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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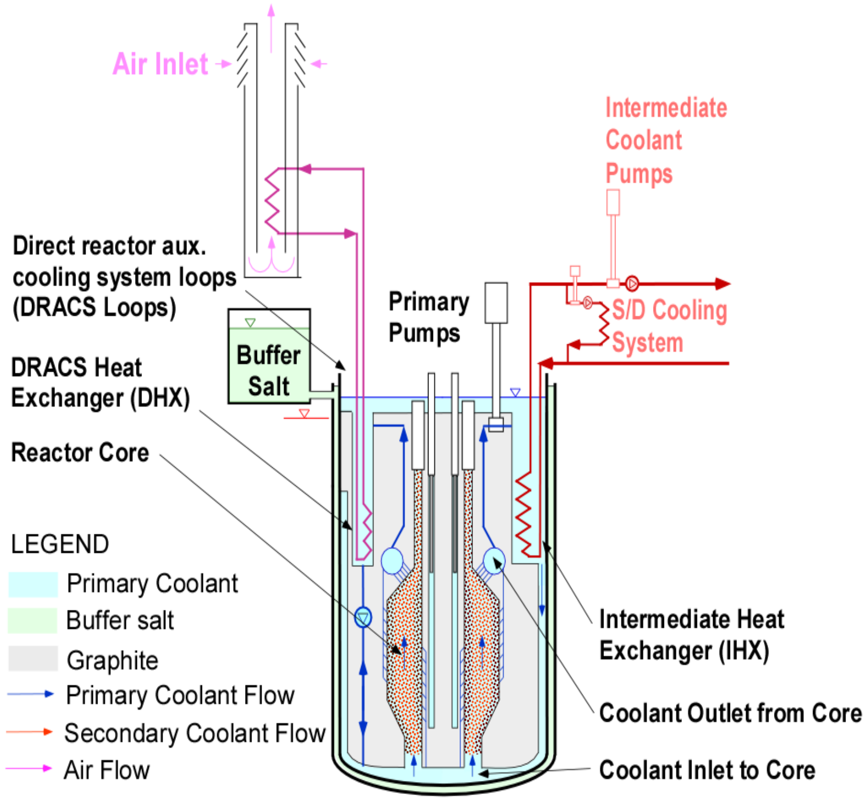
Outline

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

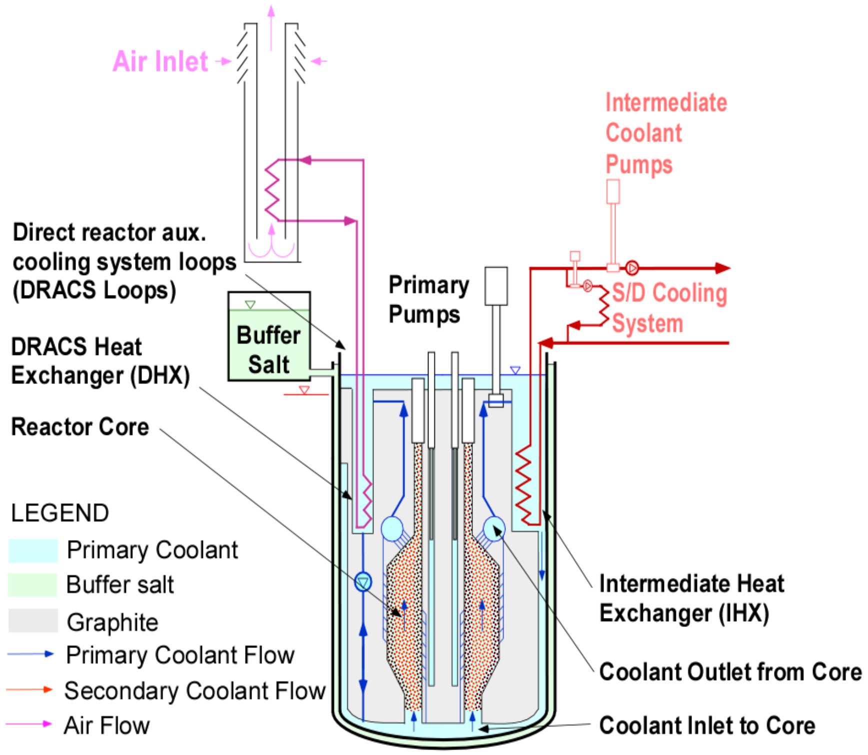
Goals

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



- Project is to develop a path forward to a commercially viable FHR
- Goals
  - Superior economics (30% less expensive than LWR)
  - Limit severe accident
  - Higher thermal efficiency to enable dry cooling (no cooling water) and process heat (700°C)
  - Better non-proliferation and waste characteristics

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



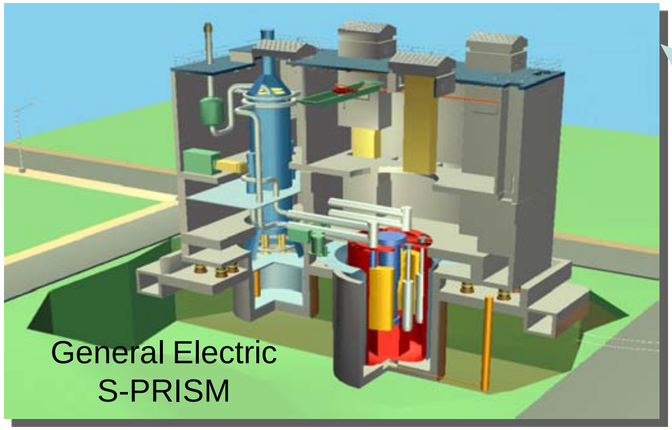
- Sponsor: U.S. Department of Energy
  - 3-year project
- Project team
  - MIT (lead)
  - U. of California
  - U. of Wisconsin
- Westinghouse advisory role

Fluoride-Salt-Cooled High-Temperature Reactor

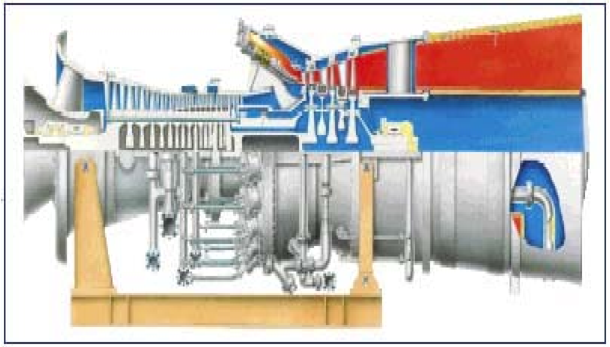
Initial Base-Line Design for University Integrated Research Project

Combining Old Technologies in a New Way

Fluoride Salt-Cooled High-Temperature Reactor (FHR)

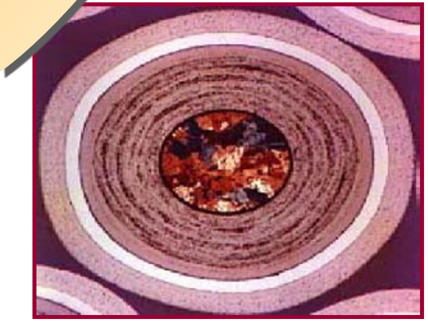


Passively Safe Pool-Type Reactor Designs



GE Power Systems MS7001FB

Brayton Power Cycles



High-Temperature Coated-Particle Fuel

High-Temp., Low-Pressure Liquid-Salt Coolant

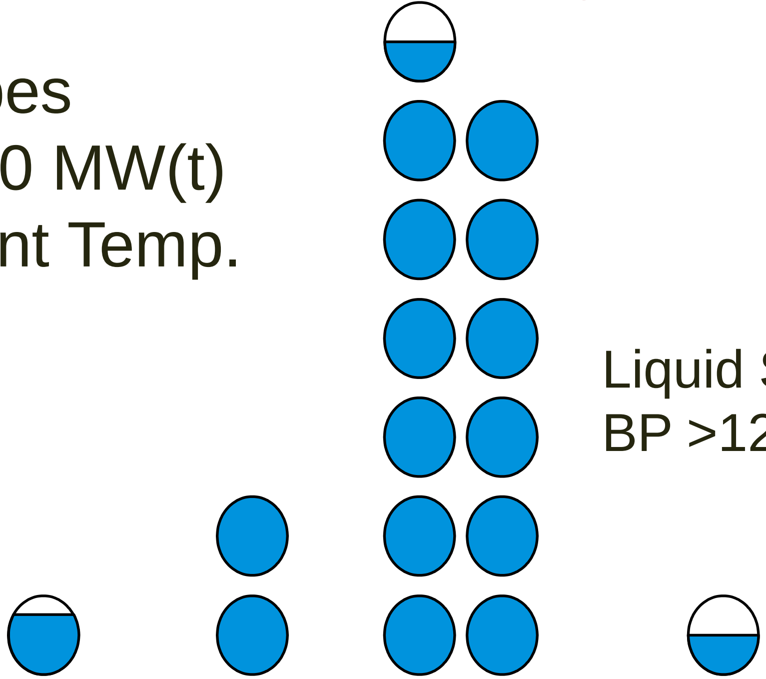
(Transparent)

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



Liquid Salt
BP >1200°C

	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**

Base Case Salt is $^{7}Li_2BeF_4$ (Flibe)

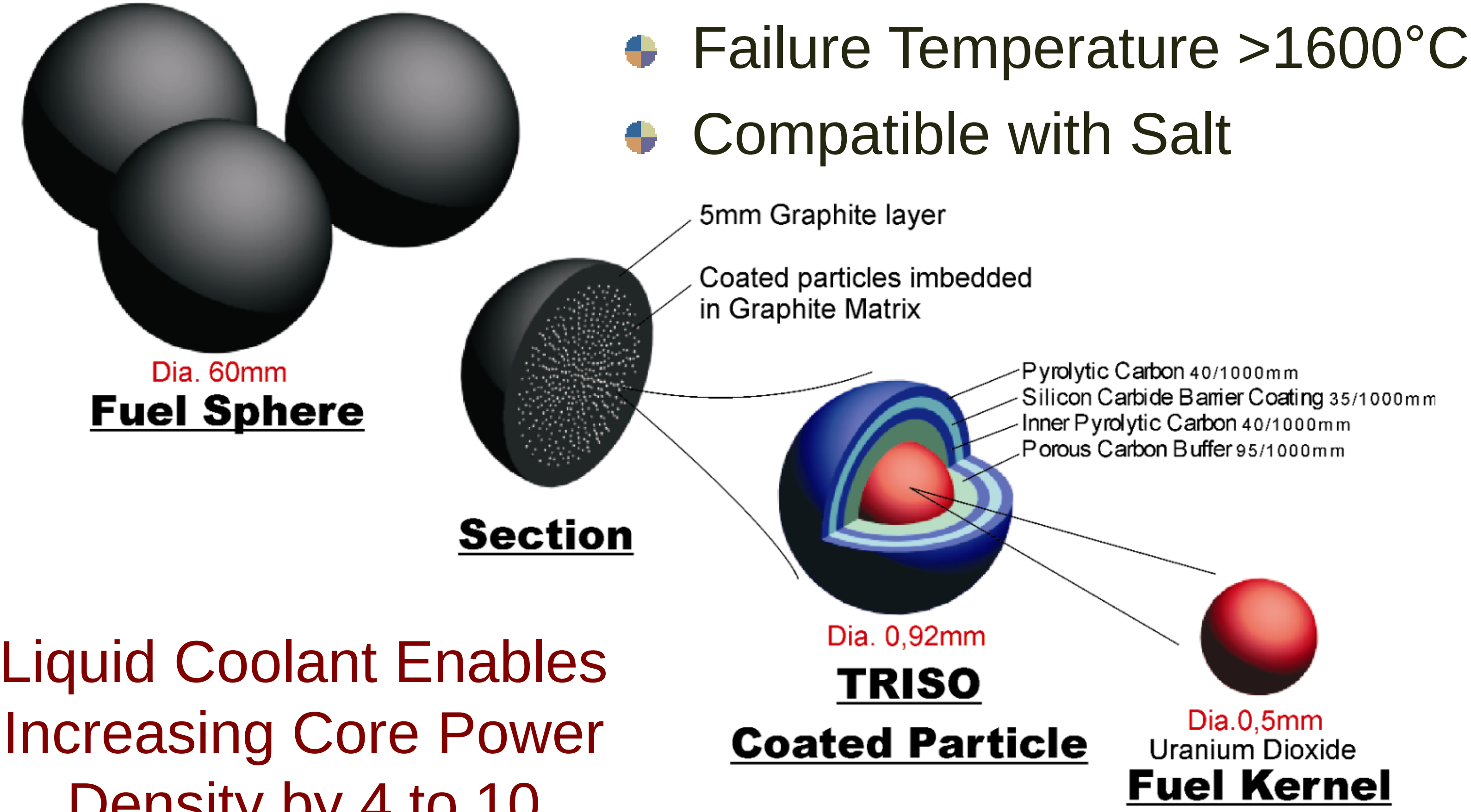
Physical Properties of Coolants

Coolant	**T_{melt} (°C)**	**T_{boil} (°C)**	**ρ (kg/m^3)**	**C_p (kJ/kg °C)**	**ρC_p (kJ/m^3 °C)**
Li_2BeF_4 (Flibe)	**459**	**1430**	**1940**	**2.42**	**4670**
$59.5NaF\text{-}40.5ZrF_4$	500	1290	3140	1.17	3670
$26LiF\text{-}37NaF\text{-}37ZrF_4$	436		2790	1.25	3500
$31LiF\text{-}31NaF\text{-}38BeF_2$	315	1400	2000	2.04	4080
$8NaF\text{-}92NaBF_4$	385	700	1750	1.51	2640
Water (7.5 MPa)	0	290	732	5.5	4040

Salt compositions are shown in mole percent. Salt properties at 700ºC and 1 atm. Sodium-zirconium fluoride salt conductivity is estimated—not measured. The $NaF\text{-}NaBF_4$ system must be pressurized above 700°C; however, the salt components do not decompose. Pressurized water data are shown at 290°C for comparison.

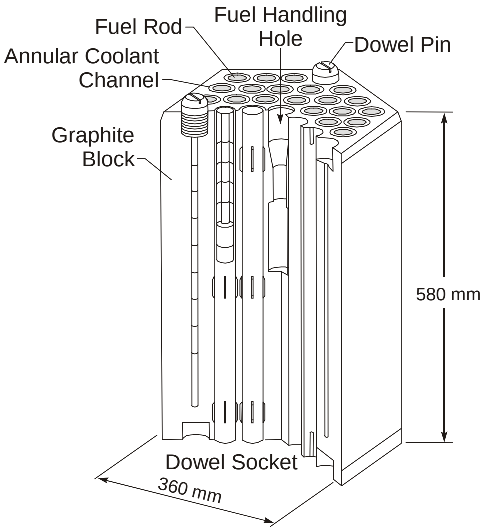
FHR Uses Graphite-Matrix Coated-Particle Fuel

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

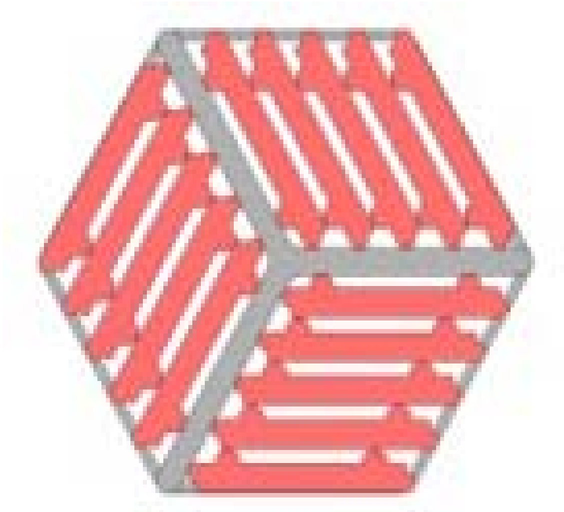


Liquid Coolant Enables Increasing Core Power Density by 4 to 10

Graphite-Matrix Coated-Particle Fuel Can Take Many Forms

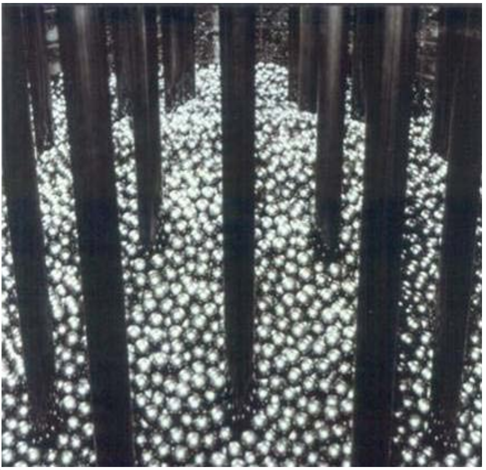


Prismatic Fuel Block



Flat Fuel Plates
in Hex Configuration

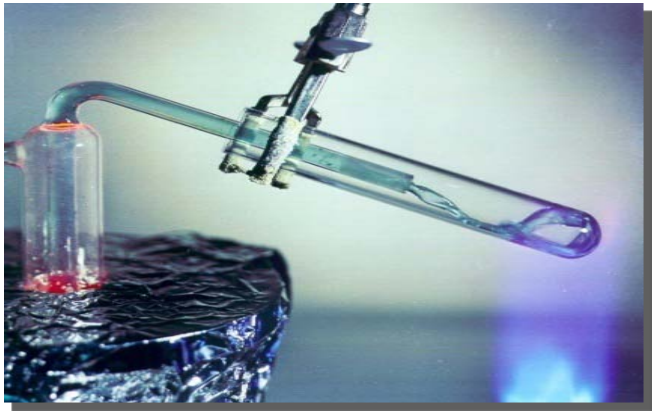
Base Case

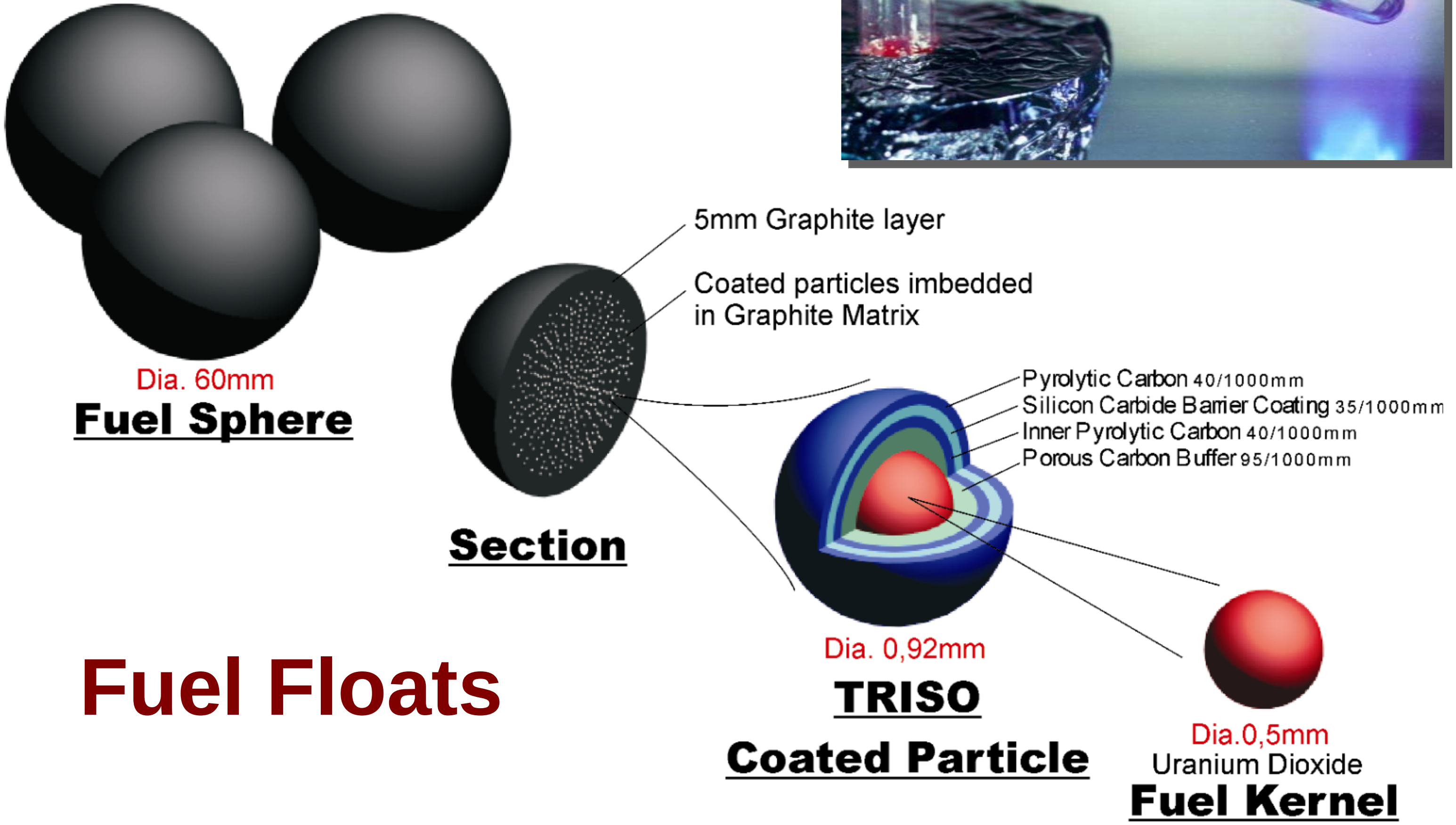


Pebble Bed

- Pebble bed
  - Lower cost
  - Easier refueling
- FHR smaller pebbles (3 cm) and higher power density

Salt Density Greater Than Fuel Density





Fuel Floats

Salt and Fuel Combination Reduces Hot Spots in Reactor Core (Nominal Exit ~700°C)

	Helium (Gas)	**Salt (Liquid)** **BP: 1430°C**
Pebble	Sinks in Helium	Floats In Salt
Fluid Flow	Down	Up: Pebbles Held in Place
Heat Transfer* with Temp. Increase	Viscosity Up; Flow Rate Down: Heat Transfer Down	Viscosity Down: Flow Rate Up; Heat Transfer Up
Margins		>500°C

*Transparent High-Heat Capacity Salt With Radiation Heat Transfer ~ T^4

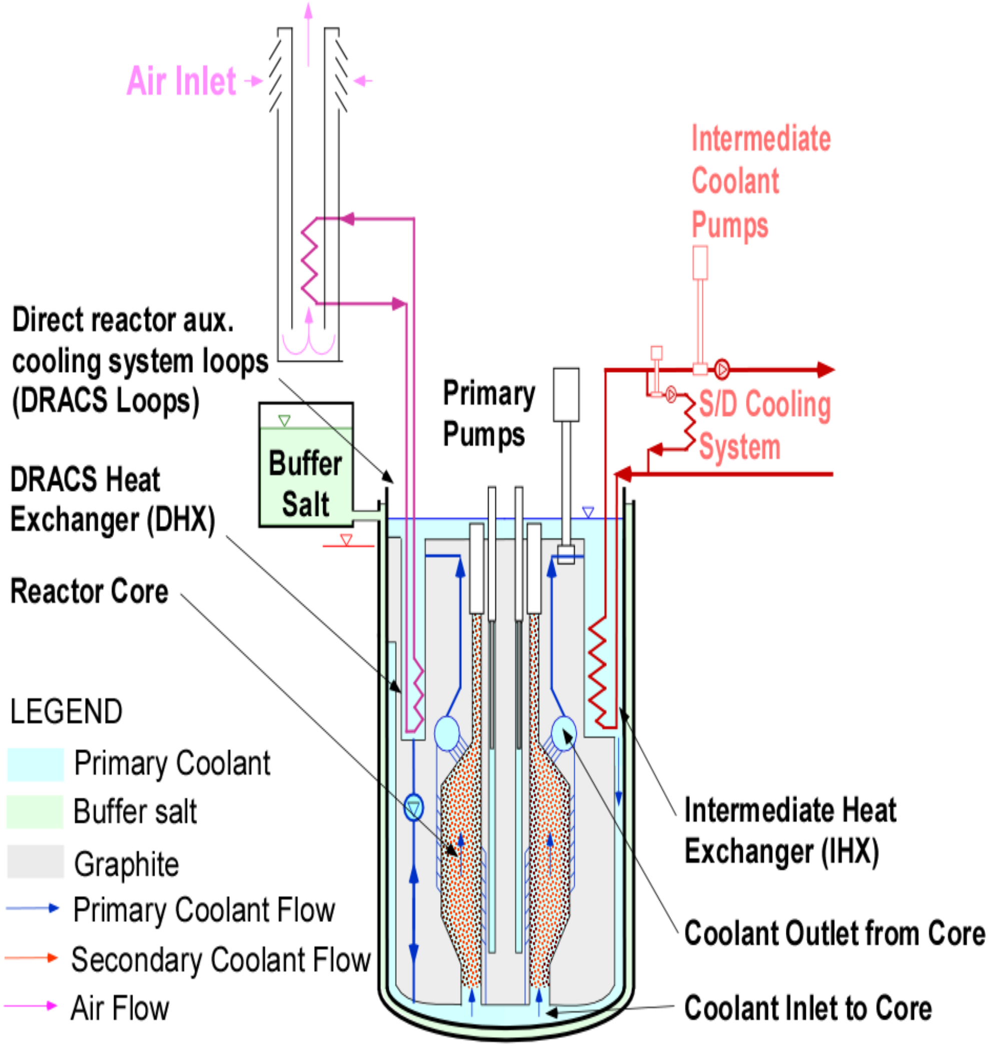
FHR Core Design: For Every Graphite Gas-Cooled Reactor, a Parallel FHR Design

- Neutronics
  - Similar to graphite-moderated gas-cooled reactors
  - Salt relatively transparent to neutrons
- Thermal hydraulics: Liquid salts versus gases
  - Liquid salt coolants are much better heat transport agents than gas coolants (Helium or Carbon dioxide)
  - FHR power densities a factor of 2 to 6 higher
  - FHRs have smaller reactor cores
  - FHRs operate at low pressures
  - FHRs use convection, not conduction, for passive decay heat removal

Compact FHR Layout

Baseline: 900 MWt

- Annular pebble bed
- Pebbles float in liquid salt
- Pebbles circulate through the core once per month, one year lifetime
- Radiation detector determines when full burnup reached

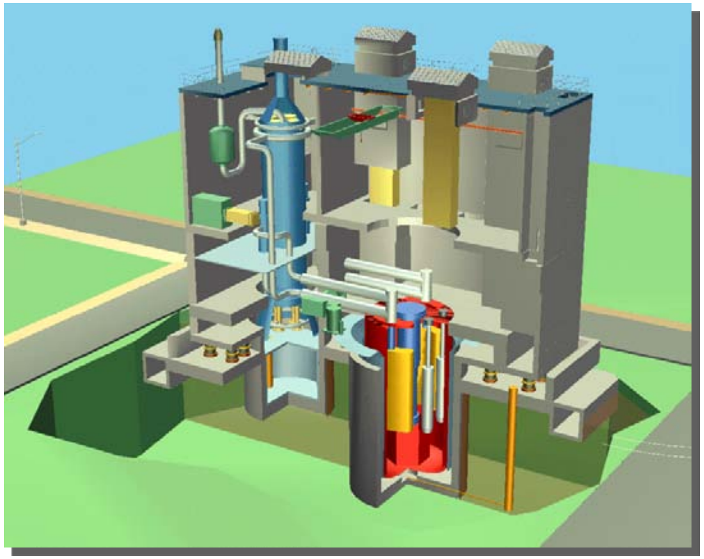


FHR Core Design: 5 Shutdown Options

- Doppler reactor shutdown on high temperature
- Conventional control rod system
- Salt temperature-driven buoyancy control rods
  - Salt denser than graphite so can build near neutral buoyancy control rods
  - If salt heats up, salt density decreases, rods drop
  - If neutral bouyancy at operating temperature, hold up by fluid flow and drop on loss of flow
- Salt temperature-driven fusible link shutdown
  - Soluble neutron absorbers in canister (boron or rare earths) with nickel-gold fusible link (like fire sprinkler systems)
  - Overheat and release to hot salt
- Buffer tank absorber (Discussed later)

FHR Safety Case Based On Several Technologies

- FHR is a liquid-cooled low-pressure reactor
  - General layout similar to sodium fast reactors
  - Many safety systems from sodium fast reactors
- FHR is a high-temperature reactor
  - Modified gas-cooled reactor fuel—higher power density
  - Very high temperature fuel
- Unique feature: salt coolant
  - High melting point: 459ºC
  - High boiling point: 1430ºC

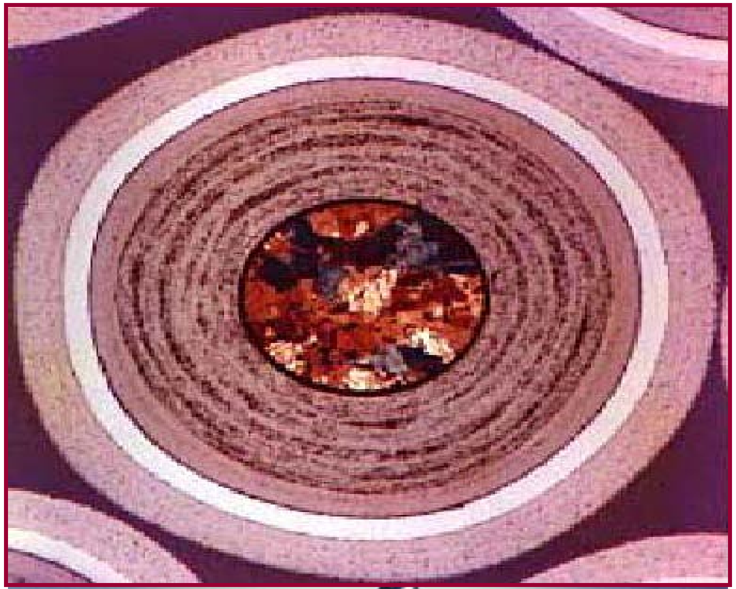


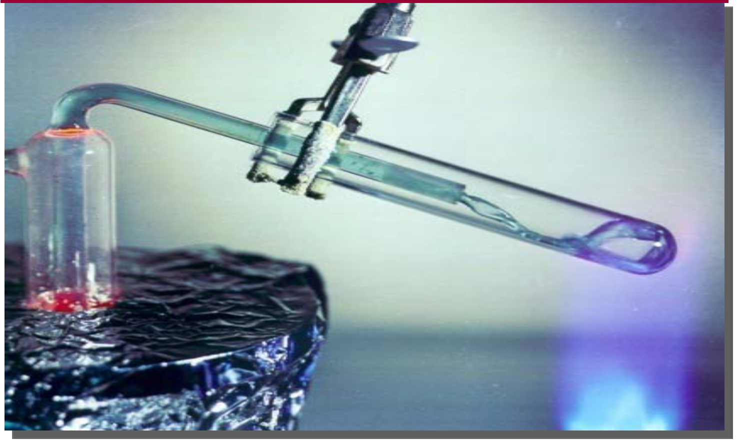
General Electric

S-PRISM

High-Temperature Fuel and Coolant Alters Safety Limits

- Safety limit LWR: fuel clad failure from high temp.
- Safety limit SFR: void coefficient from boiling coolant
- Safety limit HTGR: high-temperature fuel failure
- FHR limits not well defined
  - Metal component failure
  - Bulk temperature limit

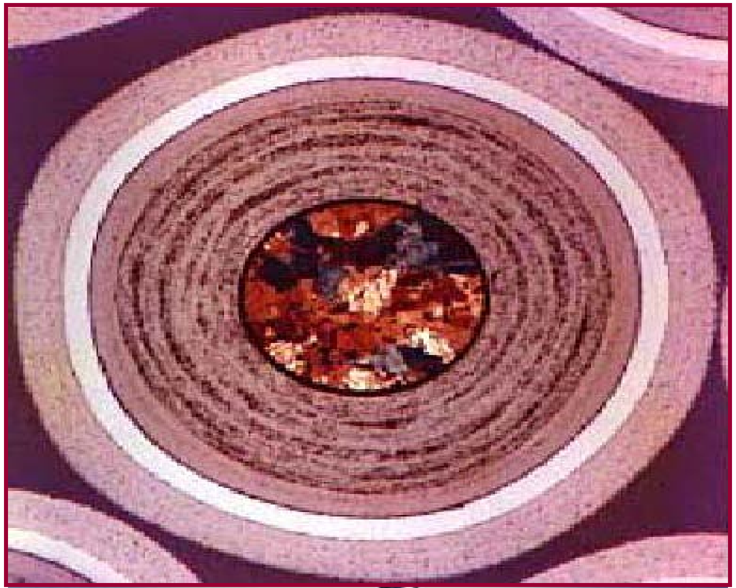


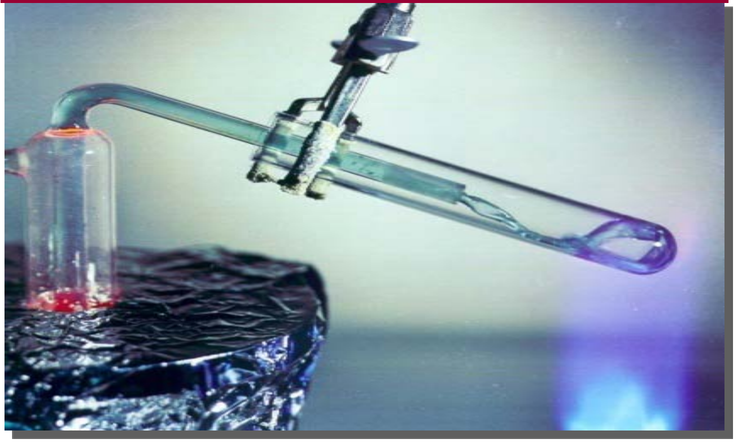


Accident Driver: Outside the Core?

Iron Melts at 1535°C, Alloys Softens at Lower Temperatures

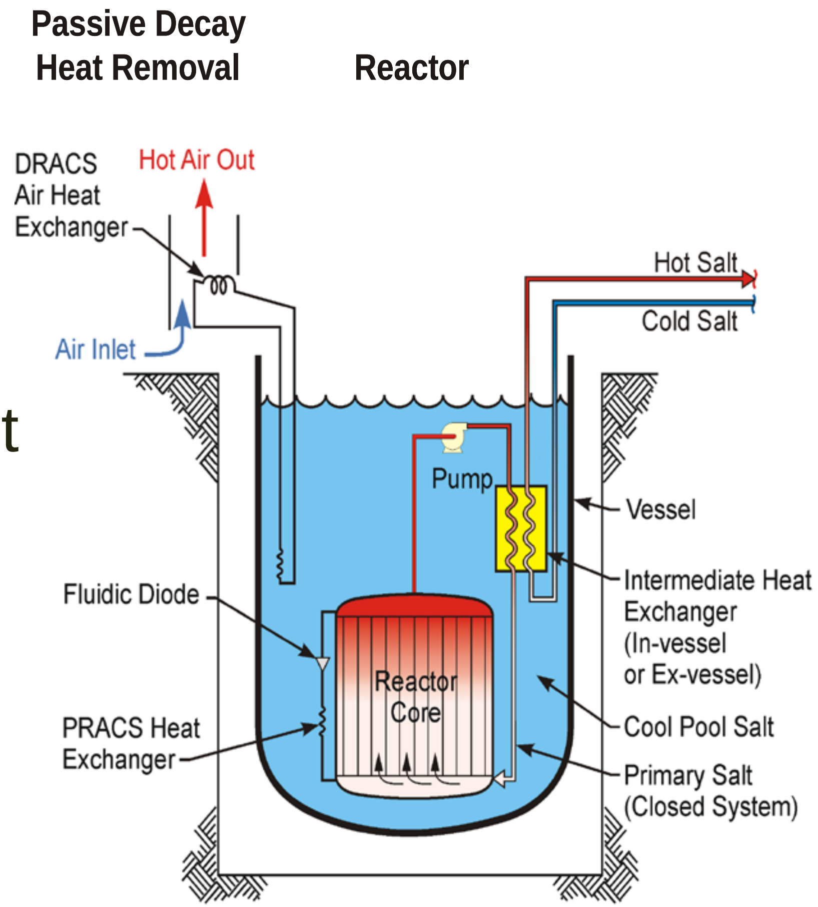
- Fuel failure ~1650°C
  - Nominal peak~800°C
- Coolant boiling ~1430°C
  - Nominal peak ~700°C
- Vessel: <1200°C
- Severe accident starts outside of the core
- Different than any other reactor and not well understood





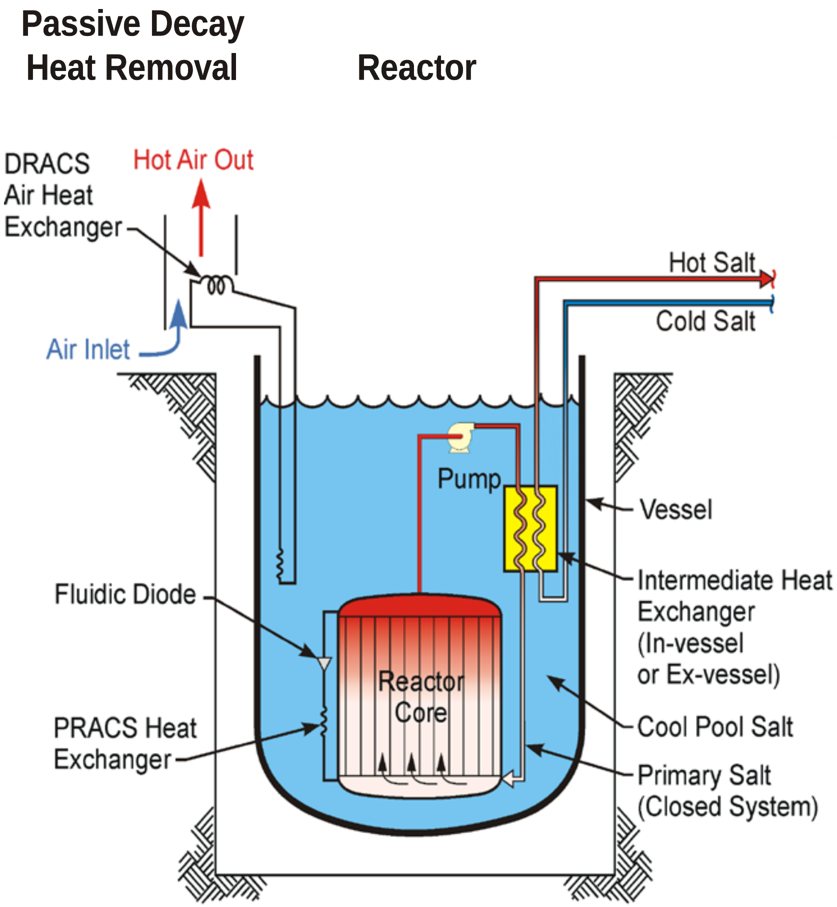
The FHR Primary System can be in a Secondary Tank Filled with Salt

- Secondary Tank Functions
  - Decay heat sink
  - Assure can not loose coolant under any conditions
  - Low surface area tank so do not freeze primary system salt piping when shut down
- Secondary Tank System
  - Soluble neutron absorbers so shut down reactor if leak
  - DRACS system to control secondary salt temperatures



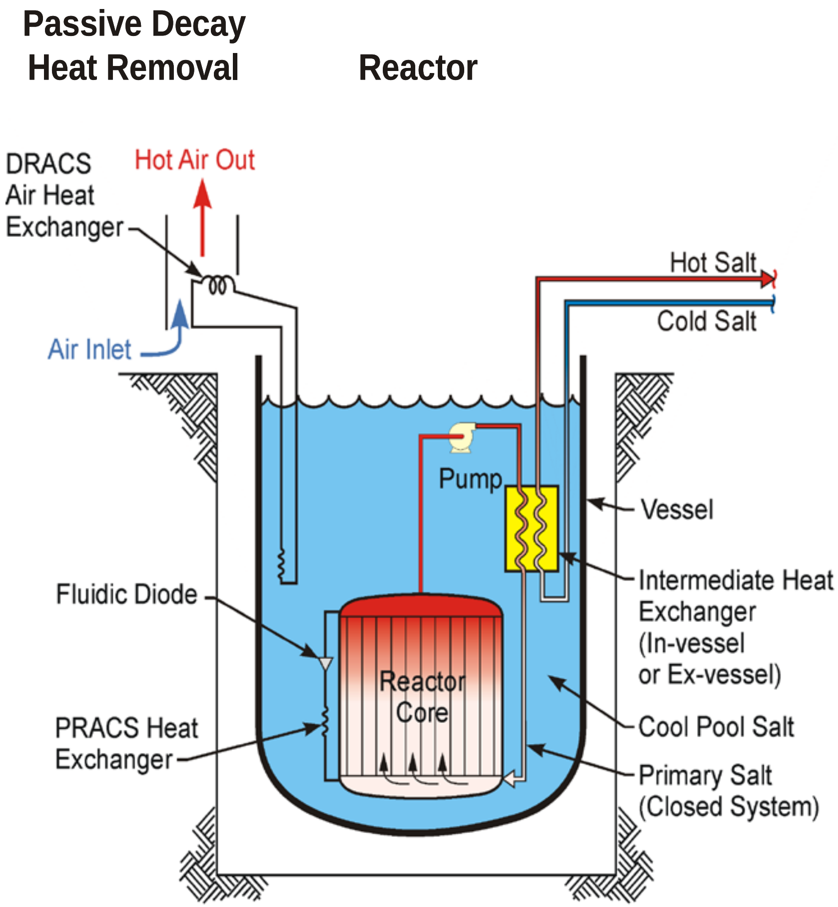
Decay Heat Dumped to Secondary Tank If Loose Primary Heat Sink (Power Cycle)

- Primary salt route
  - Reactor core
  - Primary heat exchanger to power cycle
  - Piping to reactor core
- Loss of heat sink to power cycle
  - Hot salt through HX
  - Hot salt to core through un-insulated piping
  - Dump heat to secondary salt at temperature of cold side of primary loop



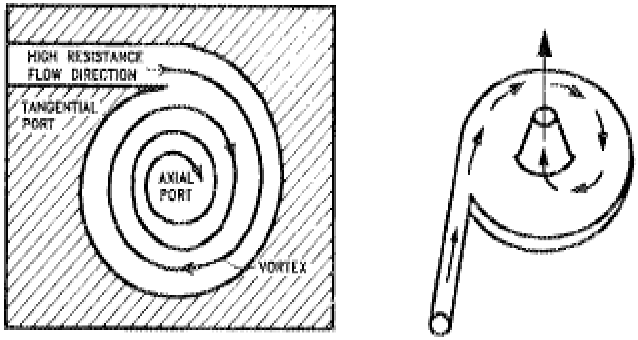
Decay Heat Dumped to Secondary Tank on Pump Trip

- Two routes for primary salt
  - Through reactor core
  - Through parallel PRACS heat exchanger that dumps heat to secondary salt
- PRACS loop
  - Heat Exchanger and fluidic diode
  - High flow resistance when pump operates
  - If pump stops, salt flows through core and down PRACS loop



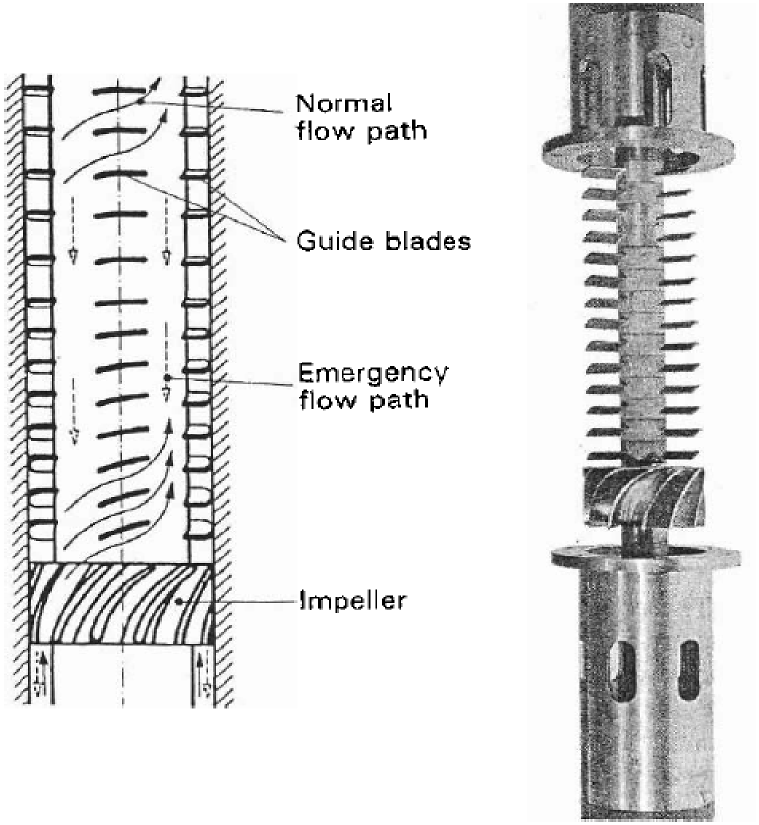
Fluidic Diodes Developed for German Fast Reactor and British Reprocessing Plants

- No moving parts diodes exhibit anisotropic flow resistance
- Nuclear experience available
- Vortex diode chosen as target design (Large version used in MHI APWR and Korean AP-1400 Accumulators)



Conventional Vortex Diode

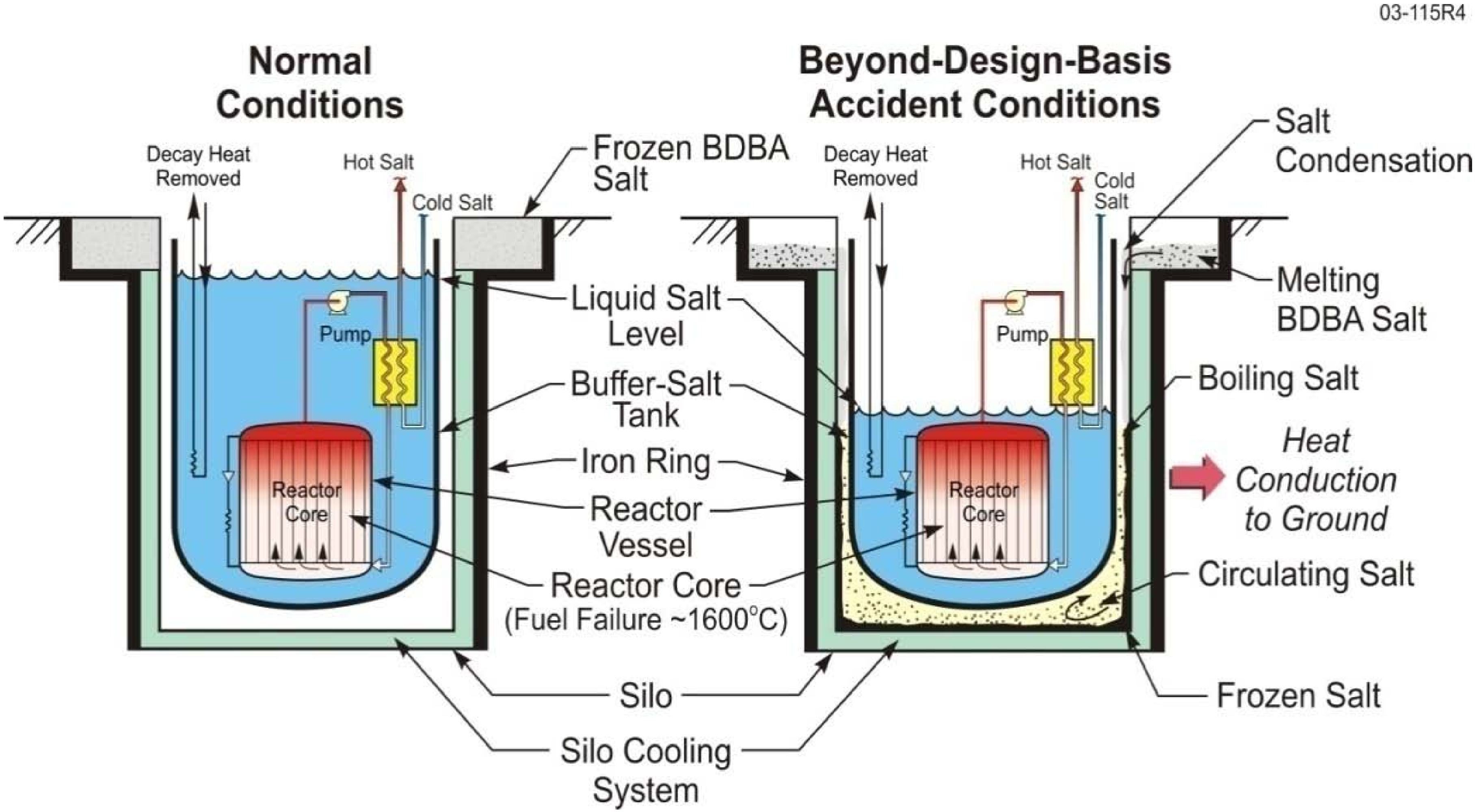
German fluidic diode for sodium (Fluid Rectifier Diode)



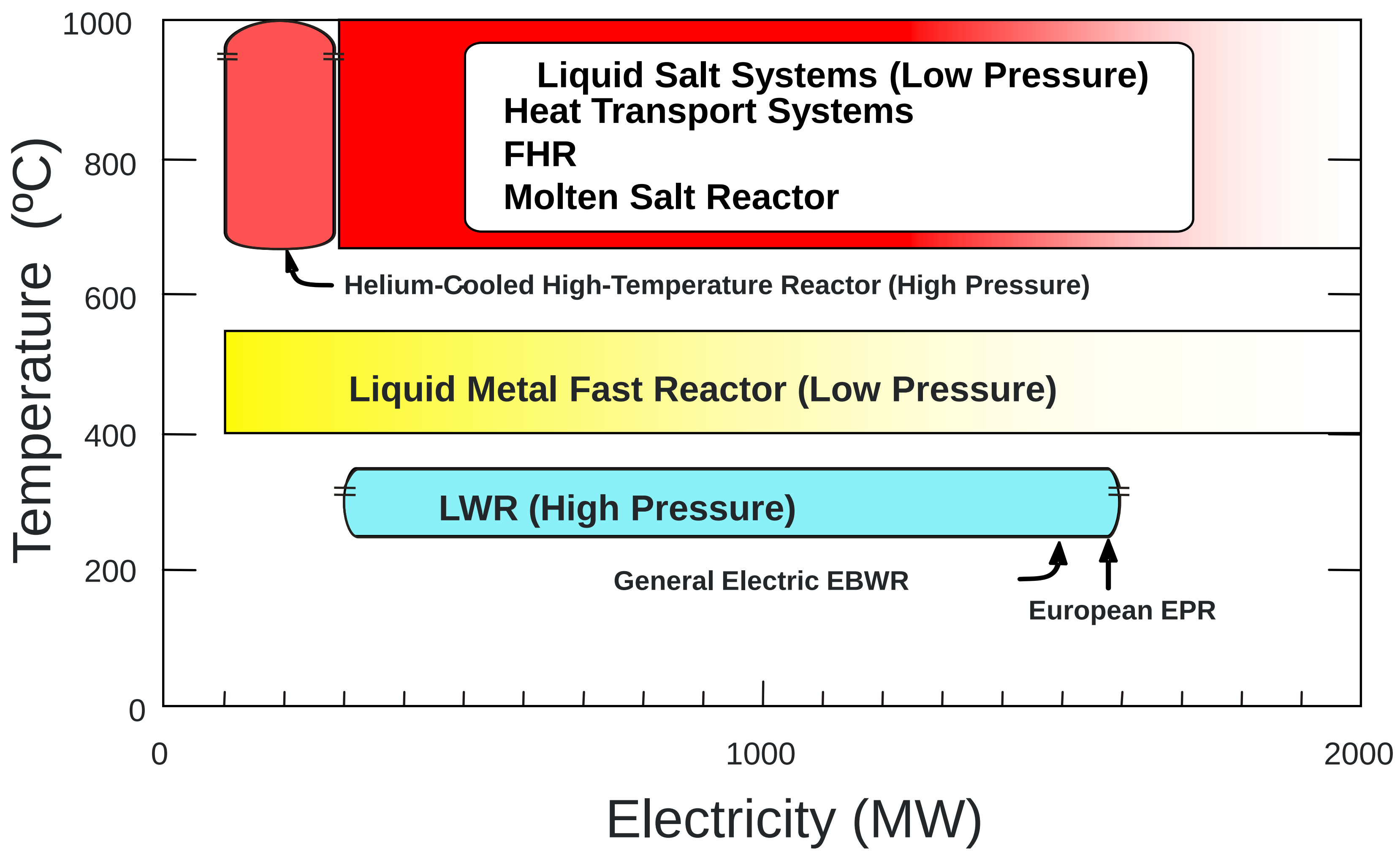
Rothfuss and F. Vogt, “Reactor Vessel Technology,” *Nuclear Technology*, Vol. 78, pg. 245, 1987.

Potential for Large Reactor That Can Not Have a Catastrophic Accident

Decay Heat Conduction and Radiation to Ground



Salt Coolants Imply High-Temperature High-Efficiency Power Cycles



FHR for Electricity

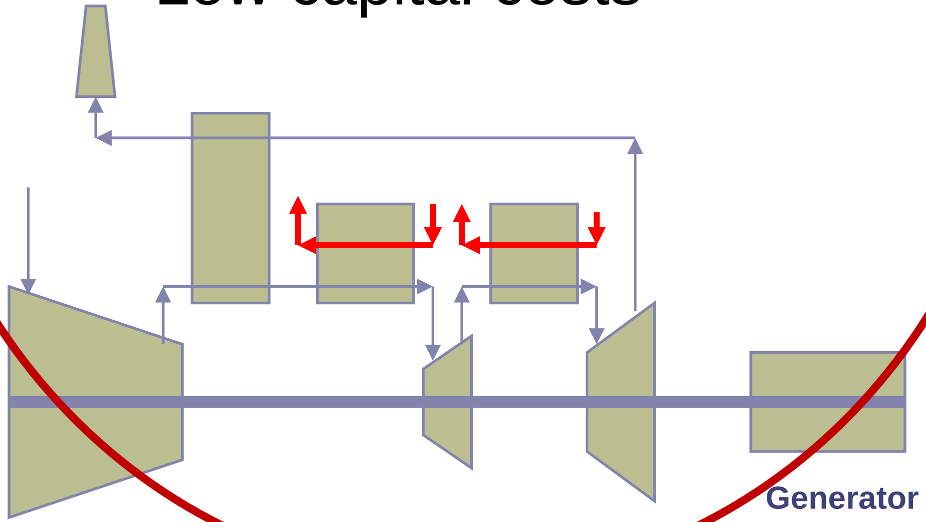
- Deliver heat from 600 to 700ºC
  - Lower temperature above salt melting point
  - Upper temperature within existing materials
- Power cycle options
  - Commercial supercritical water cycle with peak temperature of 650ºC
  - Supercritical carbon dioxide cycle with good temperature match between delivered heat and power cycle
  - Air Brayton cycle with good temperature match between delivered heat and power cycle

Many Options for Power Cycles

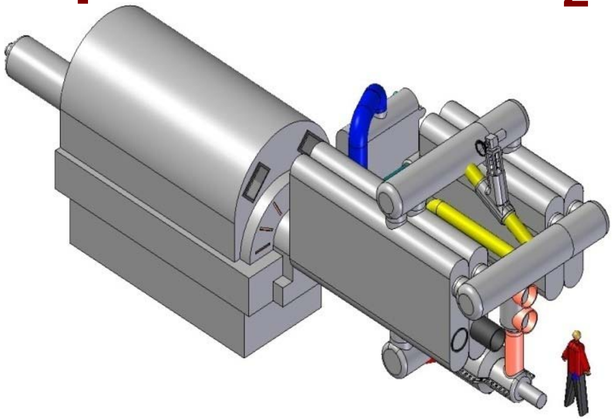
Base Case

Air Brayton Cycle

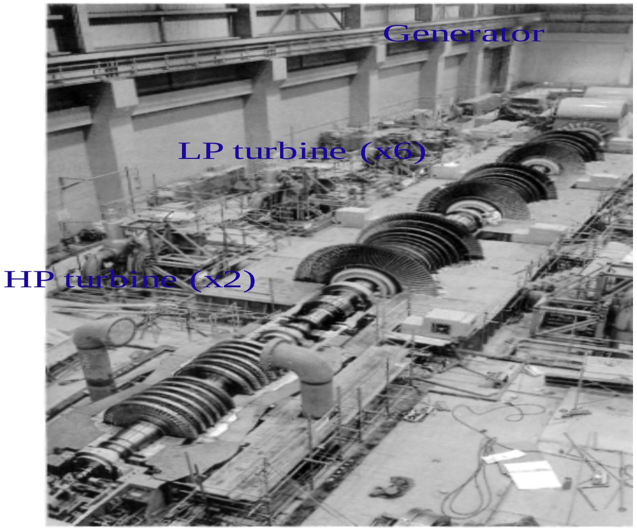
- Air Brayton cycle based on natural gas turbine
- Dry cooling
- Low capital costs



Supercritical CO$_2$



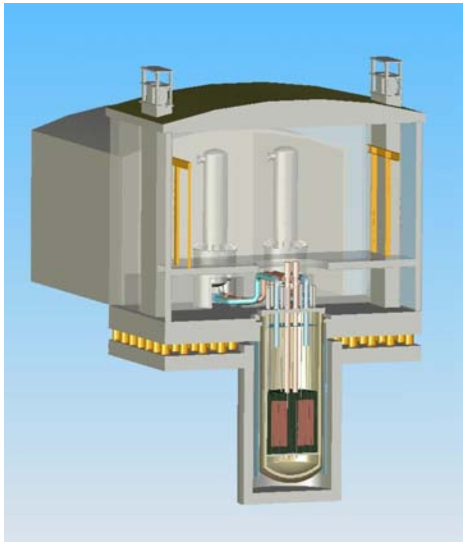
Steam



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
- Tritium control is an important design issue

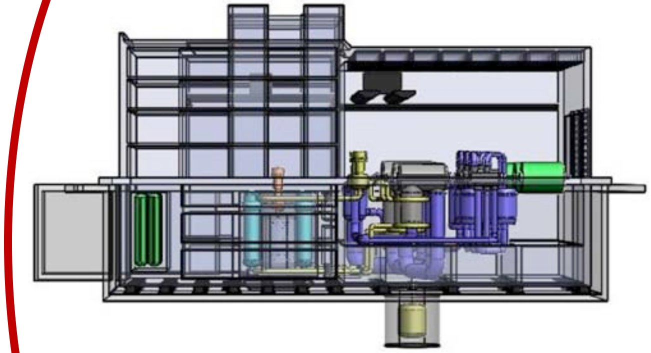
FHR Concepts Span Wide Power Range



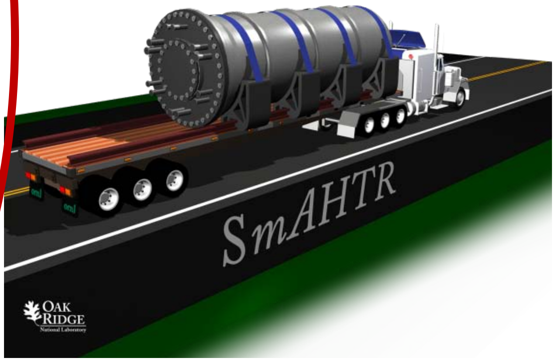
3400 MWt /

1500 MWe

Base Case



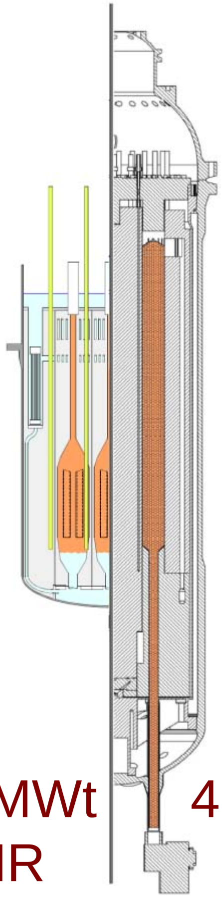
410 MWe



125 MWt/50 MWe

Preliminary Economics: FHR Lower Cost than Light-Water 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
  - Higher plant efficiency (40 to 50%)
- Much lower construction cost than high-temperature gas-cooled reactors
  - All components much smaller
  - Operate at low pressure


900 MWt
FHR

400 MWt
HTR

Status of FHR

- No FHR has ever been built: new concept
- On paper a great idea but untested concept
- Combines four technologies with changes
    - Gas-cooled reactor coated-particle fuel—but at higher power densities and with salt coolant
    - Clean molten (liquid) salt reactor coolant—but previous experience in MSR with fuel dissolved in coolant: both with high melting point coolant
    - Fast reactor safety systems—but with a high melting-point coolant
    - Power cycles—but at 700 C

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 and develop near-term path forward
- 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

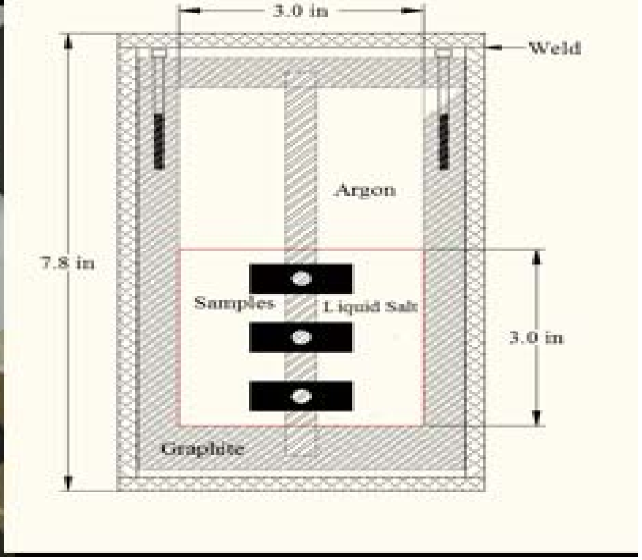
Workshops to Define Current Status and Path Forward

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 Key Materials In MIT Research Reactor

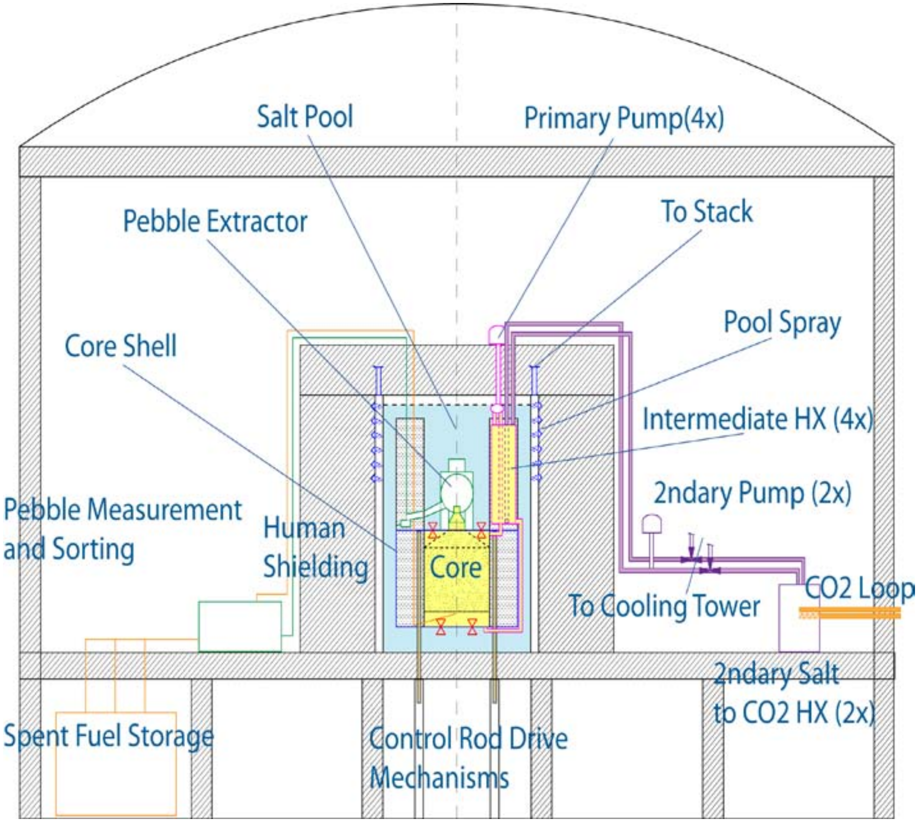
- 6-MWt Reactor
- Operates 24 hr / day, 7 days per week
- Uses water as coolant
- In core tests
  - LWR Neutron Flux Spectrum
  - Tests in 700°C flibe liquid salt in core
  - In-core materials, coated particle fuel

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

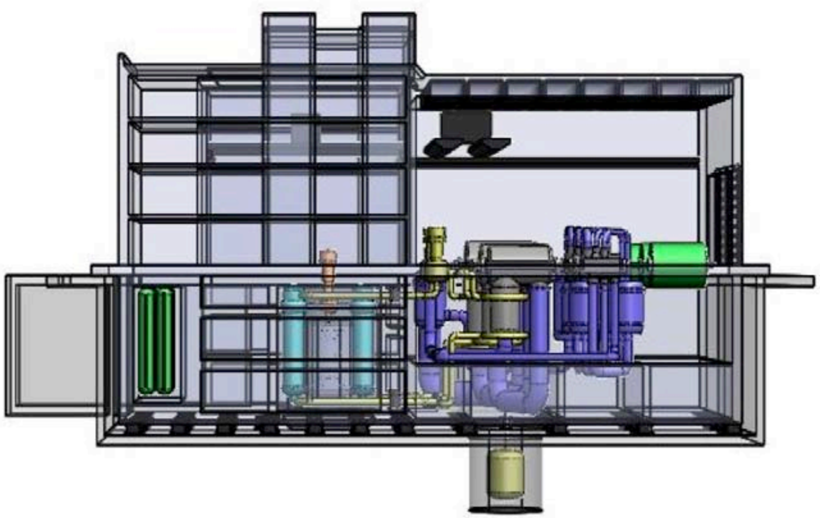
MIT To Develop Pre-Conceptual Test Reactor Design

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



UCB to Develop Commercial Reactor Pre-Conceptual Design

- Identify and quantify power-reactor functional requirements
- 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 / process heat reactor
- Identify and scope what is required and schedule
- Includes licensing strategy
- Partnership with Westinghouse Electric Company

An IRP Advisory Panel Has Been Formed

- Regis Matzie (Panel Chair) (retired senior vice president and chief technology officer of Westinghouse)
- Douglas Chapin (previous principal at MPR and current senior consultant)
- John McGaha (retired senior executive of Entergy Nuclear)
- Dan Mears (president and CEO of Technology Insights)
- James Rushton (retired head of Nuclear Science and Technology division at ORNL)

The Advisory Panel has been constituted to advise the IRP on how best to successfully complete their DOE contract in a manner that provides a viable path forward in pursuit of a commercially successful FHR.

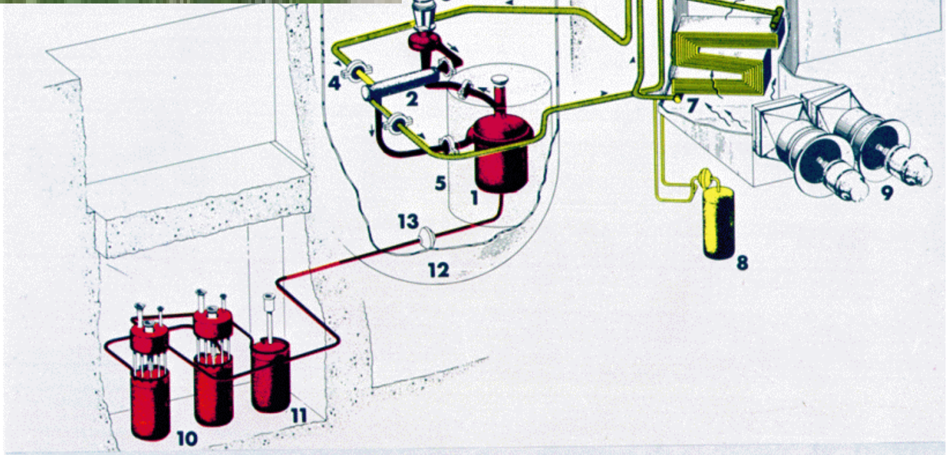
Coupled High-Temperature Salt Technologies

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

Separate from the Synergisms with Gas-Cooled High-Temperature Reactors and Sodium Fast Reactors

MSRE (1965-69) Is the Reactor-Base Experience with Salt Coolants

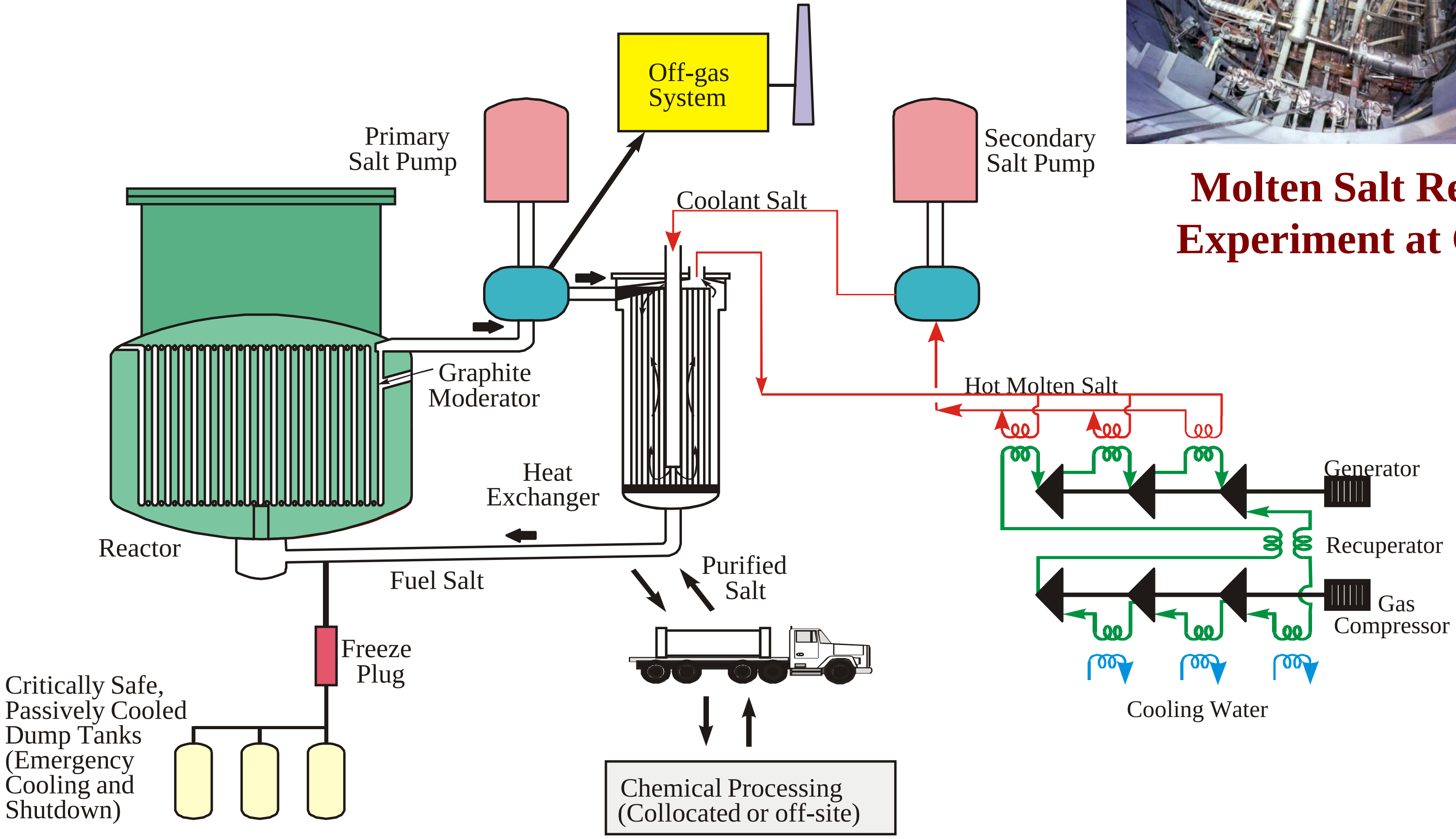
Fuel Dissolved in Salt

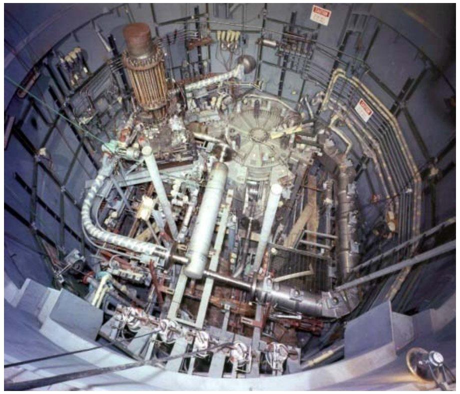


1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

Work Continues on MSR

(Fuel Dissolved in the Salt Coolant)



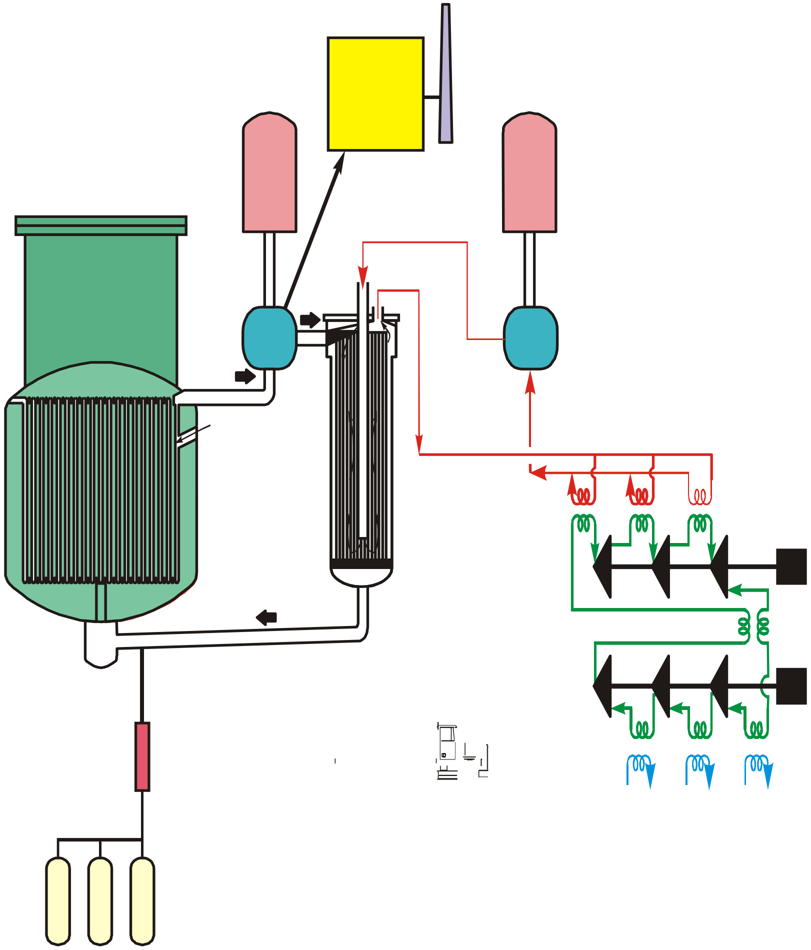


Molten Salt Reactor Experiment at ORNL

China, France, Russia, Czech Republic, United States

Work on MSR: Implications for FHR

- France
  - Fast spectrum MSR
  - Significant negative void coefficient (unique FR)
  - R&D program, not demo
- Czech Republic
  - Criticality tests for MSR and FHR
  - Chemistry
- China
  - Traditional MSR with FHR as backup
  - Chinese Academy of Science
  - To 700 people in 3 years



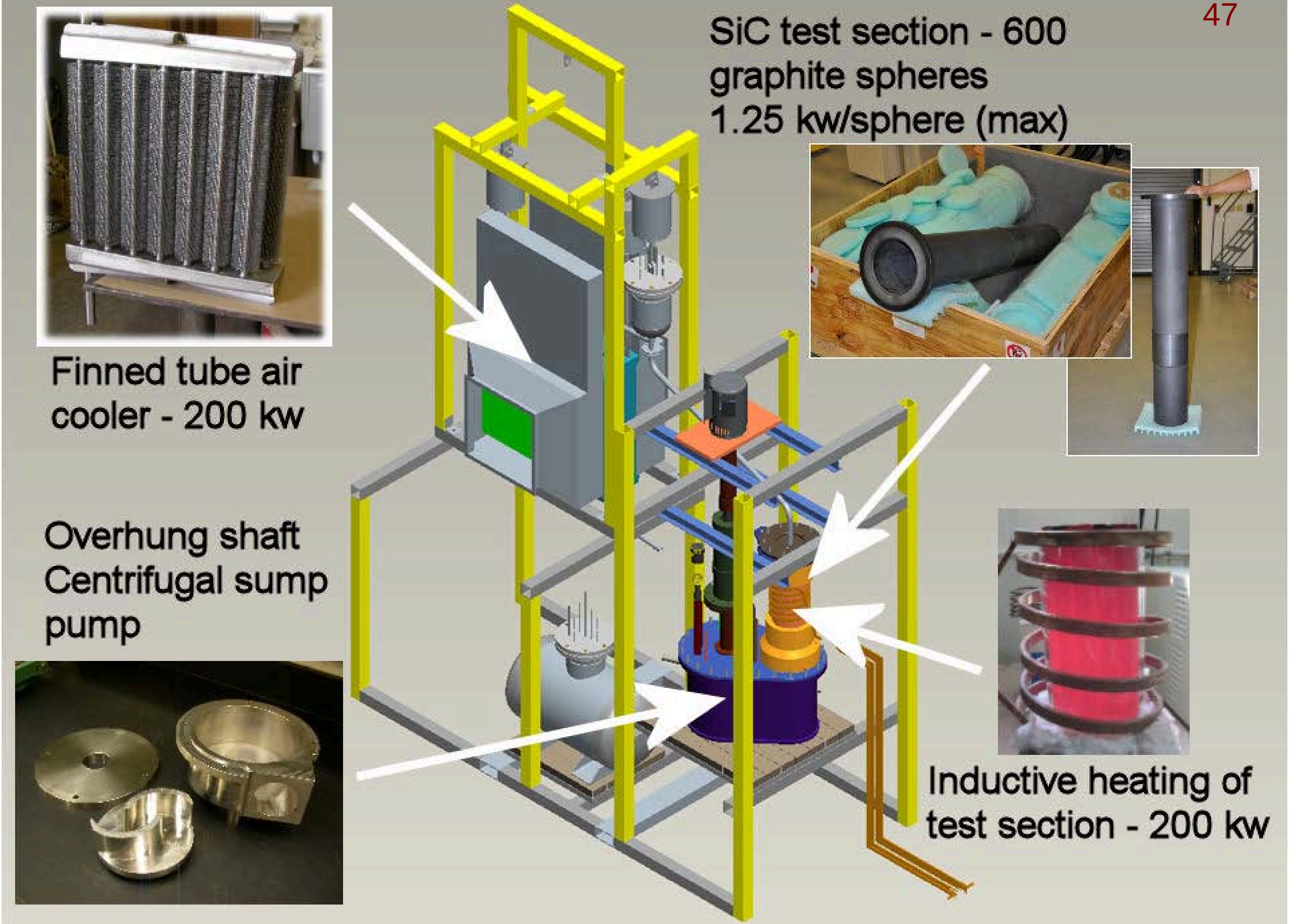
ORNL Starting Pebble-Bed Liquid-Salt Heat-Transfer Loop

- Loop specifications

Salt	FLiNaK
Operating Temperature	700°C
Flow rate	4.5 kg/s
Operating pressure	atmospheric
Material of construction	Inconel 600
Loop volume	72 liters

- FHR pebble bed heat transfer

	PB-FHR	Experiment
Coolant	FLiBe	FLiNaK
Bed Dia. (cm)	20	15
Bed height (m)	3.2	0.75
Pebble dia.(cm)	3	3
Pebble Re	3080	2570



Finned tube air cooler - 200 kw

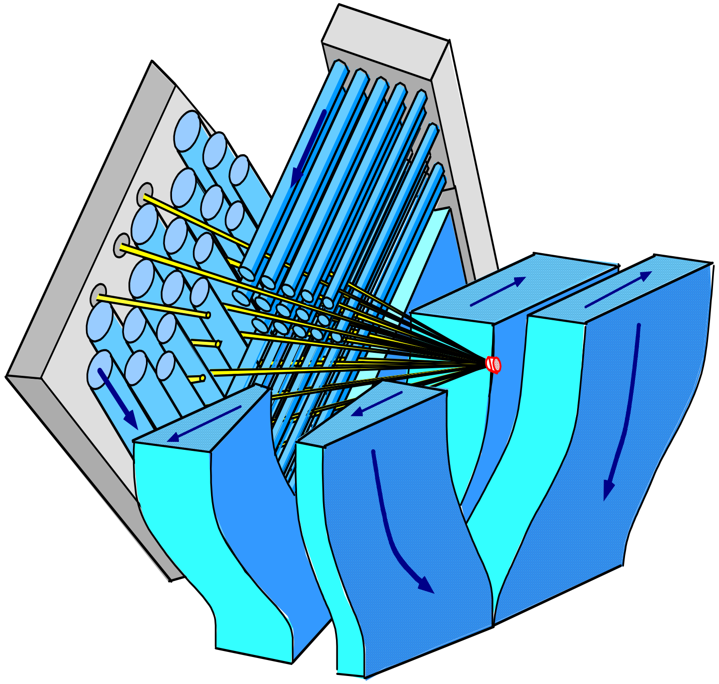
SiC test section - 600 graphite spheres 1.25 kw/sphere (max)

Overhung shaft Centrifugal sump pump

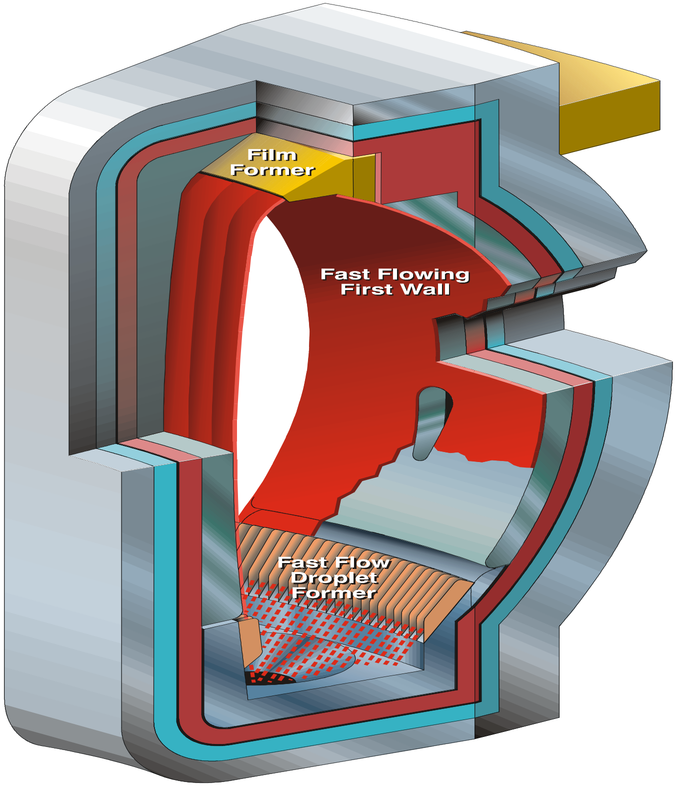
Inductive heating of test section - 200 kw

Liquid Salt Wall Fusion Machines

Higher-Power Densities and Less Radiation Damage



Heavy-Ion Inertial Fusion

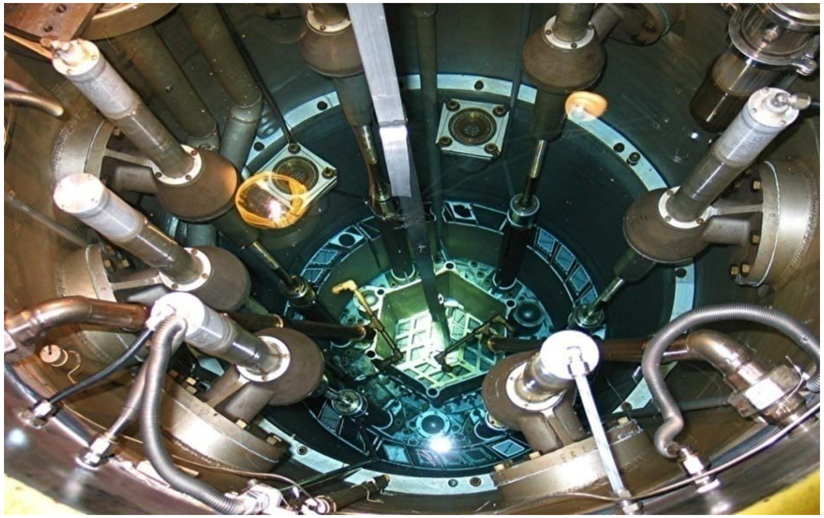


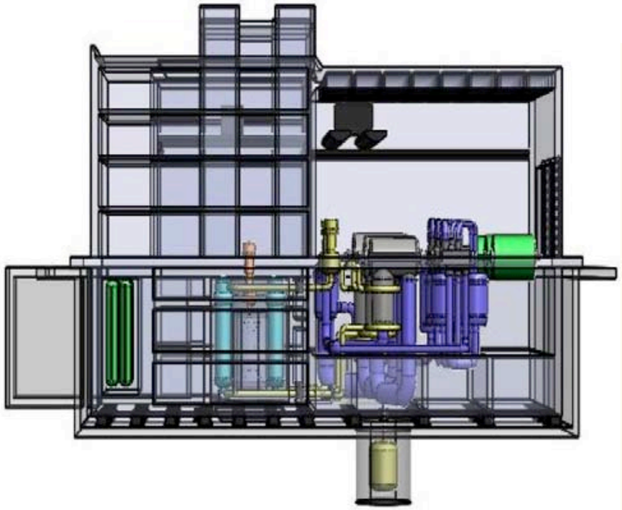
Magnet Fusion Tokamak

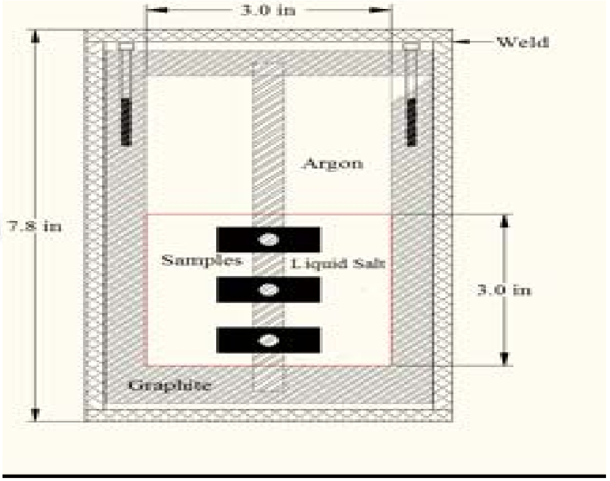
Conclusions

- 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







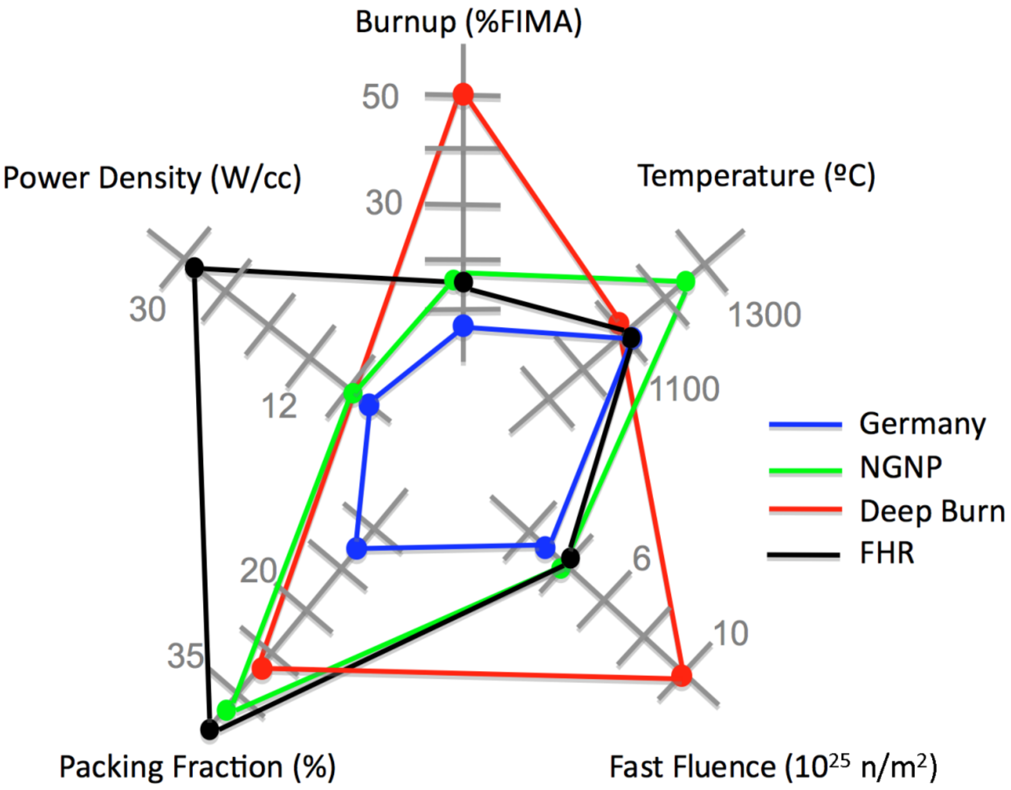
Biography: Charles Forsberg

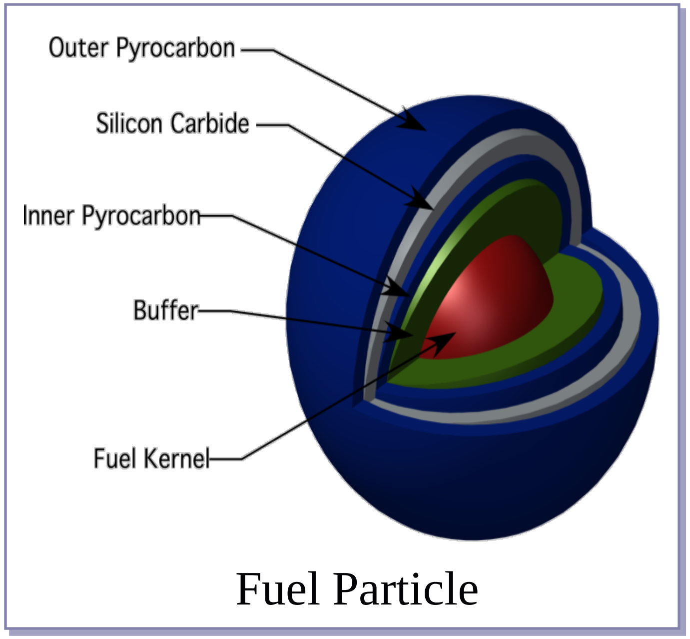
Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) 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.

http://web.mit.edu/nse/people/research/forsberg.html

FHR fuel development can use existing NGNP fuel fabrication / qualification infrastructure

- FHR fuel operates at high power density and heavy metal loading, but lower temperature, than NGNP AGR fuel
- Rapid fuel testing is possible due to short time required for FHR fuel to reach full discharge burn up





Fuel Particle

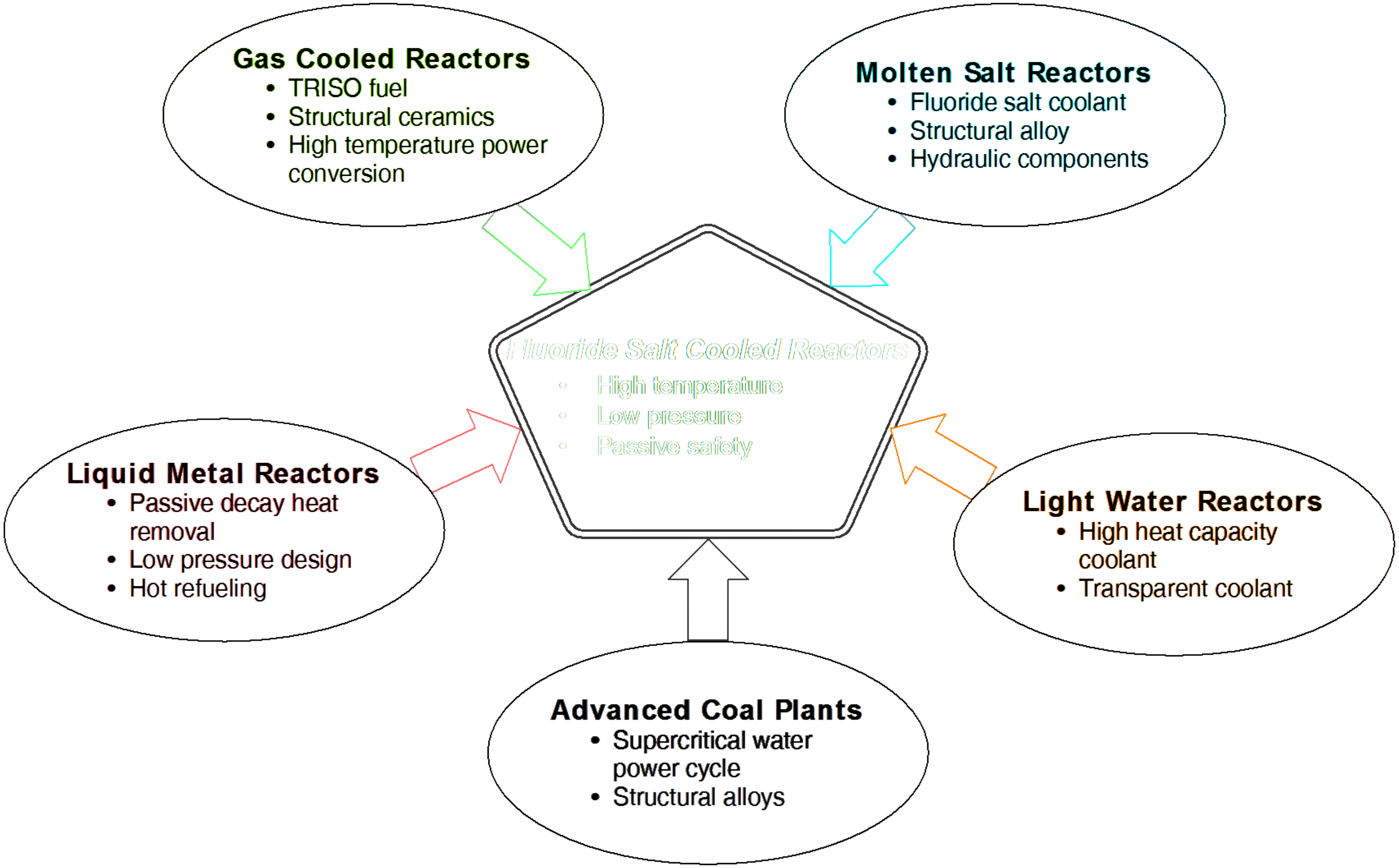
The United States Has a Competitive Advantage with FHR

- Developed and currently leads in FHR R&D
- Experience with MSR and has a working inventory of lithium-7 flibe salt
- Leads in coated-particle fuel technology because of NGNP high-temperature reactor program
- Leads in gas turbines—power side of FHR

FHR Conceptual Designs

Conceptual Design	Design	Size (MWe)
ORNL	Coated Particle Fuel Plate Supercritical Steam SFR Refueling System	1500
MIT/UCB/UW	Coated-Particle Pebble Bed Air Brayton Power Cycle Modified He Pebble Bed Refueling	410
ORNL	Coated-Particle Fuel Plate Modular	50
AREVA (Earlier)	SiC-clad UO_2 pin fuel assembly Actinide burn capability (Unique)	1500

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

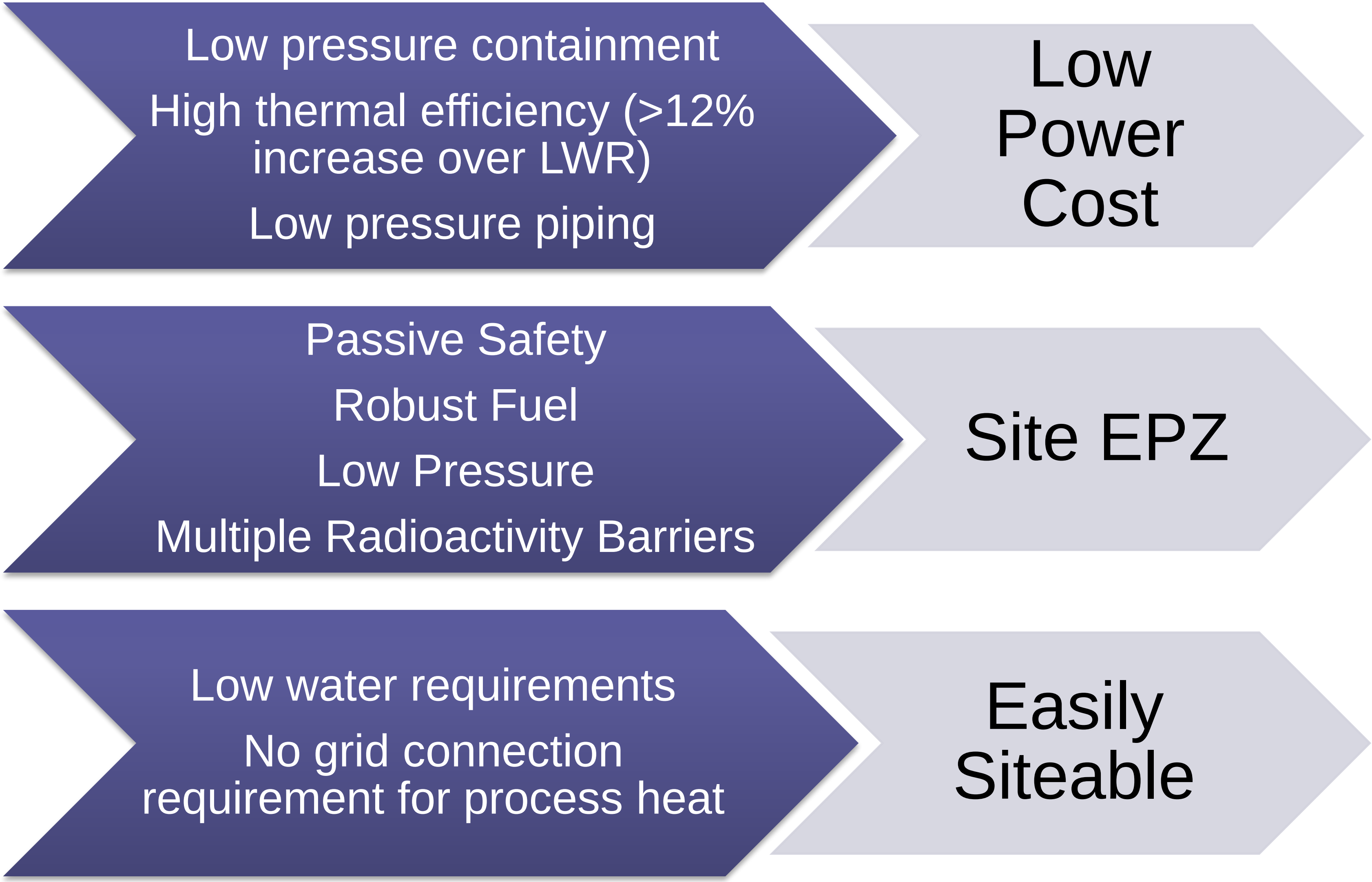
Fluoride Salt Cooled Reactors
- High temperature
- Low pressure
- Passive safety

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

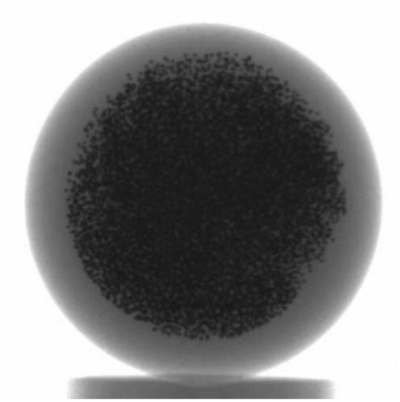
No grid connection requirement for process heat

Easily Siteable

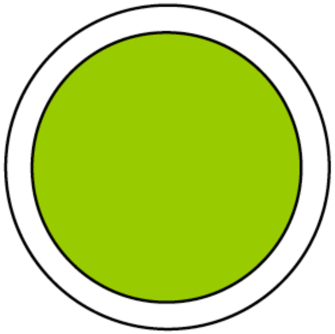
FHR History

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

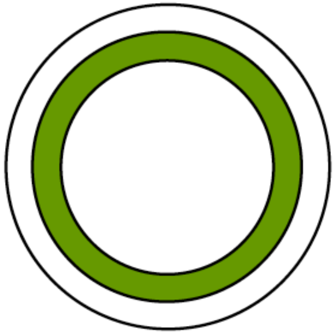
Additional development will be required for FHR fuel



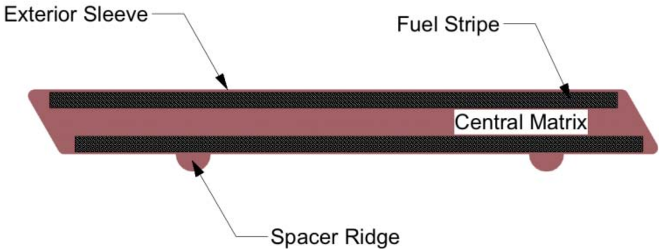
X-ray image of conventional pebble

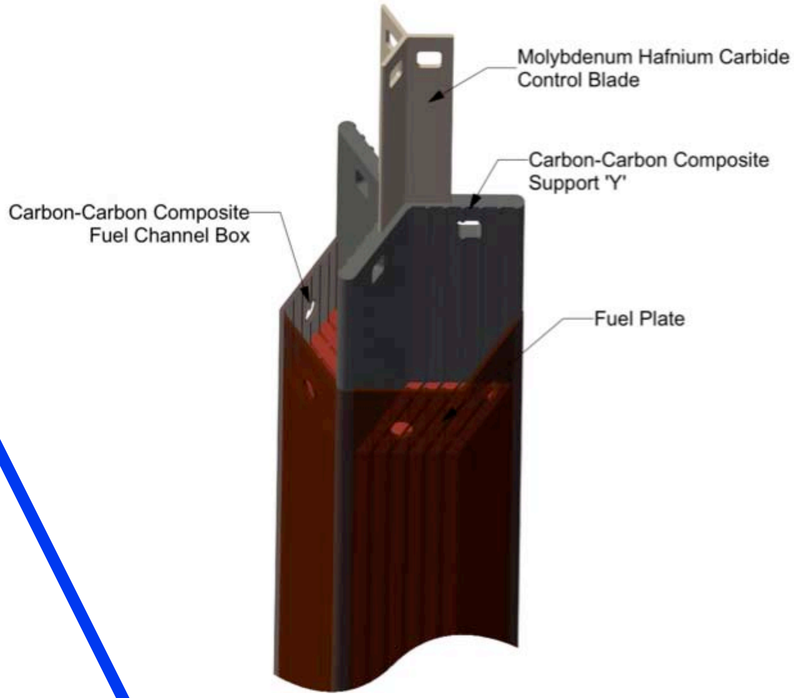


Conventional homogeneous pebble

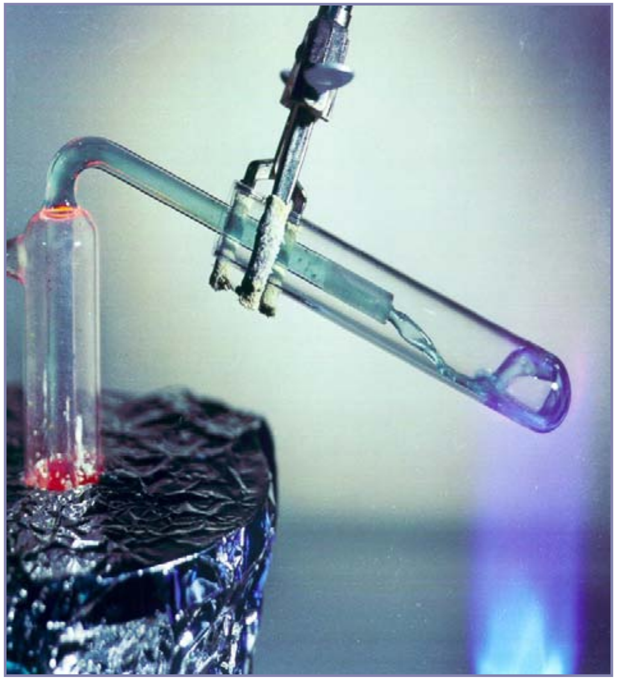


PB-FHR “Annular” pebble





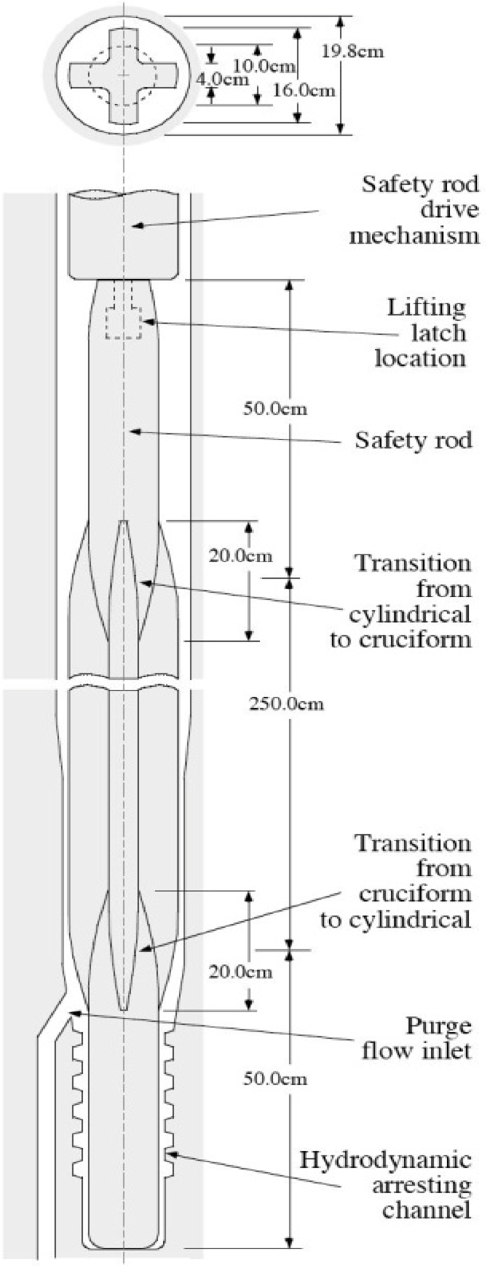
Salt Requirements



- 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

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



Buoyantly-Driven Shutdown Rod

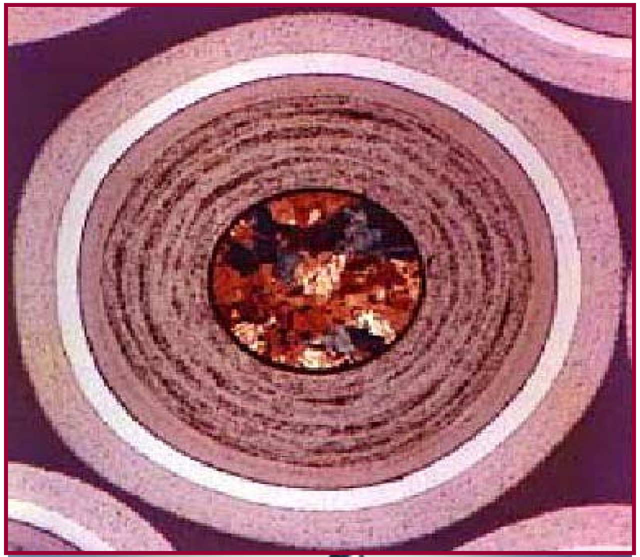
- Shutdown rods are designed to be neutrally buoyant at a flibe salt density corresponding to a temperature of 615C ± 5C
- Purge flow is metered into the bottom of each shutdown channel by a fluidic diode
- Cylinder geometry maximizes rod drop velocity, providing the minimum surface area to volume ratio
- Hydrodynamic arresting channel used as snubber

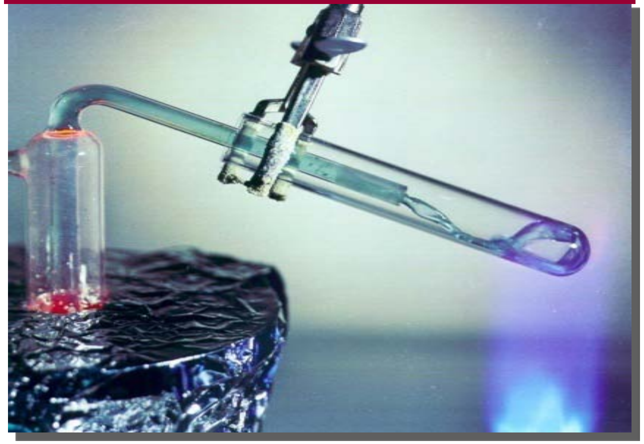
Current Modular FHR plant design is compact compared to LWRs and MHRs

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

Choice of Fuel and Coolant Enables Enhanced Safety





- Coated-particle fuel
  - Failure temperature > 1600ºC
  - Large Doppler shutdown margin
- Liquid salt coolant
  - 700ºC normal peak temp.
  - Boiling point >1400ºC
  - >500ºC margin to boiling
  - Low-pressure that limits accident potential
  - Low corrosion (clean salt)