled Reactors

Gas-Cooled: 600 MW(t); Near-Term Option

Advanced High-Temperature Reactor

Liquid-Salt-Cooled: 2400 MW(t)

Longer-term Option

Per Peterson (Berkeley): American Nuclear Society 2004 Winter Meeting

The Advanced High-Temperature Reactor

(The Liquid-Cooled Option)

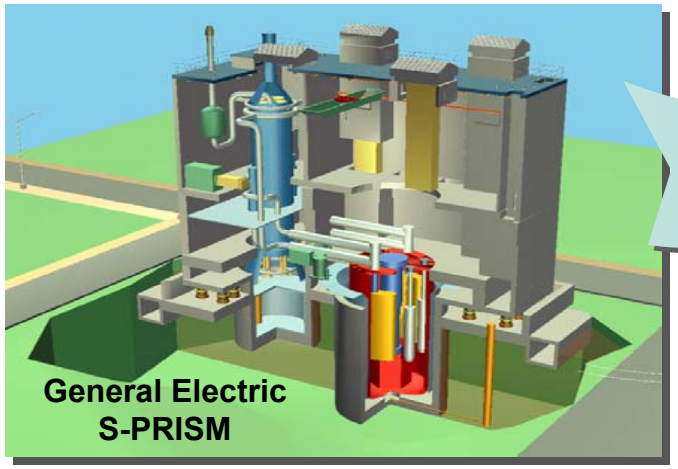
Combining Different Technologies in a New Way

New Reactor Concept Being Developed at ORNL

(Partnerships with Areva NP, the University of California at Berkeley, the University of Wisconsin, Argonne National Laboratory, Sandia National Laboratory, and Idaho National Laboratory)

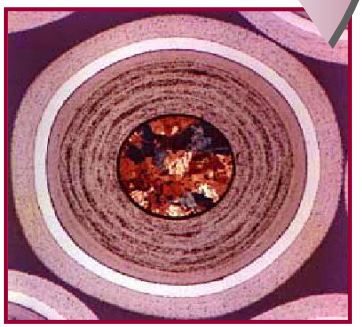
The Advanced High-Temperature Reactor

Combining Four Existing Technologies in a New Way



Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

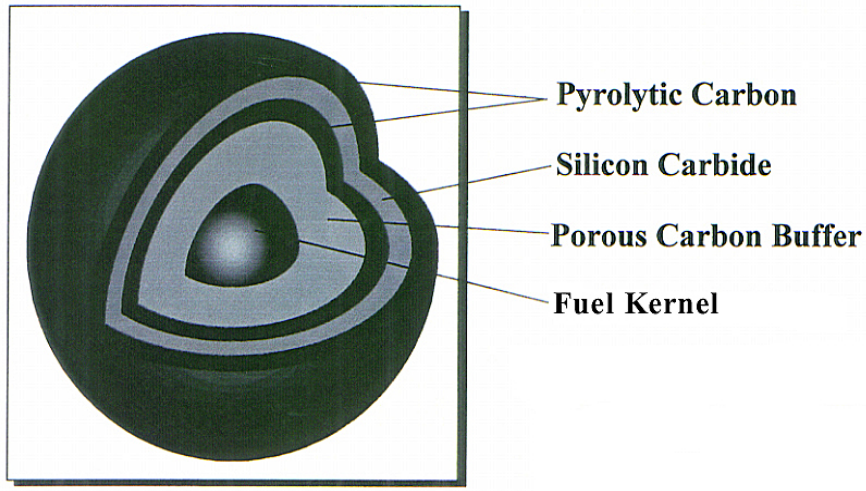


High-Temperature Coated-Particle Fuel

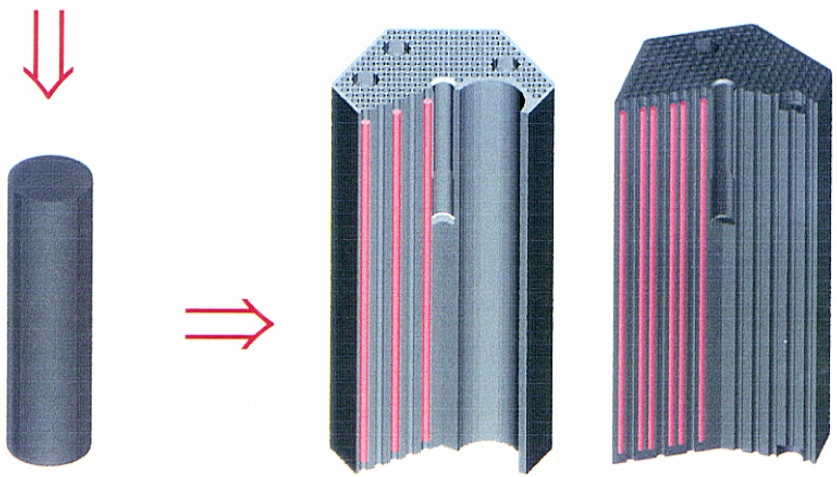
High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

The AHTR Uses High-Temperature Graphite-Matrix Fuel

The Only Demonstrated High-Temperature Reactor Fuel



FUEL PARTICLE

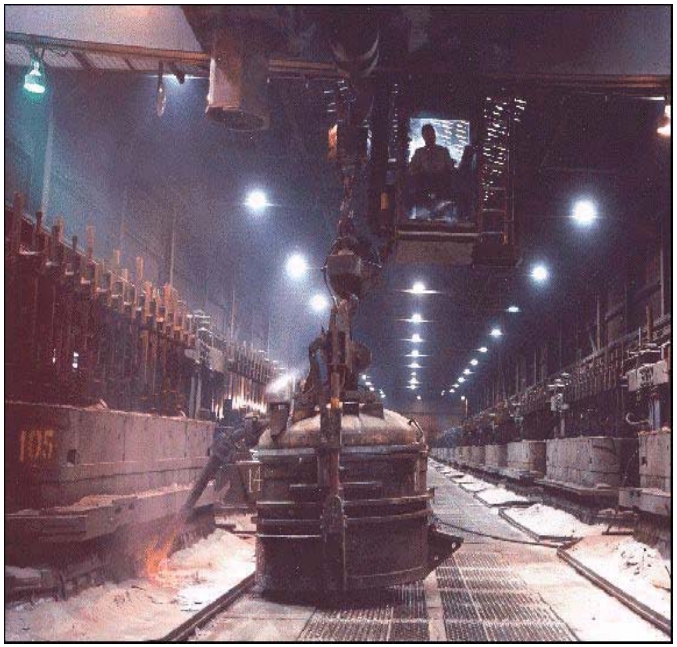


FUEL COMPACT

FUEL ASSEMBLIES

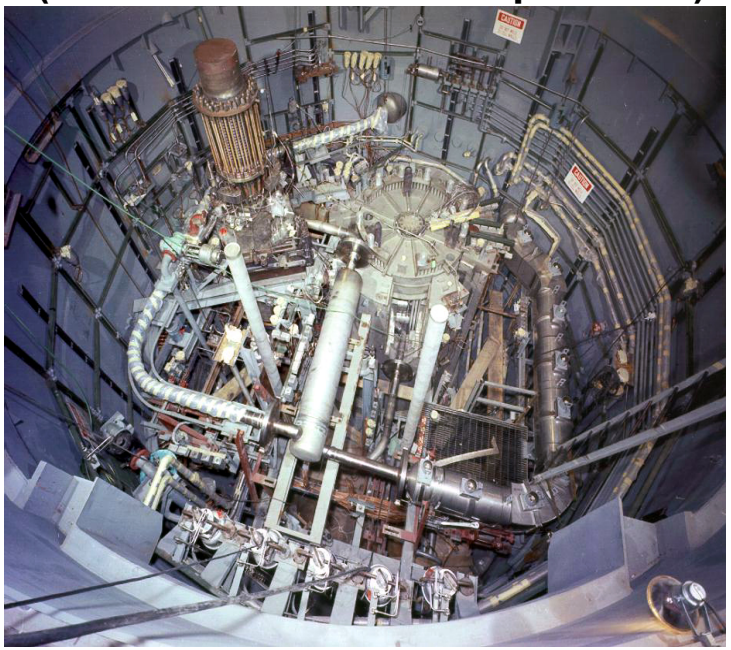
The AHTR Uses the Salt Coolant Technology Developed for MSRs

The AHTR Uses a Clean Salt Coolant while the Molten Salt Reactor Dissolved the Fuel in the Coolant)



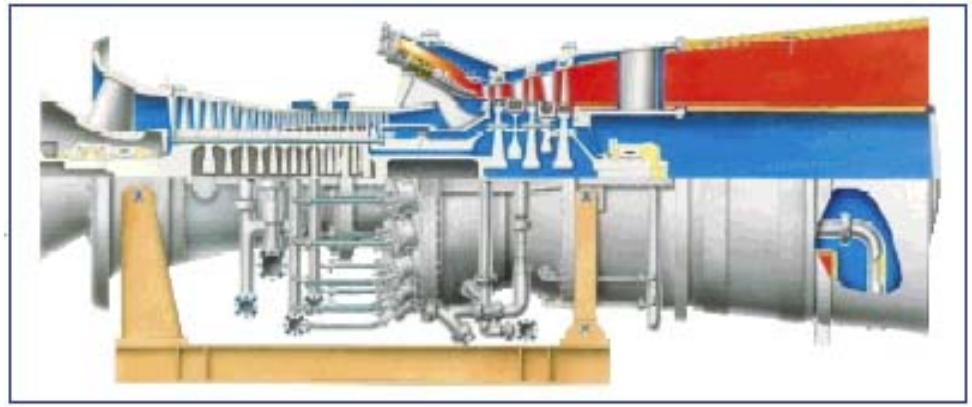
Molten Fluoride Salts are Used to Make Aluminum in Graphite Baths at 1000°C

Liquid Fluoride Salts were Used in Molten Salt Reactors with Fuel in Coolant (Molten Salt Reactor Experiment)

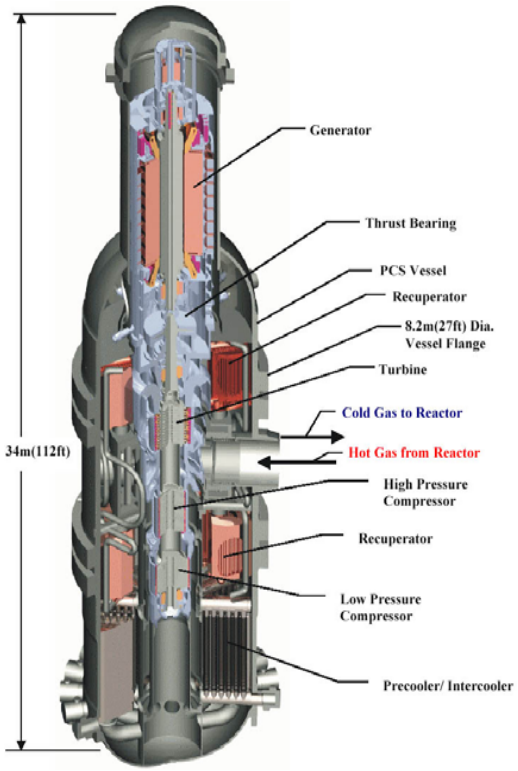


The AHTR Uses Brayton Power Cycles to Convert Heat to Electricity

- Matches AHTR heat at temperatures from 750 to 1000ºC
- Required 50 years of development to be useful for the utility industry



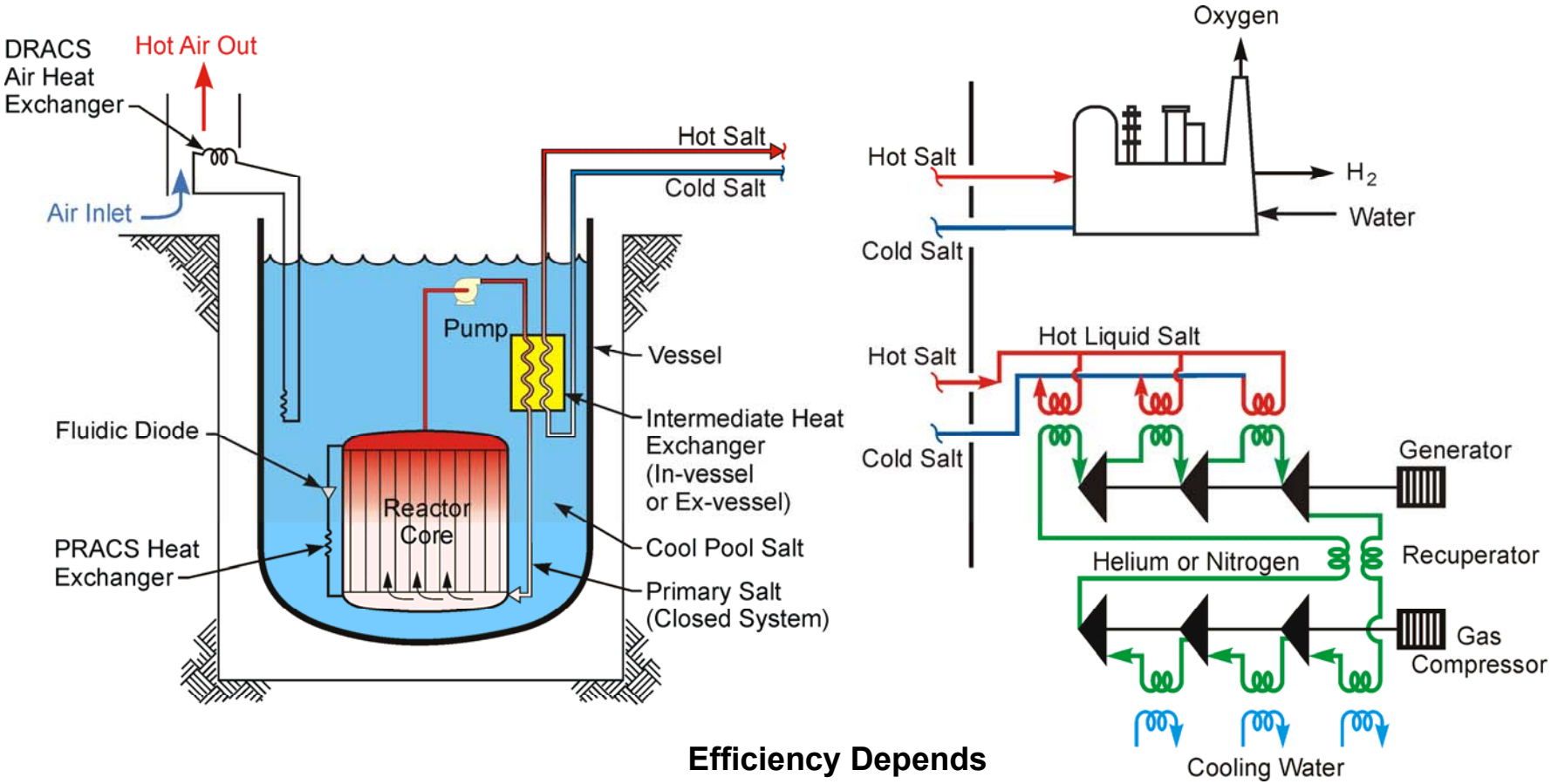
GE Power Systems MS7001FB



General Atomics GT-MHR Power Conversion Unit (Russian Design)

The Advanced High-Temperature Reactor

Passive Decay Heat Removal **Reactor** **Hydrogen/Brayton Electricity Production**

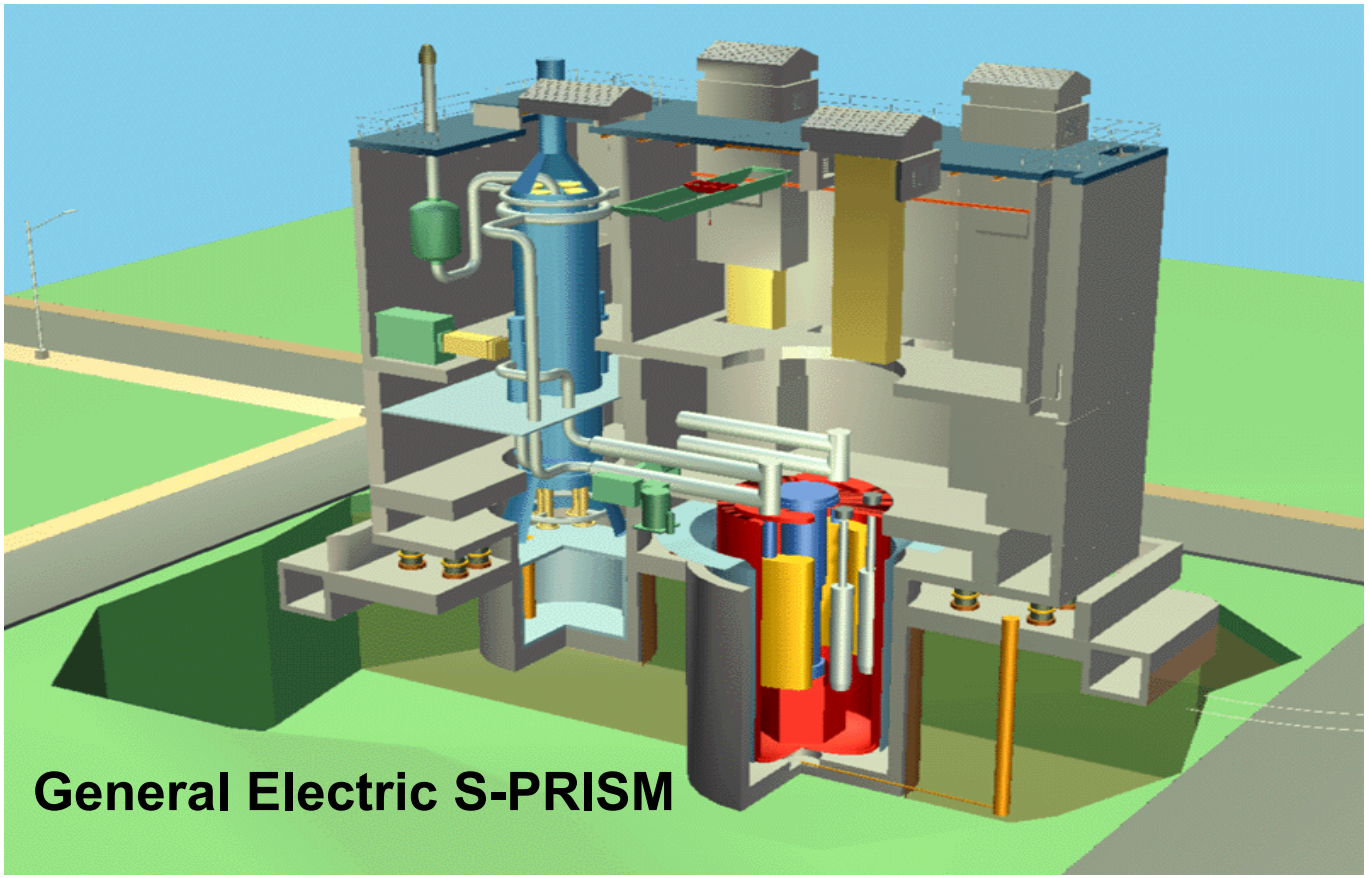


Efficiency Depends upon Temperature:

705ºC: 48.0%
800ºC: 51.5%
1000ºC: 56.6%

AHTR Facility Layouts are Based on Sodium-Cooled Fast Reactors

Low Pressure, High Temperature, Liquid Cooled



Nuclear Reactor Economics

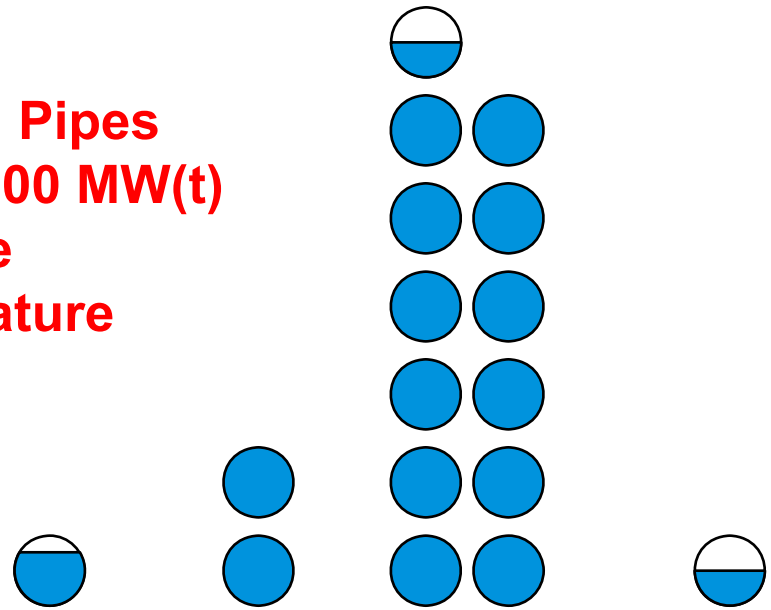
Why go Beyond Helium-Cooled Reactors?

The Incentive to Develop the AHTR

Coolant Properties Impact Reactor Size and Cost

(Determine Pipe, Valve, and Heat Exchanger Sizes)

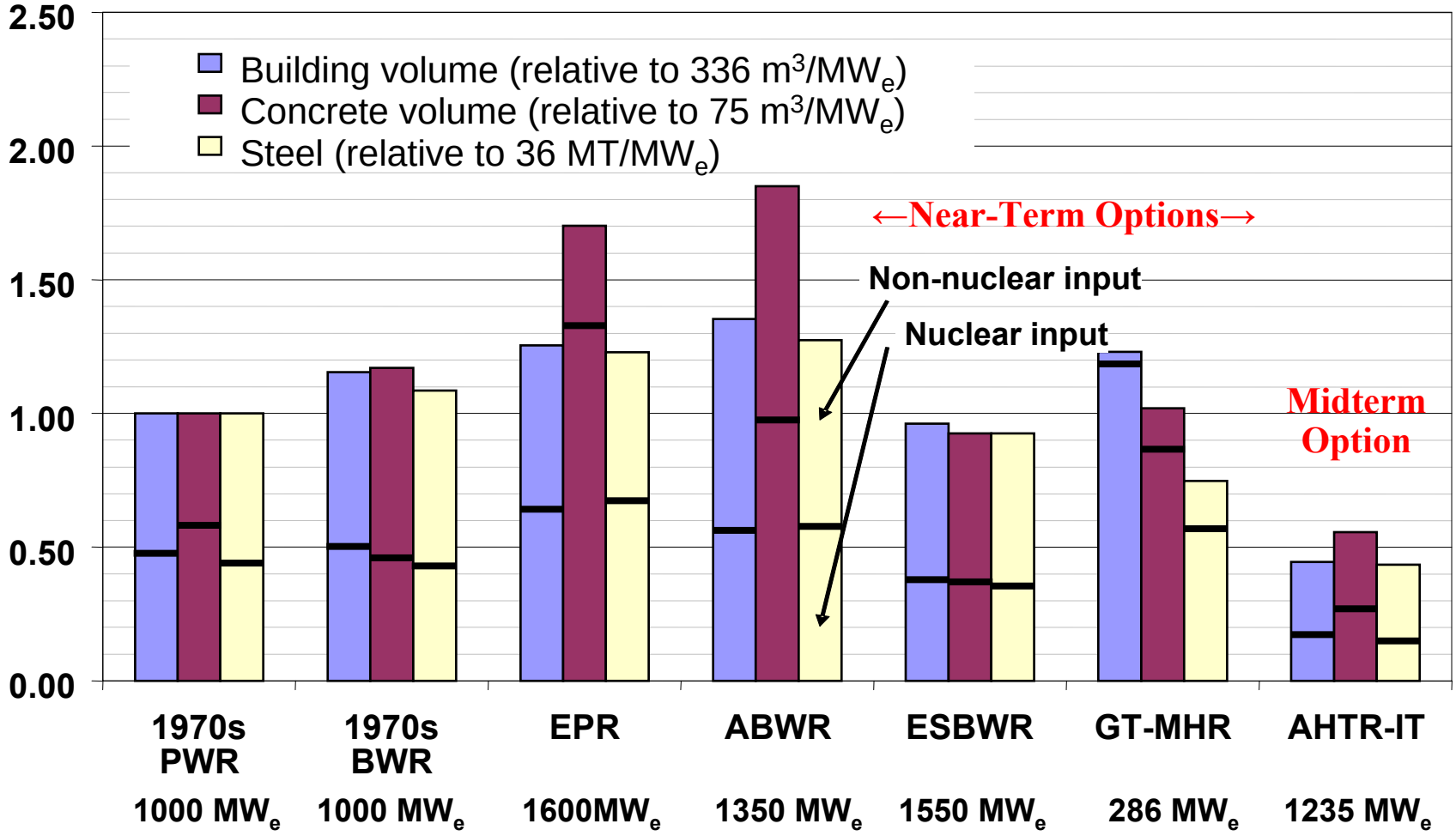
Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temperature



	Water (PWR)	Sodium (LMR)	Helium	Liquid Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocity (m/s)	6	6	75	6

Reactor Comparison of Building Volume, Concrete, and Steel Consumption Per MW(e)

(High-Temperature Reactors are Potentially Competitive Sources of Energy)



Per Peterson (Berkeley): American Nuclear Society 2004 Winter Meeting

The Challenges

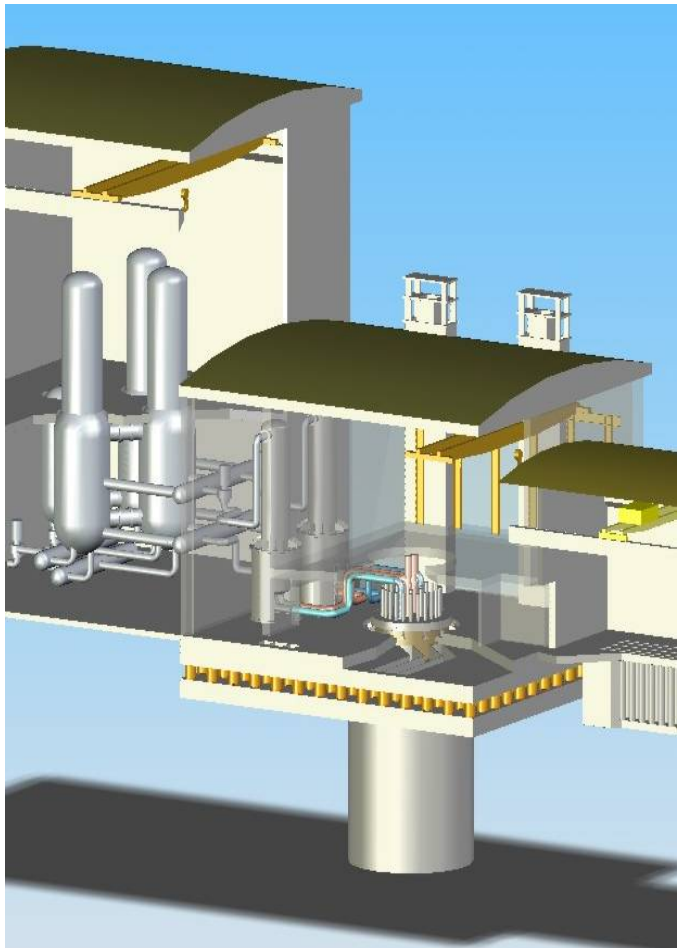
Are We Willing to Use Technology to Solve Energy Challenges?

Energy Research and Development Is a Low Priority Activity

- Since 1980, energy research has fallen from 10% to 2% of the total R&D
- Public expenditures on energy R&D continue their multi-decade downward trend
- Energy companies spend less on R&D than other industries (at the bottom of the list in percent of sales)
  - Aerospace: 8%
  - Biotech: 23%
  - Chemicals: 6%
  - Consumer products: 2%
  - Energy: <1%

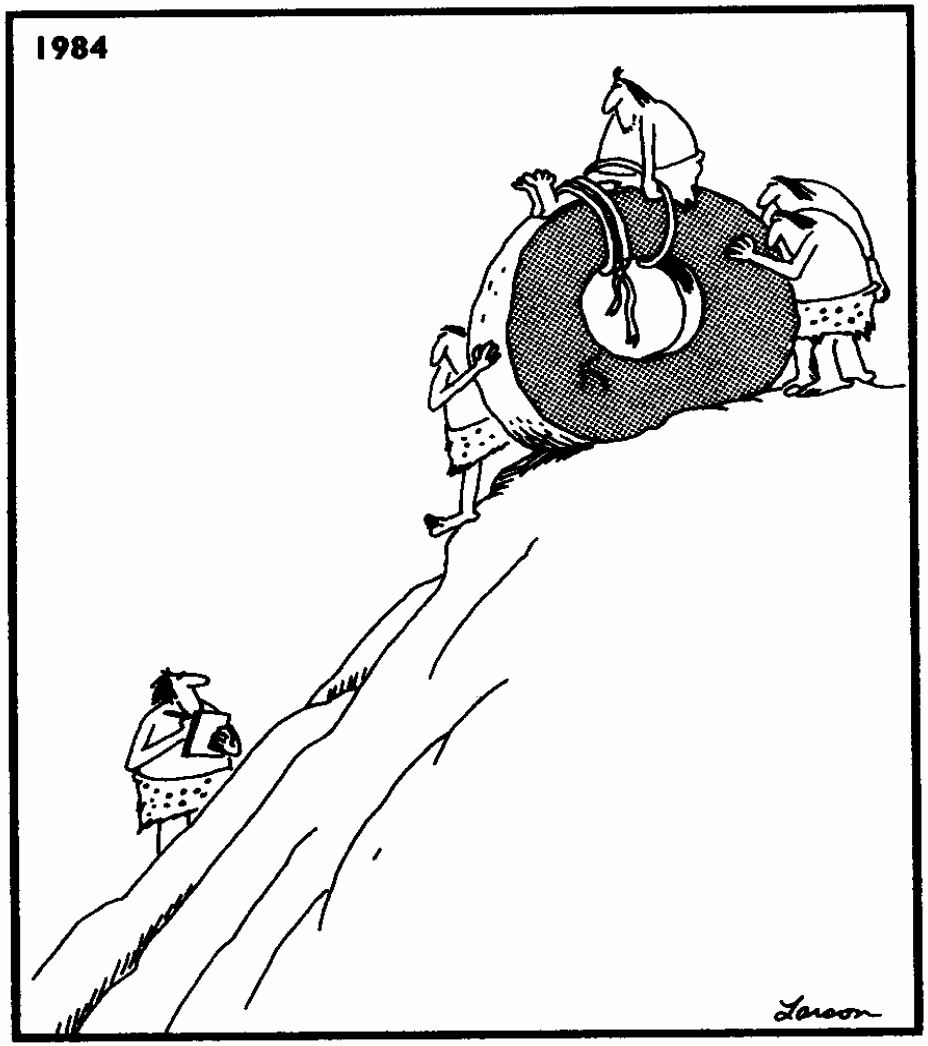
Conclusions

- The High-Temperature Reactor Rebirth is Driven by:
  - Efficient methods to convert heat to electricity
  - Need for liquid transport fuels
  - Need to reduce water use
- AHTR Goals
  - High temperature
  - Passive safety
  - Superior economics
- Vendor interest
- Early in development



The AHTR

A good idea that still needs some work



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End

Biography: Charles Forsberg

Dr. Charles Forsberg received his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. After working for Bechtel Corporation, he joined the staff of Oak Ridge National Laboratory, where he is presently a senior scientist and the Senior Reactor Technical Advisor. Dr. Forsberg is a fellow of the American Nuclear Society and received the 2005 American Institute of Chemical Engineers Nuclear Energy Division Robert E. Wilson Award for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and other technologies to use nuclear energy. He also received the Oak Ridge National Laboratory Engineer of the Year Award in 2005. Dr. Forsberg has been awarded 10 patents and has published over 200 papers, many on hydrogen futures.

Plug-In Hybrid Electric Vehicles (PHEVs)

Cutting Light-Vehicle Liquid-Fuel Consumption in Half

The Other Option to Cut Liquid Fuel Use with Nuclear Energy

150 to 200 Nuclear Plants Each Producing 1000 MW(e)

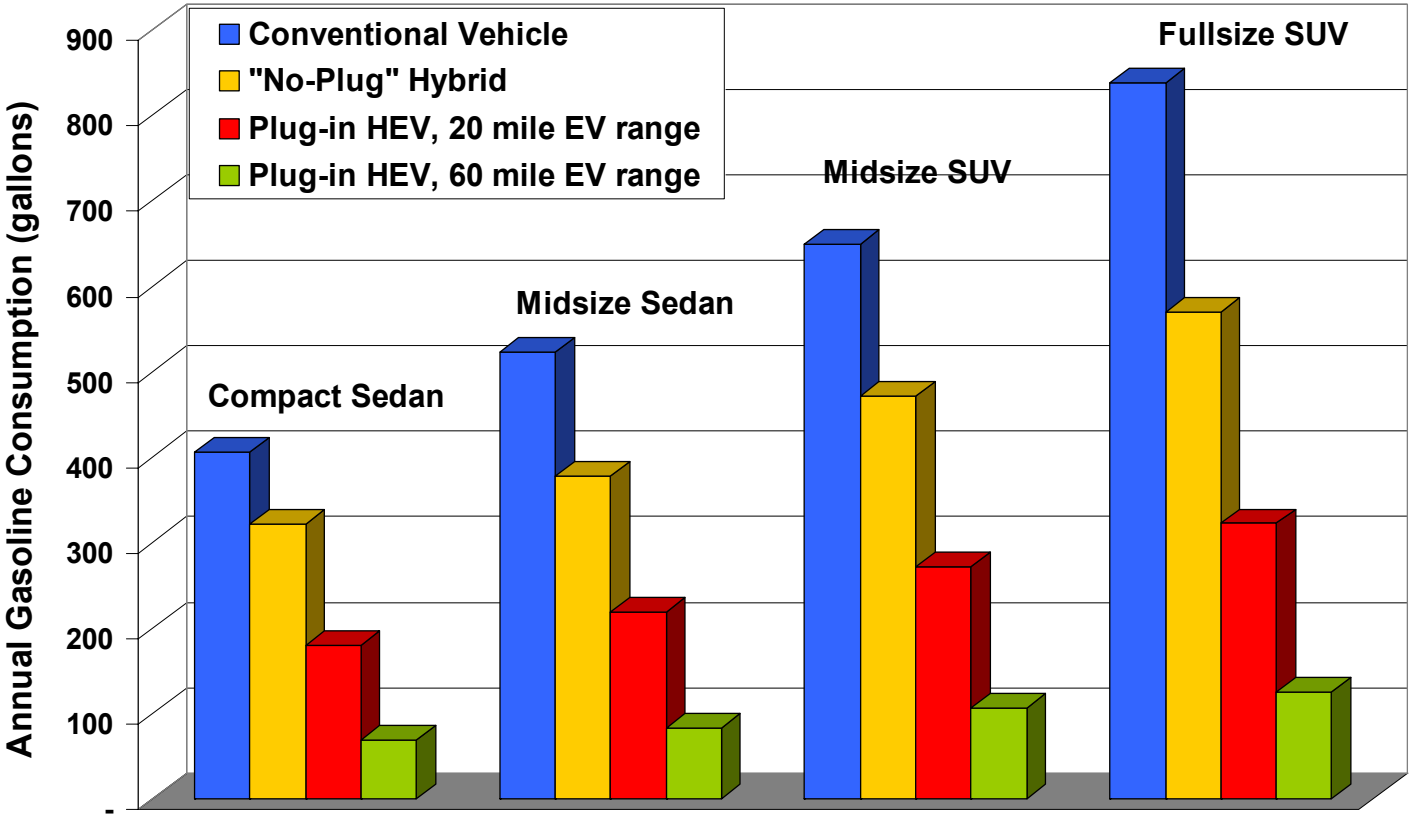
PHEVs: Recharge Batteries from the Electric Grid Plus Use of Gasoline

- **Two major battery-connected limitations of electric cars**
  - **Limited range**
  - **Recharge time (Gasoline refueling rate is ~10 MW)**
- **Plug-in hybrid electric vehicle**
  - **Electric drive for short trips**
  - **Recharge battery overnight**
  - **Hybrid engine with gasoline or diesel engine for longer trips**
- **Connects cars and light trucks to the electrical grid**

Courtesy of the Electric Power Research Institute

PHEVs: Annual Gasoline Consumption

Connecting to the Electric Grid (Nuclear Energy) Cuts Light-Vehicle Fuel Consumption in Half



Courtesy of the Electric Power Research Institute