Fluoride-Salt-Cooled High-Temperature Reactors for Power and Process Heat

Integrated Research Project of the Massachusetts Institute of Technology, University of California at Berkeley, and the University of Wisconsin

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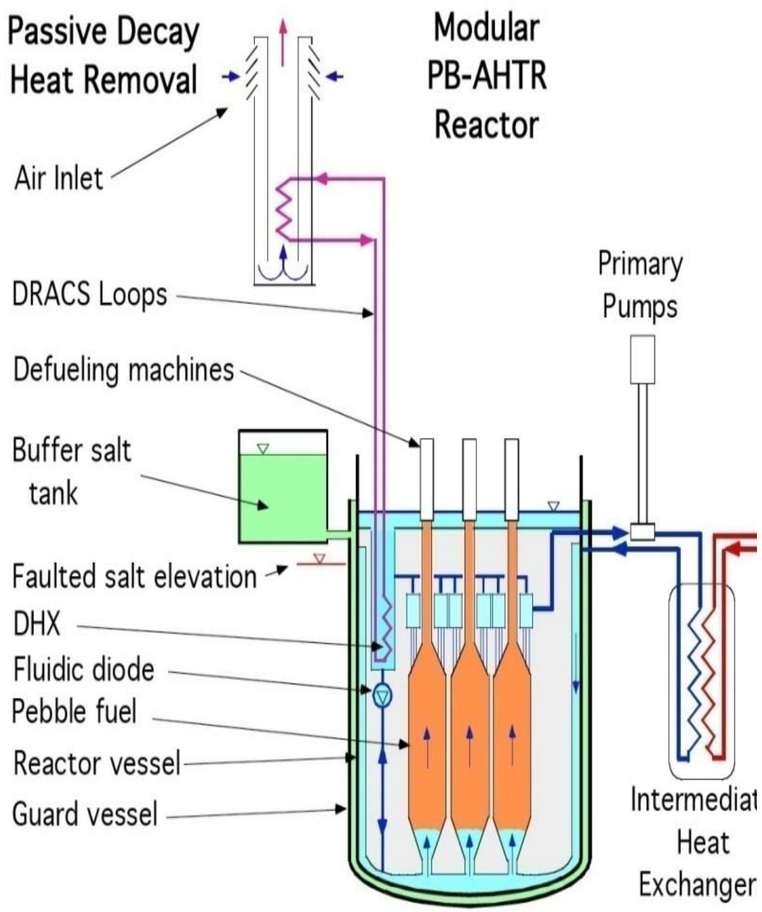
Outline

- Goals
- Reactor Description
- University Integrated Research Project
- Coupled High-Temperature Salt Activities
- Conclusions

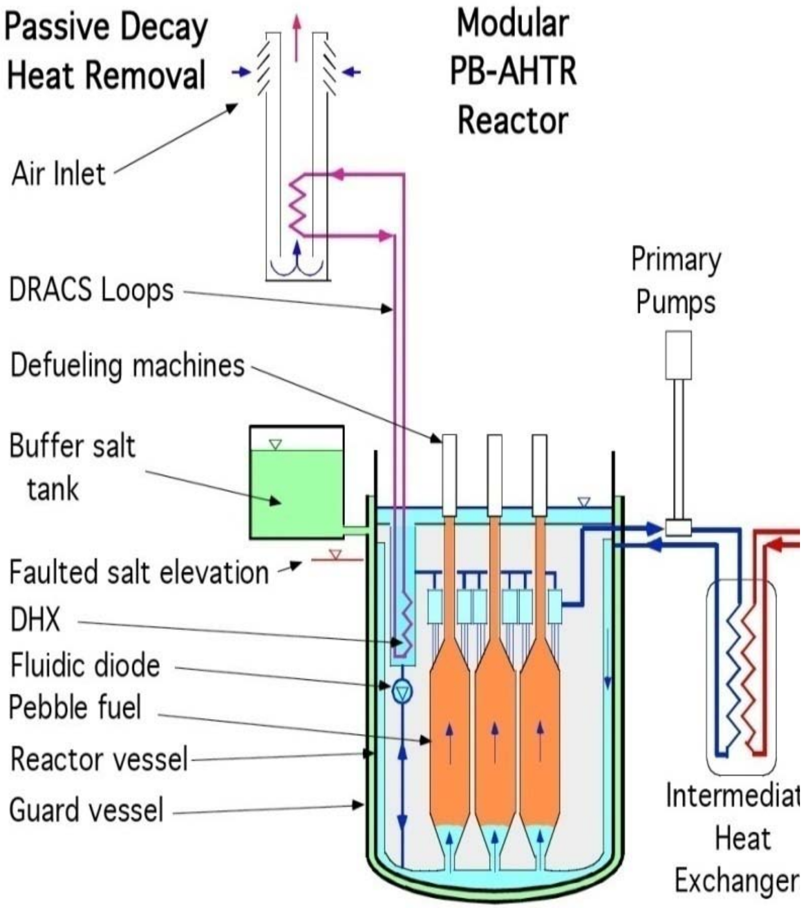
Goals

Fluoride Salt-Cooled High-Temperature Reactor (FHR) Project



- Project is to develop path forward to a commercially viable FHR
- Goals
  - Superior economics (30% less expensive than LWR)
  - No severe accident possible
  - Higher thermal efficiency to enable dry cooling (no cooling water)
  - Better non-proliferation and waste characteristics

Fluoride-Salt-Cooled High-Temperature Reactor (FHR) Partnership



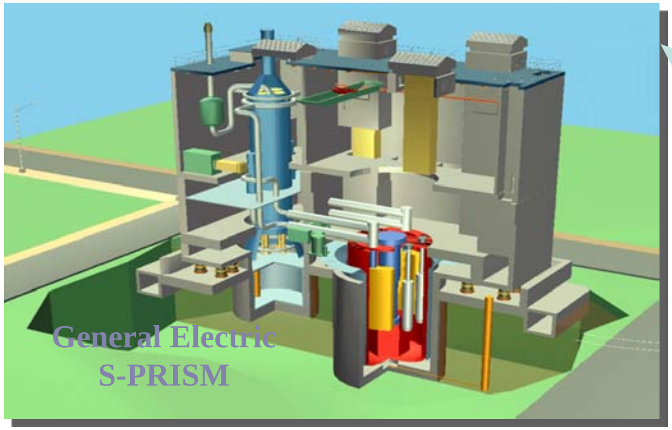
- Sponsor: U.S. Department of Energy
  - $\$7.5 \cdot 10^6$
  - 3-year project
- Project team
  - MIT (lead)
  - U. of California
  - U. of Wisconsin
- Westinghouse advisory role

Fluoride-Salt-Cooled High-Temperature Reactor

Initial Base-Line Design for University Integrated Research Project

Combining Old Technologies in a New Way

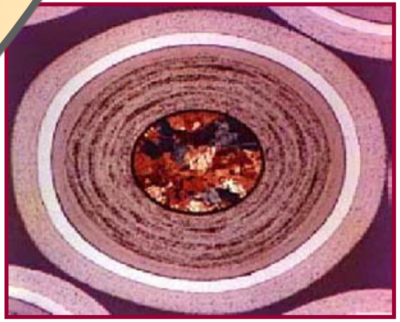
Fluoride Salt-Cooled High-Temperature Reactor (FHR)


General Electric
S-PRISM

Passively Safe Pool-Type Reactor Designs


GE Power Systems MS7001FB

Brayton Power Cycles



High-Temperature Coated-Particle Fuel

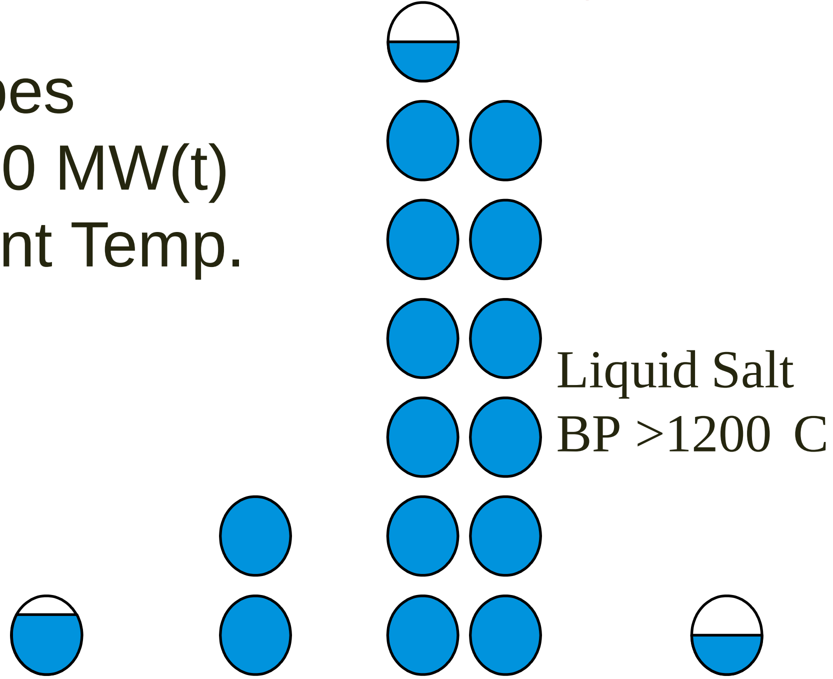
High-Temperature, Low-Pressure Transparent Liquid-Salt Coolant

Salt Coolant Properties Can Reduce Equipment Size and Costs

(Determine Pipe, Valve, and Heat Exchanger Sizes)

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

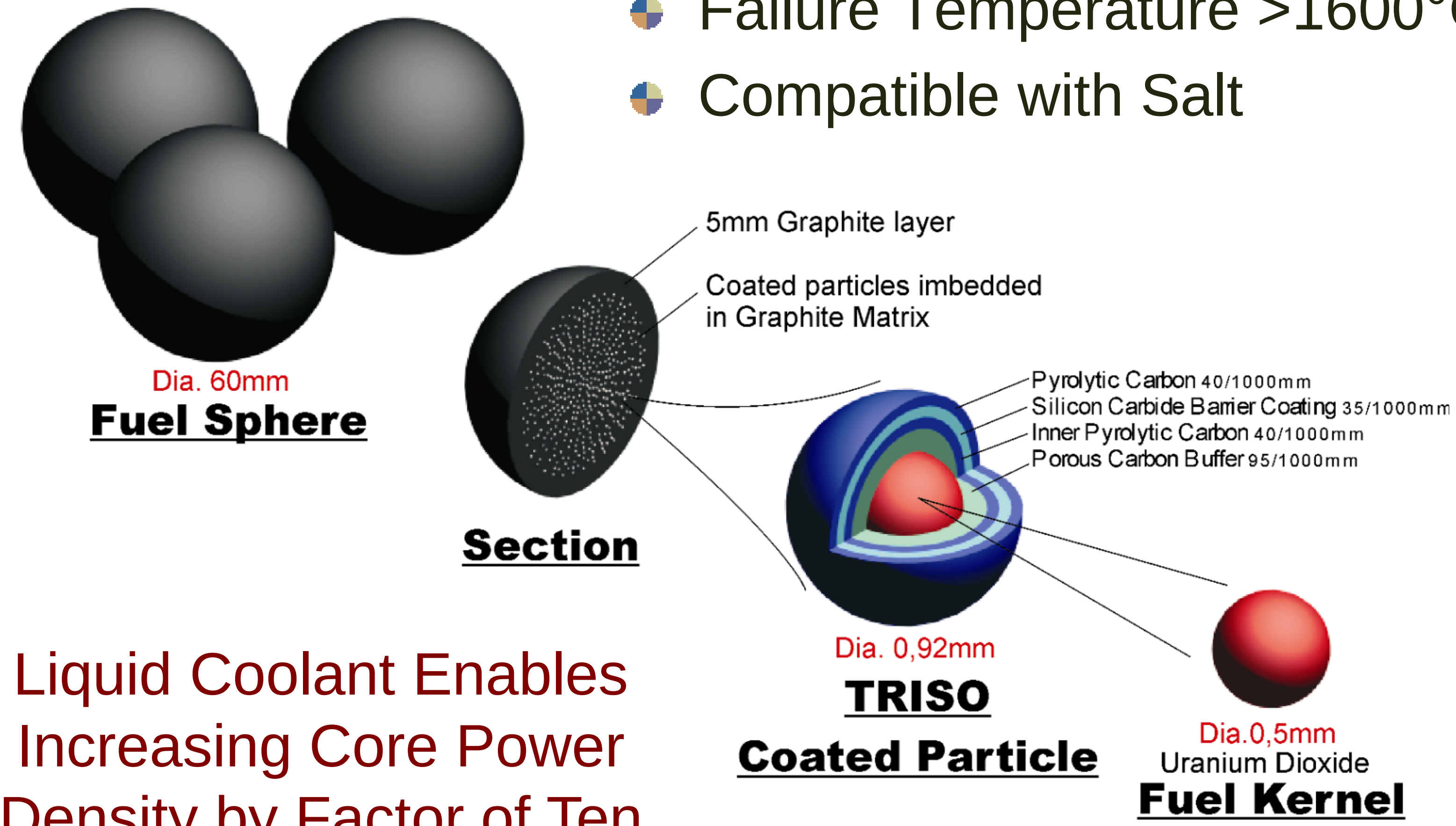
Baseline salt: Flibe



	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**

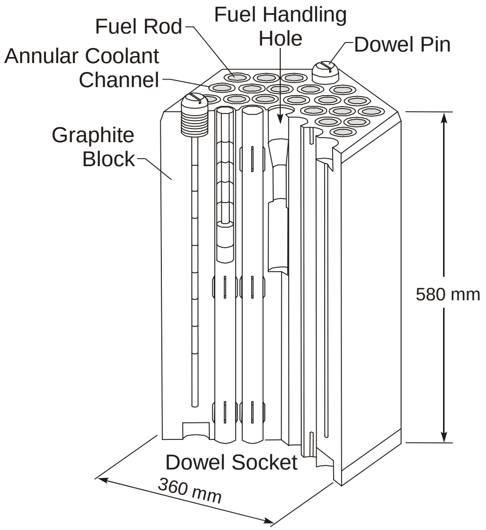
FHR Uses Coated-Particle Fuel

- Demonstrated in gas-cooled high-temperature reactors
- Failure Temperature >1600°C
- Compatible with Salt

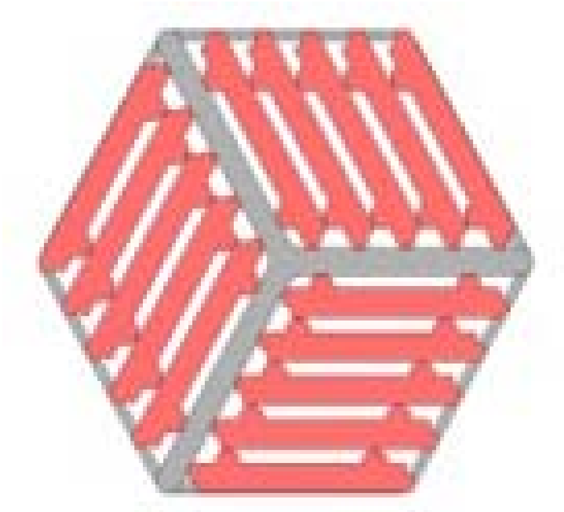


Liquid Coolant Enables Increasing Core Power Density by Factor of Ten

Graphite-Matrix Coated-Particle Fuel Can Take Many Forms

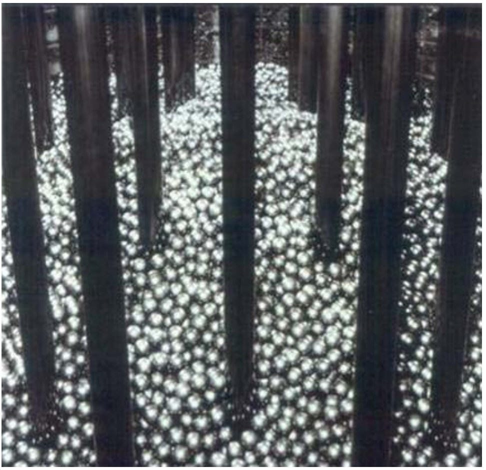


Prismatic Fuel Block



Flat Fuel Plates
in Hex Configuration

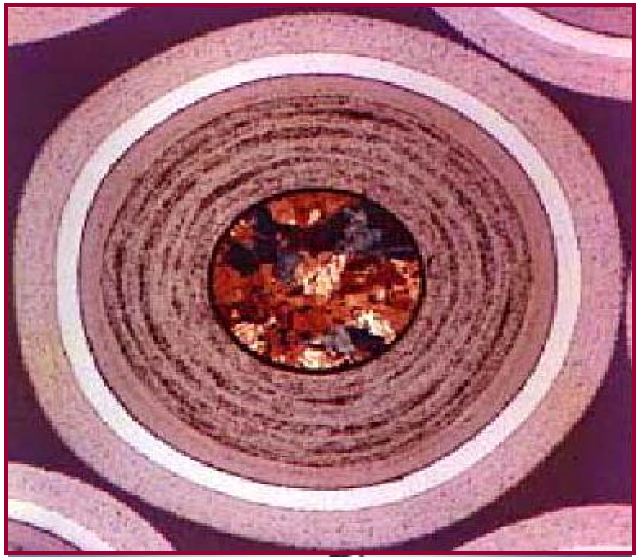
Base Case

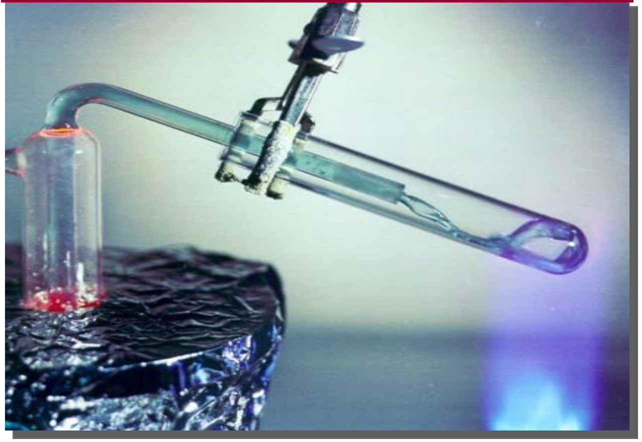


Pebble Bed

- Pebble bed
  - Lower cost
  - Easier refueling
- FHR smaller pebbles and higher power density

Choice of Fuel and Coolant Enables Enhanced Safety

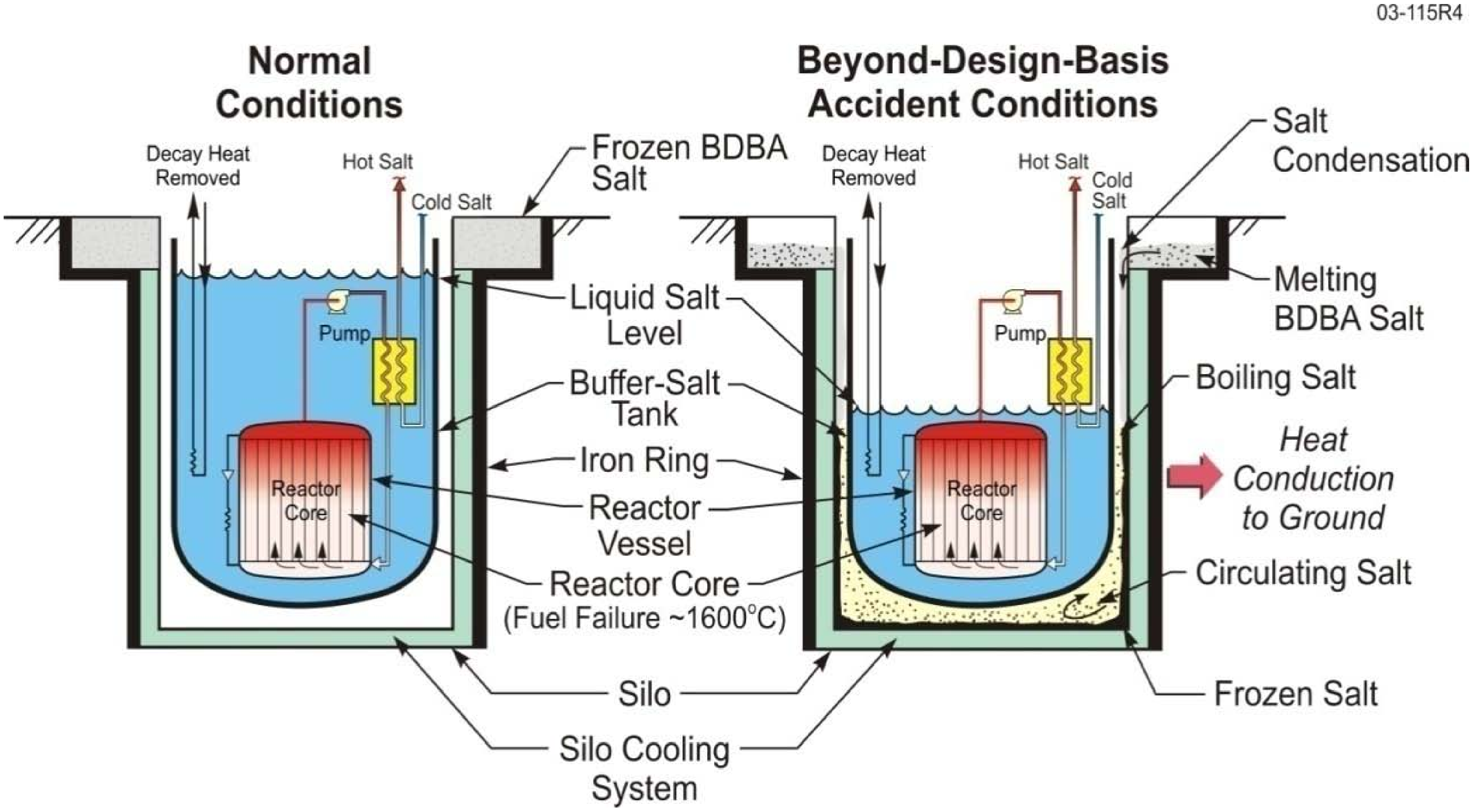




- Coated-particle fuel
  - Failure temperature > 1600°C
  - Large Doppler shutdown margin
- Liquid salt coolant
  - 700°C normal peak temp.
  - Boiling point >1200°C
  - >500° margin to boiling
  - Low-pressure that limits accident potential
  - Low corrosion (clean salt)

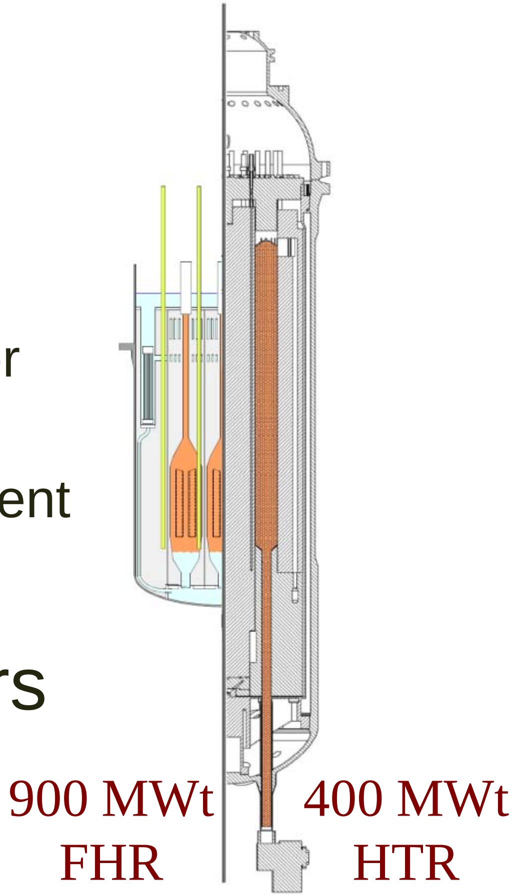
Potential for Large Reactor That Can Not Have a Catastrophic Accident

Decay Heat Conduction and Radiation to Ground



Preliminary Economics Favorable Compared to LWR and Gas-Cooled High-Temperature Reactors

- Lower energy costs than Advanced Light Water Reactors (LWRs)
  - Primary loop components more compact than ALWRs (per MWth)
  - No stored energy source requiring a large-dry or pressure-suppression-type containment
  - Gas-Brayton power conversion 40% more efficient
- Much lower construction cost than high-temperature gas-cooled reactors
  - All components much smaller
  - Operate at low pressure

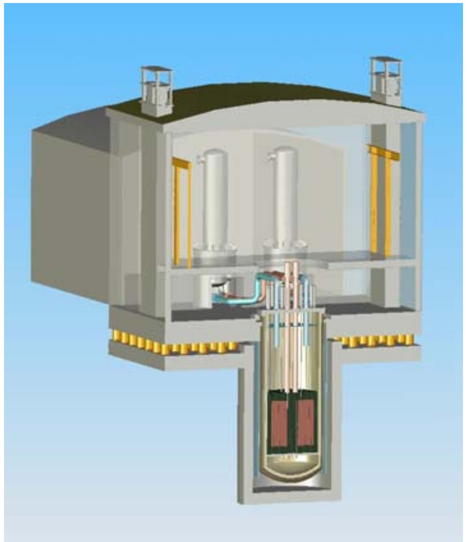


Current Modular FHR plant design is compact compared to LWRs and MHRs

Reactor Type	Reactor Power (MWe)	Reactor & Auxiliaries Volume (m^3/MWe)	Total Building Volume (m^3/MWe)
1970's PWR	1000	129	336
ABWR	1380	211	486
ESBWR	1550	132	343
EPR	1600	228	422
GT-MHR	286	388	412
PBMR	170	1015	1285
Modular FHR	**410**	**98**	**242**

Potentially Competitive Economics

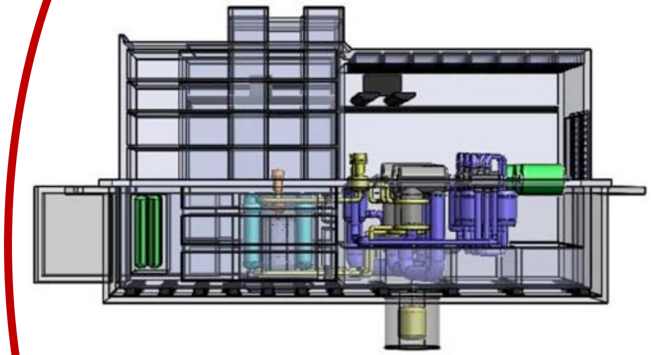
FHR Concepts Span Wide Power Range



3400 MWt /
1500 MWe

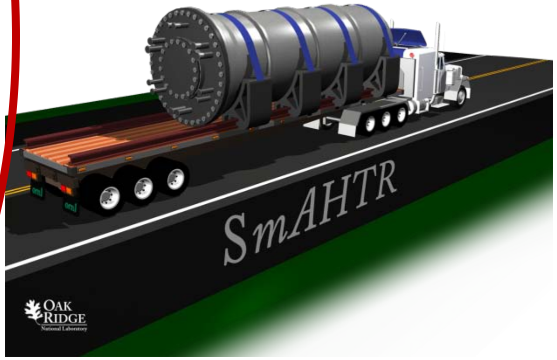
Oak Ridge
National Laboratory

Base Case



410 MWe

Berkeley
University of California



125 MWt/50 MWe

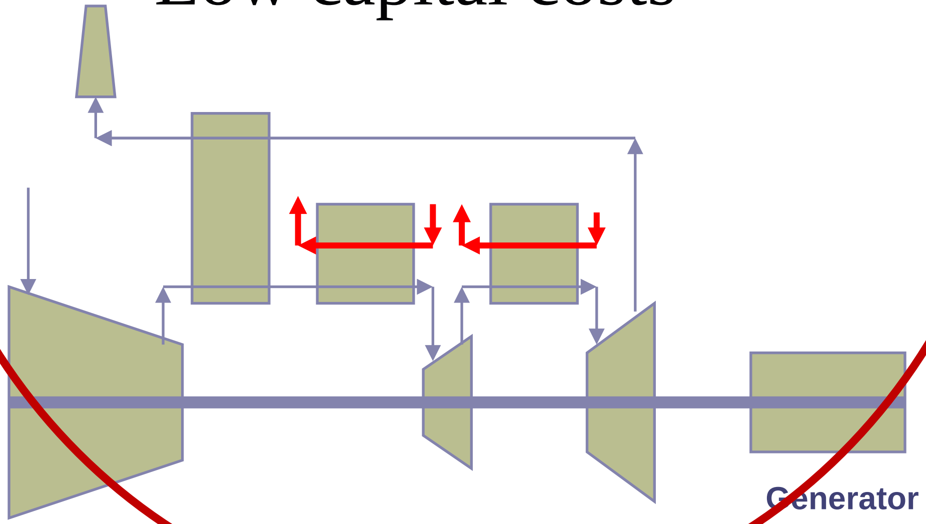
Oak Ridge
National Laboratory

Many Options for Power Cycles

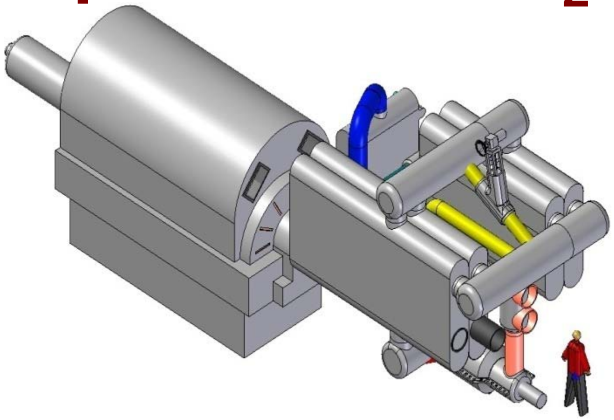
Base Case

Air Brayton Cycle

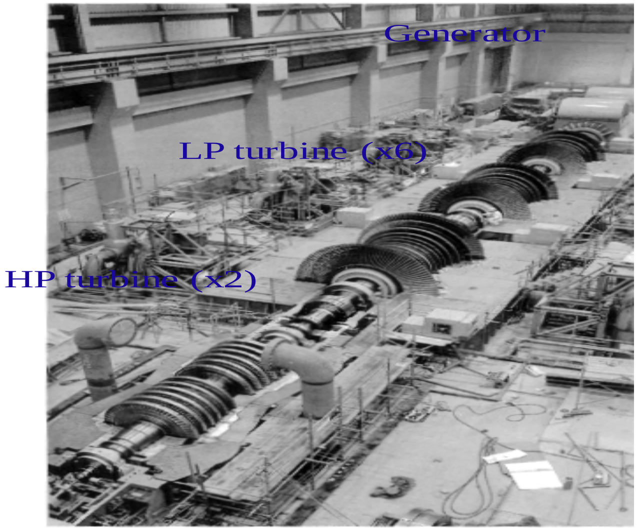
- Air Brayton cycle based on natural gas turbine
- Dry cooling
- Low capital costs



Supercritical CO_2



Steam



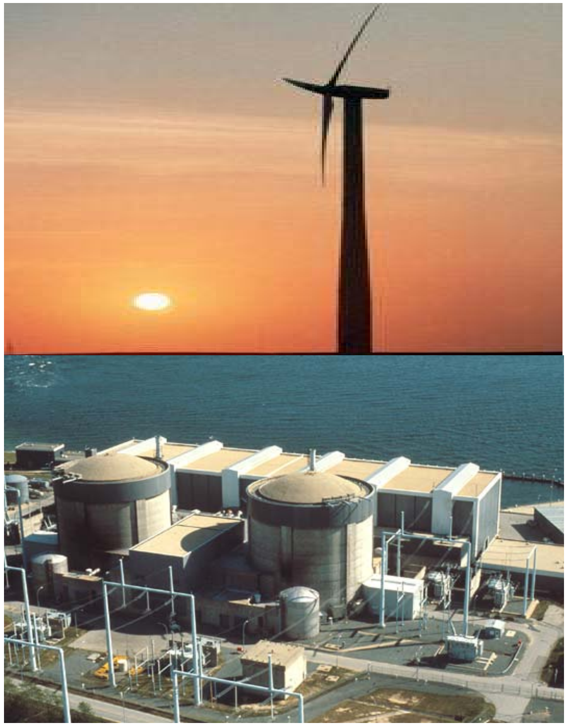
Exit Temperatures Meet Most Process Heat Requirements

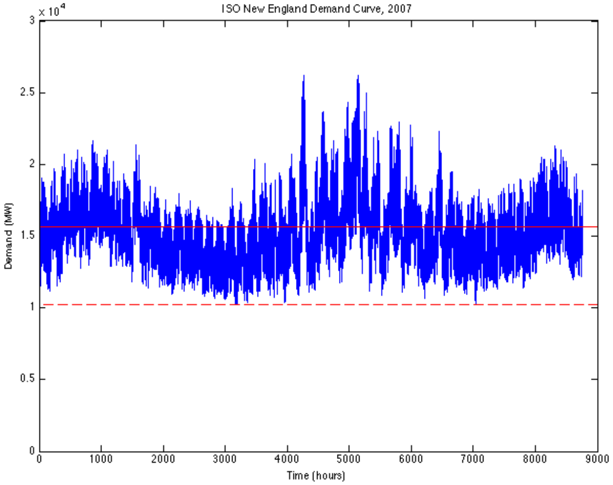
- Initial version: 700°C
  - Use existing materials
- Refinery peak temperatures ~600°C (thermal crackers)
- Meet heavy oil, oil shale, oil sands and biorefinery process heat requirements

FHR Couples to Hybrid Nuclear-Renewable Systems

Base-Load Nuclear Plant For Variable Electricity and Process Heat

Maximize Capacity Factors of Capital Intensive Power Systems = Meet Electricity Demand + Efficient Use of “Excess” Energy for Fuels Sector





- Biofuels
- Oil shale
- Refineries
- Hydrogen

http://canes.mit.edu/sites/default/files/pdf/NES-115.pdf

University Integrated Research Project

Massachusetts Institute of Technology (Lead)
University of California at Berkeley
University of Wisconsin at Madison

Cooperation and Partnership With

United States Department of Energy
Westinghouse Electric Company
Oak Ridge National Laboratory
Idaho National Laboratory

Three Part University FHR Integrated Research Program

- Status of FHR
- Technology Development
  - Materials development
  - In-Reactor Testing of materials and fuel
  - Thermal-hydraulics, safety, and licensing
- Integration of Knowledge
  - Pre-conceptual Design of Test Reactor
  - Pre-conceptual Design of Commercial Reactor
  - Roadmap to test reactor and pre-commercial reactor

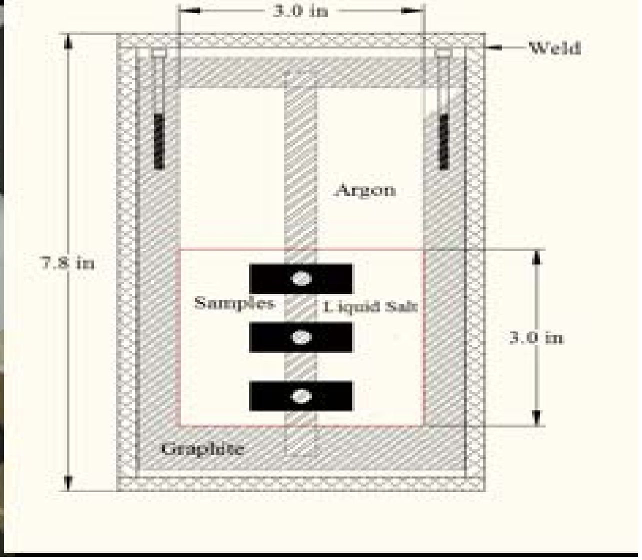
Workshops to Define Current Status and Path Forward

Strategy to Drive Program, Technical, and Design Choices

- FHR subsystems definition, functional requirement definition, and licensing basis event identification (UCB)
- FHR transient phenomena identification and ranking (UCB)
- FHR materials identification and component reliability phenomena identification and ranking (UW)
- FHR development roadmap and test reactor performance requirements (MIT)

The University of Wisconsin Will Conduct Corrosion Tests

- Evaluate salts and materials of construction
- Strategies to monitor and control salt chemistry
- Support reactor irradiations



MIT To Test Materials In MIT Research Reactor

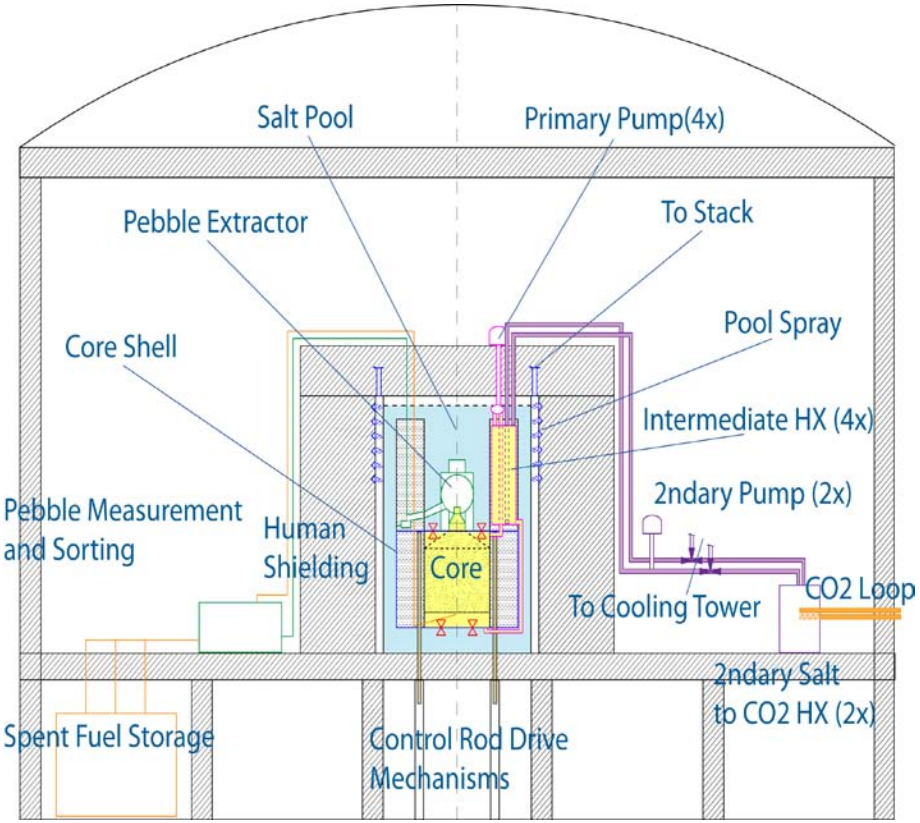
- 6-MWt Reactor
- Operates 24 hr / day,
  7 days per week
- Uses water as coolant
- In core tests
  - LWR Neutron Flux Spectrum
  - Tests in 700°C F^{7}LiBe Liquid Salt in Core
  - In-Core Materials, Coated Particle Fuel

UCB to Conduct Thermal Hydraulics, Safety, and Licensing Tests

- Experimental test program using organic simulants
- Analytical models to predict thermohydraulic behavior
- Support simulation of reactor irradiation experiments

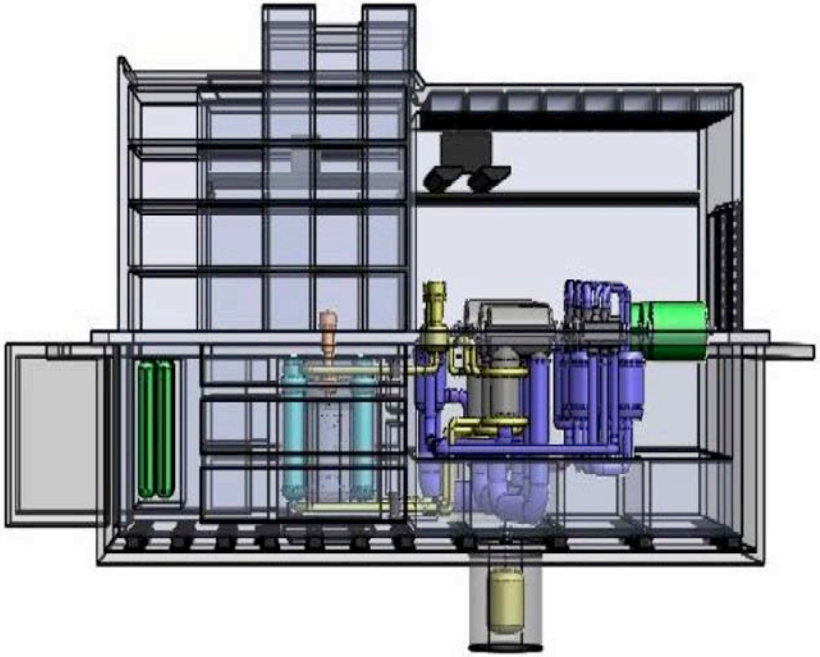
MIT To Develop Pre-Conceptual Test Reactor Design

- Identify and quantify functional requirements for test reactor
- Examine alternative design options
- Develop pre-conceptual design



UCB to Develop Commercial Reactor Pre-Conceptual Design

- Identify and quantify functional requirements for power reactor
- Integrated conceptual design to flush out technical issues that may not have been identified in earlier work



MIT Leads Development of Roadmap to Test Reactor and Pre-Commercial Power Reactor

- Roadmap to power reactor
- Identify and scope what is required and schedule
- Includes licensing strategy
- Partnership with Westinghouse Electric Company

Advisory Panel Chair: Regis Matzie
Chief Technical Officer Westinghouse (Retired)

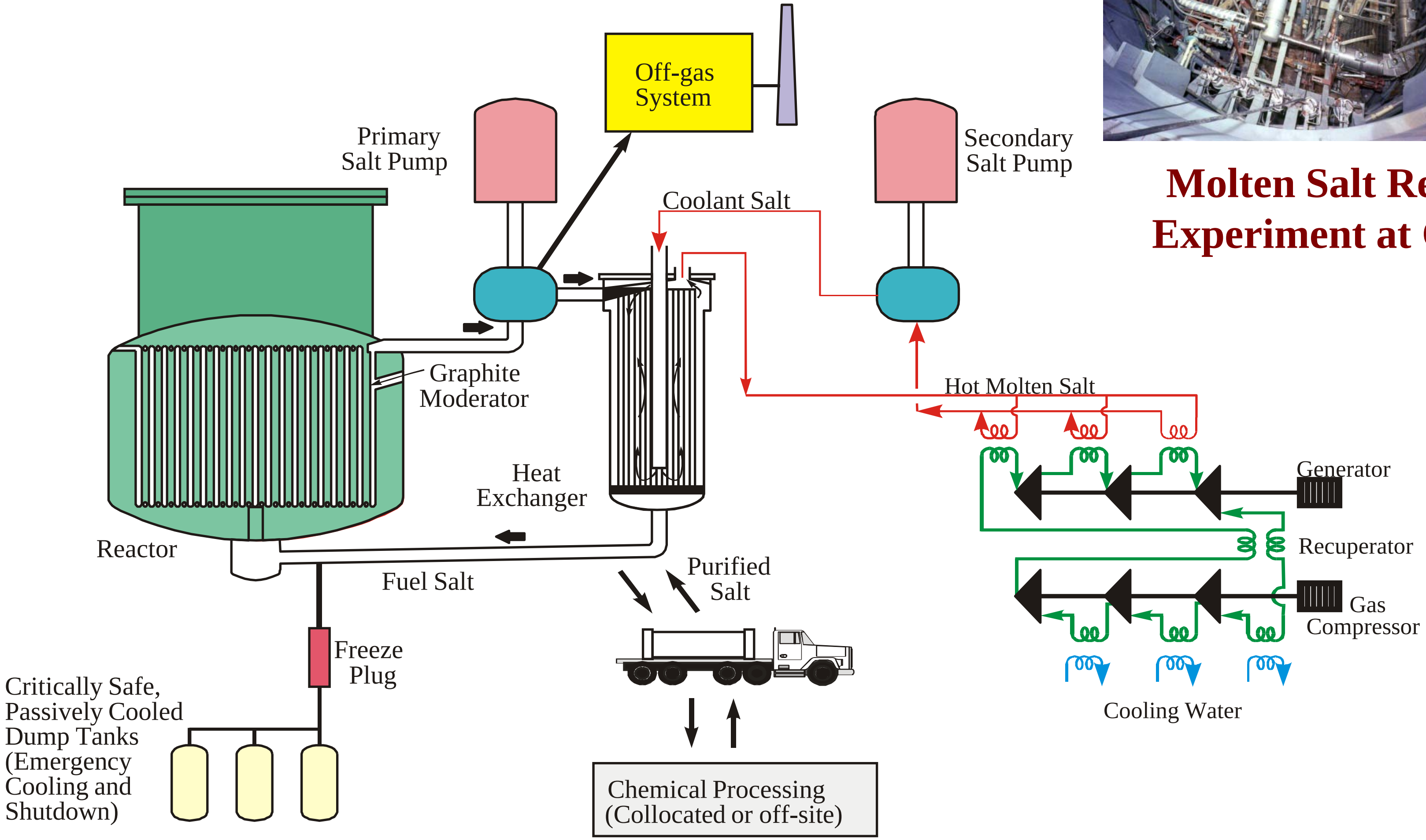
Coupled High-Temperature Salt Technologies

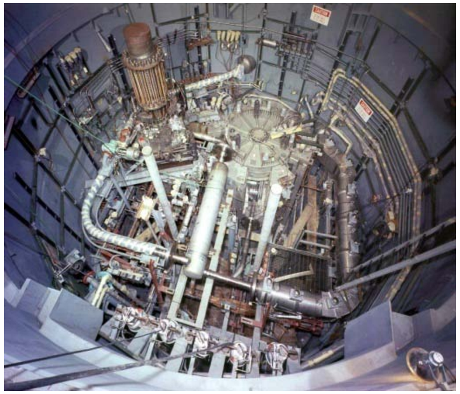
Multiple Salt-Cooled High-Temperature (700 C) Power Systems Being Developed With Common Technical Challenges—Incentives for Partnerships in Development

Molten Salt Reactors
Concentrated Solar Power on Demand (CSPond)
Fusion

Molten Salt Reactor

(Fuel Dissolved in the Salt Coolant)

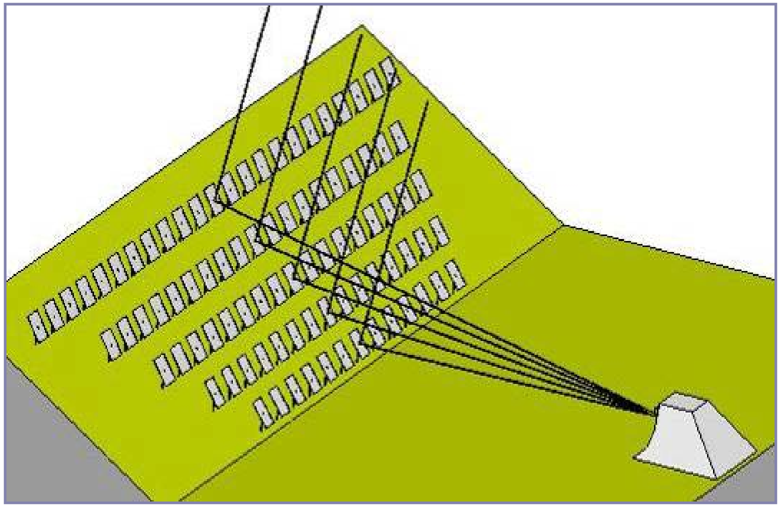




Molten Salt Reactor Experiment at ORNL

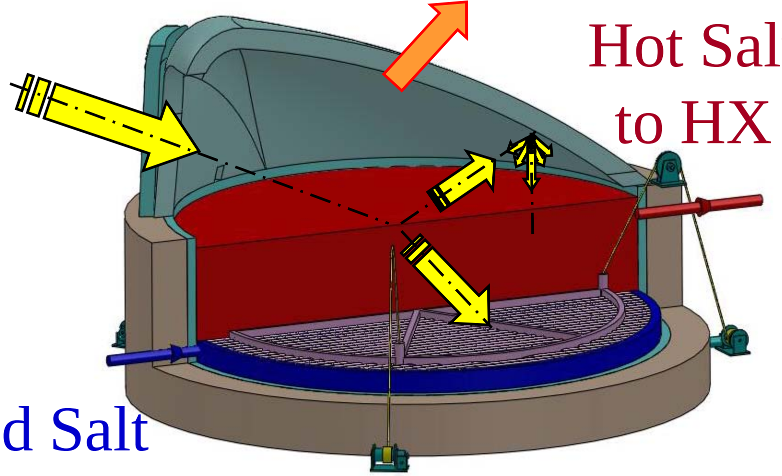
China, France, Russia, Czech Republic, United States

Concentrated Solar Energy on Demand: CSPond (MIT)



(Not to scale)

Light Reflected From Hillside Heliostat rows to CSPonD System



Non-Imaging Refractor Lid

Lid Heat Extraction

Hot Salt to HX

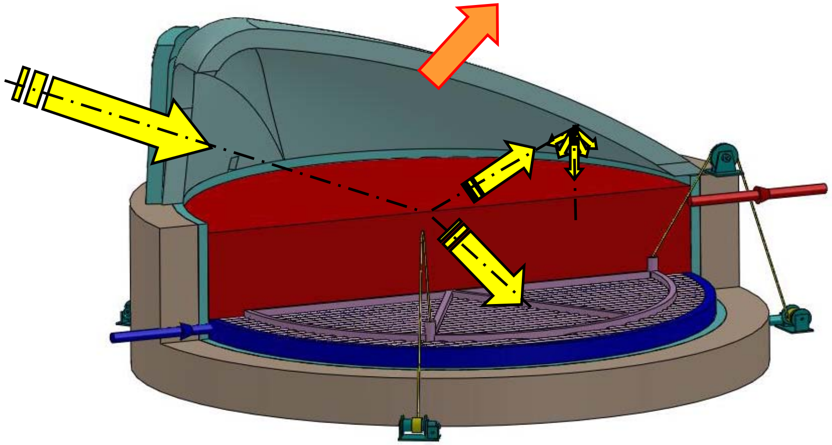
Cold Salt from HX

Light Collected Inside Insulated Building With Open Window

Shared Salt / Power Cycle Technology with FHR (700 C)

Light Focused On “Transparent” Salt

- Light volumetrically absorbed through several meters of salt
- Liquid salt experience
  - Metal heat treating baths
  - Molten salt nuclear reactor
- Advantages
  - Higher efficiency
  - No mechanical fatigue from temperature transients
  - Built in heat storage

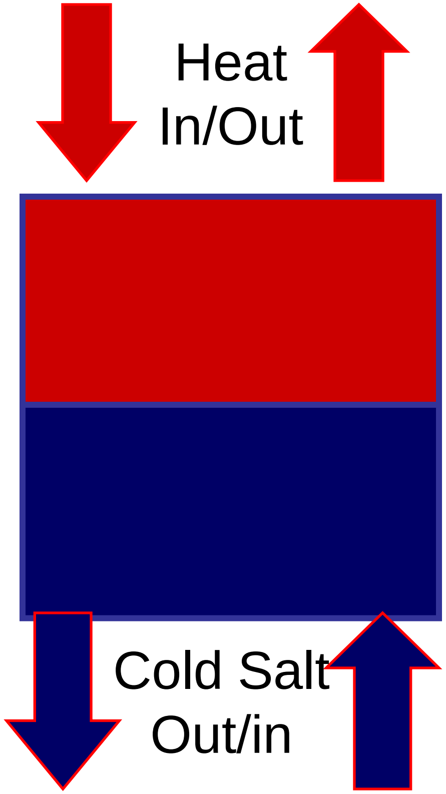


Molten Chloride Salt Metallic Heat Treatment Bath (1100°C)

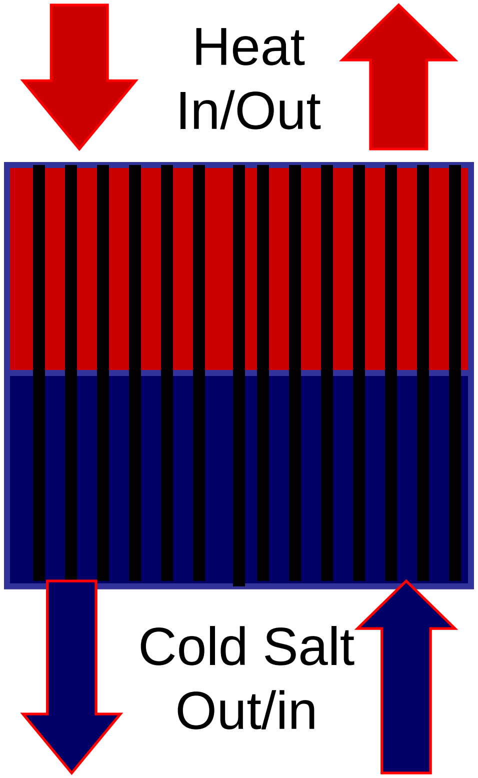
High-Temperature Heat Storage

Three Single-Tank Heat Storage Systems

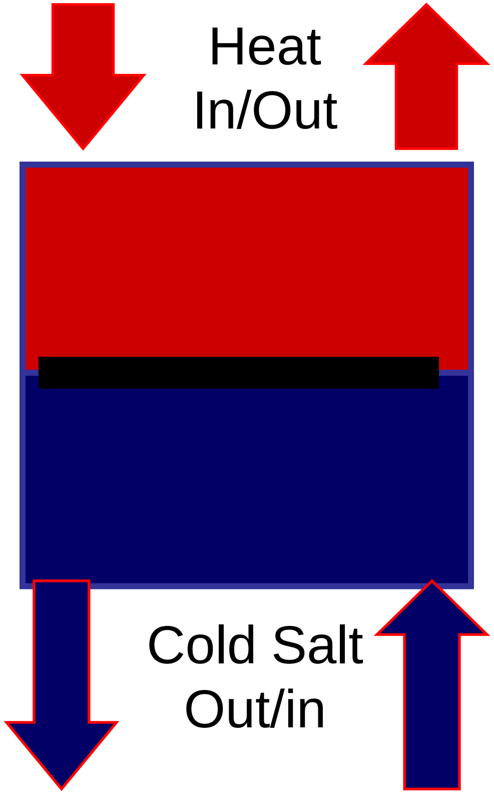
Hot Salt on Top of Cold Salt



Hot Salt on Top of Cold Salt with Solid Fill

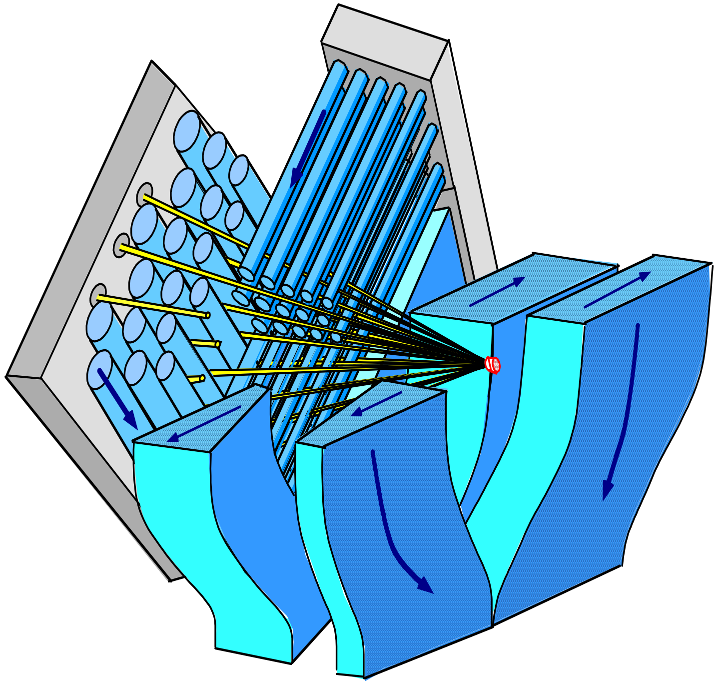


Hot Salt on Top of Cold Salt Separated With Insulated Floating Plate

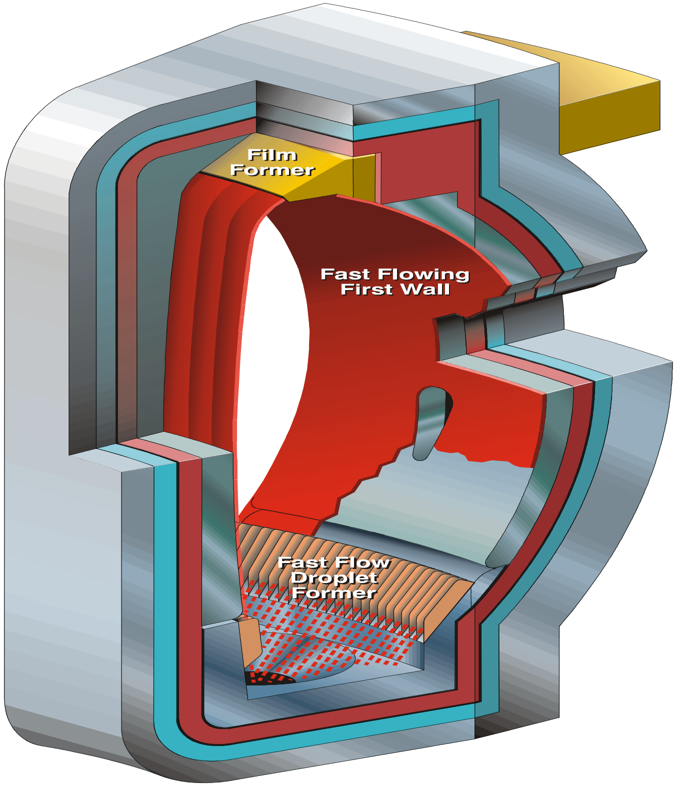


Liquid Salt Wall Fusion Machines

Higher-Power Densities and Less Radiation Damage



Heavy-Ion Inertial Fusion

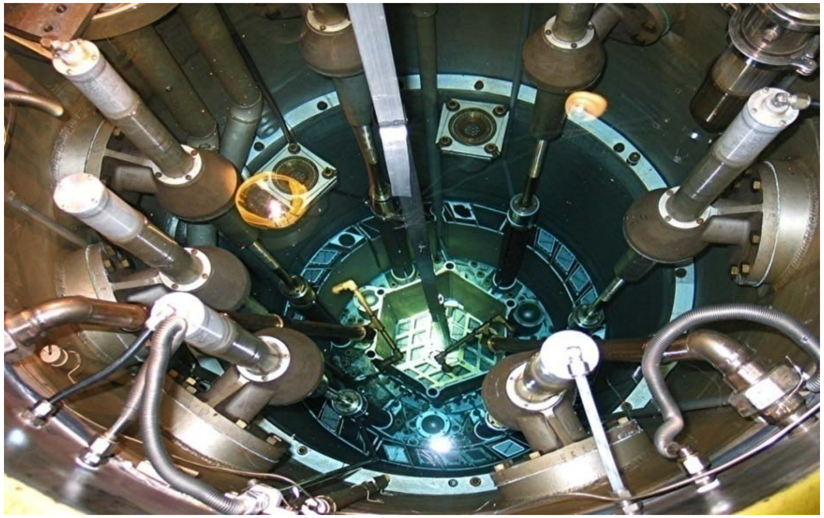


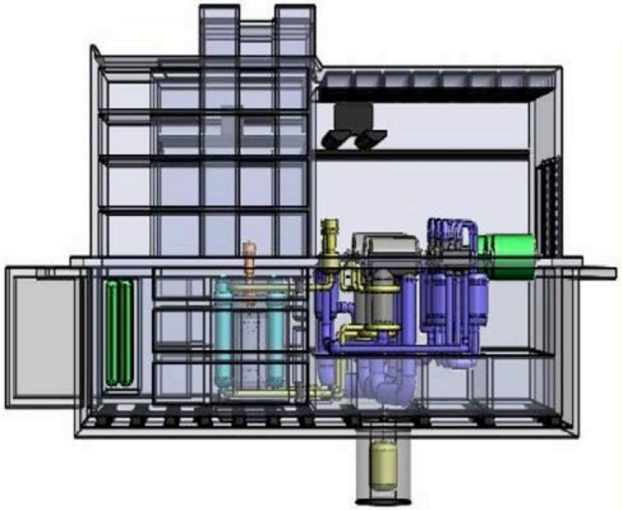
Magnet Fusion Tokamak

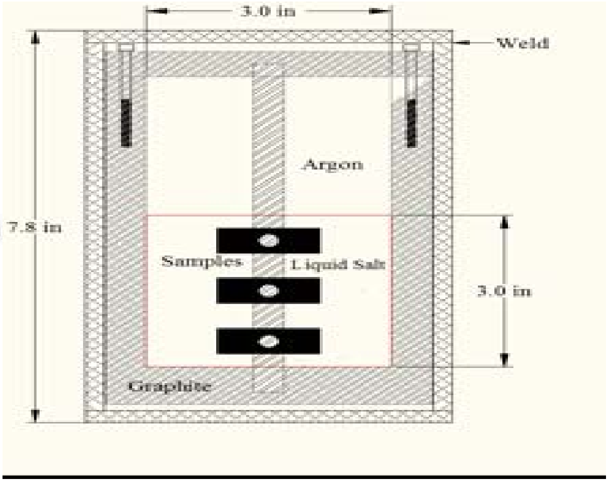
Conclusions

- FHR combines existing technologies into a new reactor option
- Initial assessments indicate improved economics, safety, waste management and nonproliferation characteristics
- Significant uncertainties—joint MIT/UCB/UW integrated research project starting to address challenges
- Interested in partnerships

Questions







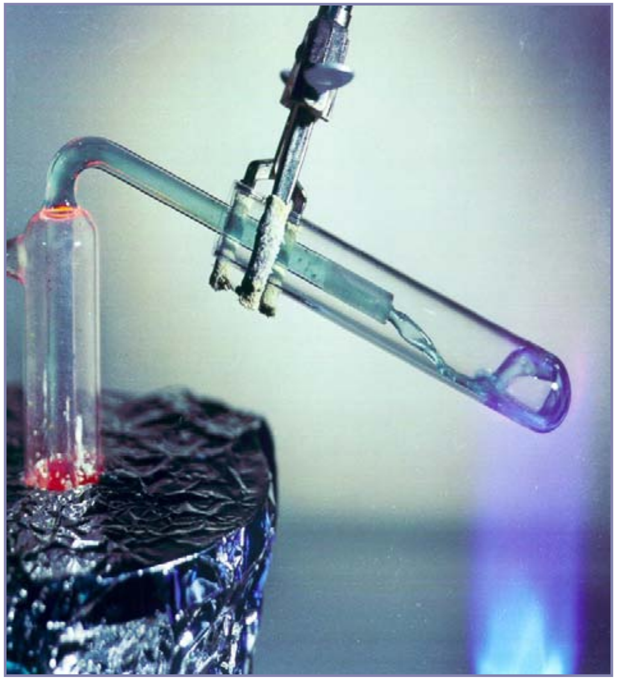
Biography: Charles Forsberg

Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, 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 on salt-cooled reactors. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

FHR History

- New concept about a decade old
    - Charles Forsberg (ORNL, now MIT)
    - Per Peterson (Berkeley)
    - Paul Pickard (Sandia Retired)
    - Lifting out of the competition
- Growing interest
    - Department of Energy
    - Oak Ridge National Laboratory and Idaho National Laboratory
    - Areva, Westinghouse

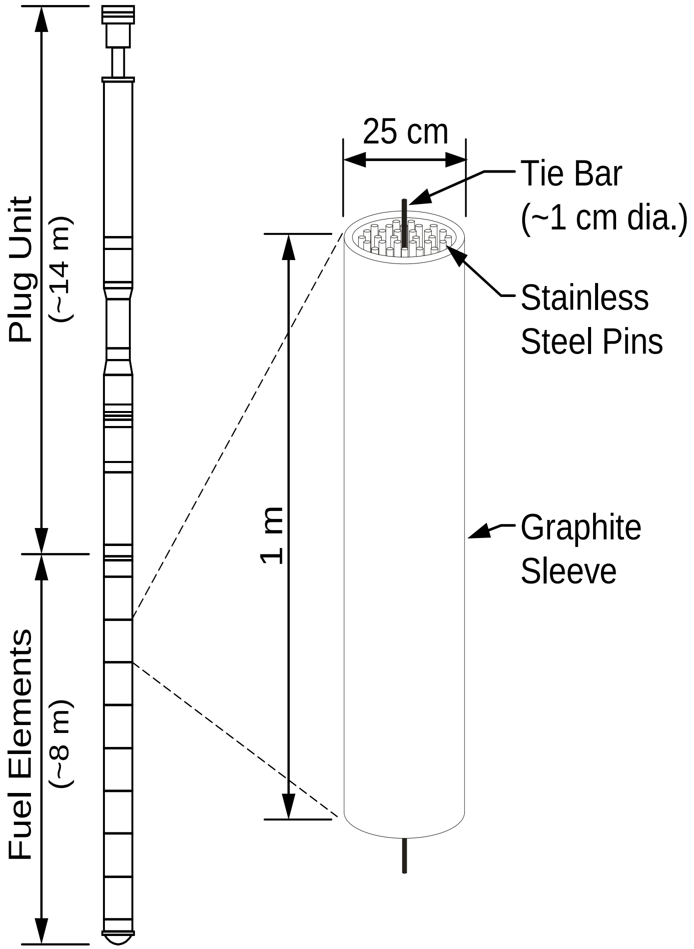
Salt Requirements



- Requirements
  - Low neutron cross section
  - Chemical compatibility
  - Lower melting point
- Salt
  - Fluoride salt mixture
  - ^{7}Li Salt: 99.995%
    - Can burn out ^{6}Li if higher concentration
    - Tradeoff between uranium and Li enrichment costs
  - Flibe baseline salt

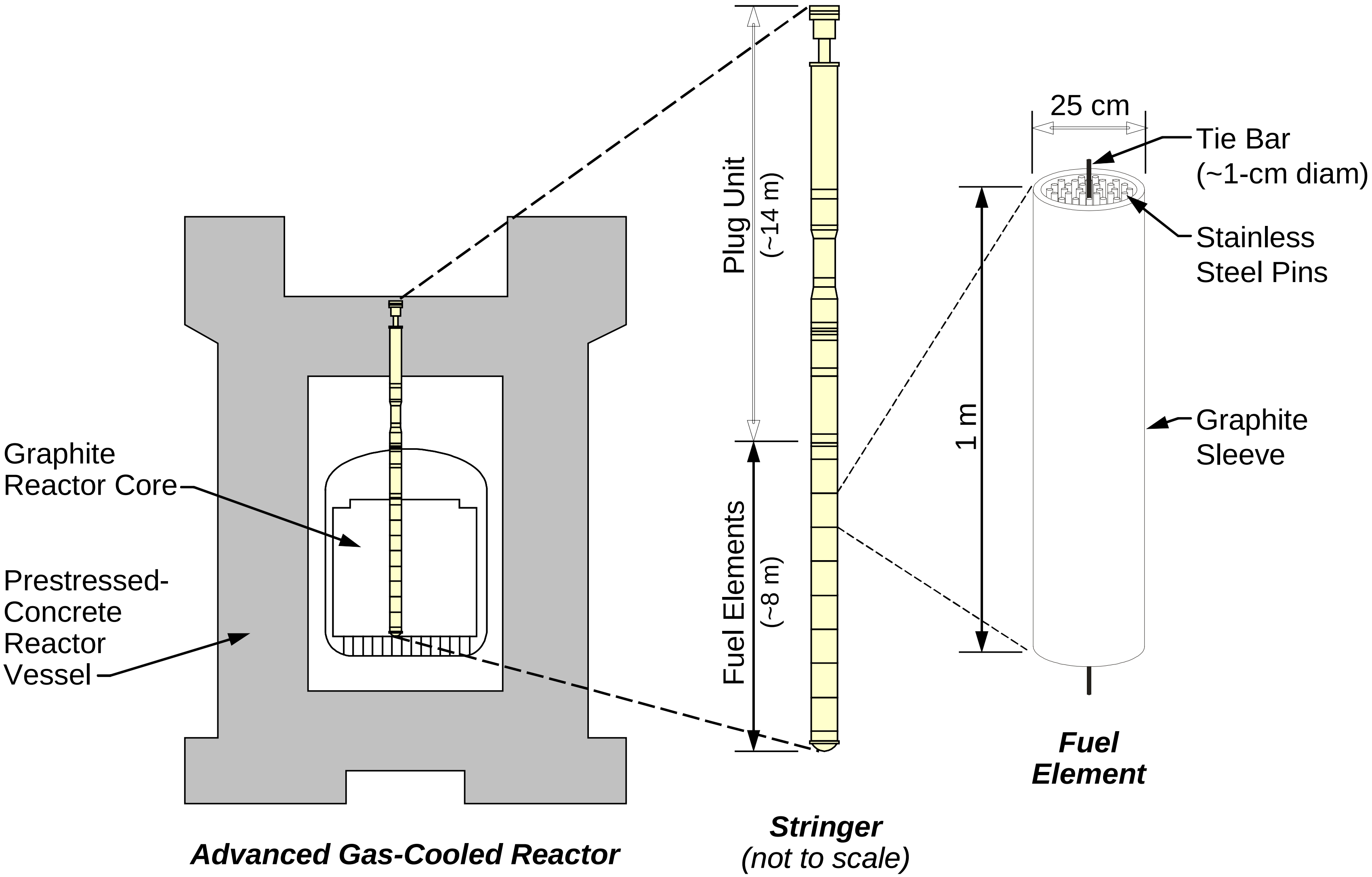
Other FHR Fuel Options

- British Advanced Gas-Cooled Reactor
  - Graphite moderated
  - Uranium dioxide in stainless steel clad
- Salt-cooled version
  - SiC or other high-temperature clad
  - Limited work to date
  - Much smaller reactor with liquid cooling (higher power density and low pressure)



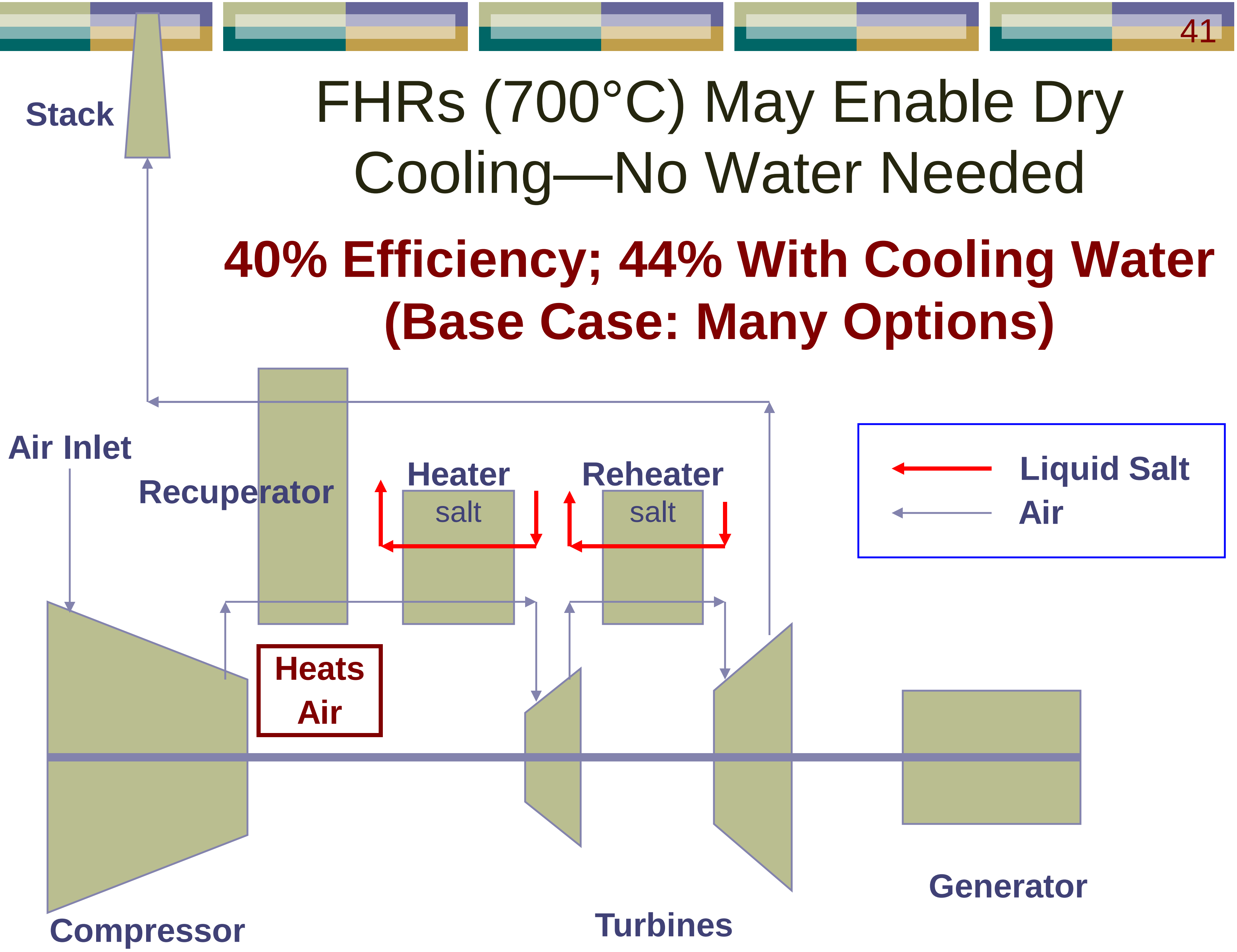
Stringer Assembly
(Not to Scale)

British Advanced Gas-Cooled Reactor



FHRs (700°C) May Enable Dry Cooling—No Water Needed

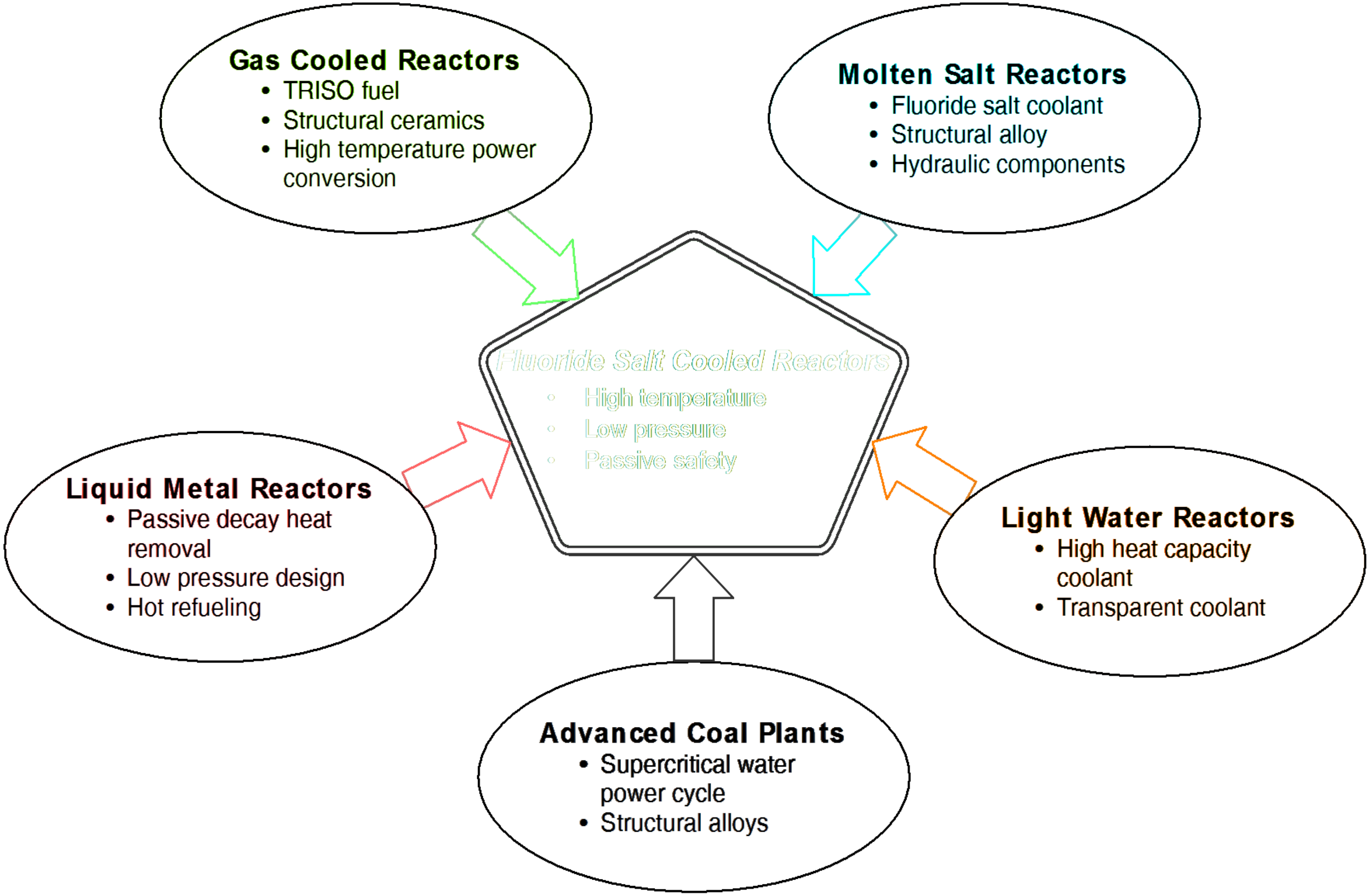
40% Efficiency; 44% With Cooling Water (Base Case: Many Options)



Salt Cooled Fusion Reactors

- Flibe salt serves three functions
  - Radiation shielding
  - Heat transport
  - Tritium breeding
- Energy producing and breeding reactions
  - ^{3}H (tritium) + $^{2}H \rightarrow {}^{4}He$ (helium) + η
  - $\eta + {}^{6}Li \rightarrow {}^{3}H$ (tritium) + ^{4}He (helium)

FHRs Combine Desirable Attributes From Other Power Plants



Gas Cooled Reactors
- TRISO fuel
- Structural ceramics
- High temperature power conversion

Molten Salt Reactors
- Fluoride salt coolant
- Structural alloy
- Hydraulic components

Fluoride Salt Cooled Reactors
- High temperature
- Low pressure
- Passive safety

Liquid Metal Reactors
- Passive decay heat removal
- Low pressure design
- Hot refueling

Light Water Reactors
- High heat capacity coolant
- Transparent coolant

Advanced Coal Plants
- Supercritical water power cycle
- Structural alloys

Lower Cost Power at Arbitrary Scale is the Primary FHR Value Argument

Low pressure containment

High thermal efficiency (>12% increase over LWR)

Low pressure piping

Low Power Cost

Passive Safety

Robust Fuel

Low Pressure

Multiple Radioactivity Barriers

Site EPZ

Low water requirements

No grid connection requirement for process heat

Easily Siteable