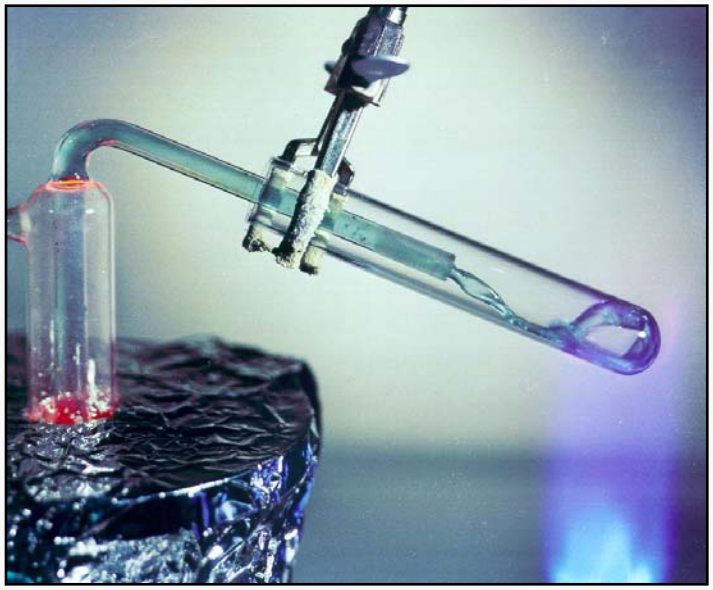
Developments in Molten Salt and Liquid-Salt-Cooled Reactors

Charles W. Forsberg



International Congress on Advanced Nuclear Power Plants

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Oak Ridge National Laboratory*
P.O. Box 2008, Oak Ridge, TN., 37831
United States of America
E-mail: forsbergcw@ornl.gov

OAK RIDGE NATIONAL LABORATORY

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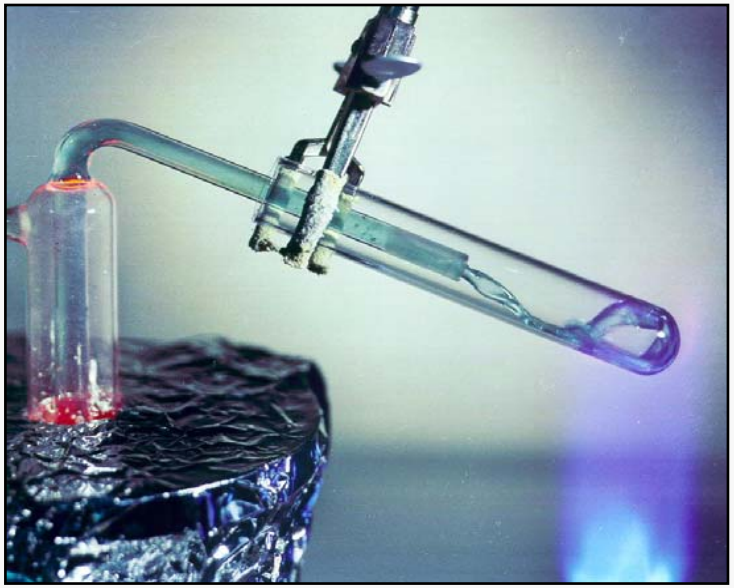
Molten and Liquid Salts Are High-Temperature Coolants

- **Fluoride salts**
  - **Molten: fuel dissolved in the salt**
  - **Liquid: clean salt**
- **Characteristics**
  - **Melting points between 350 and 500ºC**
  - **Boiling points above 1200ºC**
  - **Physical properties similar to water**
  - **Transparent**
- **Only usable in high-temperature systems**

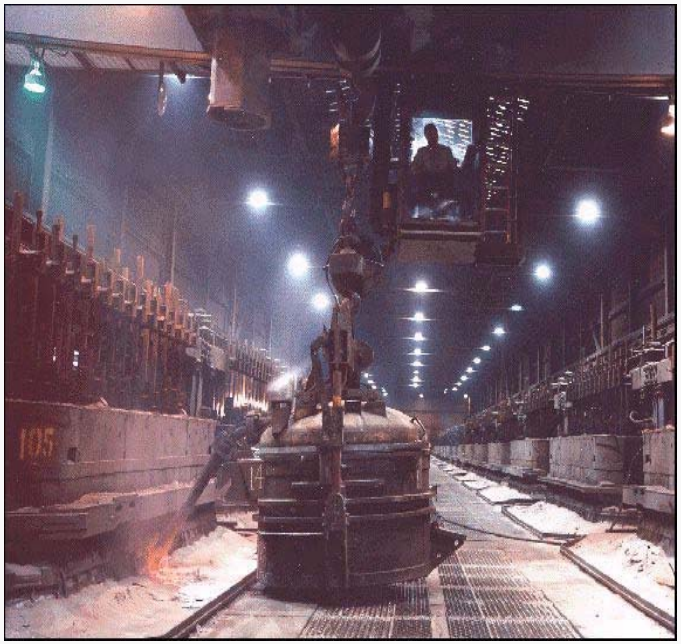


Liquid Fluoride Salts

(Low Pressure/Transparent)

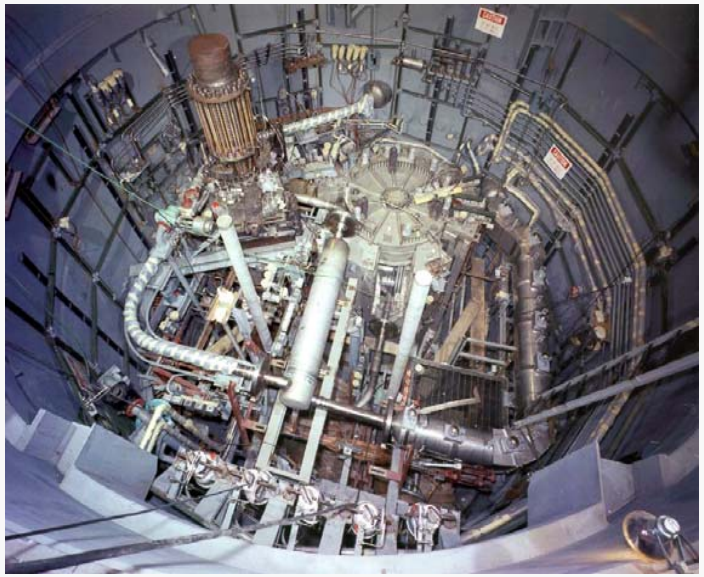
There is Significant Experience with Molten and Liquid Fluoride Salts

Good Heat Transfer, Low-Pressure Operation, and Transparent (In-Service Inspection)



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: 8 MW(t)]



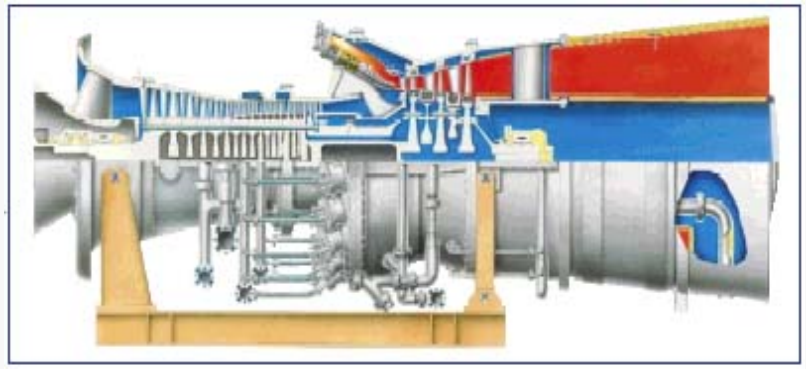
There is a Renewed Interest in High-Temperature Reactors (HTRs)

.....And Thus in Liquid Salt Coolants, the High-Temperature Coolant

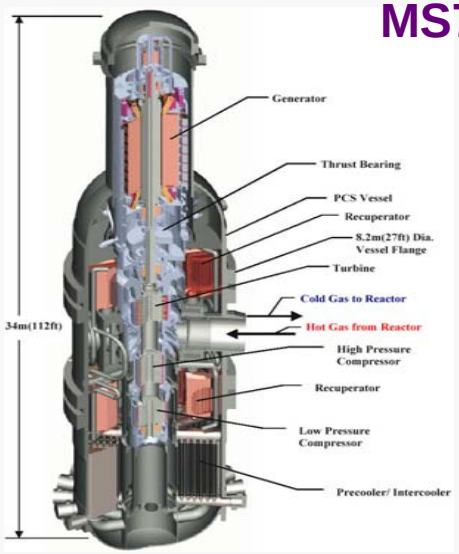
Brayton Power (Jet Engine) Cycles may Make High-Temperature Reactors Viable

(Helium or Nitrogen Brayton Power Cycles)

- **High-temperature heat is only useful if it can be converted to electricity**
- **Steam cycles have had a temperature limit of ~ 550ºC**
- **New Brayton cycles can efficiently convert high-temperature heat to electricity and make <u>high-temperature reactors useful</u>**
- **Boost heat-to-electricity efficiency to 50%**



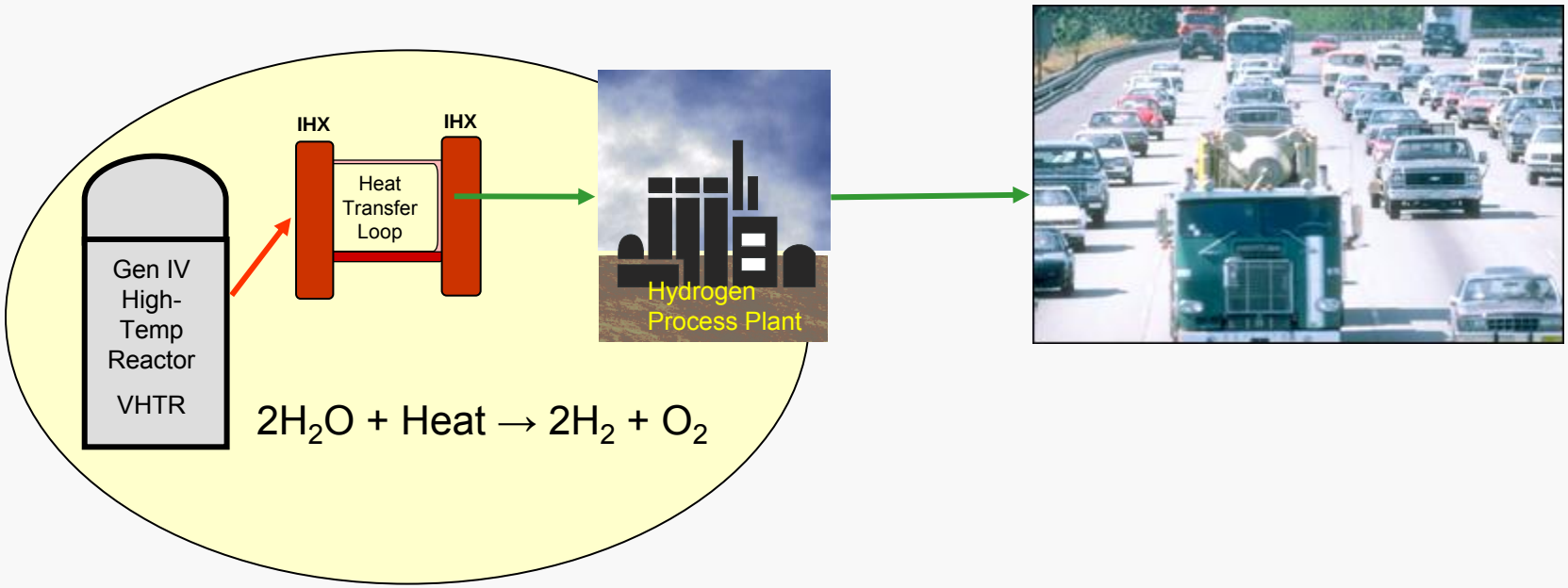
GE Power Systems MS7001FB



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

There is a Growing Interest in Hydrogen Production for Transportation

(High Temperatures Required for Hydrogen Production)



Near-Term: Hydrogen Used to Increase Yields of Liquid Fuels per Barrel of Oil

Long-term: Hydrogen as a Transport Fuel

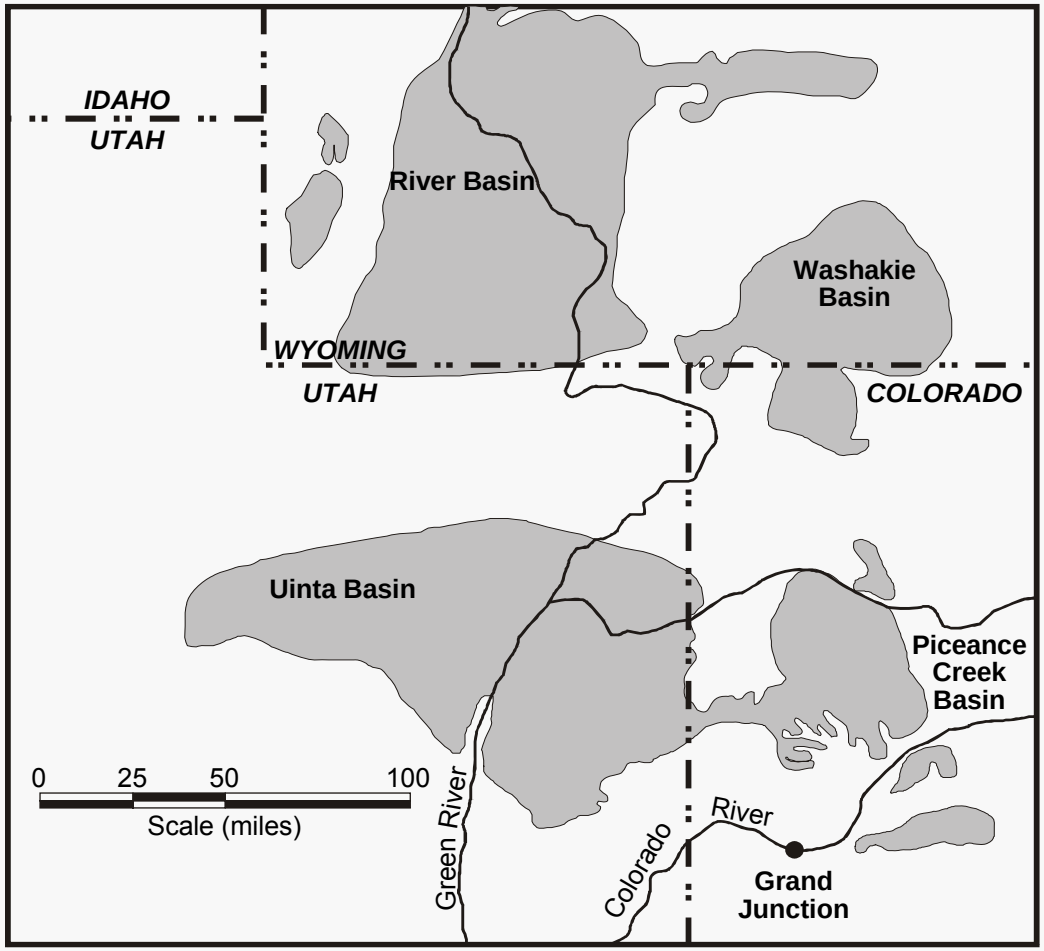
High-Temperature Reactors Reduce Water Requirements and Enable Dry Cooling

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

- **Higher efficiency reduces heat rejection**
  - **LWR: 2 units of heat rejection per unit of electricity**
  - **HTR: 1 unit of heat rejection per unit of electricity**
- **Avoid water-power conflicts**
  - **Enable desert siting in the western United States**

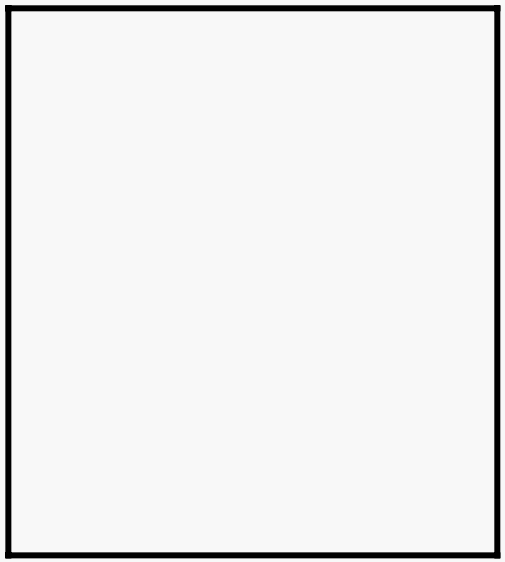
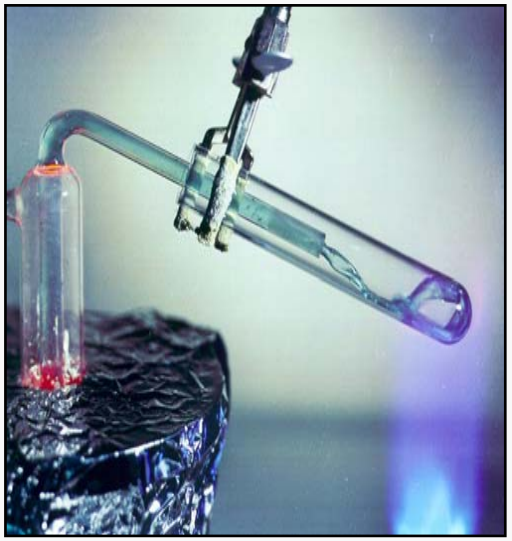
Shale Oil is a Massive American Resource for High-Quality Crude Oil

- **~800 billion barrels of oil**
- **Three times the oil resources of Saudi Arabia**
- **~100-year oil supply for the United States**
- **Requires massive quantities of high-temperature heat to convert oil shale to syncrude**



Choice of High-Temperature Reactor Coolants

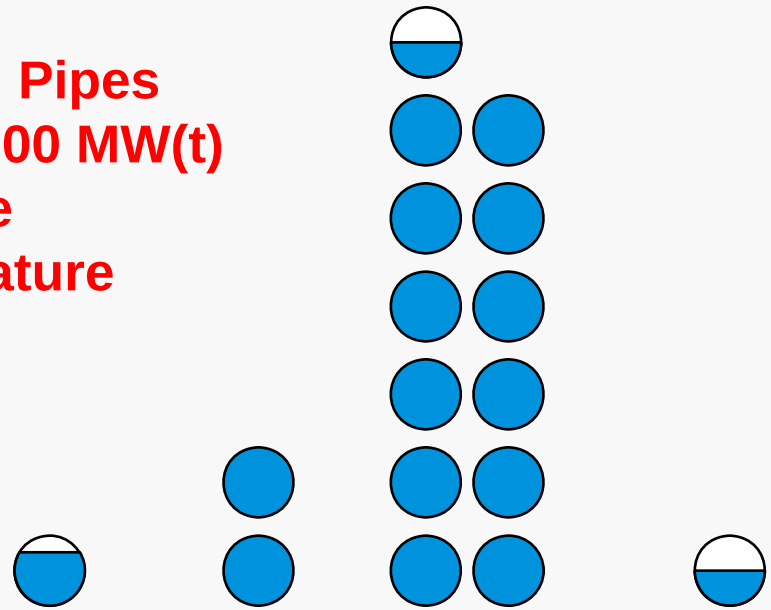
High-Temperature Reactor Coolants

Helium	Sodium	Liquid Salts
		
High pressure	Atmospheric	Atmospheric
Transparent	Opaque	Transparent
BP: N.A.	BP: 883ºC	BP: >1200ºC
Inert	Highly-Reactive	Slightly Reactive

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

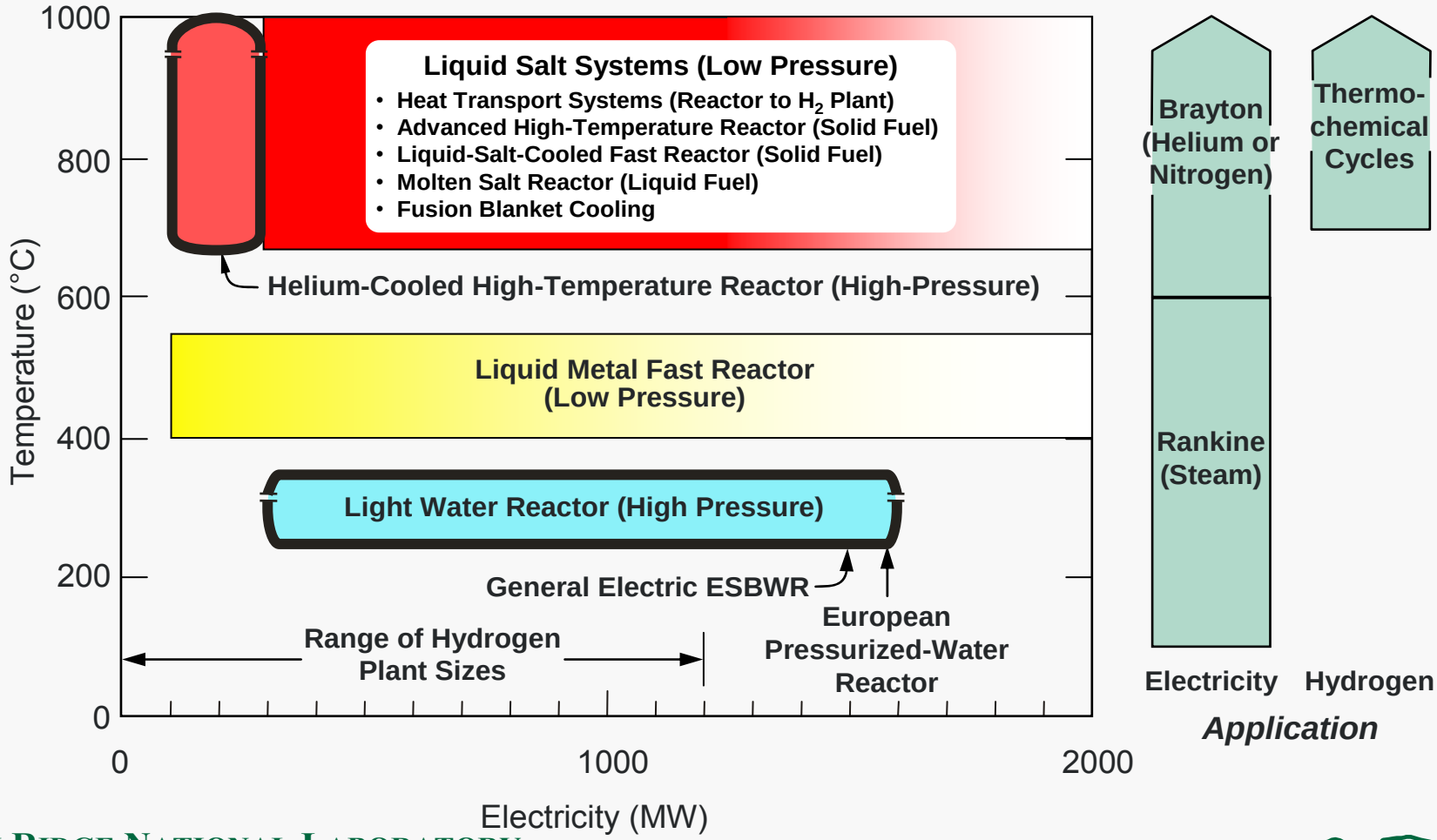
Nuclear Salt-Cooled Applications

Crosses Multiple Programs

Generation IV (Gen IV)
Nuclear Hydrogen Initiative (NHI)
Global Nuclear Energy Partnership (GNEP)
Fusion

Salt Coolants can be Used for High-Temperature Nuclear Applications

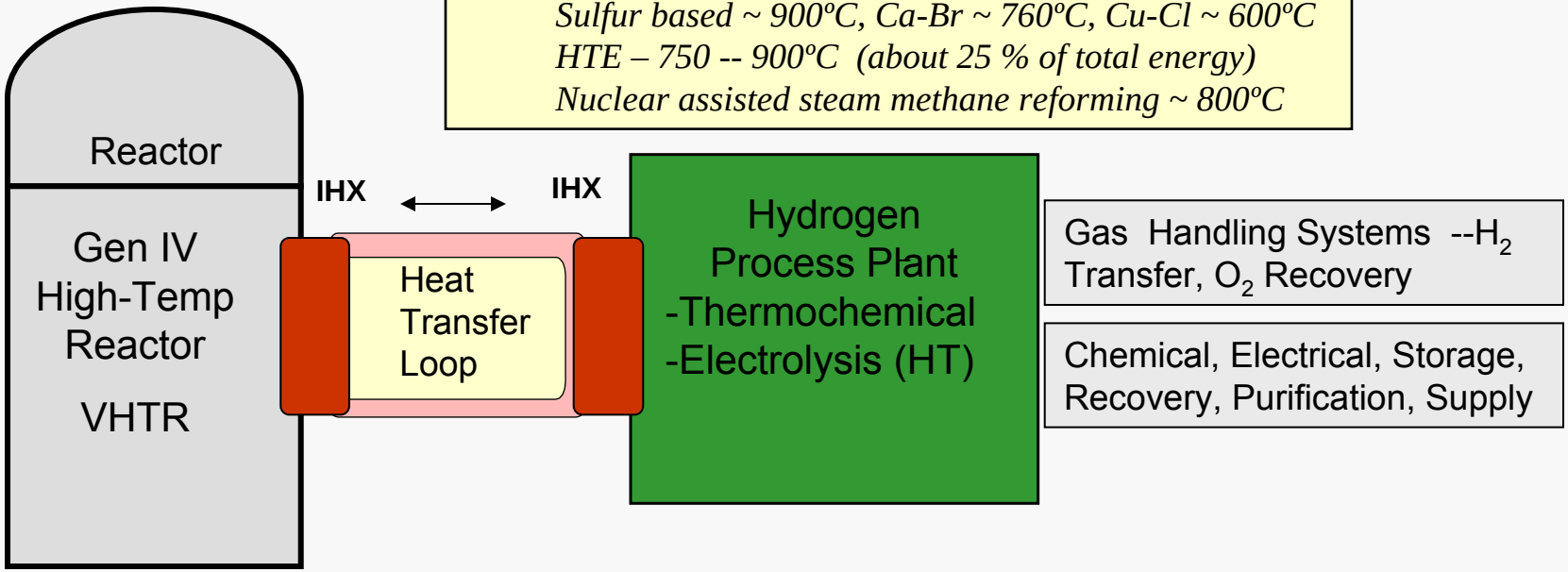
(Liquid Salt Reactors: Clean Coolant with Solid Fuel or Fuel in Coolant)



H_2 Production Requires High-Temperature Heat Transfer from Reactor to H_2 Plant

(Nuclear Hydrogen Initiative: NHI)

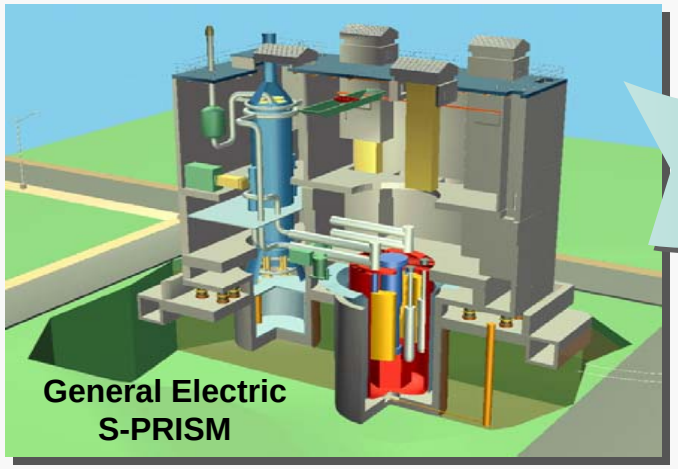
H_2 Process temperature requirements
Sulfur based ~ 900ºC, Ca-Br ~ 760ºC, Cu-Cl ~ 600ºC
HTE – 750 -- 900ºC (about 25 % of total energy)
Nuclear assisted steam methane reforming ~ 800ºC



Liquid salts are leading candidates for heat transfer

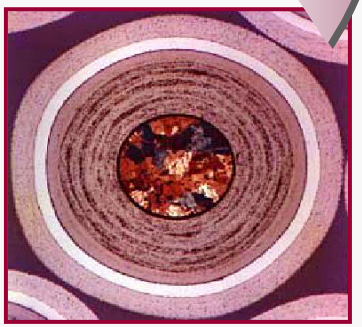
The Advanced High-Temperature Reactor

Gen IV: Liquid-Salt-Cooled VHTR



Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

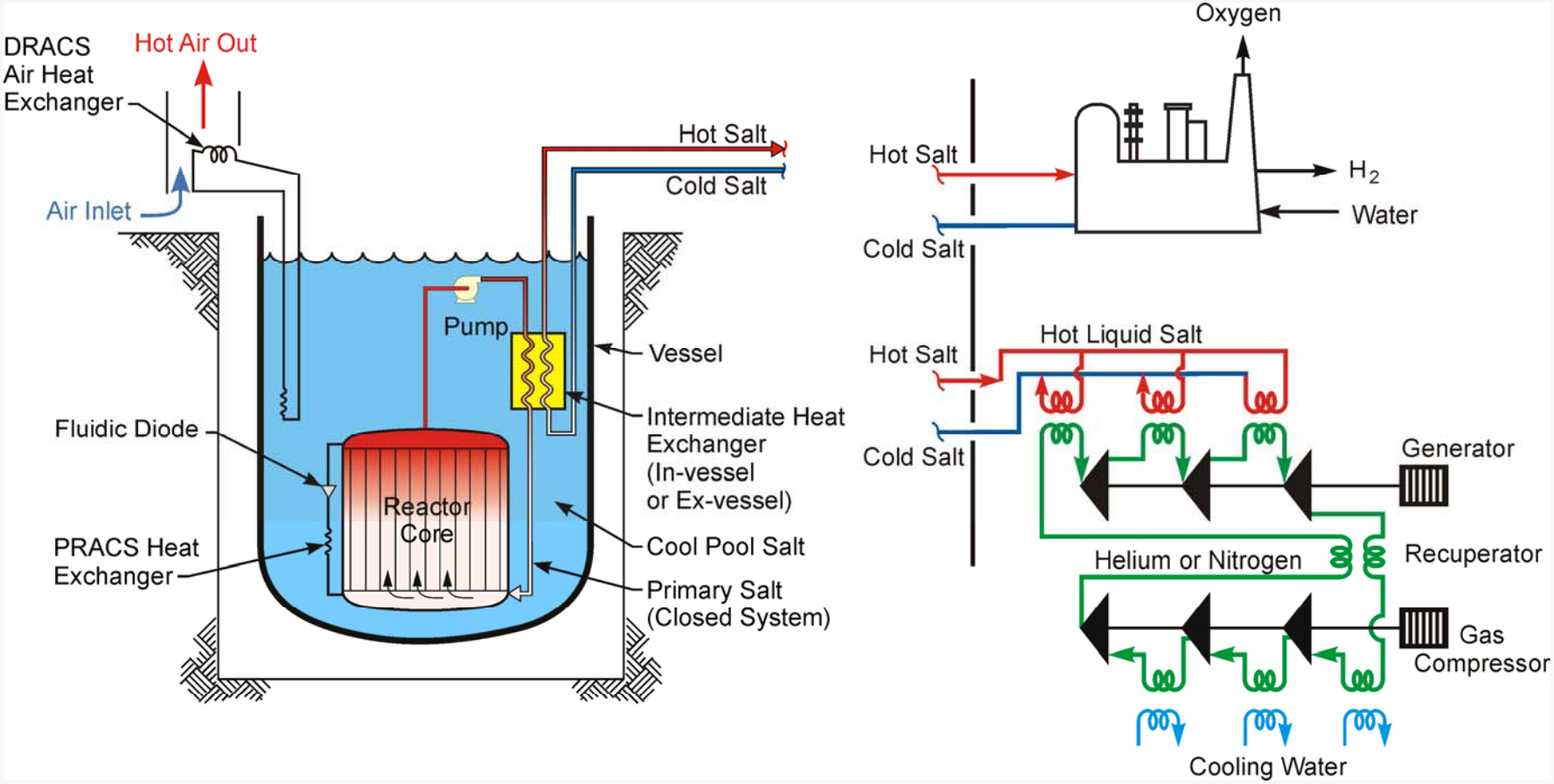


High-Temperature Coated-Particle Fuel

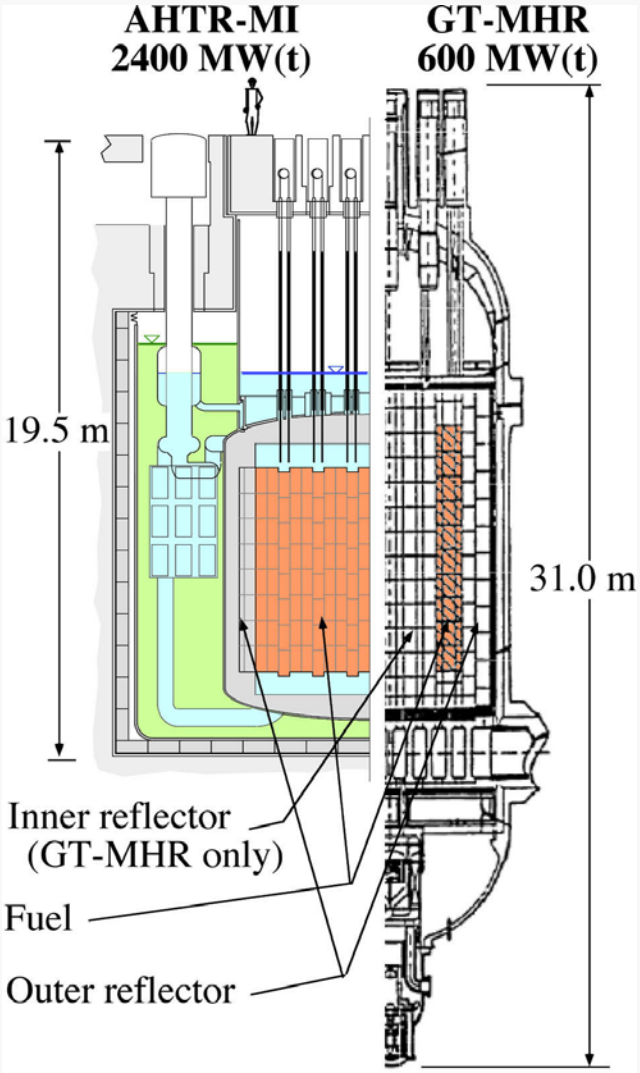
High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

The Advanced High-Temperature Reactor

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



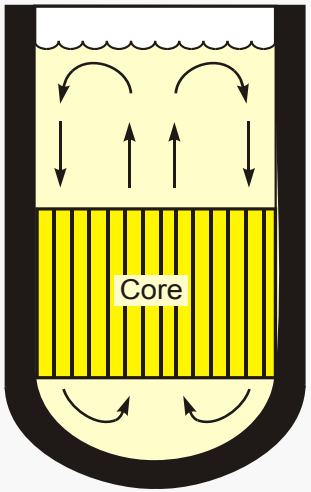
AHTR Goals: Superior Economics While Matching Gas-Cooled HTR Performance



- **AHTR system requirements**
  - **Match passive safety of modular gas-cooled reactors**
  - **Match temperature of delivered high-temperature heat**
  - **Large reactor output: 2400 to 4000 MW(t)**
- **AHTR economic goal is a <u>large reactor</u> with superior economics**
  - **Capital costs 50 to 60% of those for modular reactors per kW(t)**
  - **Capital costs one-third less than a 2025 ALWR per kW(e)**

Liquid Cooling Allows Large Reactors with Passive Decay Heat Removal

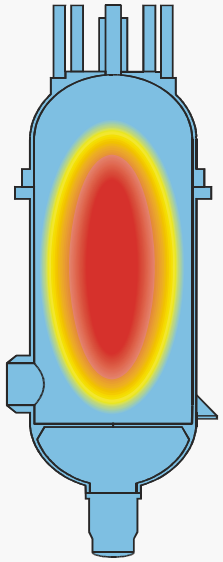
Liquid
[1000s of MW(t)]



Decay Heat Removal Limited by Convective Cooling

(Added benefit of full use of internal heat capacity)

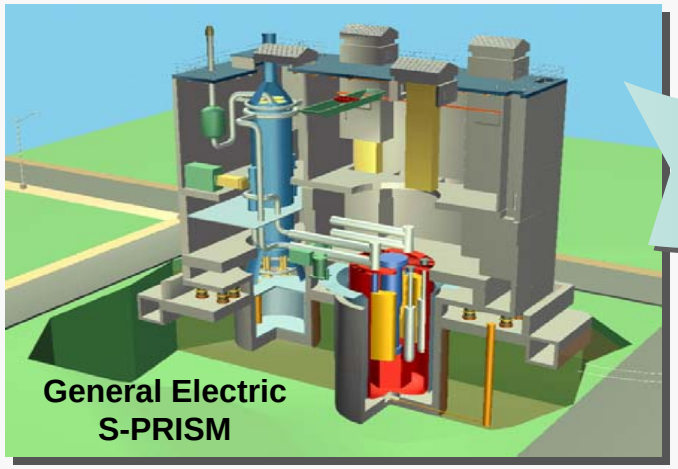
Gas
[~600 MW(t)]



Decay Heat Removal Limited by Conduction Cooling

The Liquid-Salt-Cooled Fast Reactor

Higher-Temperature Liquid-Salt Coolant Replacing Sodium



Fast Reactor Facility Design

High Temperature Brayton Power Cycles

Fast Reactor Core

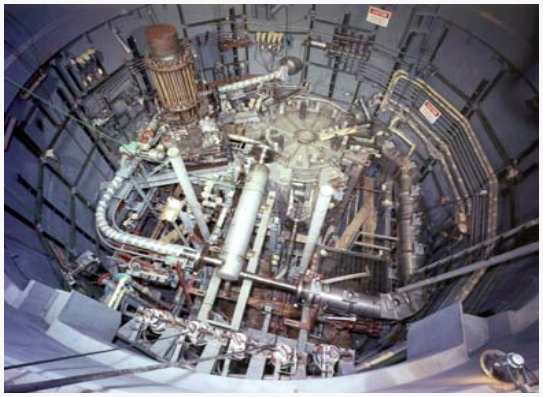
(Picture of PFR Core)

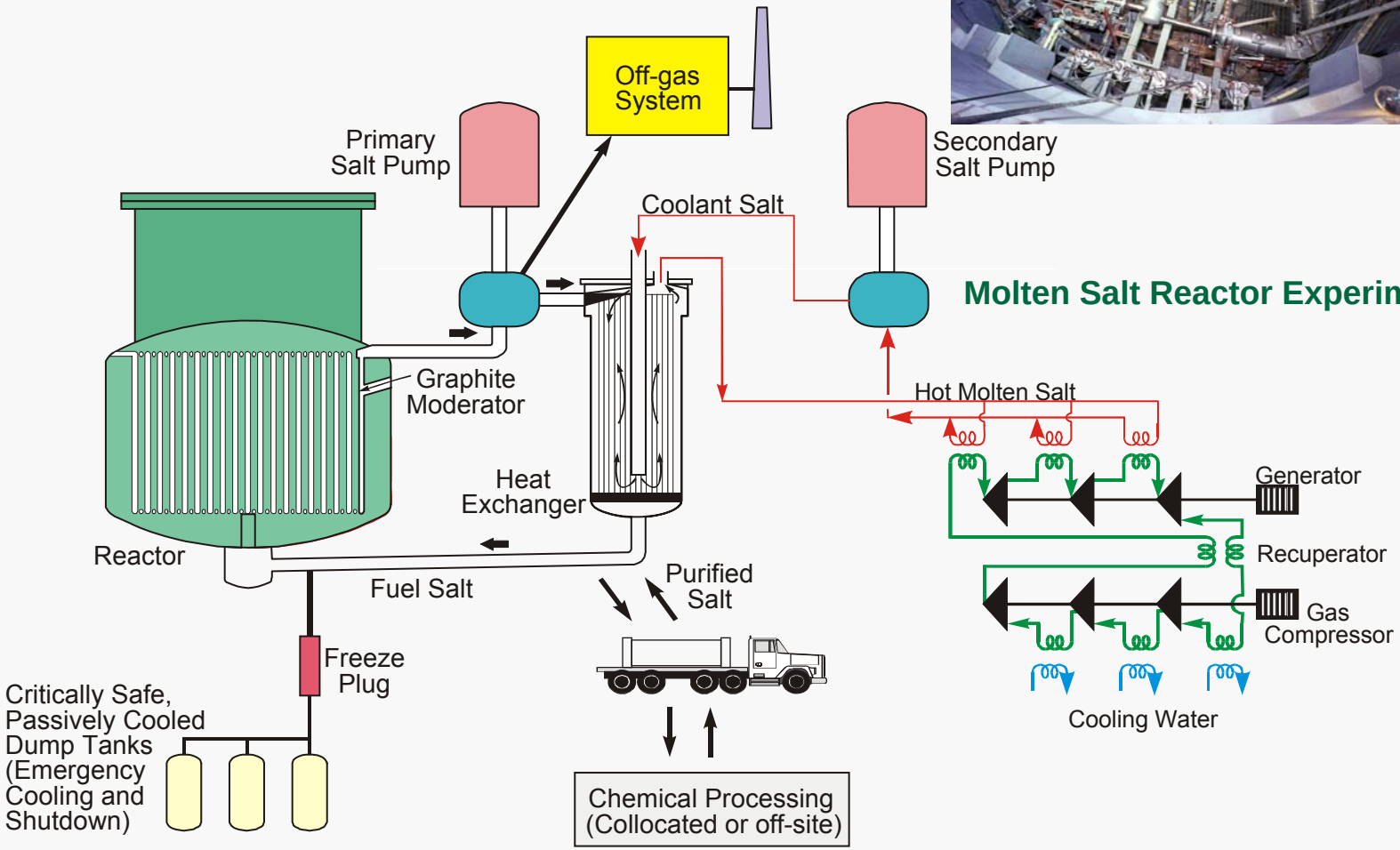
High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

Chloride salts may also be a potential candidates for this system

Molten Salt Reactor

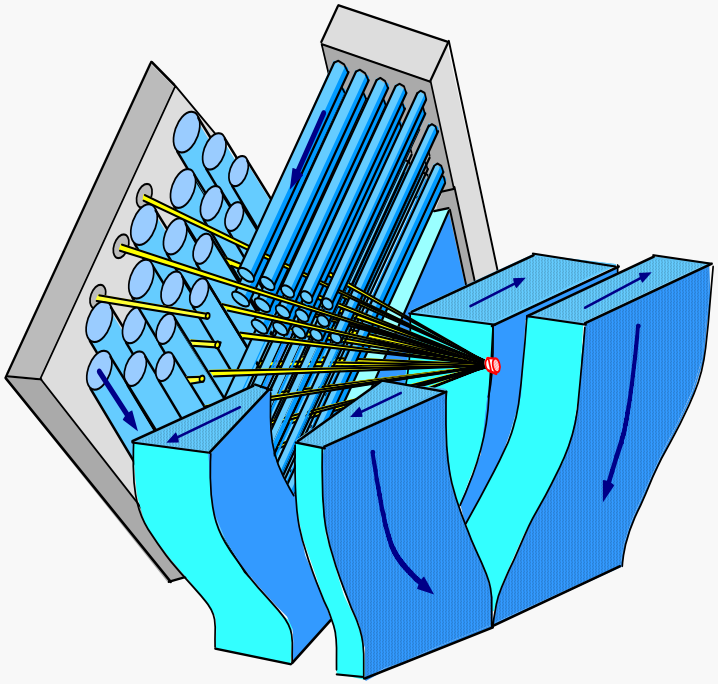
(Gen IV: Modern Version with Brayton Power Cycle)



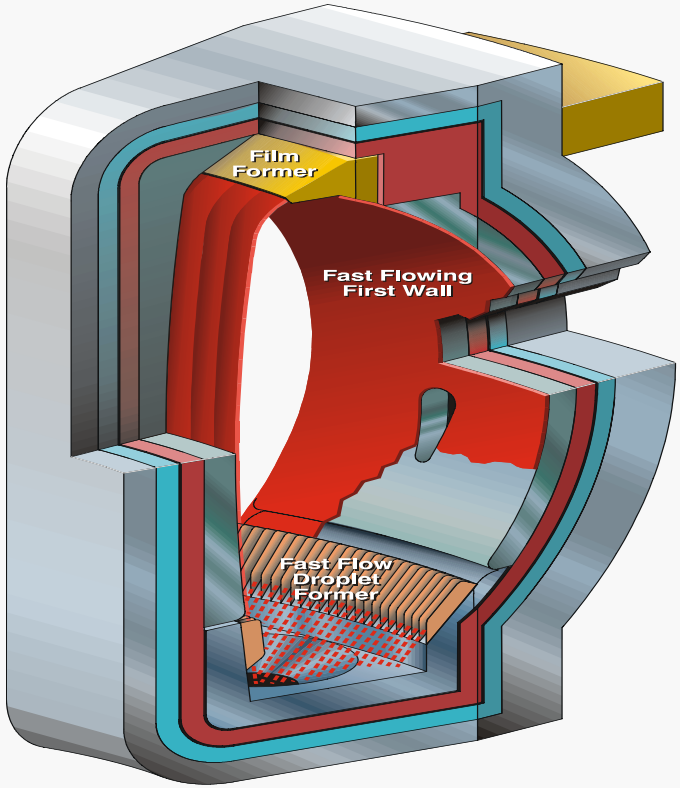


Liquid-Salt-Wall Fusion Machines

(Higher-Power Densities and Less Radiation Damage)



Heavy-Ion Inertial Fusion



Magnet Fusion Tokamak

U. S. R&D Activities

Program	Participants
Heat Transport* (NHI)	Laboratories: INL, ORNL, Sandia Universities: UC-Berkeley, U. of Nevada, U. of Wisconsin Industry: Westinghouse
AHTR* (Gen IV: Liquid-Salt-Cooled VHTR)	Laboratories: ORNL, INL, ANL, Sandia Universities: UC-Berkeley, U. of Nevada, U. of Tennessee Vendors: Areva NP International: Russia, Netherlands
LSFR (GNEP)	Laboratories: ORNL, ANL Universities: UC-Berkeley, MIT International: France
MSR (Gen IV)	Laboratories: ORNL, LLNL Universities: UC-Berkeley International: France, Russia, European Community

*Significant U.S. Programs

Conclusions

- **Liquid and molten salts are high-performance high-temperature coolants**
- **Renewed interest in high-temperature reactors**
  - **Development of industrial methods to efficiently convert high-temperature heat to electricity**
  - **Need for transport fuels**
  - **Need to reduce water consumption**
- **Rapidly growing interest in salt-cooled systems**
  - **Heat transport (NHI)**
  - **Advanced High-Temperature Reactor (Gen IV: Liquid Salt Cooled VHTR)**
  - **Liquid-Salt Fast Reactor**
  - **Molten Salt Reactor (Gen IV)**
  - **Fusion**

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 2002 ANS Special Award for Innovative Nuclear Reactors. He also received the 2005 American Institute of Chemical Engineers Nuclear Energy Division Robert E. Wilson Award for outstanding chemical engineering contributions to nuclear energy and the Oak Ridge National Laboratory Engineer of the Year Award in 2005 for his work on advanced high-temperature reactors. Dr. Forsberg has been awarded 10 patents and has published over 200 papers, many on advanced reactors, hydrogen, and repository systems.

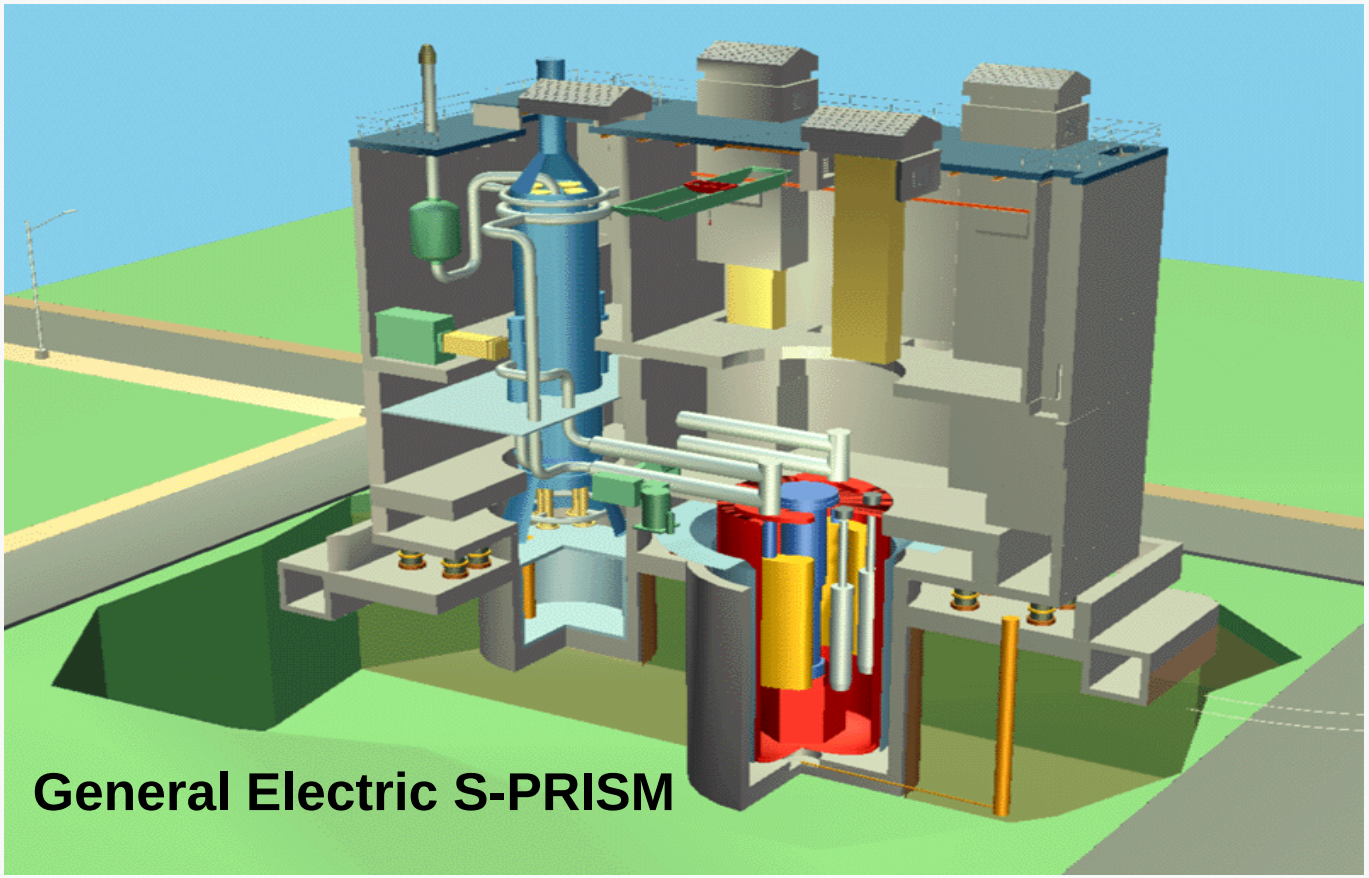
Developments in Molten Salt and Liquid-Salt-Cooled Reactors

Charles W. Forsberg
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6165,
Tel: 865-574-6783; Fax: 865-574-0382; E-mail: forsbergcw@ornl.gov

Abstract — *In the last 5 years, there has been a rapid growth in interest in the use of high-temperature (700 to 1000°C) molten and liquid fluoride salts as coolants in nuclear systems. This renewed interest is a consequence of new applications for high-temperature heat and the development of new reactor concepts. Fluoride salts have melting points between 350 and 500°C; thus, they are of use only in high-temperature systems. Historically, steam cycles with temperature limits of ~550°C have been the only efficient method to convert heat to electricity. This limitation produced few incentives to develop high-temperature reactors for electricity production. However, recent advances in Brayton gas-turbine technology now make it possible to convert higher-temperature heat efficiency into electricity on an industrial scale and thus have created the enabling technology for more efficient nuclear reactors. Simultaneously, there is a growing interest in using high-temperature nuclear heat for the production of hydrogen and shale oil. Five nuclear-related applications are being investigated: (1) liquid-salt heat-transport systems in hydrogen and shale oil production systems; (2) the advanced high-temperature reactor, which uses a graphite-matrix coated-particle fuel and a liquid salt coolant; (3) the liquid-salt-cooled fast reactor which uses metal-clad fuel and a liquid salt coolant; (4) the molten salt reactor, with the fuel dissolved in the molten salt coolant; and (5) fusion energy systems. The reasons for the new interest in liquid salt coolants, the reactor concepts, and the relevant programs are described.*

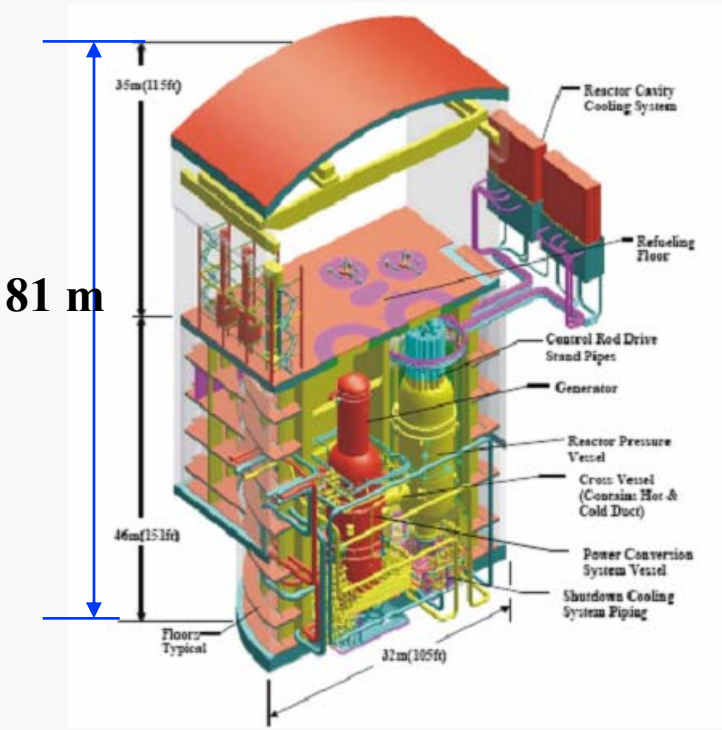
AHTR Facility Layouts are Based on Sodium-Cooled Fast Reactors

Low Pressure, High Temperature, Liquid Cooled



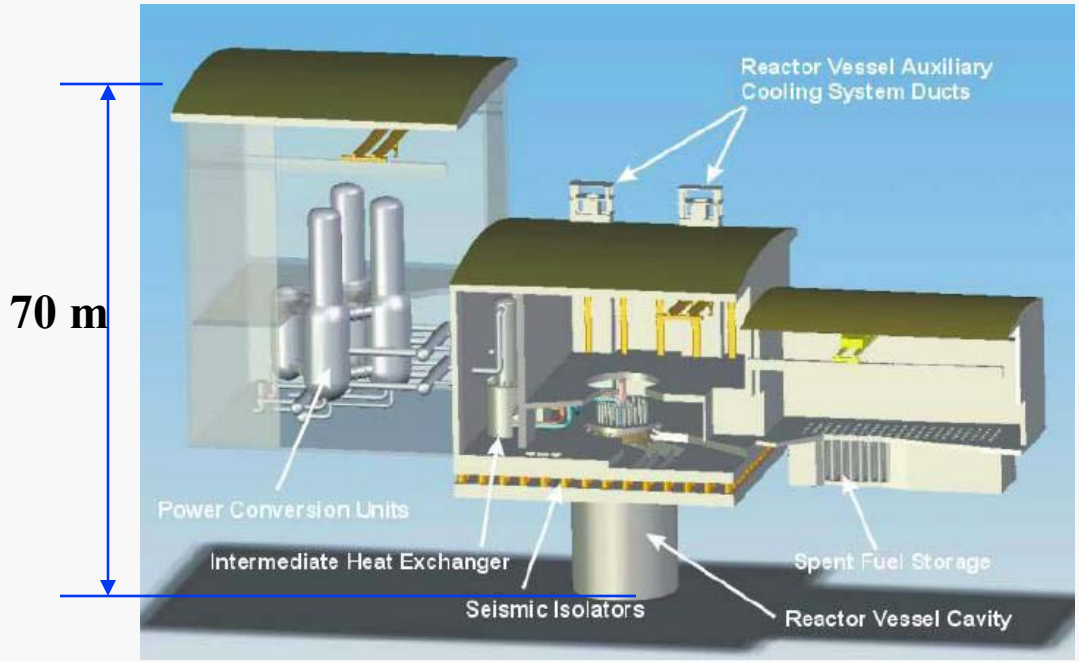
Two Types of High-Temperature Reactors are Being Developed

(MHTGR: Near Term; AHTR: Medium Term)



Modular High-Temperature Gas-Cooled Reactor

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



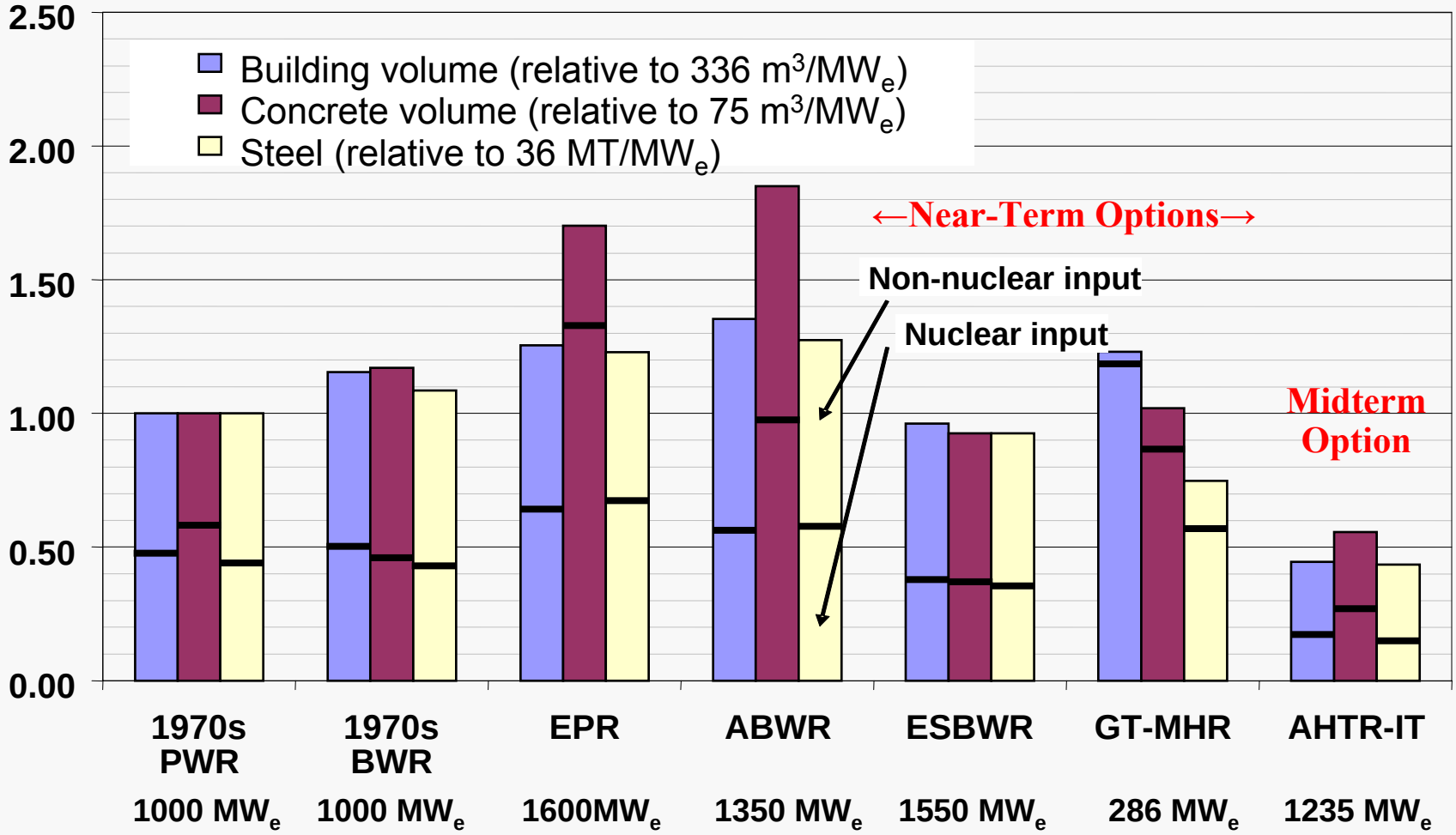
Advanced High-Temperature Reactor

Liquid Salt Cooled: 2400 MW(t); Medium-Term Option

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

Reactor Comparison of Building Volume, Concrete Volume, and Steel Consumption Based on Arrangement Drawings

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



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