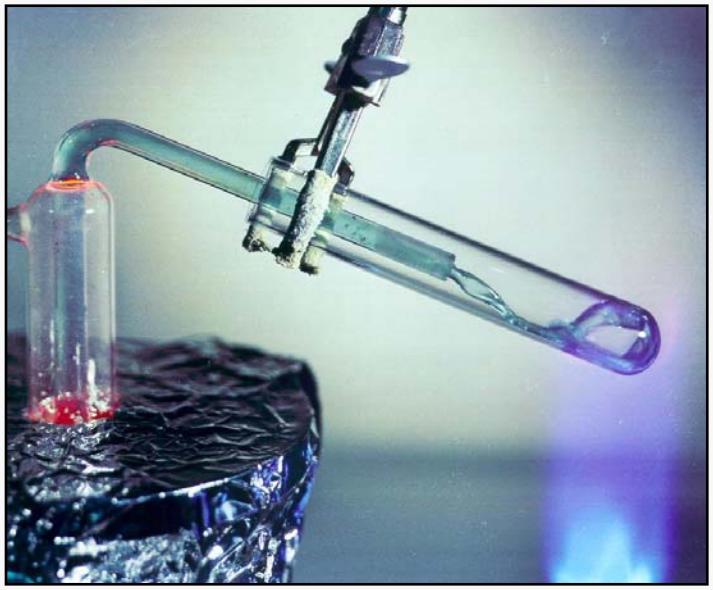
Liquid-Salt-Cooled Reactors: Five Pathways to the Future

Charles W. Forsberg

Brown Bag Seminar
Oak Ridge National Laboratory
Oak Ridge, TN. 37831
October 30, 2006

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

*Notice: This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. File: AHTR Viewgraphs: BrownBag06

Abstract

In the last 5 years, there has been a rapid growth in interest in the use of high-temperature (700 to 950°C) molten and liquid fluoride salts as coolants in nuclear and other power 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 500ºC; 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 using high-temperature heat from nuclear reactors and other sources to efficiently produce electricity. It is now possible to convert heat to electricity with efficiencies in excess of 50%. Simultaneously, there is a growing interest in using high-temperature nuclear heat for the production of hydrogen and shale oil.

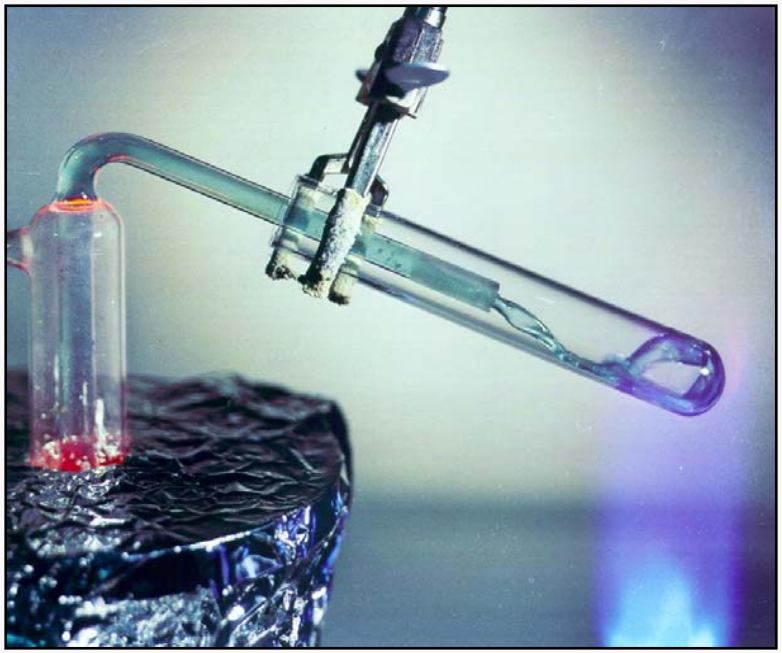
Liquid salts are now being investigated for liquid-salt heat-transport systems in hydrogen and shale oil production systems. They are also the key technology for five advanced energy systems: (1) the advanced high-temperature reactor (AHTR), which uses a graphite-matrix coated-particle fuel and a liquid salt coolant; (2) the liquid-salt-cooled fast reactor (LSFR) which uses metal-clad fuel and a liquid salt coolant; (3) the molten salt reactor (MSR), with the fuel dissolved in the molten salt coolant; (4) fusion energy systems, and (5) advanced solar power towers. In each of these energy systems, the liquid salt transfers heat from a high-temperature heat source to an advanced Brayton power cycle for the production of electricity. In the fusion systems, there is also the option of using the flowing salts as the inner wall of the fusion machine rather than the use of a solid wall.

UT-BATTELLE

Reactors Before Their Time

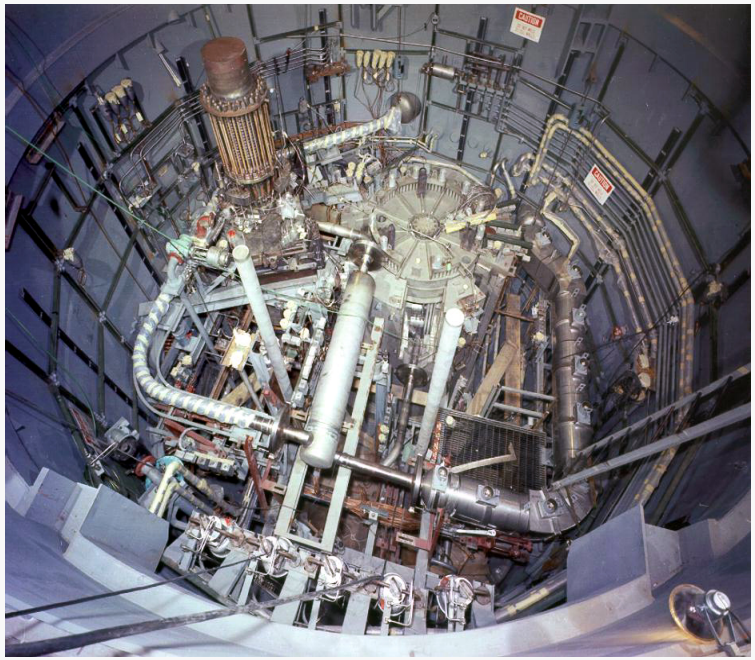
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

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



Liquid Salts

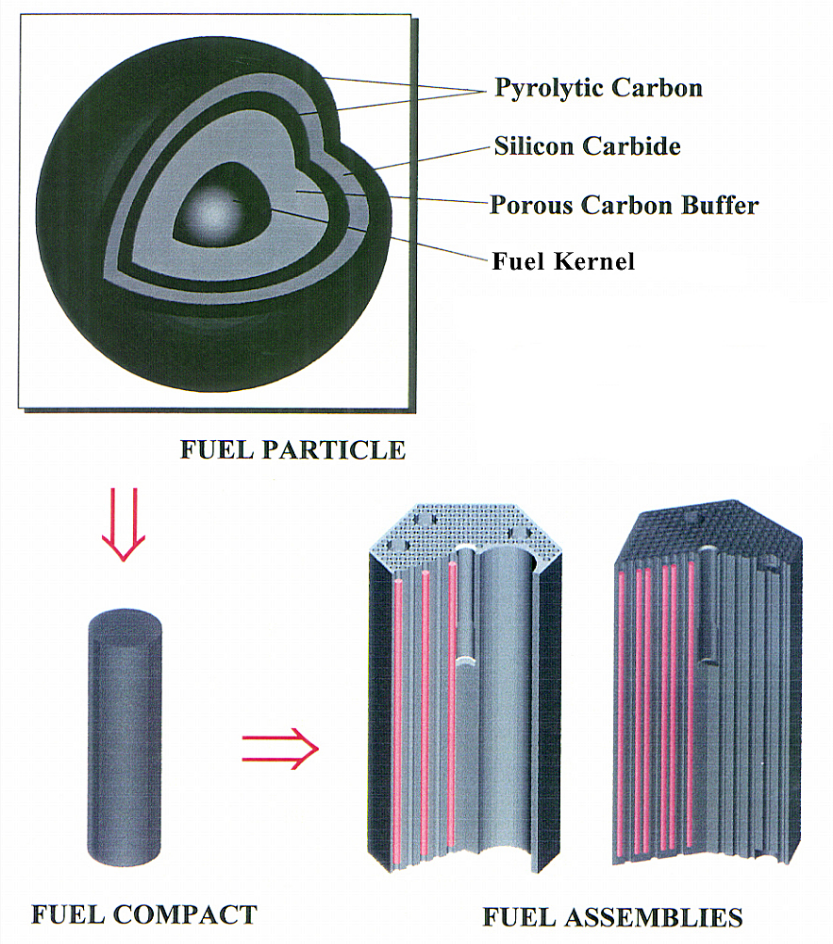
← Melting points: 350 to 500ºC
Boiling points: >1200ºC



Molten Salt Breeder Reactor Program

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

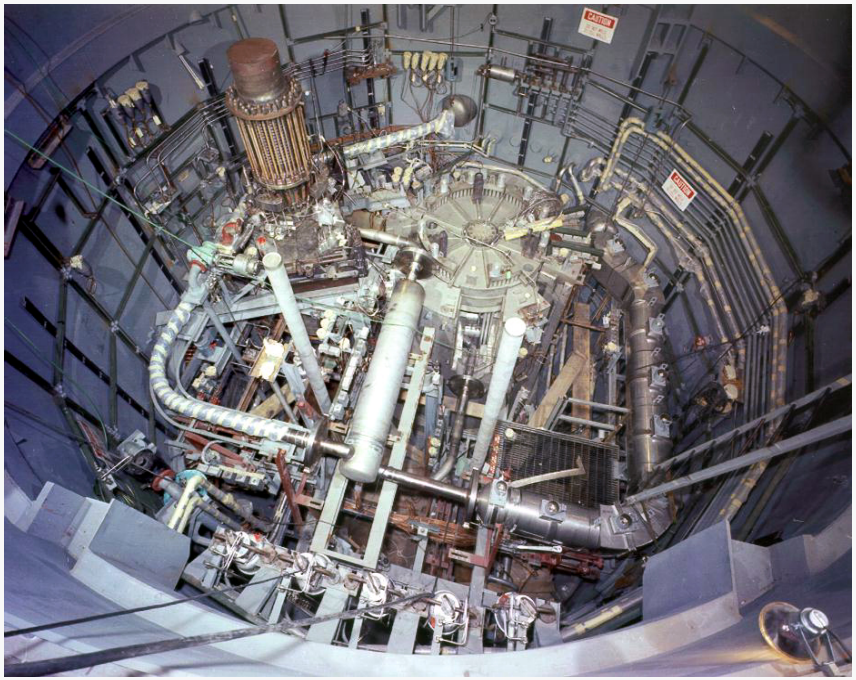
High-Temperature Gas-Cooled Reactors were Developed in the 1970s



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....

UT-BATTELLE

Back to the Future:
The Rebirth of Interest in High-Temperature Reactors

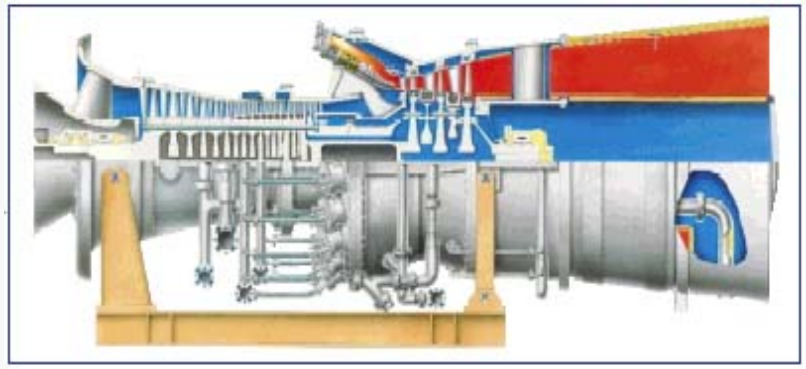
What has Changed?

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

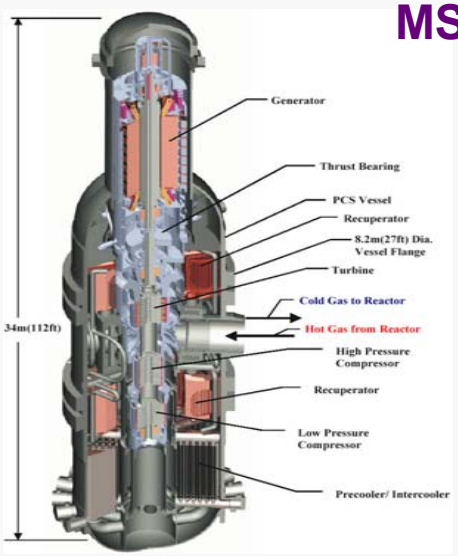
Brayton Power Cycles Make High-Temperature Utility Power Systems Viable

(Helium or Nitrogen Brayton Power Cycles)

- **High-temperature heat is only useful if it can be converted to electricity**
- **Steam cycle limit ~550ºC**
  - **40% efficient heat-to-electricity**
  - **The high-temperature option until the 1990s**
- **New utility-grade Brayton cycles operate efficiently (50%) at higher temperatures**
- **The technology now exists to economically convert high-temperature heat to electricity**



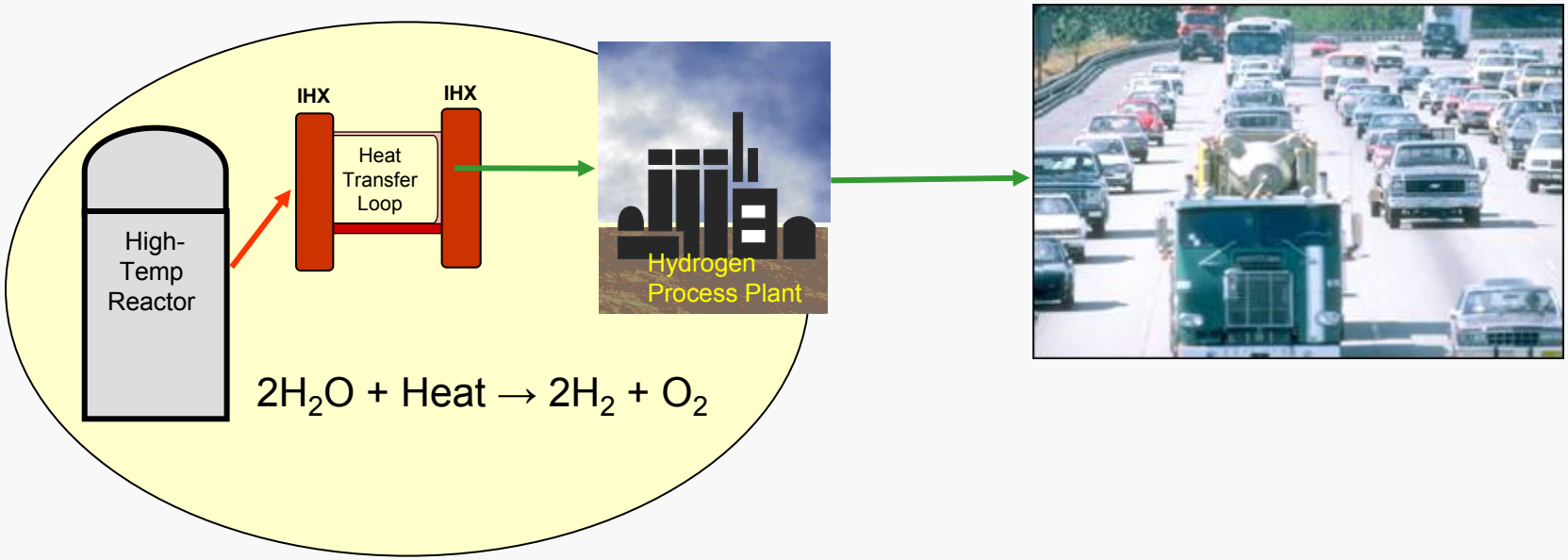
GE Power Systems MS7001FB



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

There is a Growing Interest in Hydrogen Production for Transportation

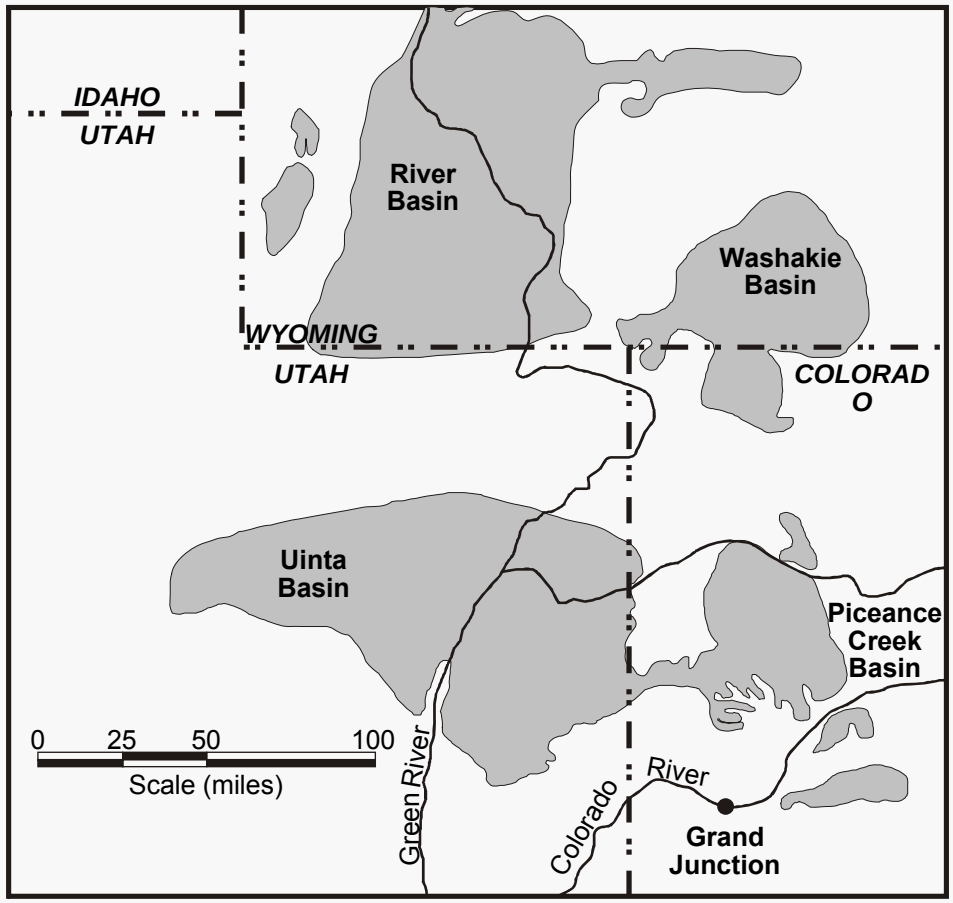
(High Temperatures Required for Hydrogen Production)



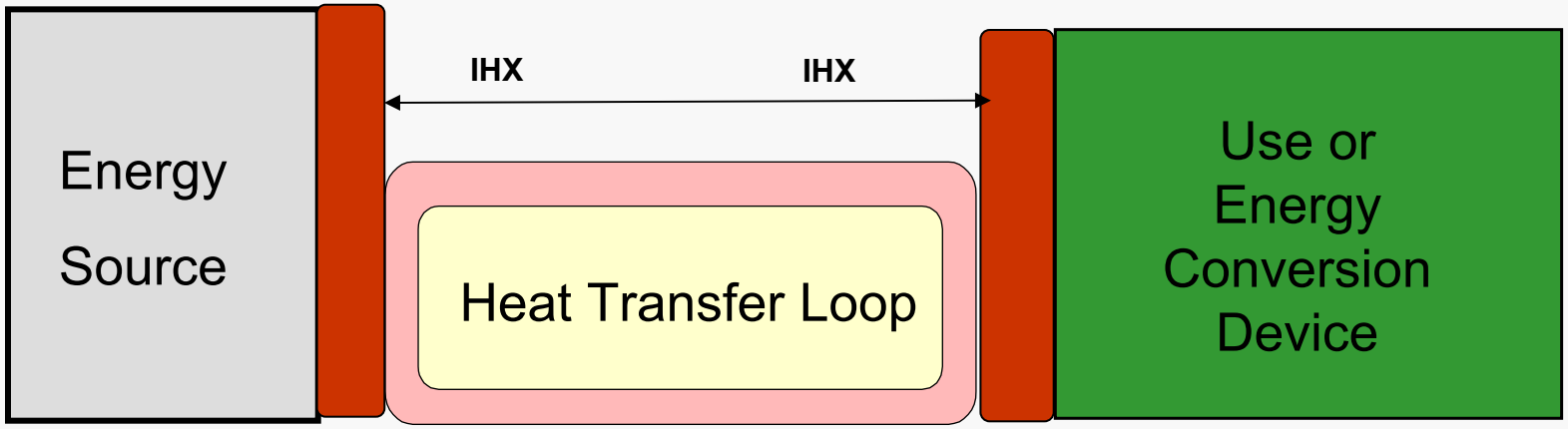
Need to Move Heat from High-Temperature Reactors to Hydrogen Production Systems

Shale Oil Recovery Requires Massive Quantities of High-Temperature Heat

- **U.S. resources equivalent to ~800 billion barrels of oil**
- **Three times the oil resources of Saudi Arabia**
- **~100-year oil supply for the United States**
- **Oil Shale + High-Temperature Heat → Shale Oil**



There is Now a Need for Moving High-Temperature Heat

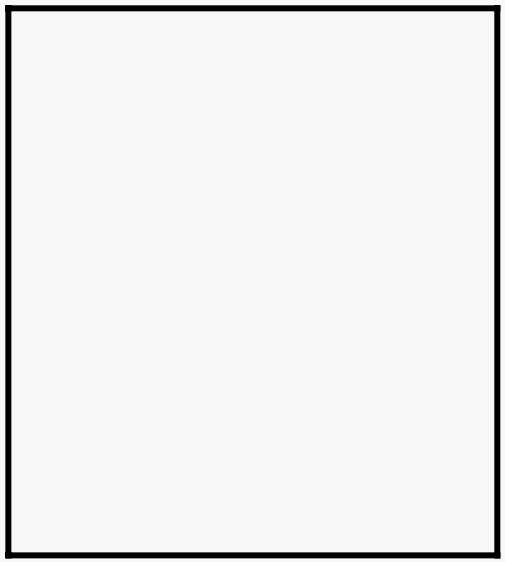


But How?

Alternatives to Move High-Temperature Heat

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

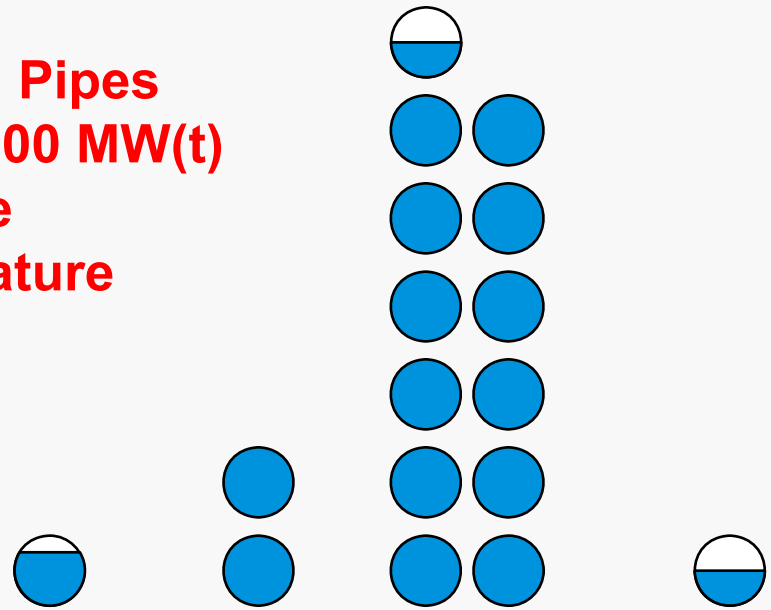
High-Temperature Reactor Coolants

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

Coolant Properties Impact Reactor Size and Cost

(Determine Pipe, Valve, and Heat Exchanger Sizes)

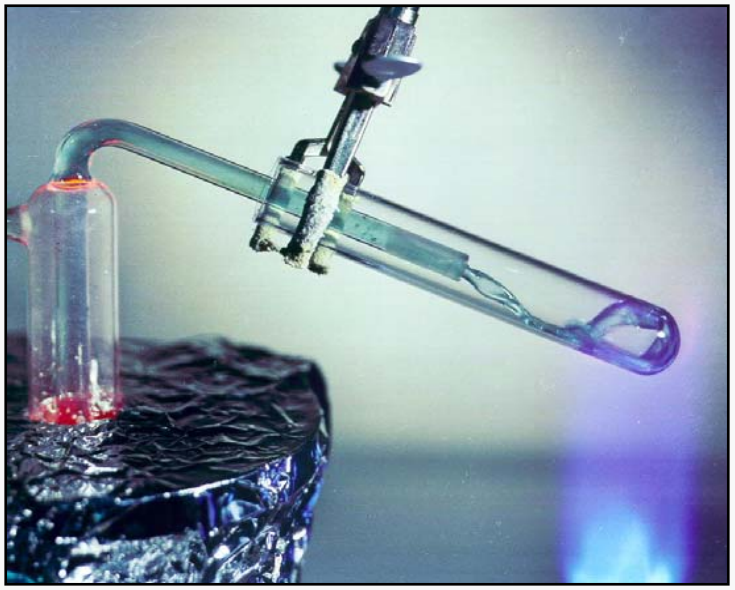
Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t) with 100ºC Rise in Coolant Temperature



	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

Molten and Liquid Salts are High-Temperature Coolants

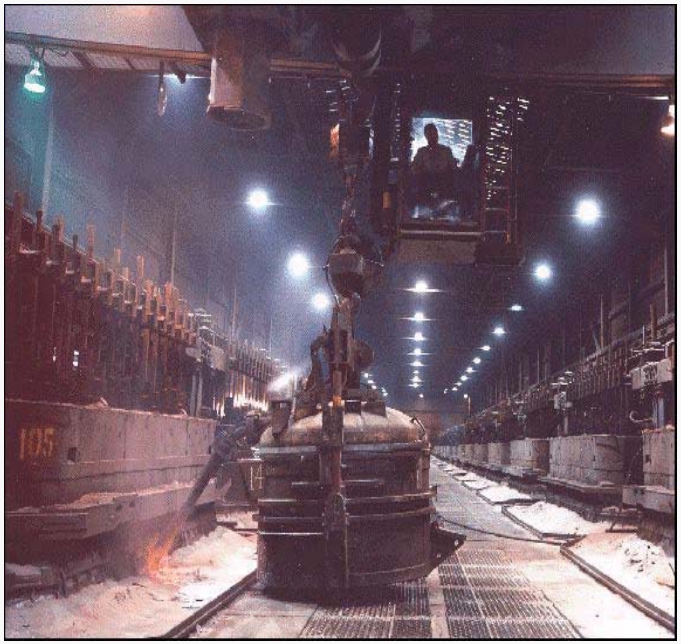
- **Fluoride and chloride salts**
- **Characteristics**
  - **Melting points between 350 and 500ºC**
  - **Boiling points above 1200ºC**
  - **Physical properties similar to water**
  - **Transparent**
- **ORNL worldwide lead**
- **Only usable in high-temperature systems**



Liquid Fluoride Salts

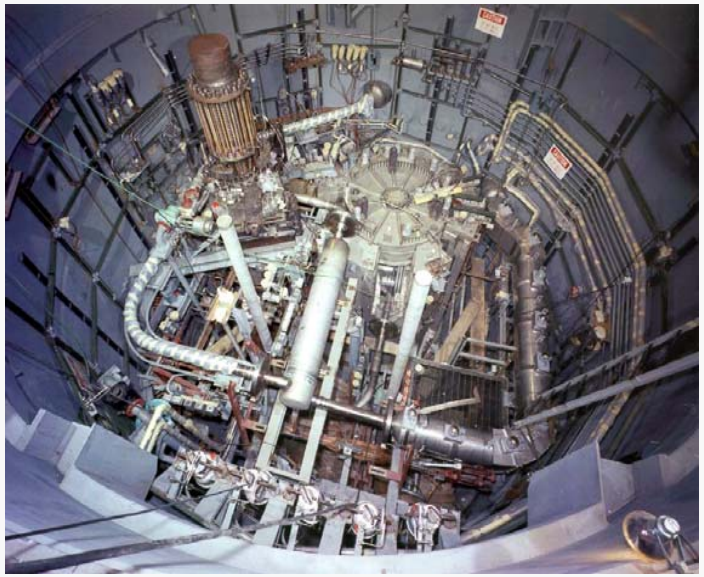
(Low Pressure/Transparent)

There is Experience with Molten and Liquid Fluoride Salts



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

Molten Fluoride Salts were Used in Molten Salt Reactors with Fuel in Coolant [Molten Salt Reactor Experiment: 8 MW(t)]

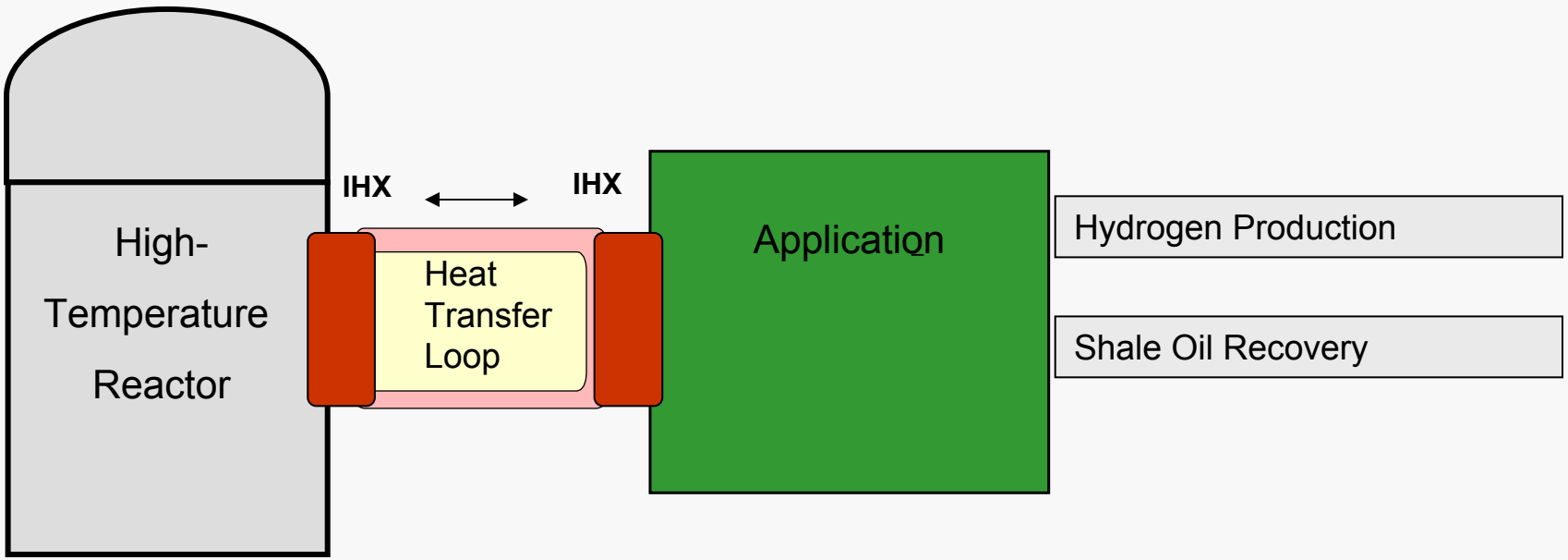


Because of Changes in Technology and Markets, It's Back to the Future with:

High Temperature Reactors and Heat Transport With Liquid Salts

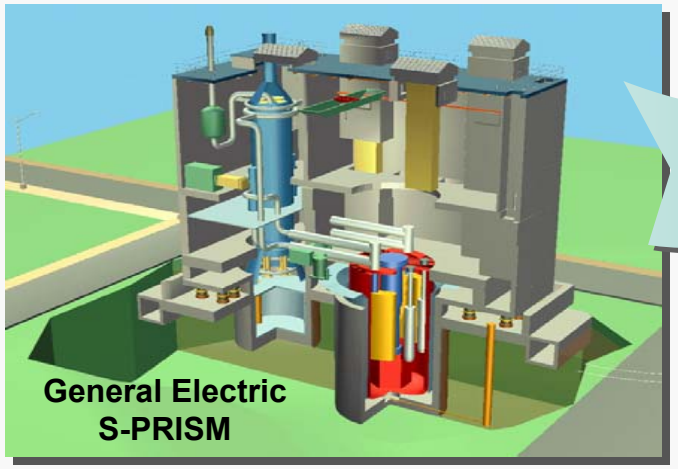
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

Liquid Salts are Leading Candidates to Move Heat from Any High-Temperature Reactor to Any Application



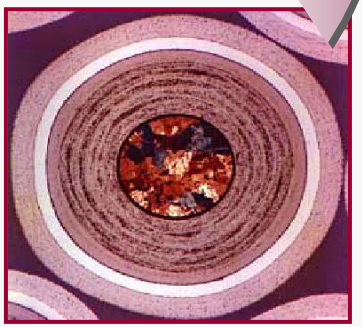
The Advanced High-Temperature Reactor

The Near-Term Option



Passively Safe Pool-Type Reactor Designs

Brayton Power Cycles

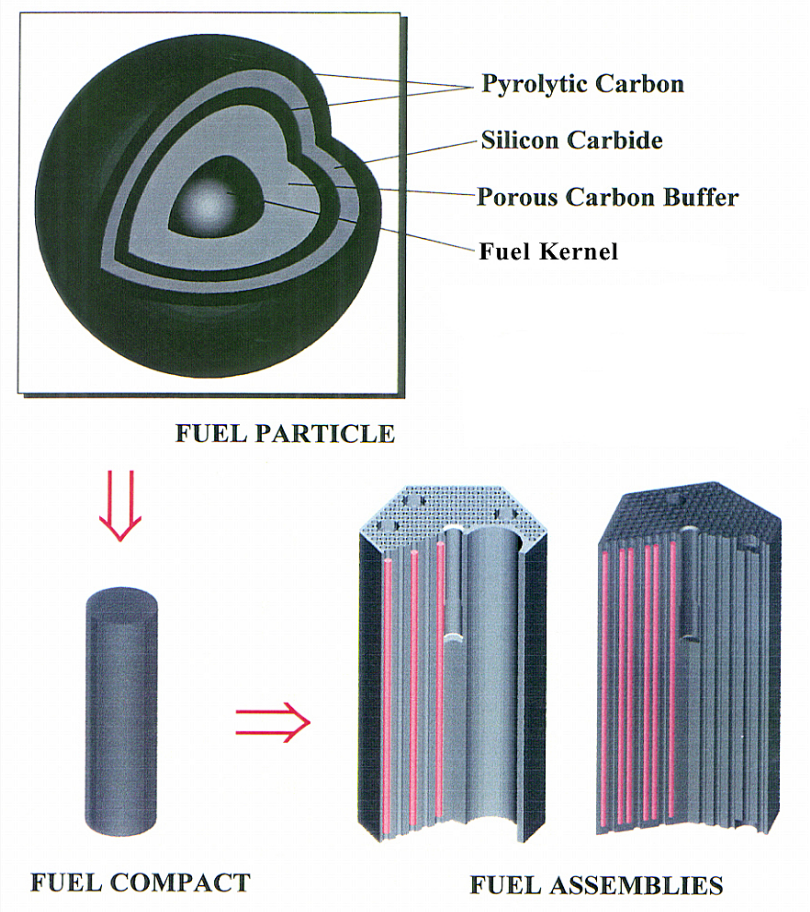


High-Temperature Coated-Particle Fuel

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

High-Temperature Reactors Use Graphite-Matrix Coated-Particle Fuel

- **Fuel encapsulated in multilayer microspheres**
  - **Carbon layers**
  - **Silicon carbide layers**
- **Microspheres in a graphite matrix**
- **Only demonstrated high-temperature fuel**
  - **Operating temperatures to 1200ºC**
  - **Accident capability to ~1650°C for limited time**



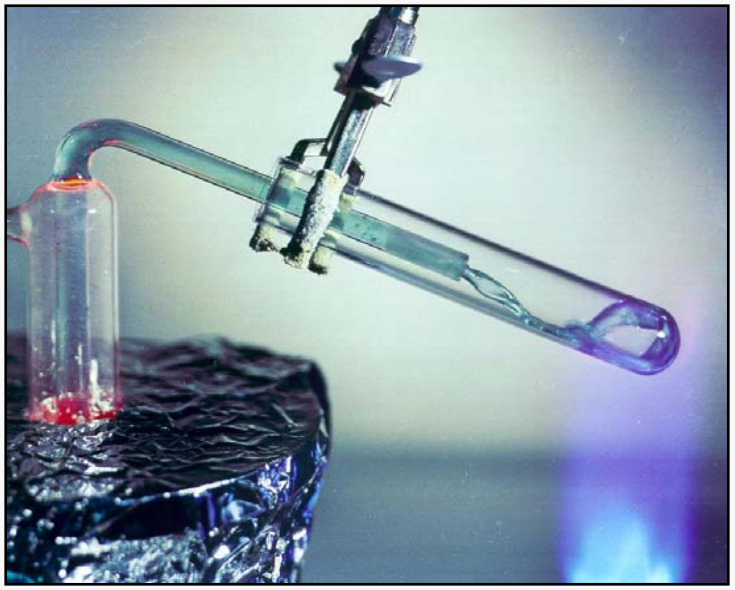
Two Reactor Coolants are Chemically Compatible with Graphite-Matrix Fuel

Modular High-Temperature Gas-Cooled Reactor

Helium

(High Pressure/Transparent)

Advanced High-Temperature Reactor



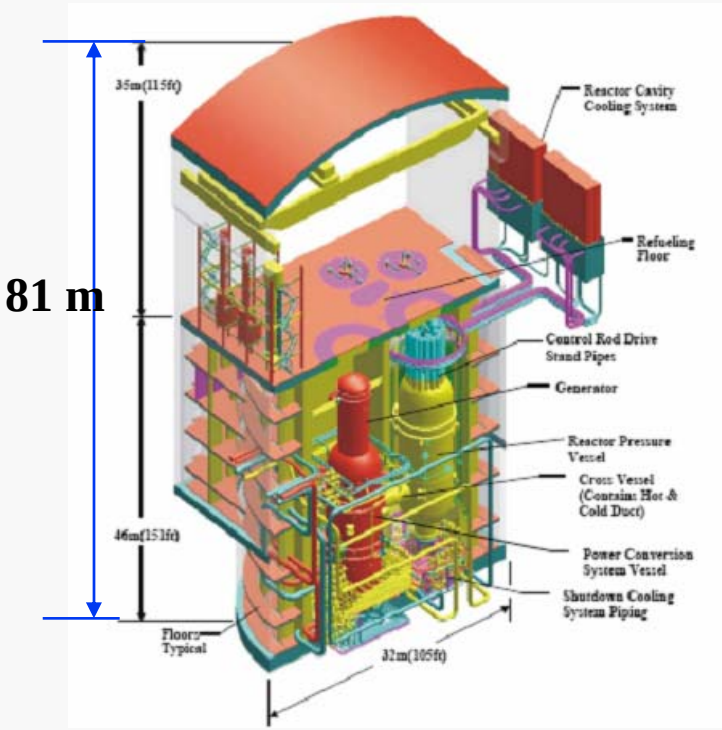
Liquid Fluoride Salts

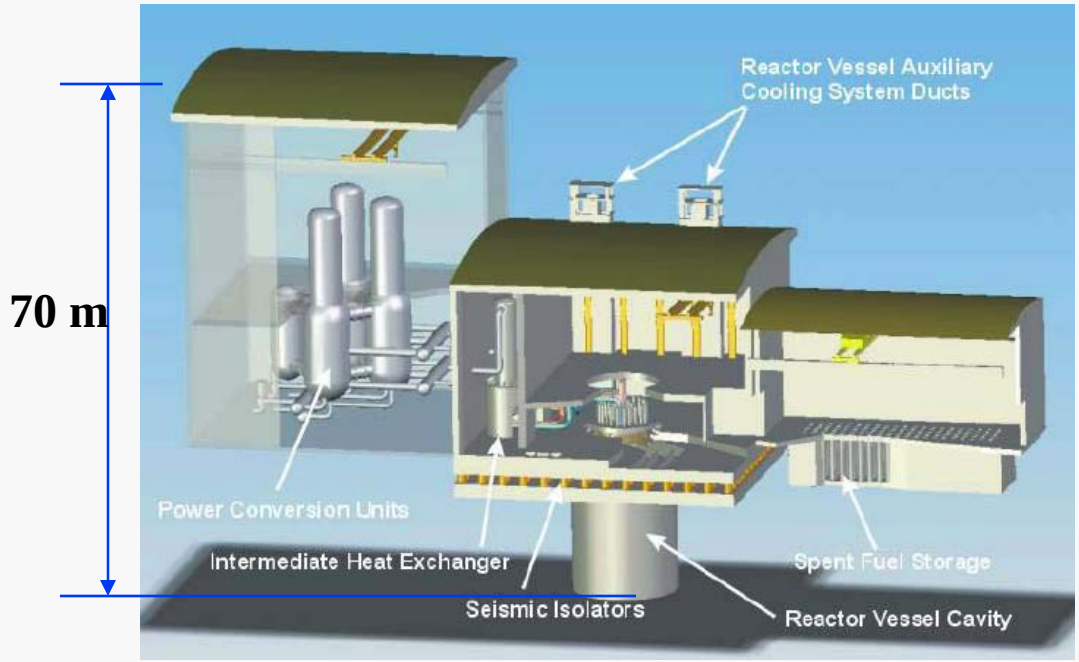
(Low Pressure/Transparent)

Two Reactor Options Based on Choice of Coolant

Two Types of High-Temperature Reactors are Being Developed

(Gas-Cooled: Near Term; AHTR: Medium Term)





Modular High-Temperature Gas-Cooled Reactor

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

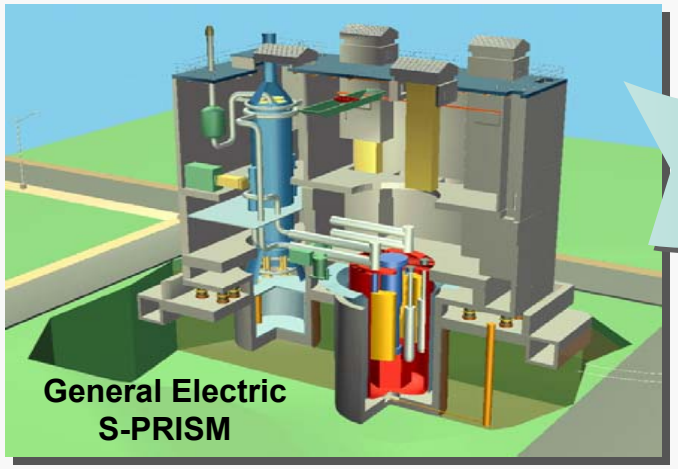
Advanced High-Temperature Reactor

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

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

The Liquid-Salt-Cooled Fast Reactor

Higher-Temperature Liquid-Salt Coolant Replacing Sodium (Very Early in Development)



Fast Reactor Facility Design

High Temperature Brayton Power Cycles

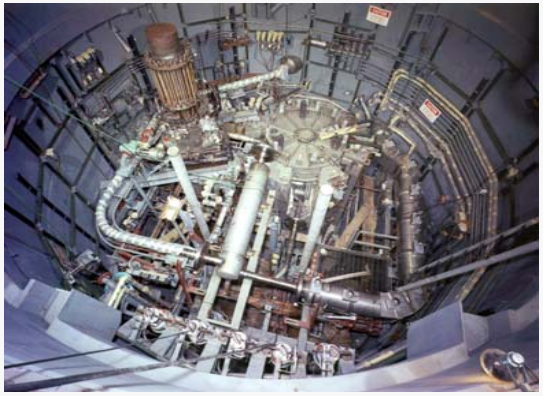
Fast Reactor Core

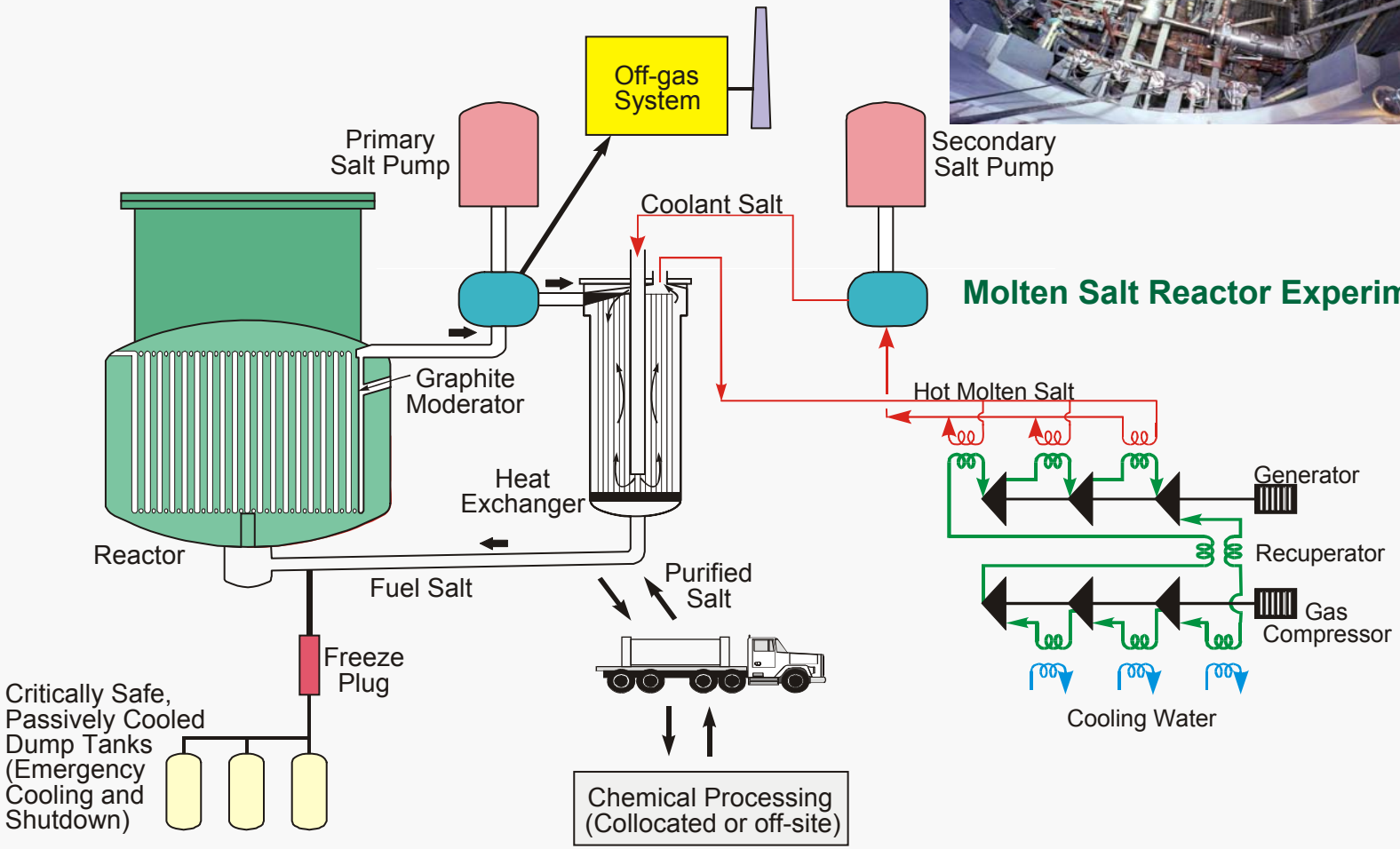
(Picture of PFR Core)

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

Chloride salts may also be a potential candidates for this system

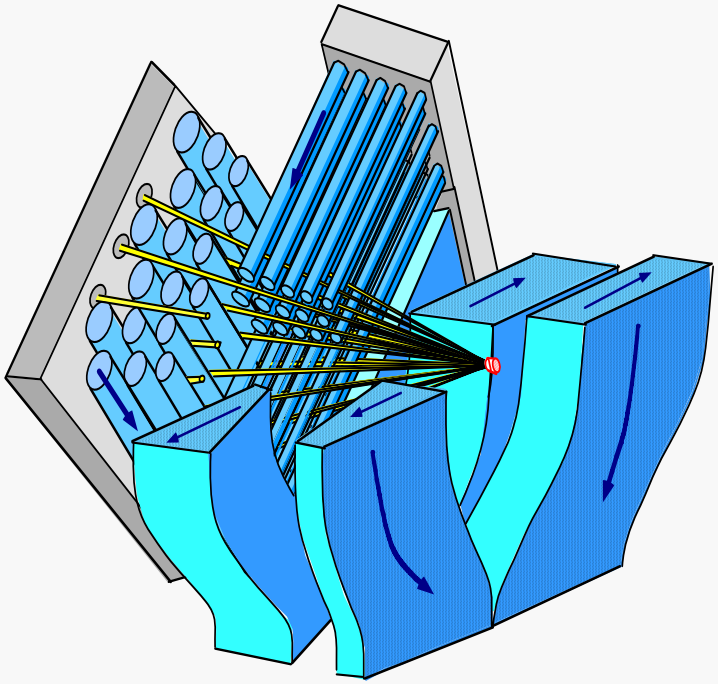
Molten Salt Reactor
(Fuel Dissolved in the Salt Coolant)



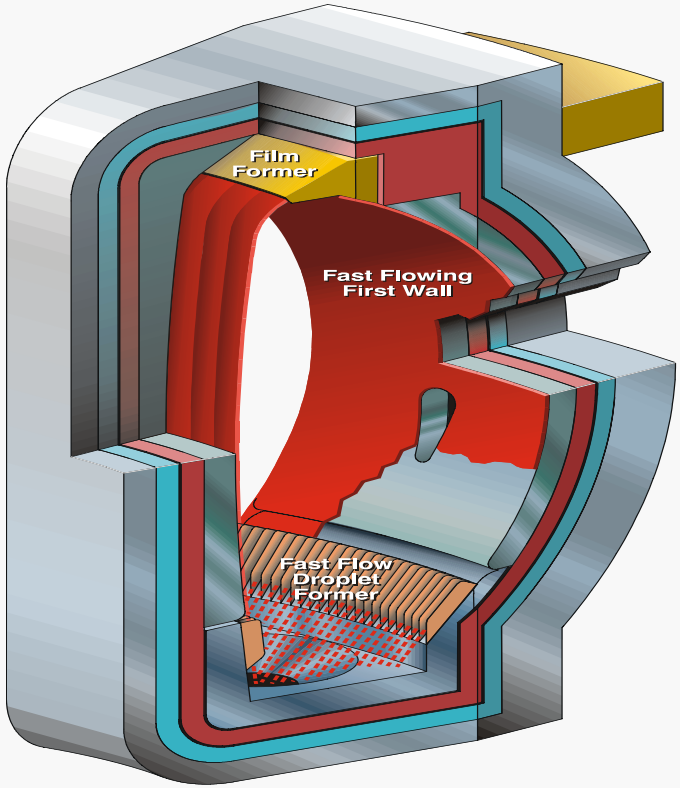


Liquid-Salt-Wall Fusion Machines

(Higher-Power Densities and Less Radiation Damage)



Heavy-Ion Inertial Fusion

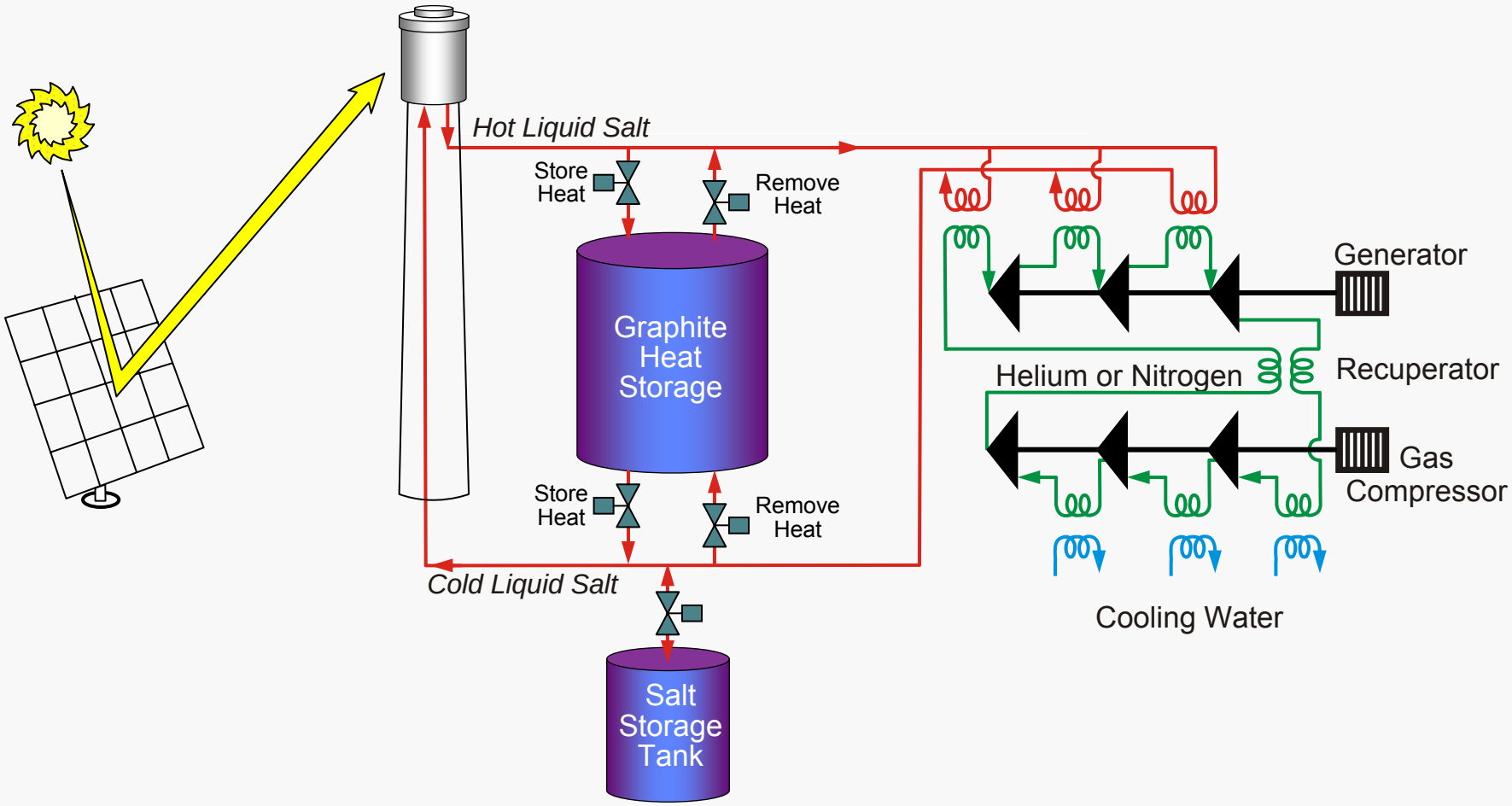


Magnet Fusion Tokamak

Solar Power Tower

(Higher Efficiency and Lower Cost with Liquid Salts)

Solar Power Tower **Heat and Salt Storage** **Brayton Power Cycle**



The Challenges

The Goals: A New Commercial Coolant and New Reactor Options

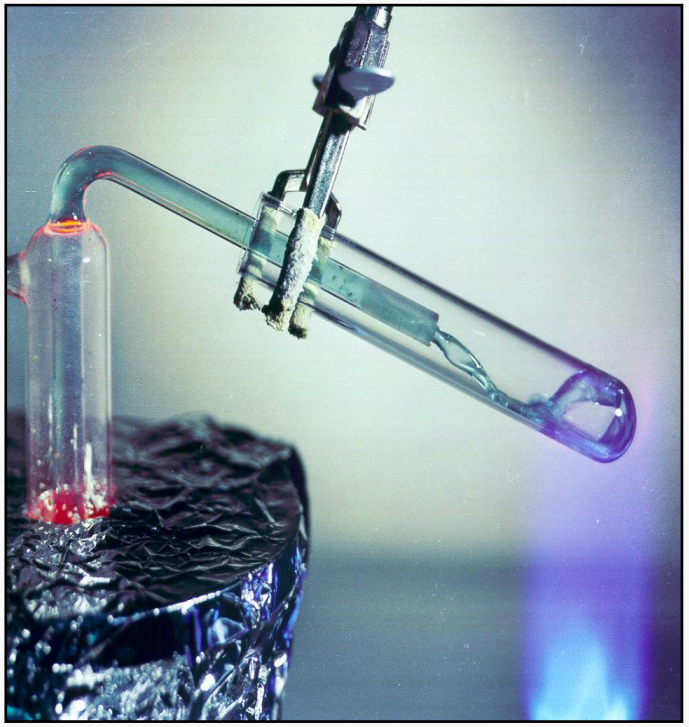
- **There are very few commercial coolants (All <600ºC)**
  - **Air**
  - **Water**
  - **Organics (Limited)**
  - **Sodium (Limited)**
  - **Nitrate Salts (Limited)**
- **Commercial coolants have**
  - **Suppliers**
  - **Text book design**
  - **Economic**
- **Converting liquid salts to a commercial coolant and developing the reactors: A true national challenge**

U. S. R&D Activities

Application	Participants
Heat Transport	Laboratories: INL, ORNL, Sandia Universities: UC-Berkeley, U of Nevada, U. of Wisconsin Industry: Westinghouse
AHTR	Laboratories: ORNL, INL, ANL, Sandia Universities: UC-Berkeley, U. of Nevada, U. of Tennessee Vendors: Areva NP International: Russia, Netherlands, Sweden
Liquid-Salt Fast Reactor	Laboratories: ORNL, ANL Universities: UC-Berkeley, MIT International: France
MSR	Laboratories: ORNL, LLNL Universities: UC-Berkeley International: France, Russia, European Community, Czech Republic

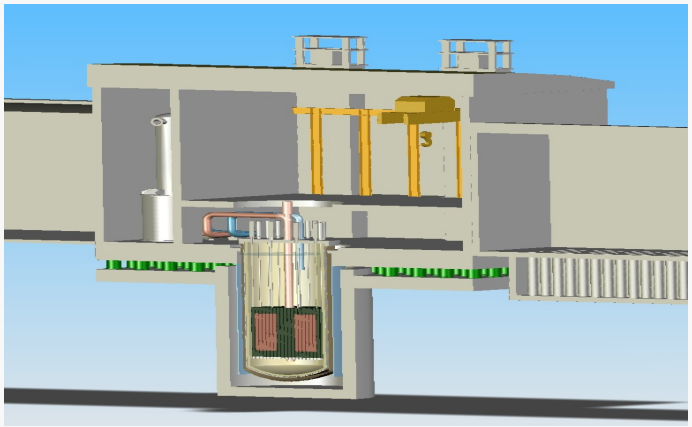
*Significant U.S. Programs

Conclusions

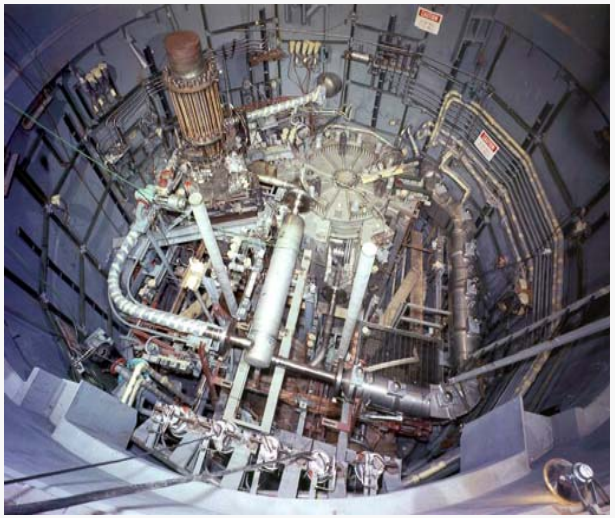


- **Liquid and molten salts are high-performance high-temperature coolants**
- **Renewed interest in high-temperature coolants and reactors**
  - **New methods to convert high-temperature heat to electricity**
  - **Need for hydrogen**
  - **Need for shale oil**
- **The Challenge**
  - **Develop a new commercial coolant**
  - **Develop the reactors**

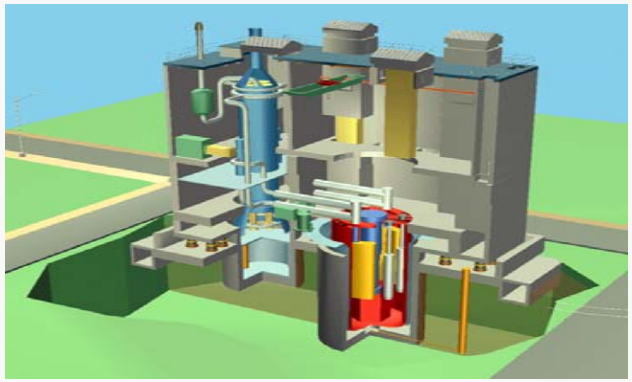
Questions



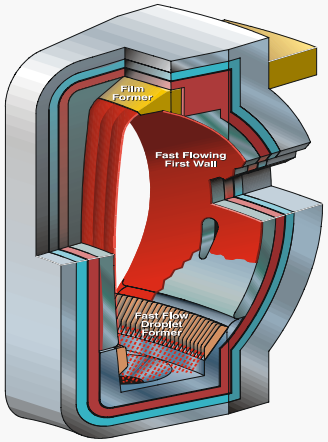
Advanced High-Temperature Reactor



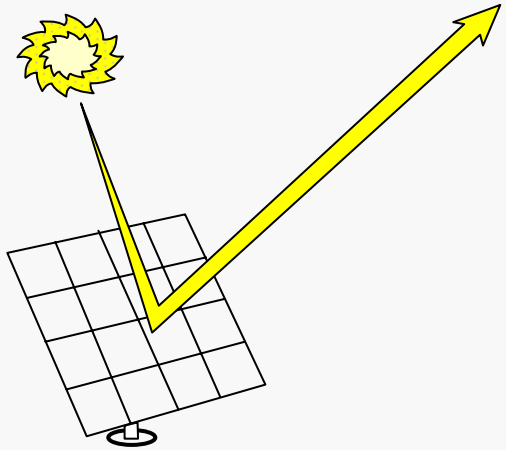
Molten Salt Reactor



Liquid-Salt-Cooled Fast Reactor

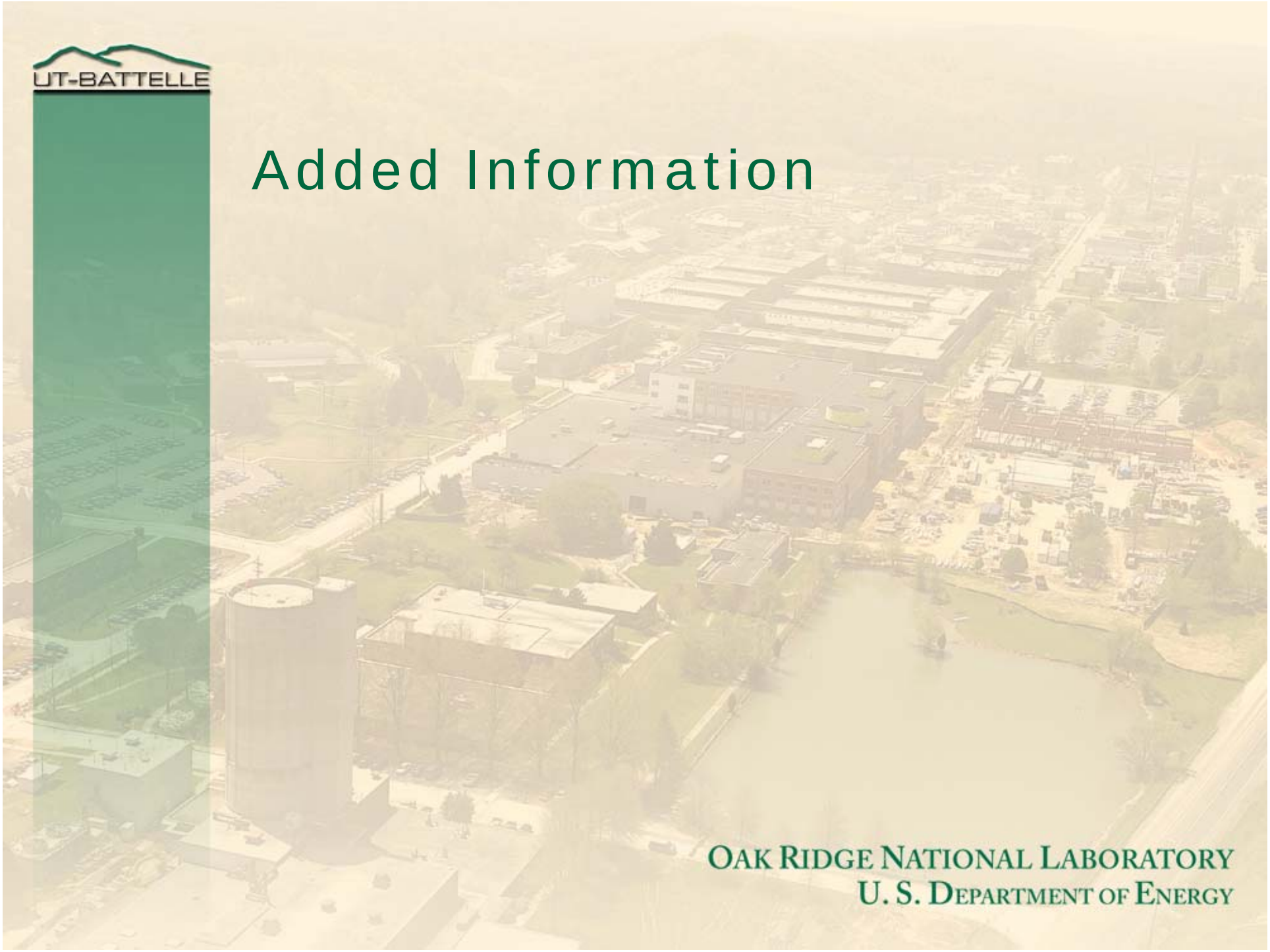


Fusion



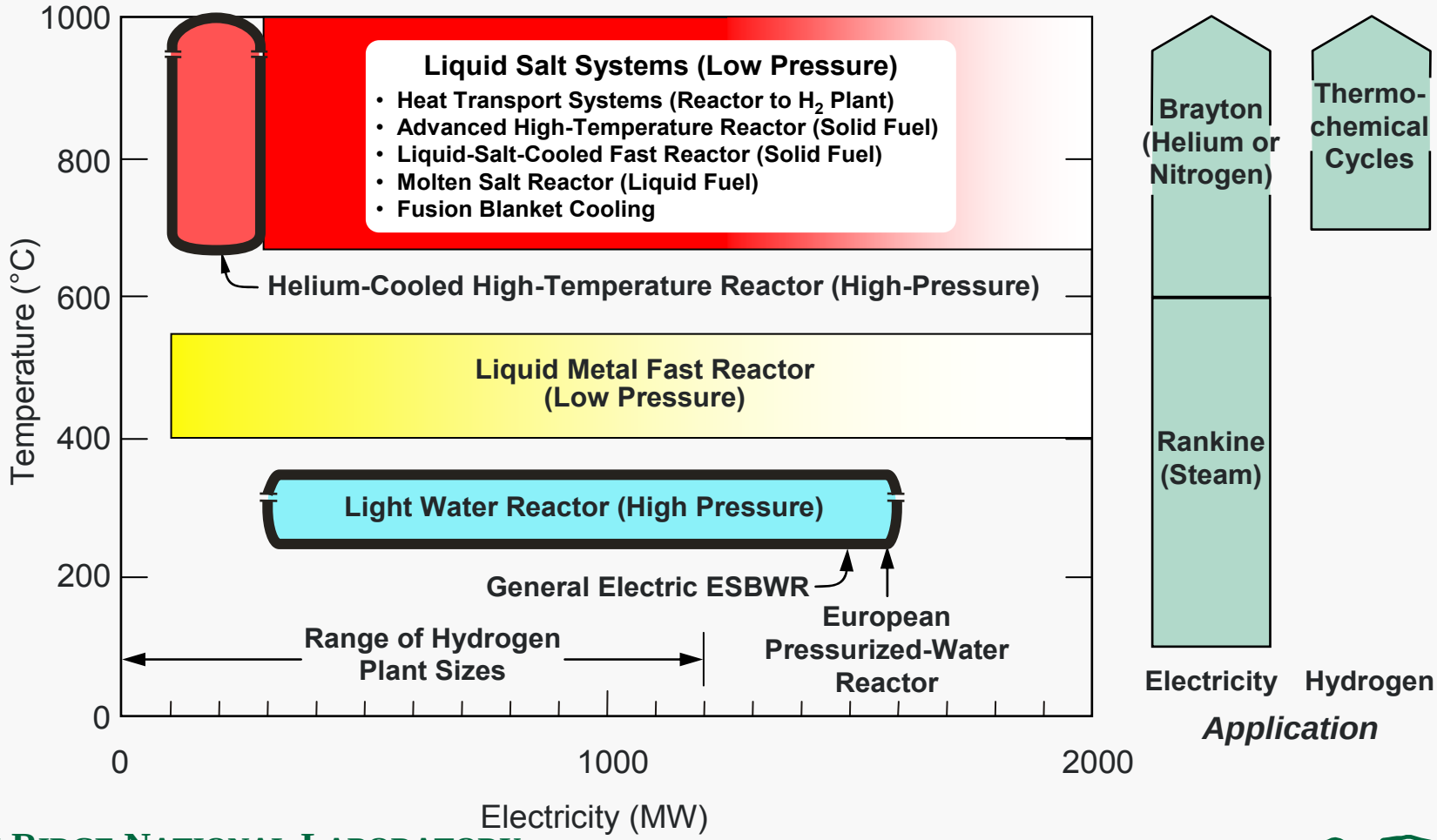
Solar Power Tower

Added Information



Salt Coolants can be Used for High-Temperature Nuclear Applications

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



Biography: Charles Forsberg

Dr. Charles Forsberg is a Corporate Fellow at Oak Ridge National Laboratory, a Fellow of the American Nuclear Society, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design and the Oak Ridge National Laboratory Engineer of the Year Award.

Dr. Charles Forsberg earned 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 the Senior Reactor Technical Advisor. Dr. Forsberg has been awarded 10 patents and has published over 200 papers in advanced energy systems, waste management, and hydrogen futures.