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

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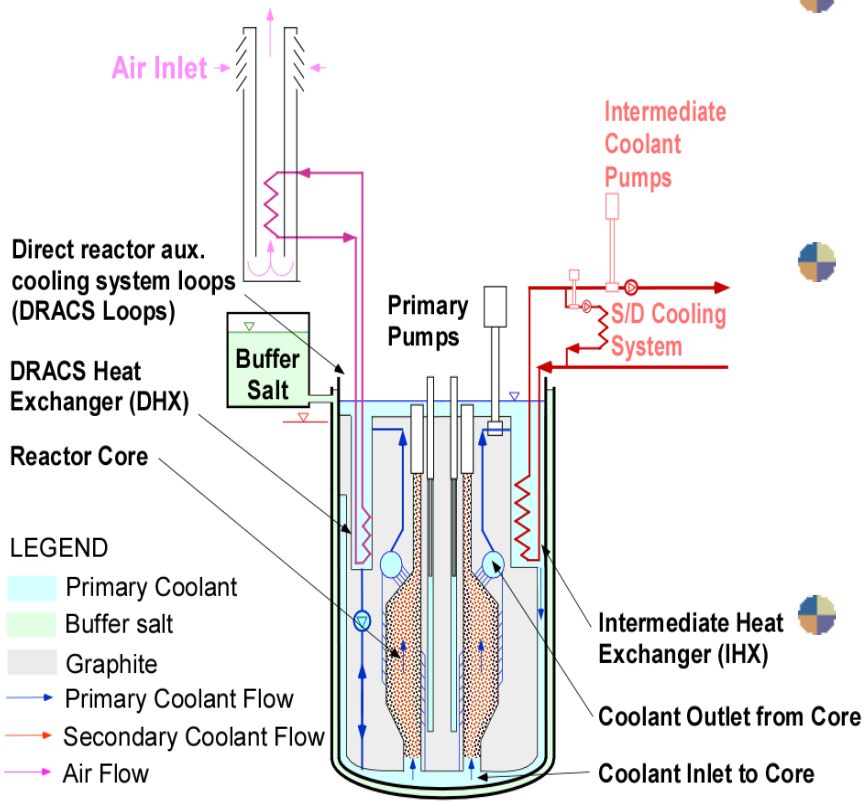
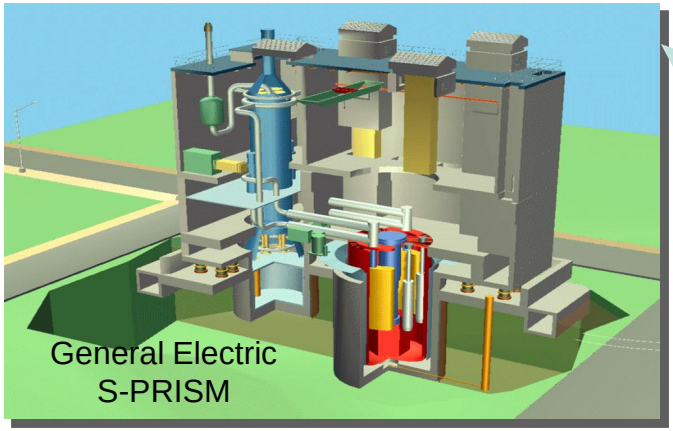
Fluoride Salt-Cooled High-Temperature Reactor (FHR)



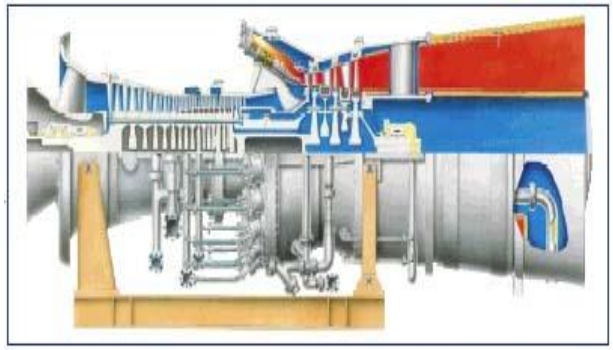
- New power reactor concept
  - About a decade old
  - Forsberg/Peterson/Pickard
- U.S. Research Activities
  - MIT, UCB, UW, OSU, other
  - ORNL, INL
  - Industrial
- Chinese Academy of Science
  - Build 2-MWt FHR by 2017
  - **First new reactor concept to be tested in decades**

New Reactor Combines Old Technologies



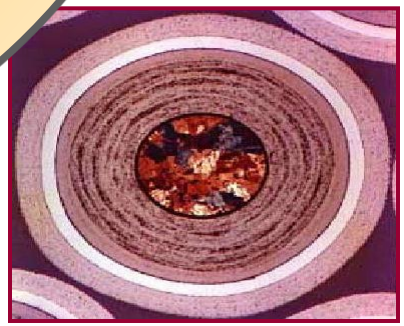
Passively-Safe Pool-Type Reactor

Fluoride Salt-Cooled High-Temperature Reactor (FHR)

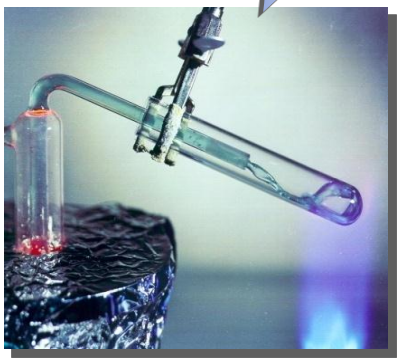


GE Power Systems MS7001FB

Air-Brayton Power Cycles



High-Temperature Coated-Particle Fuel



High-Temp., Low-Pressure Liquid-Salt Coolant (Transparent)

FHR Is in Different Reactor Design Space

Coolant Temperature	System Pressure	
	Low	**High**
Low 280°C		Light-Water Reactor
Medium ~550°C	Sodium Fast Reactor	
High >700°C	FHR	High-Temperature Gas-Cooled Reactor

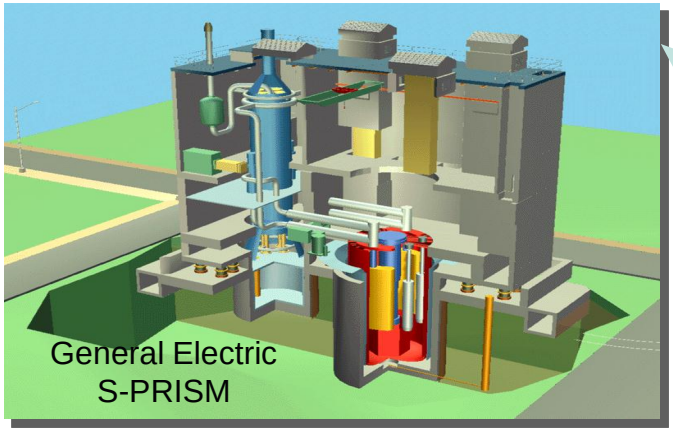
Fluoride-Salt-Cooled High-Temperature Reactor

Base-Line Design for
University Integrated Research Project

Massachusetts Institute of Technology
University of California at Berkeley
University of Wisconsin at Madison
Westinghouse

Chinese Design Similar
Other Teams Have Variants

New Reactor Combines Old Technologies



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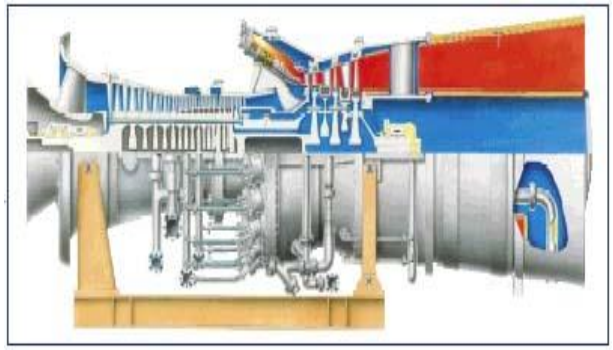
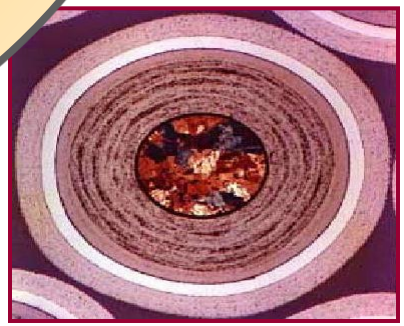


GE Power Systems MS7001FB

Brayton Power Cycles



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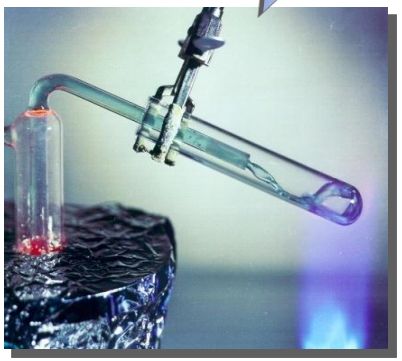


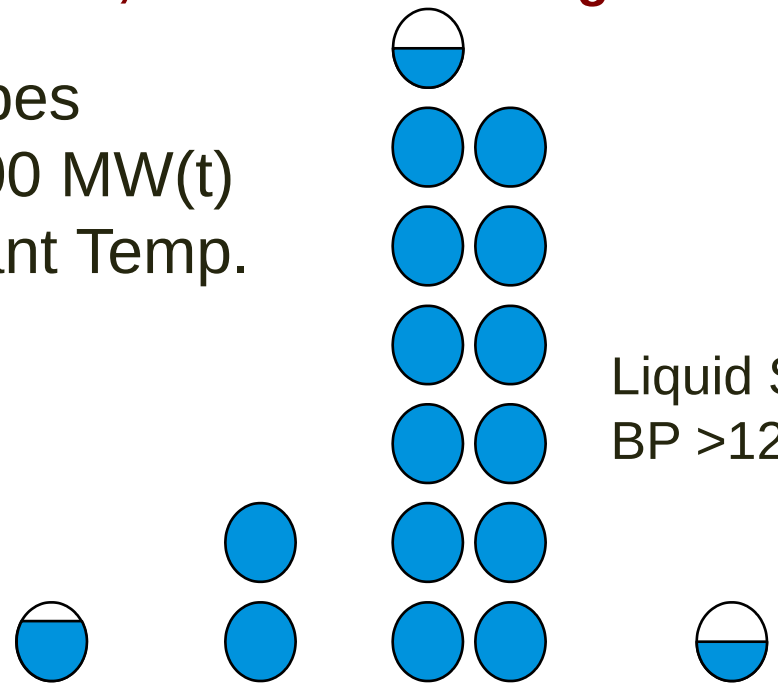
High-Temp., Low-Pressure Liquid-Salt Coolant (Transparent)

Salt Coolant Properties Can Reduce Equipment Size and Thus 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)

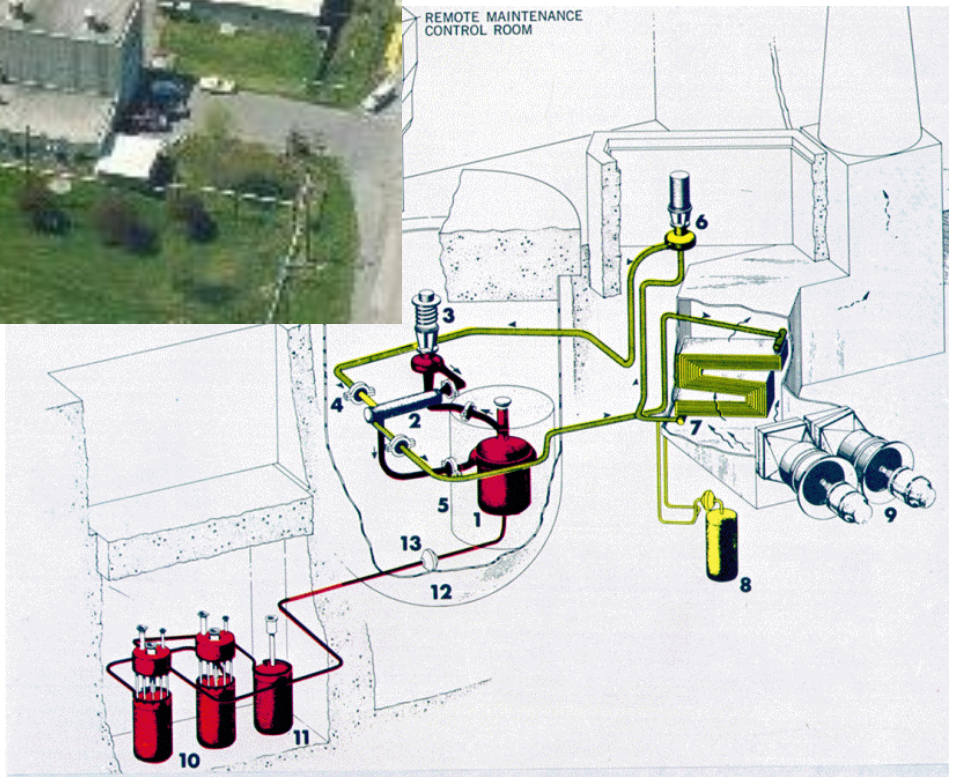
Physical Properties of Coolants

Coolant	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m³)	C_p (kJ/kg °C)	ρC_p (kJ/m³ °C)
Li_2BeF_4 (Flibe)	**459**	**1430**	**1940**	**2.42**	**4670**
59.5NaF-40.5ZrF_4	500	1290	3140	1.17	3670
26LiF-37NaF-37ZrF_4	436		2790	1.25	3500
31LiF-31NaF-38BeF_2	315	1400	2000	2.04	4080
8NaF-92$NaBF_4$	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-$NaBF_4$ system must be pressurized above 700°C; however, the salt components do not decompose. Pressurized water data are shown at 290°C for comparison.

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

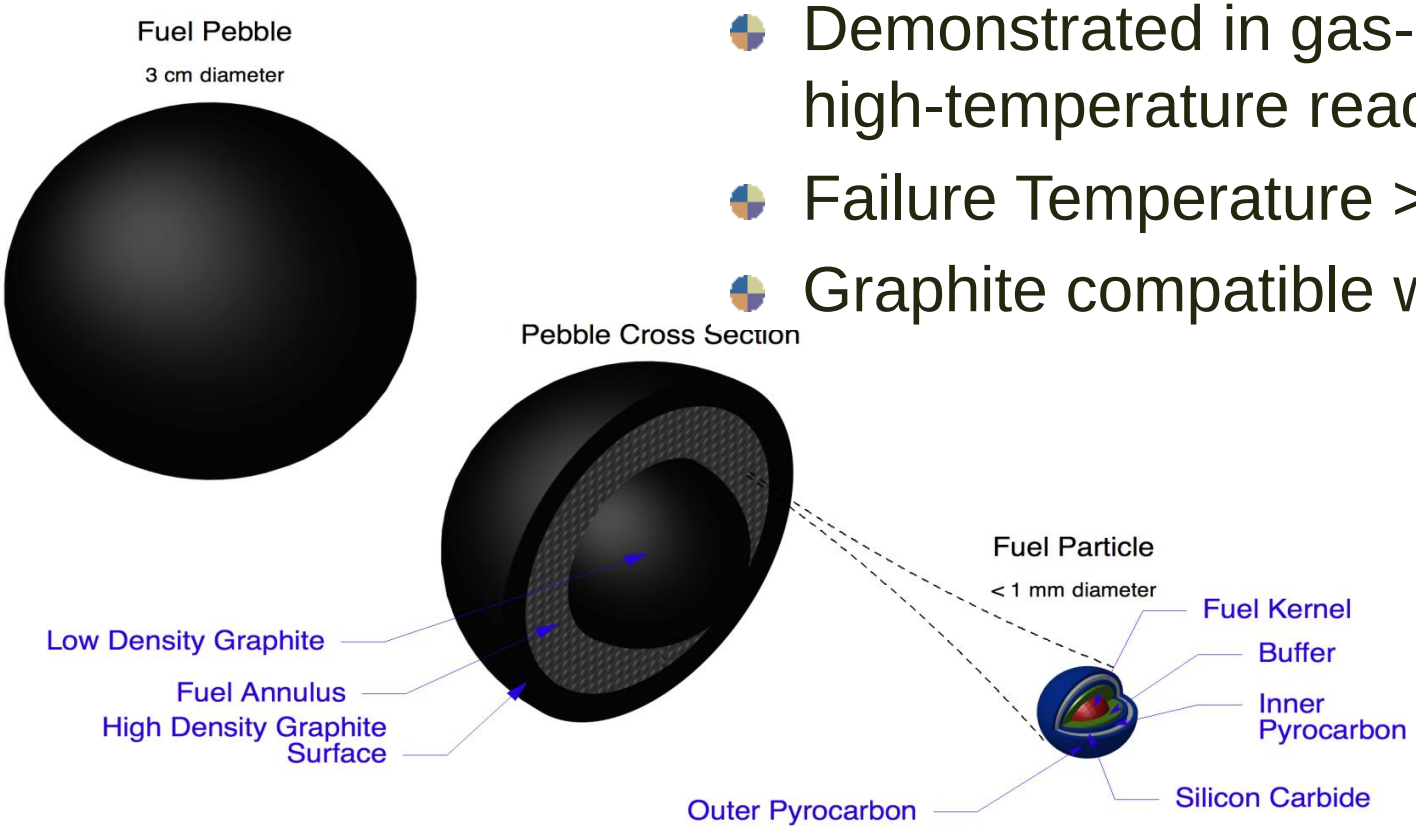
Fuel Dissolved in Salt; Much of this Work Directly Applicable to FHR



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.

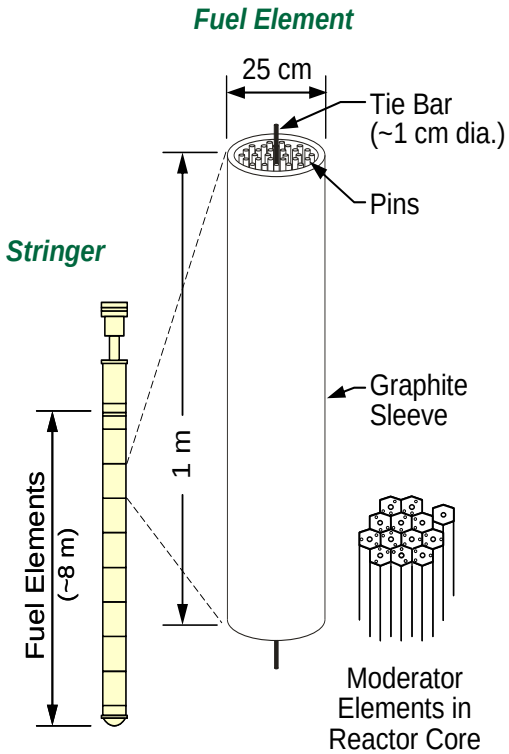
FHR Uses Graphite-Matrix Coated-Particle Fuel

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



Liquid Coolant Enables Increasing Core Power Density by 4 to 10

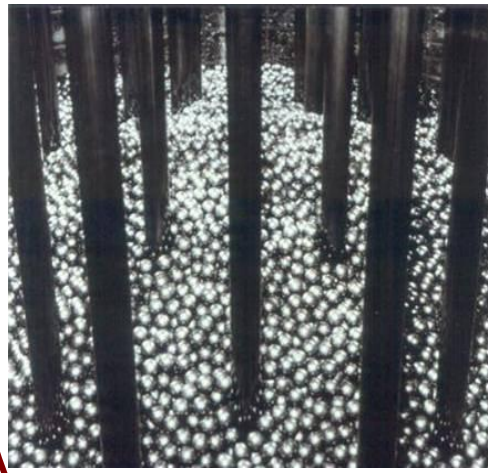
Many Fuel Options



Pin Assembly in Graphite Pile

Flat Fuel Plates in Hex Configuration

Base Case



Pebble Bed

- Pebble bed: Current technology
- Flat fuel: Existing materials, new design
- Pin assembly: New materials

Advantages / Disadvantages of Fuel Options

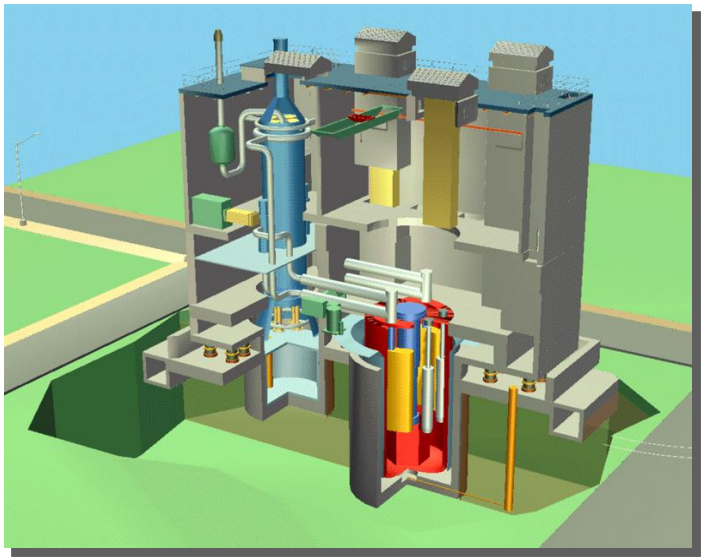
- Pebble bed
  - Graphite-matrix coated-particle fuel
  - Used in helium-cooled reactors
  - **Demonstrated and Available: Base Case Choice**
- Flat fuel plates in hex configuration
  - Graphite-matrix coated-particle fuel
  - New fuel geometric form, old materials
- Pin assembly in graphite pile
  - Conventional fuel in SiC clad
  - Salt-cooled version of British Advanced Gas-Cooled Reactor
  - SiC clad only partly developed—major unresolved questions

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

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

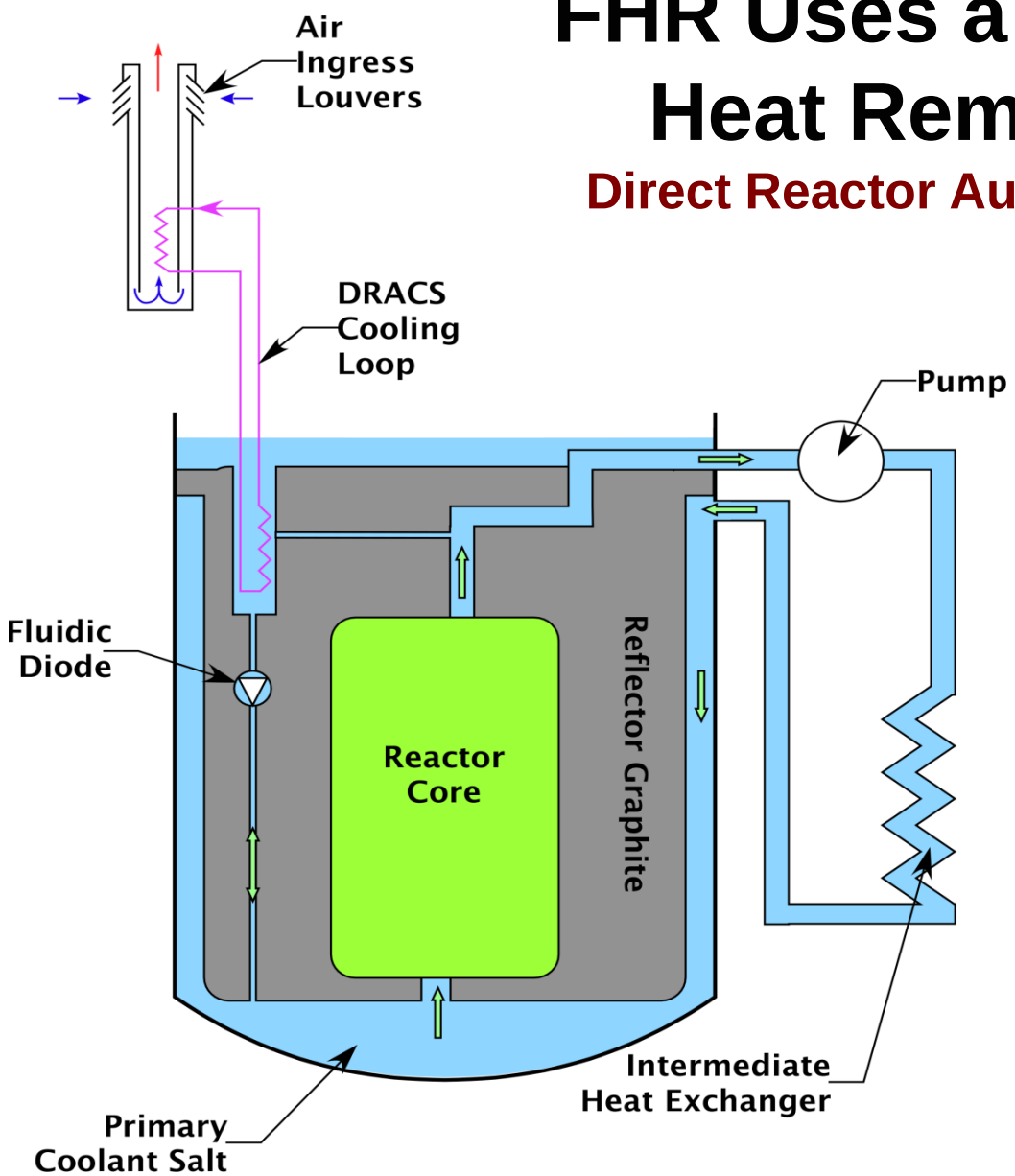


General Electric

S-PRISM

FHR Uses a Passive Decay Heat Removal System

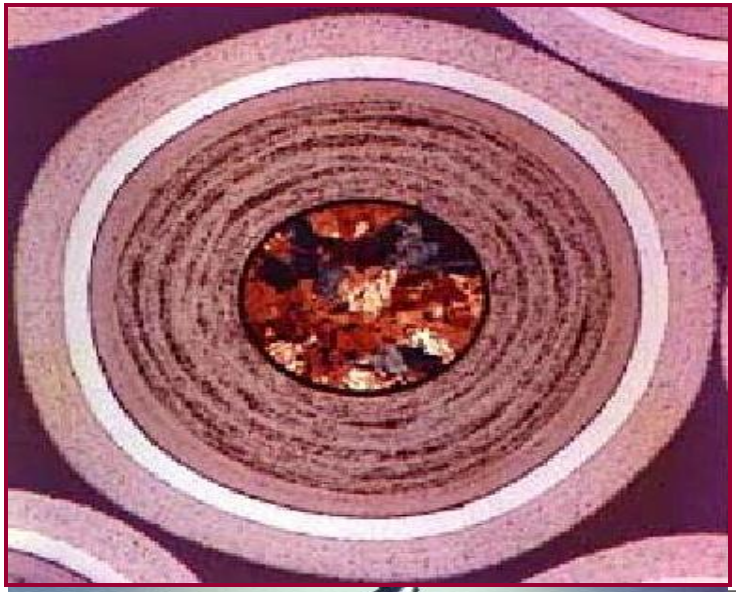
Direct Reactor Auxiliary Cooling System

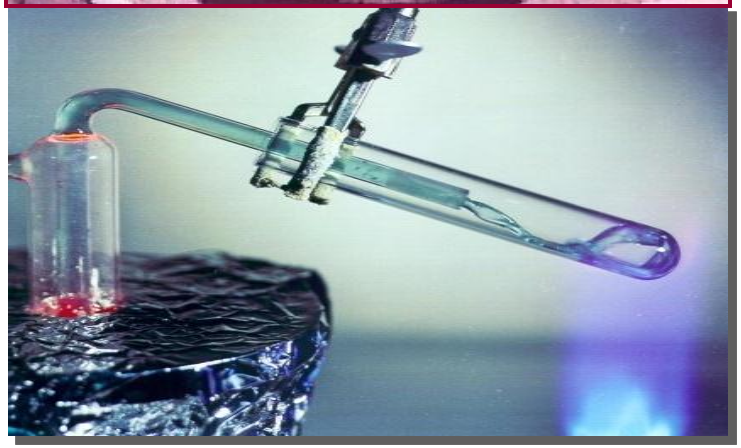


- No moving parts fluidic diodes exhibit high resistance to flow in one direction
- Upon pump shut down, natural circulation salt dumps heat to DRACS

High-Temperature Fuel and Coolant Alters Safety Limits

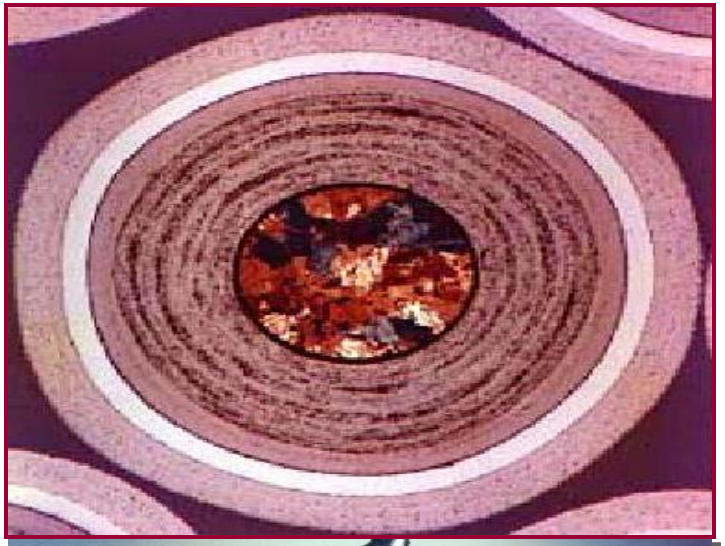
- Safety limit LWR: fuel clad failure from high temp.
- Safety limit SFR: void coefficient from boiling coolant with power surge
- Safety limit HTGR: high-temperature fuel failure
- FHR limits not well defined
  - Metal component failure
  - Bulk temperature limit

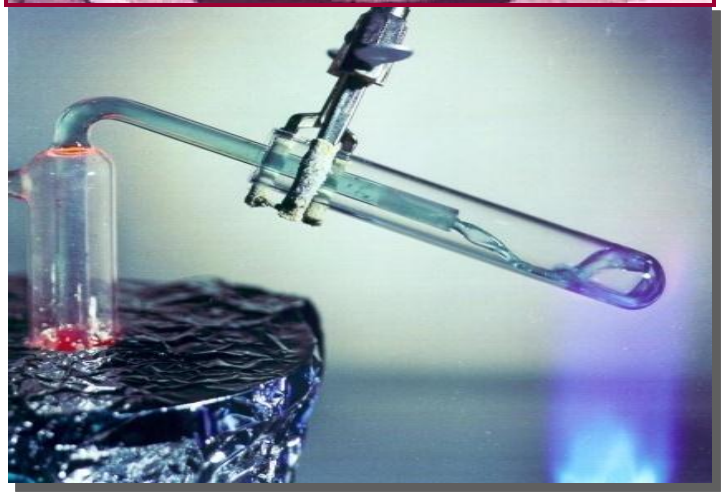




FHR Accidents May Not Damage Core

- Fuel failure ~1650° C
  - Iron melts at 1535° C
  - Nominal peak~800° C
- Coolant boiling ~1430° C
  - Nominal peak ~700° C
- Vessel: <1200° C
  - **Vessel failure before fuel damage**
- Different than any other reactor and not fully understood

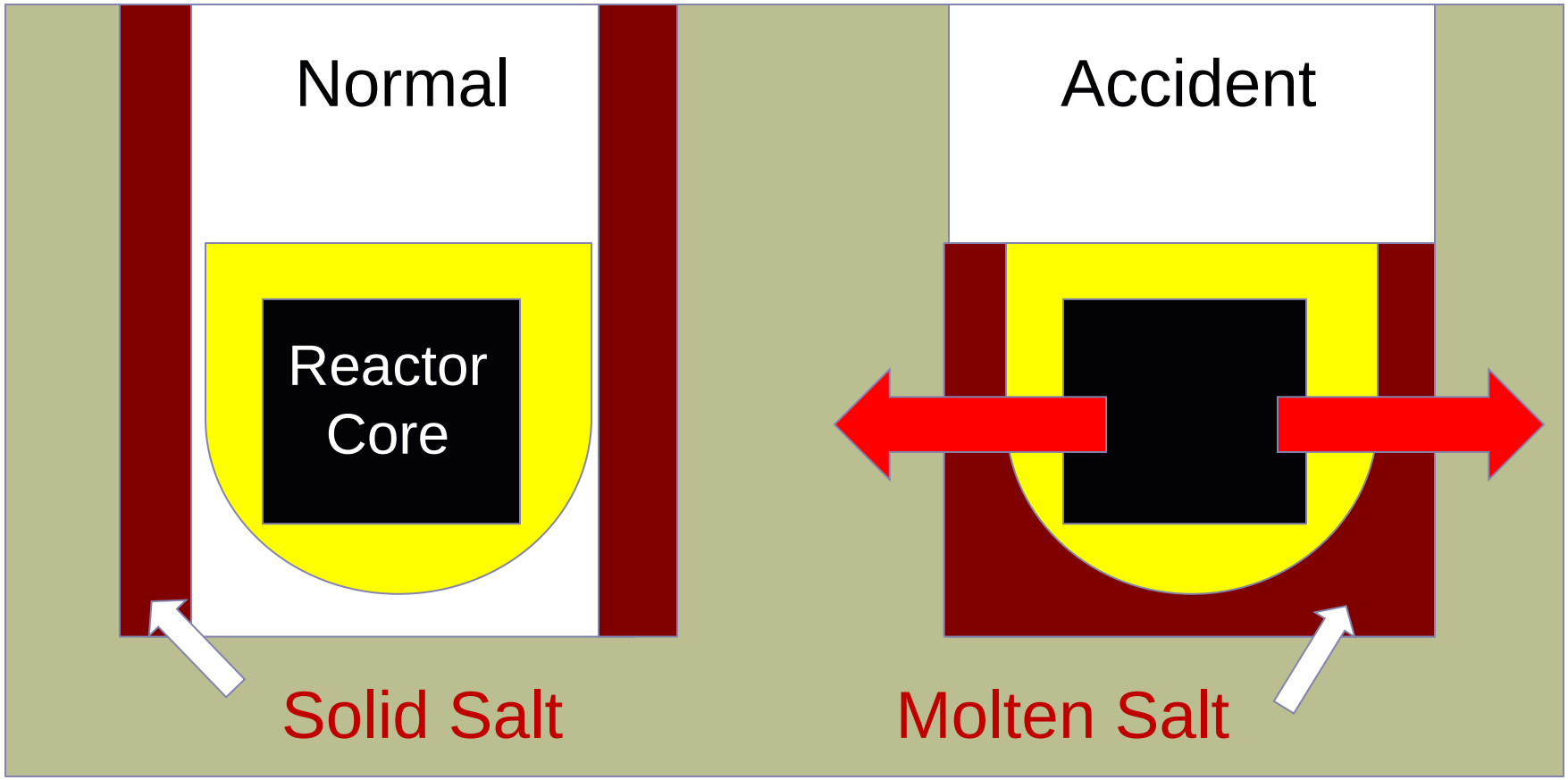




In core feedback: higher temperatures yield negative Doppler with power drop, lower salt viscosity with higher flows and T^4 radiation heat transfer

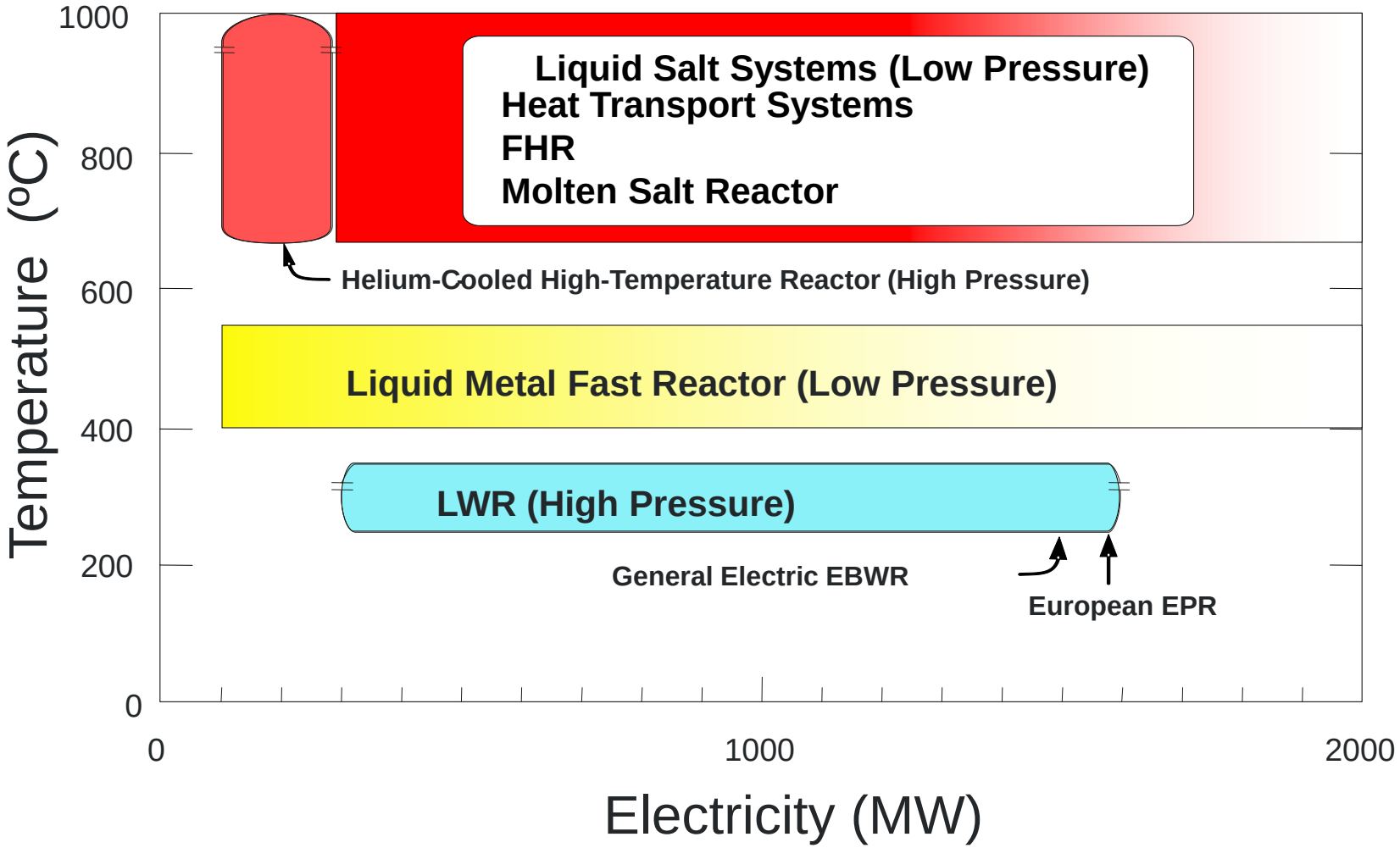
FHR High-Temperature Capabilities May Eliminate Offsite Accident Impacts

If Severe Accident, Silo Structure Conducts Decay Heat
To Ground Below Temperatures of Major Fuel Failure



Severe Accident Destroys Reactor But No Large Radioactive Releases Even If Large-Scale Structural Failures

Salt Coolants Imply High-Temperature High-Efficiency Power Cycles



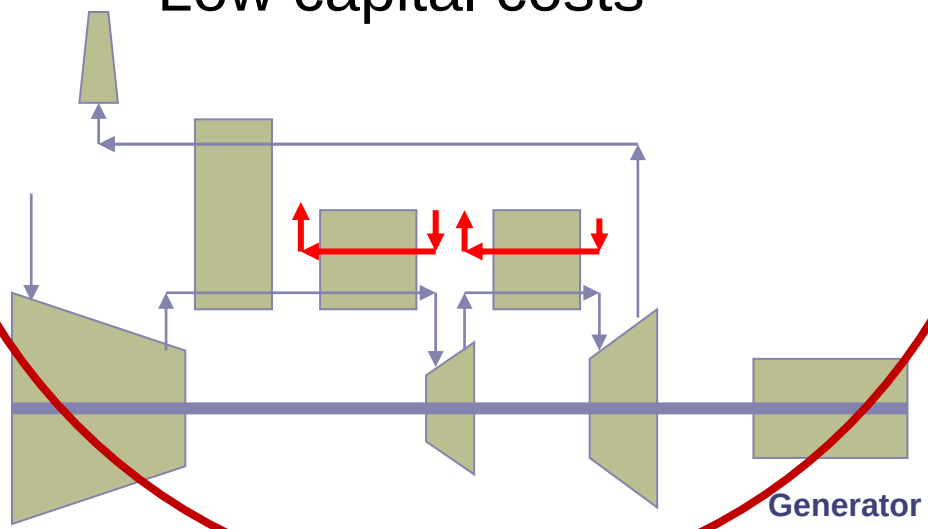
FHR for Electricity

- 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

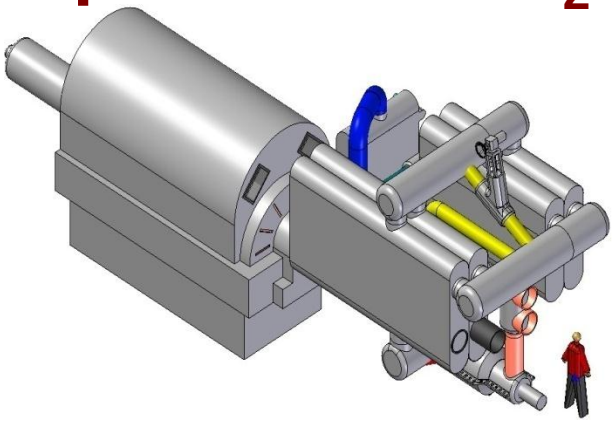
Power Cycle Options with 700° C Salt

Base Case
Air Brayton Cycle

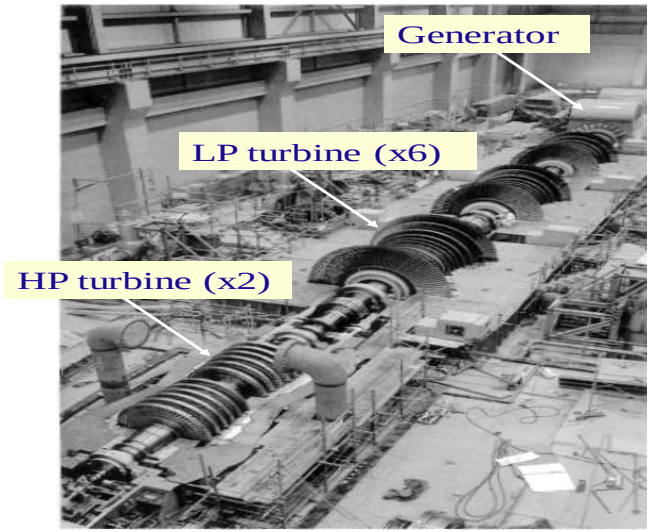
- Air Brayton cycle based on natural gas turbine
- Dry cooling
- Low capital costs



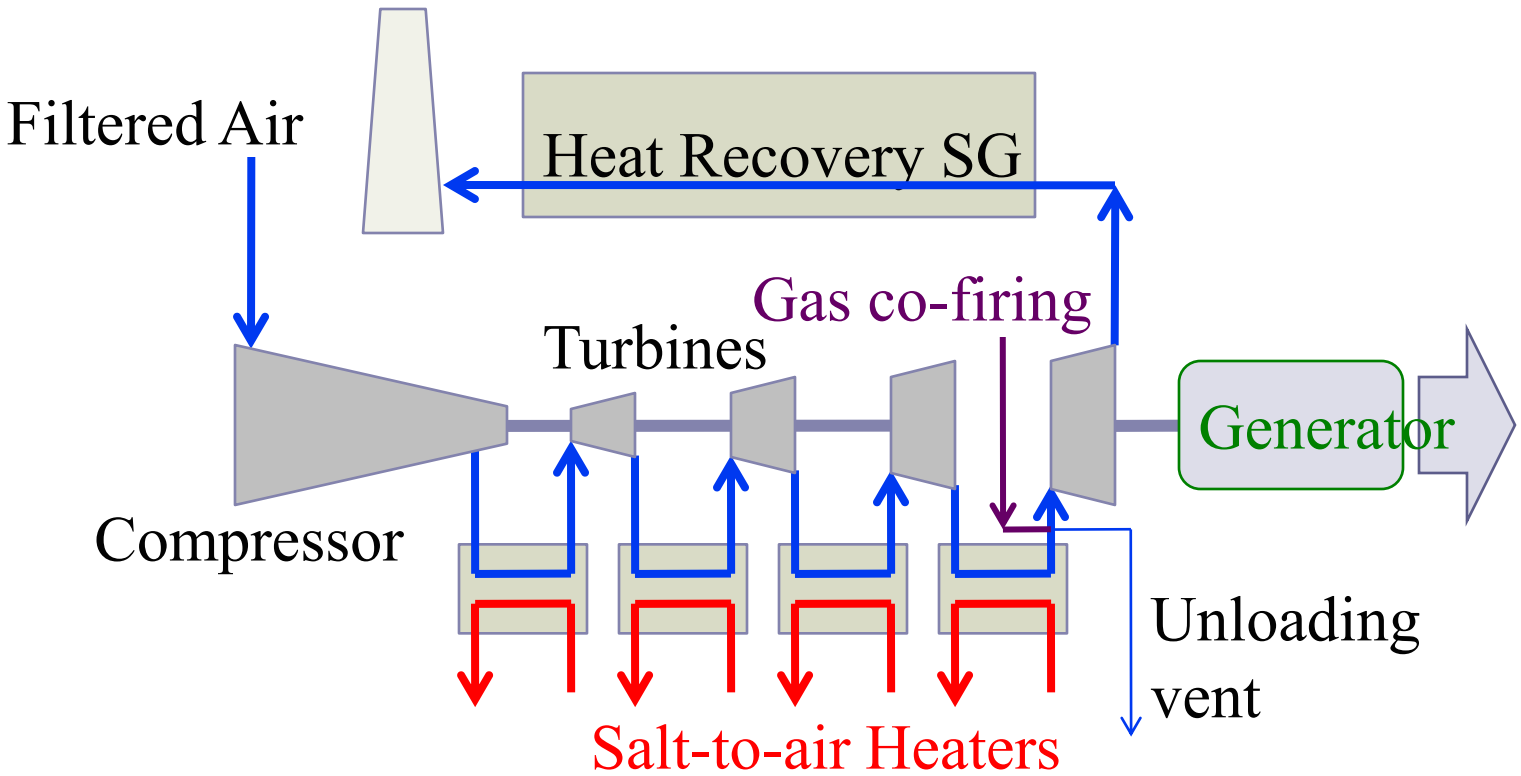
Supercritical CO_2



Steam



Open-Air Brayton Combined Cycle



- **Use conventional, commercial compressor**
  - (GE, Siemens, Mitsubishi have 400 MWt appropriate designs)
- Efficiency 47%
- Base-load with natural gas (NG) peak-power option

Combined Nuclear and Natural-Gas Combined-Cycle Power System Option

- At 700° C two operating modes
  - Base-load nuclear (47%)
  - Base-load nuclear with natural gas (NG) peaking
  - Very long-term option: hydrogen rather than NG
- Inject natural gas after hot-salt heating for variable power output
  - Low capital cost peaking unit because front end compressor unchanged—only turbines and boiler
  - Potentially more efficient than natural-gas Brayton cycle
- **Better economics: Major increase in plant revenue at low incremental cost**

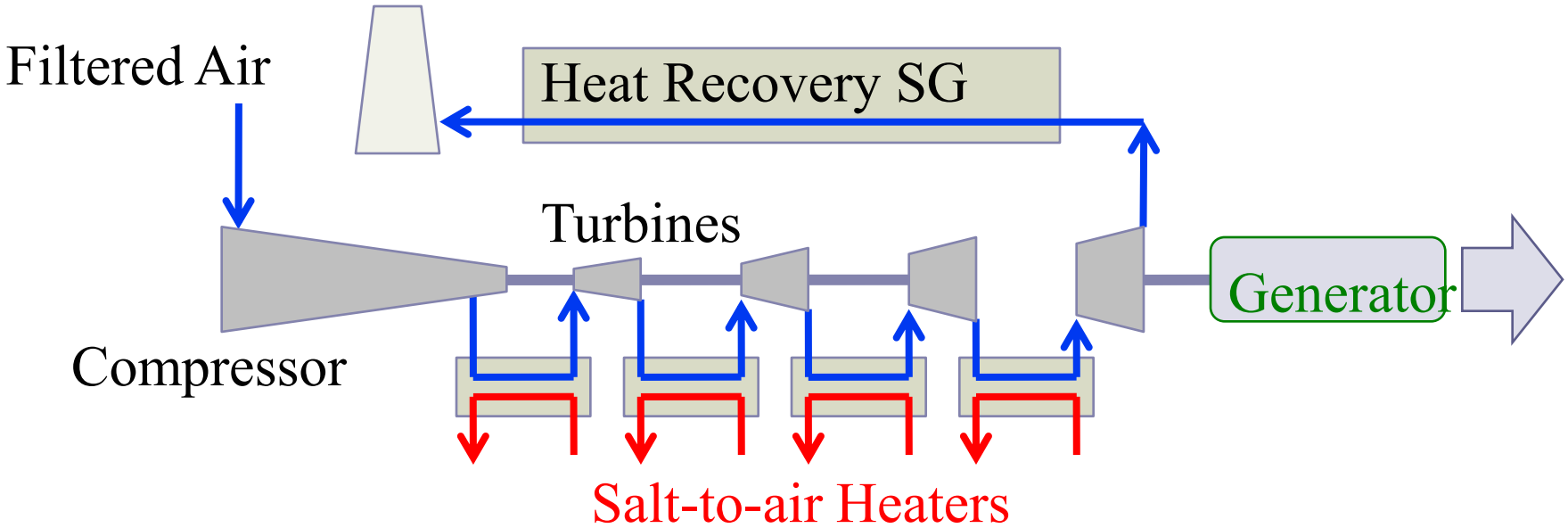
Only Salt-Cooled Reactors Couple to Air-Brayton Cycles

FHR and Molten Salt Reactor

- Air-Brayton compressor exit temperature >400° C
- Air-Brayton turbine temperature > 600° C
- Other reactors can't couple to air-Brayton cycles
  - Light-water reactor and sodium fast reactor peak temperatures are too low
  - High-temperature gas-cooled reactor minimum coolant temperature is too low (<400° C)

Unique Process Heat Capabilities

- Steam cycle separated from reactor by hot air: Air-Brayton to steam recovery system
  - No credible tritium transfer to steam
  - Steam cycle independent of reactor design
- >500° C (Shale oil, biofuels, etc.)



Current FHR plant design is compact compared to LWRs and MHRs

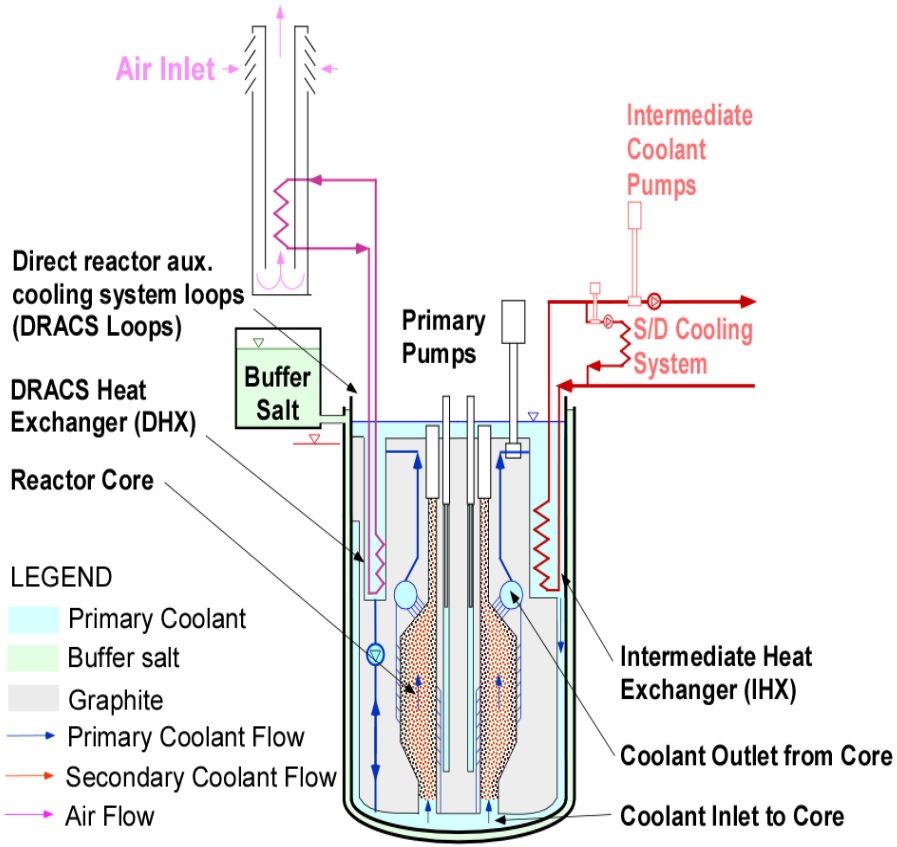
Reactor Type	Reactor Power (MWe)	Reactor & Auxiliaries Volume (m^3/MWe)	Total Building Volume (m^3/MWe)
1970's PWR	1000	129	336
ABWR	1380	211	486
ESBWR	1550	132	343
EPR	1600	228	422
GT-MHR	286	388	412
PBMR	170	1015	1285
Modular FHR	**410**	**98**	**242**

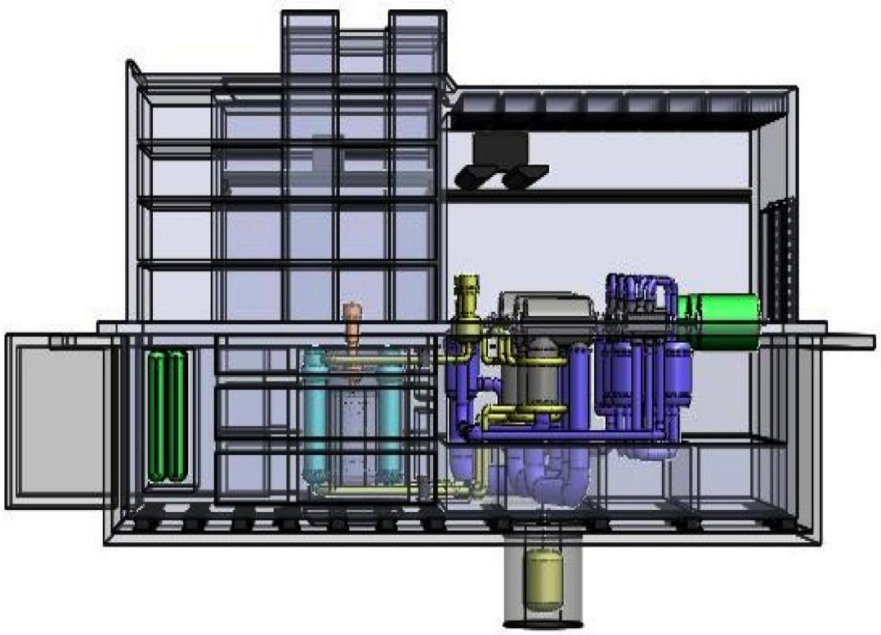
Potentially Competitive Economics

Conclusions

- No FHR has ever been built: new concept
- Rapid growth in interest: Small reactor to be built by the Chinese Academy of Sciences
- Combines existing technologies with changes
  - Gas-cooled reactor coated-particle fuel—but at higher power densities, lower temperatures and salt coolant
  - Clean molten (liquid) salt reactor coolant—but previous experience in MSR with fuel dissolved in coolant: both with high melting point coolants
  - Fast reactor safety systems—but with a high melting-point coolant
  - Power cycles—but at 700 C

Questions


Air Inlet
Intermediate Coolant Pumps
Direct reactor aux. cooling system loops (DRACS Loops)
Primary Pumps
S/D Cooling System
Buffer Salt
DRACS Heat Exchanger (DHX)
Reactor Core
LEGEND
Primary Coolant
Buffer salt
Graphite
Primary Coolant Flow
Secondary Coolant Flow
Air Flow
Intermediate Heat Exchanger (IHX)
Coolant Outlet from Core
Coolant Inlet to Core



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

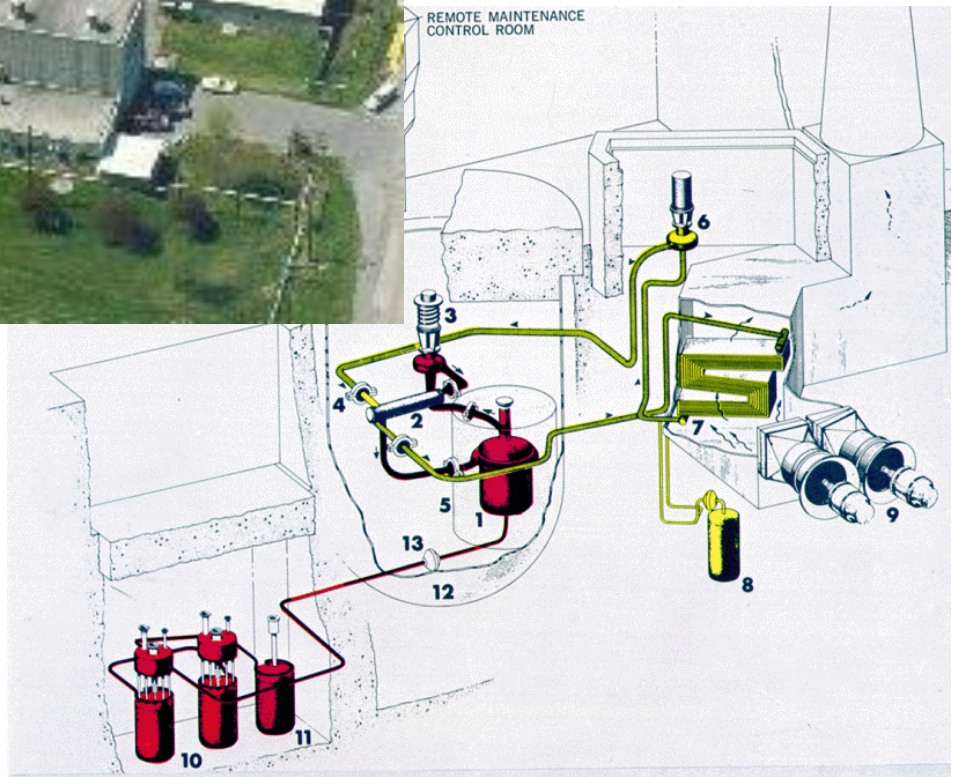
Coupled High-Temperature Salt Technologies

Multiple Salt-Cooled High-Temperature (700 C) Power Systems Being Developed With Common Technical Challenges

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: Much of this Work Directly Applicable to FHR



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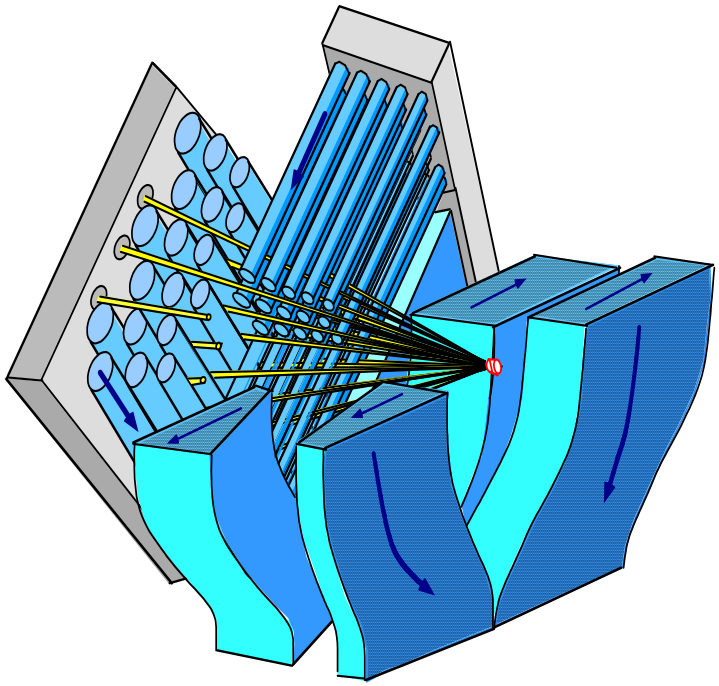
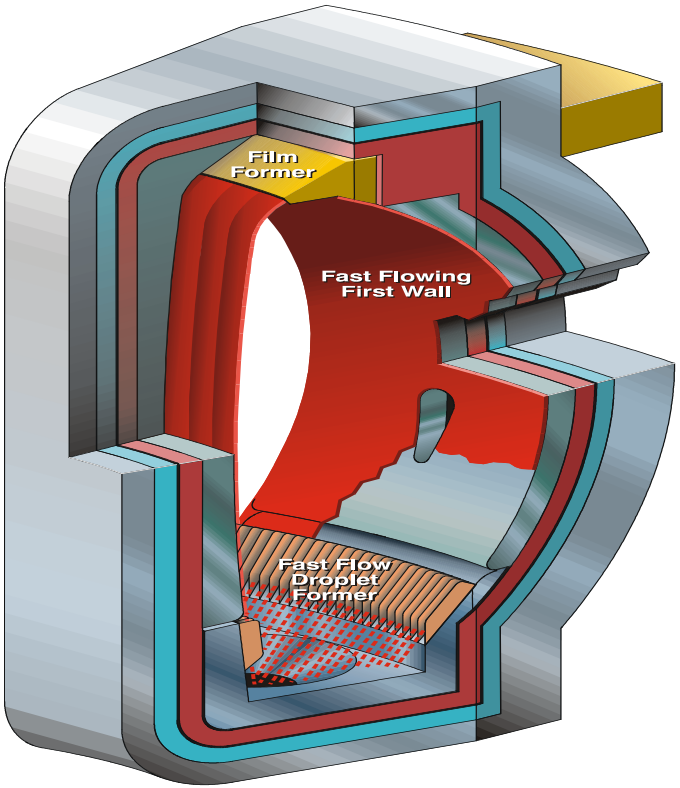
Salts Being Considered for Fusion

Fusion Requires ^{6}Li to Make Tritium Fuel



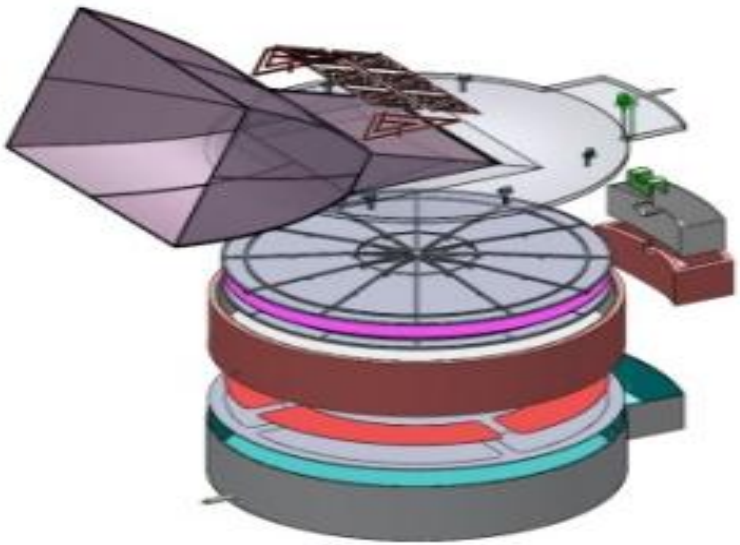
Heavy-Ion Inertial Fusion



Magnet Fusion Tokamak

High-Temperature Salts Being Considered for Solar Power Systems

- Same temperature range
- Same power cycles
- Similar development challenges
- Massive technology overlap



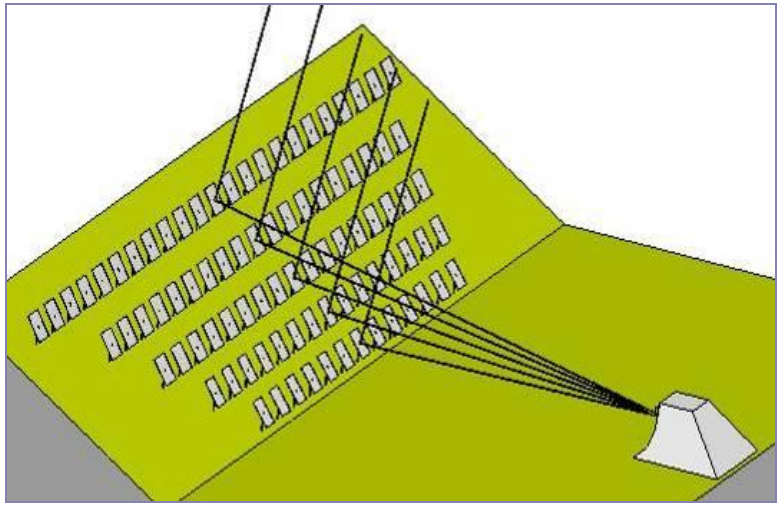
Concentrated Solar Power on Demand (CSPonD)

CSPonD Description

Figure Next Page

- Mirrors shine sunlight to receiver
- Receiver is a high-temperature liquid salt bath inside insulated structure with open window for focused light
  - Light volumetrically absorbed through several meters of liquid salt
  - Building minimizes heat losses by receiver
  - Enables salt temperatures to 900° C
- Small window minimizes heat losses but very high power density of sunlight through open window
  - Power density would destroy conventional boiler-tube collector
  - Light absorbed volumetrically in several meters in salt
- Requires high-temperature (semi-transparent) salt—Similar salt requirements as for FHR heat transfer loop

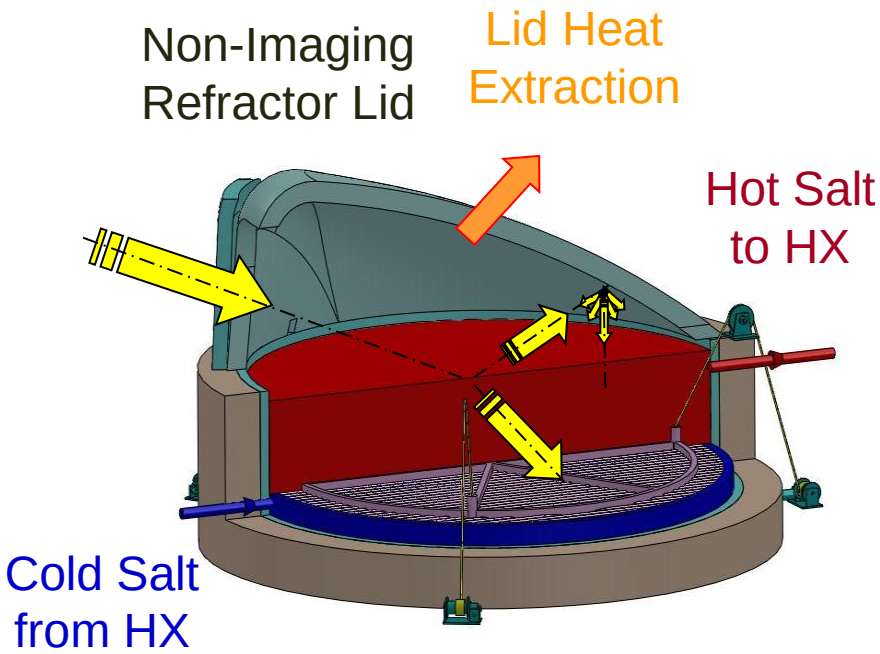
Two Component System



Light Reflected From Hillside Heliostat rows to CSPonD System

(Not to scale)

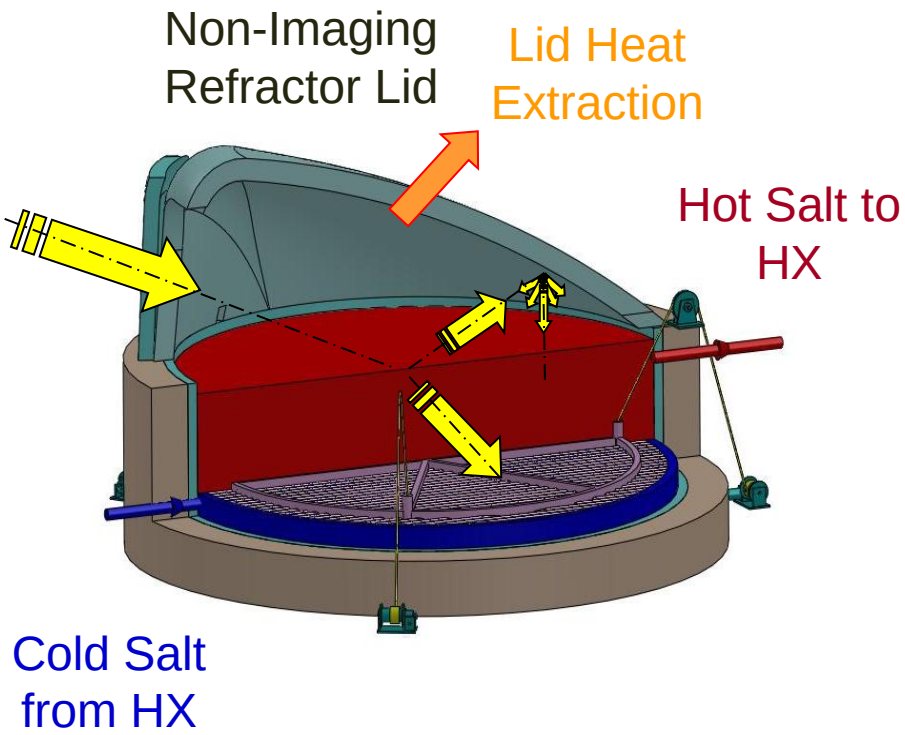
Flat Land Options Exist



Light Collected Inside Insulated Building With Open Window

CSPonD Heliostats Shine Light Through "Pinhole" into Liquid-Salt Collector

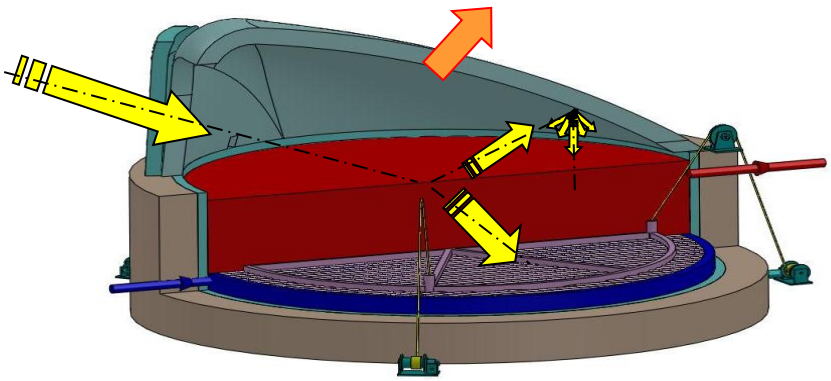
- Efficient light-to-heat collection
  - Concentrate light
  - Focus light through open window in insulated structure
  - Minimize heat losses
- Challenge
  - Light energy per unit area very high
  - Will vaporize solid collectors



Light Collected Inside Insulated Building With Open Window

Light Focused On "Transparent" Salt

- Light volumetrically absorbed through several meters of salt
- Molten salt experience
  - Metal heat treating baths (right bottom)
  - Molten salt nuclear reactor
- Advantages
  - No light-flux limit
  - No thermal fatigue
  - High efficiency
  - Energy storage



Like Ocean Absorption of Sunlight

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

FHR Research Activities

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

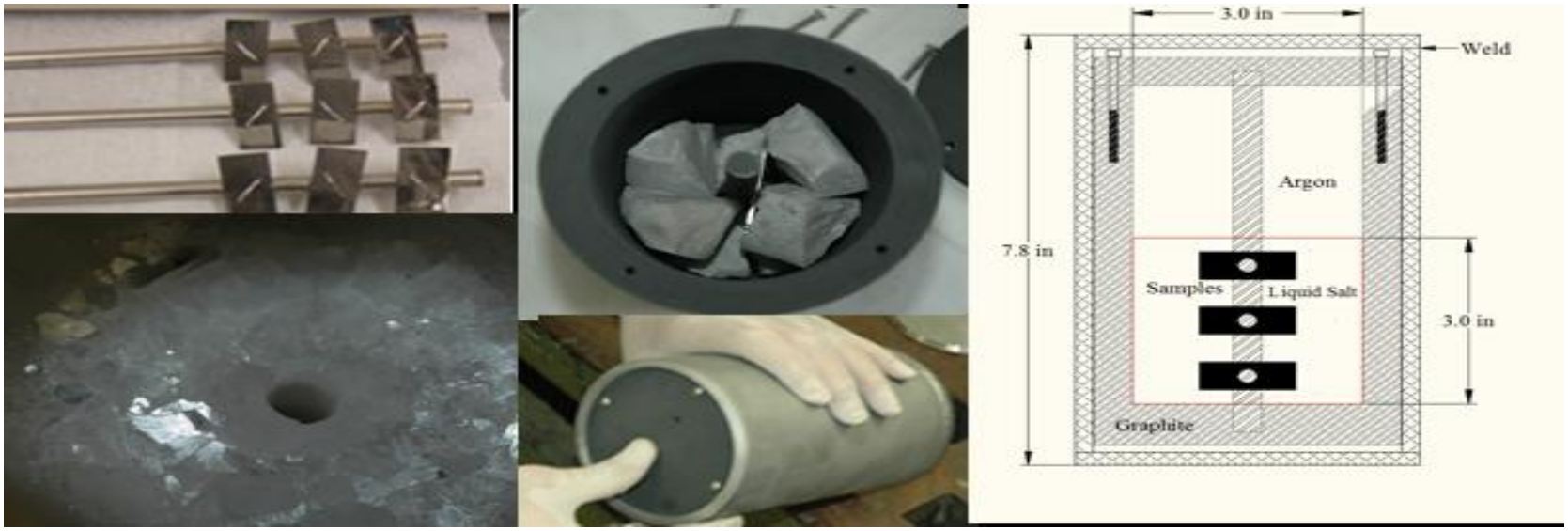
Idaho National Laboratory

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

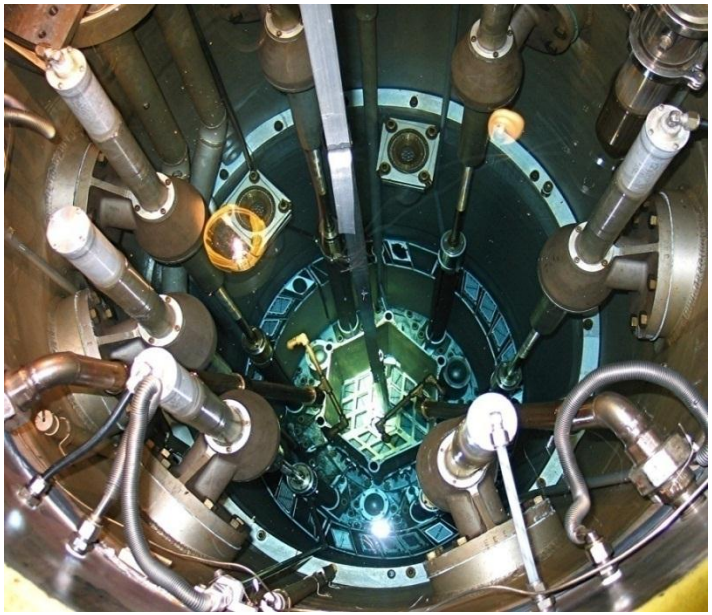
The University of Wisconsin Will Conduct Corrosion Tests

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

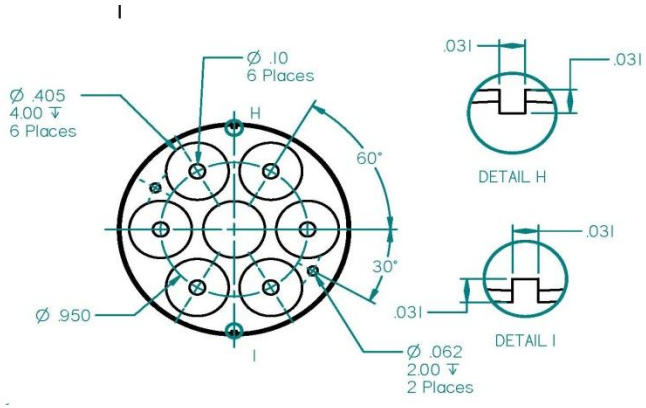


Materials Tests In MIT Research Reactor

6 MWt water cooled: 24/7 Ops



- In-core tests
  - In 700° C Flibe liquid salt
  - 1st low-temperature in-core safety tests completed
  - Exploratory: no previous data
- Test samples: 1st round
  - ZrO_2 surrogate coated-particles (corrosion salt inward)
  - SiC structural (corrosion)
  - Carbon (^3H uptake)



In-Core Capsule

UCB Conducting Thermal Hydraulics, Safety, and Licensing Tests

- Discovery: Dowtherm®-A (organic) can simulate hot salts cheaply at low temperatures and pressures
- Small experiments to simulate reactor thermal hydraulics
  - Unique to salt-cooled reactors
  - Potential for licensing-quality simulation in small laboratory
  - Massive cost / schedule savings
  - **Major implications for licensing**
- Analytical models to predict thermohydraulic behavior
- Support MIT irradiations

Can Laboratory Experiments Substitute for $10s Millions Multi-story Experiments?

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

- Loop specifications

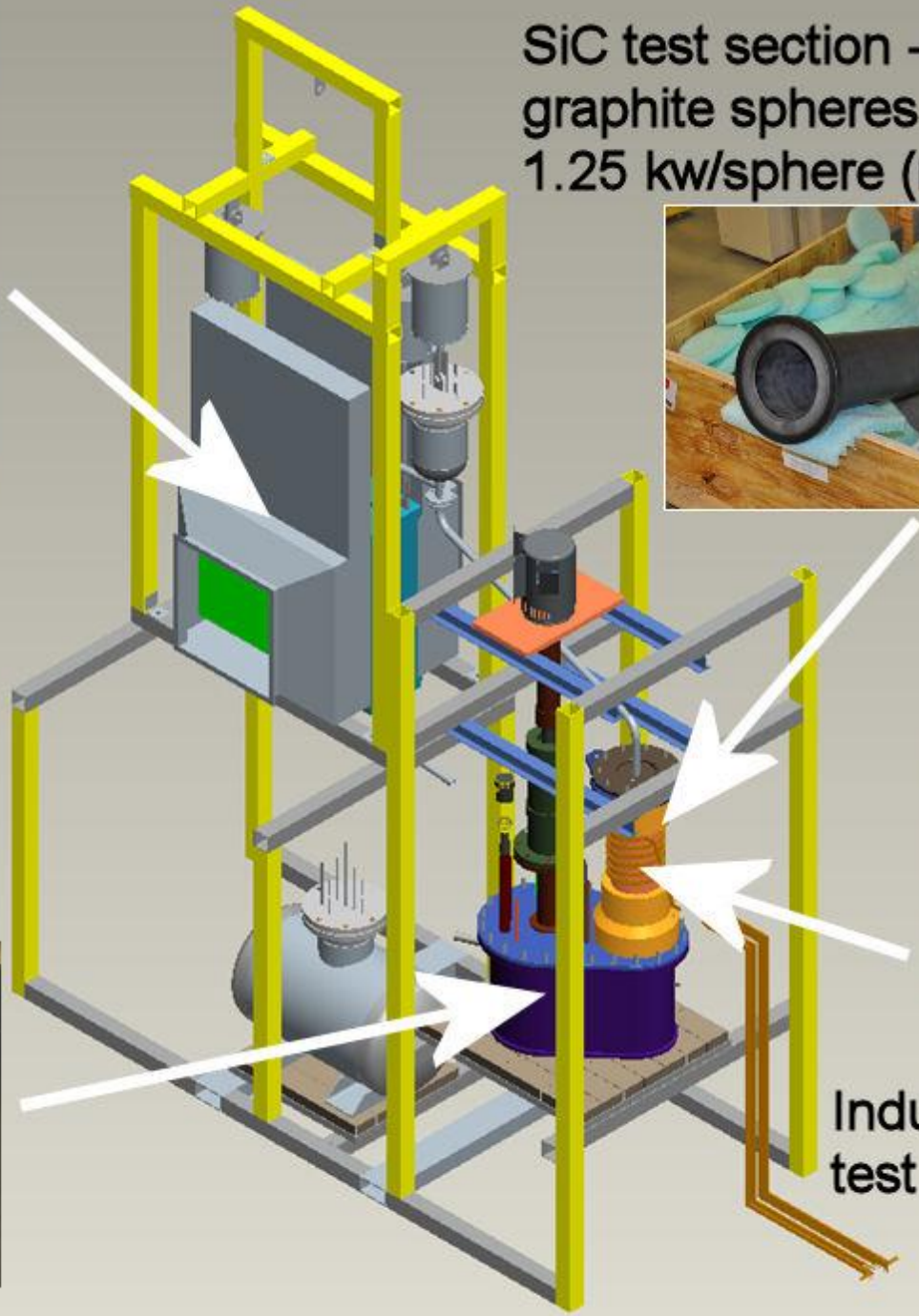
Salt	FLiNaK
Operating Temperature	700°C
Flow rate	4.5 kg/s
Operating pressure	atmospheric
Material of construction	Inconel 600
Loop volume	72 liters

- 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)



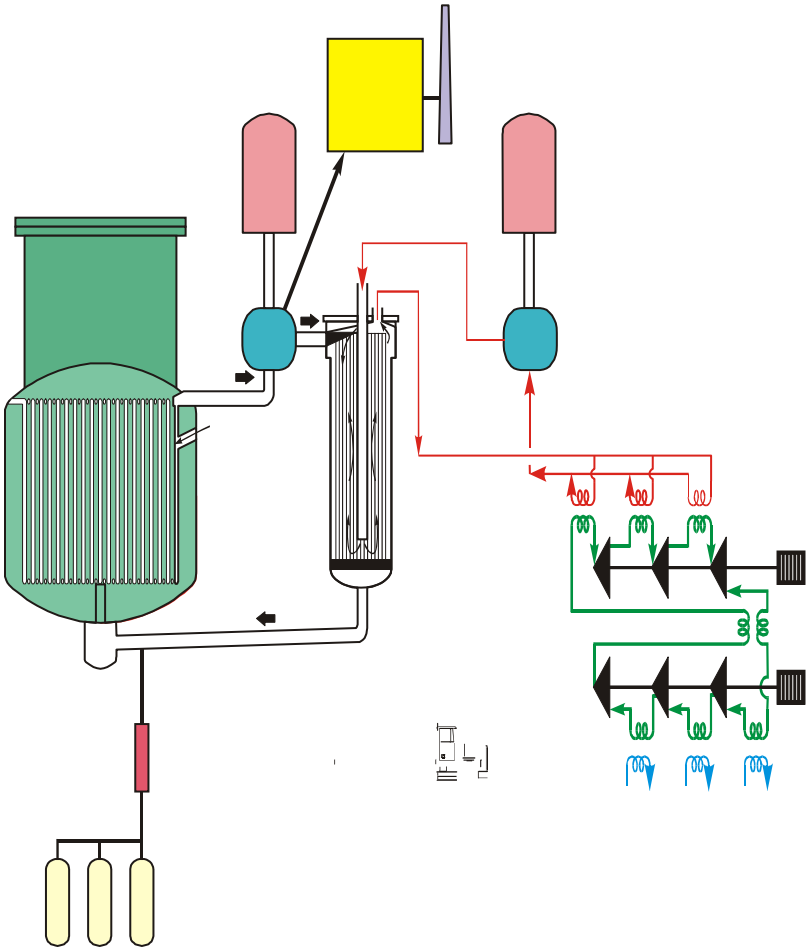
Overhung shaft Centrifugal sump pump

Inductive heating of test section - 200 kw

Work on Molten Salt Reactor

Fuel Dissolved in Salt: 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
  - FHR and MSR
  - Chinese Academy of Science
  - To 700 people in 3 years

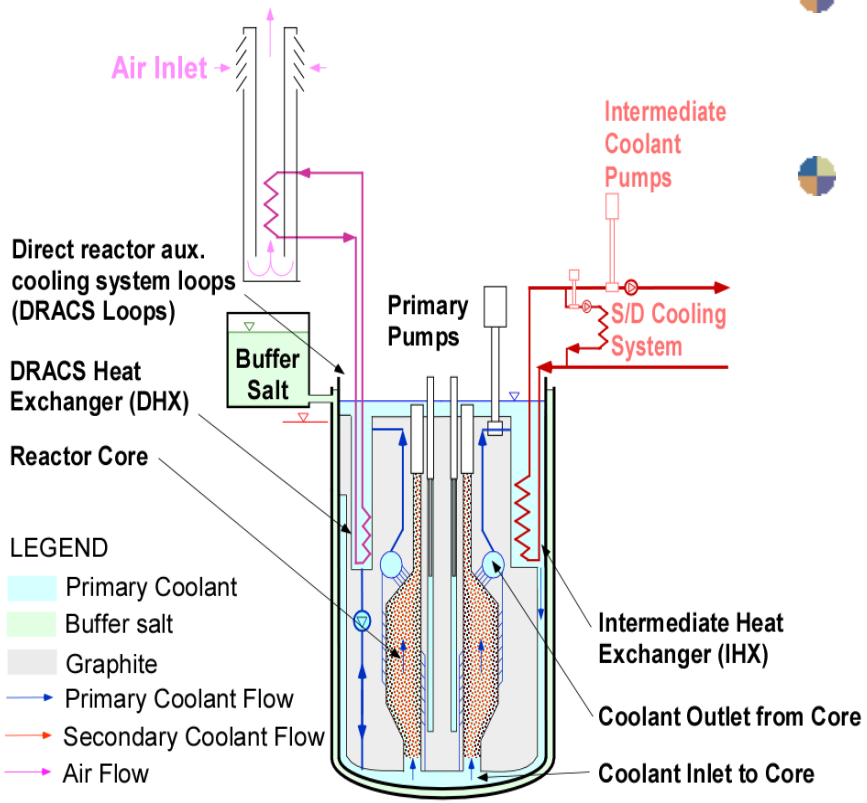


Chinese Academy of Science: 2 MWt FHR

- The CAS has decided to build two small salt reactors (April 12, 2012)
  - 2 MWt FHR (2015-2017)
  - 2 MWt MSR (2017-2020)
- Memorandum of Understanding Between the U.S. Department of Energy and the CAS
  - C. W. Forsberg university contact
  - CAS 2-MWt FHR could become a validation test for development of FHR

Added FHR Information

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



- Develop a path forward to a commercially viable FHR
- Goals
  - Superior economics (30% less expensive than LWR)
  - Limit severe accidents
  - 700° C for higher thermal efficiency and process heat
  - Better non-proliferation and waste characteristics
- Project start January 2012

FHR Core Design: Shutdown Options

- Doppler reactor shutdown on high temperature
- Conventional control rod system
  - Optional fusible link to drop control rods on high temperature
- Salt temperature-driven buoyancy control rods
  - Salt denser than graphite; build near neutral buoyancy control rods
  - If salt heats up, salt density decreases, rods drop
  - If neutral buoyancy 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 earth fluorides) with nickel-gold fusible link (like fire sprinkler systems)
  - Overheat and release to hot salt

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

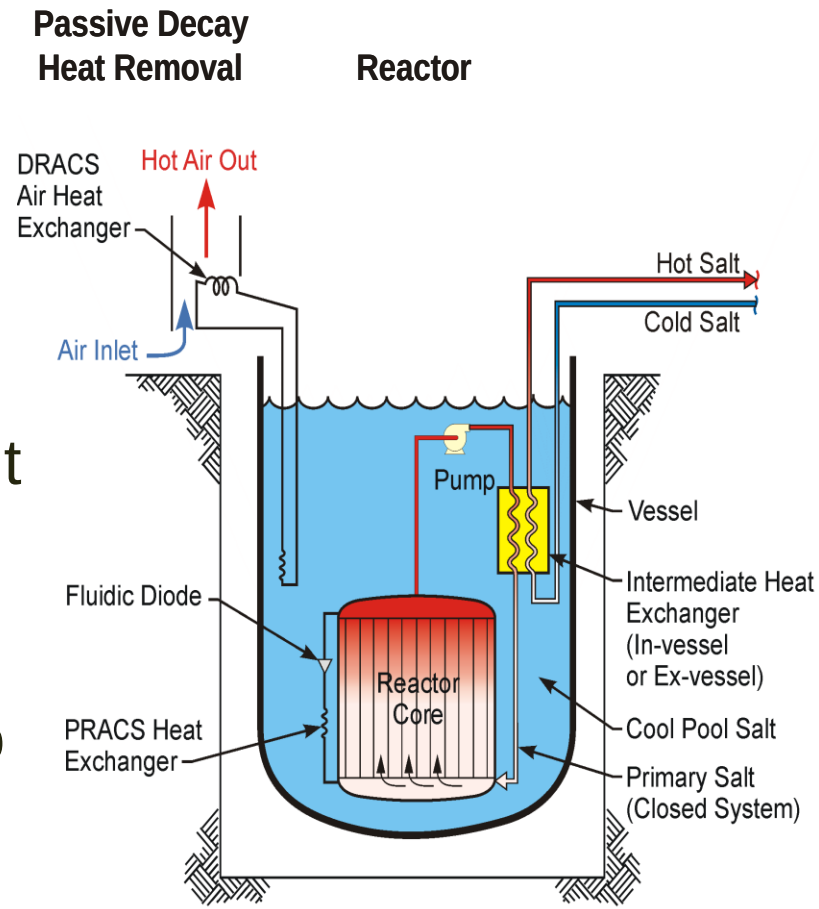
Is an Accident in the Core Possible?

	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	100° C?	>500° C

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

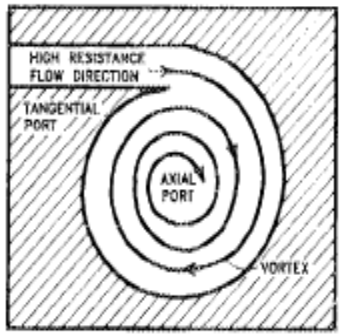
The FHR Primary System can be in a Secondary Tank Filled with Salt

- 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



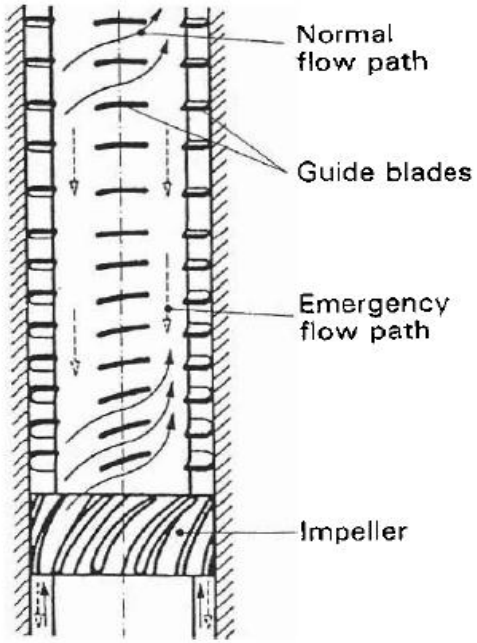
Fluidic Diodes Developed for German Fast Reactor and British Reprocessing Plants

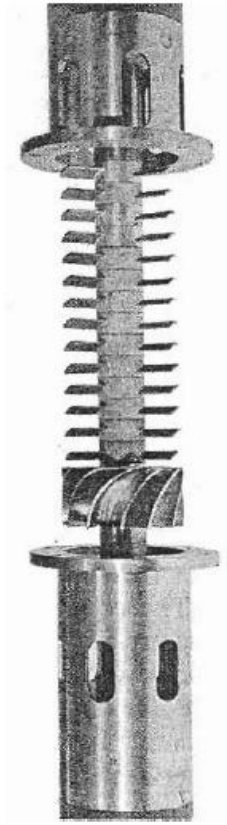
- No moving parts diodes exhibit anisotropic flow resistance
- Nuclear experience available
- Vortex diode chosen as target design (Large version used in MHI APWR and Korean AP-1400 Accumulators)



Conventional Vortex Diode

German fluidic diode for sodium (Fluid Rectifier Diode)

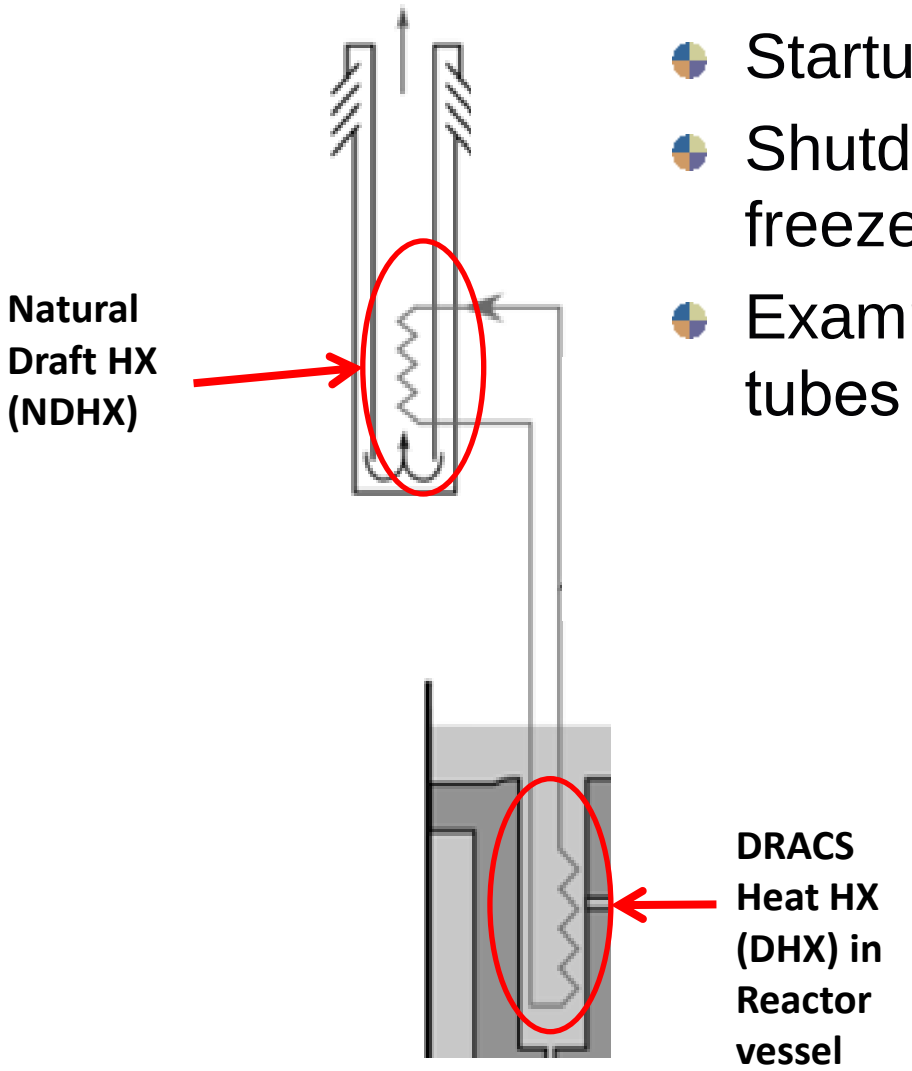


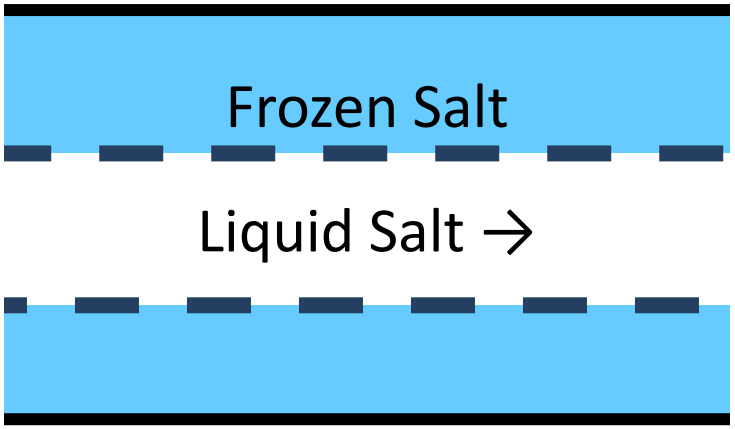


Roth fuss and F. Vogt, "Reactor Vessel Technology," *Nuclear Technology*, Vol. 78, pg. 245, 1987.

Examining Advanced DRACS

- No moving parts
- Startup if T>700° C
- Shutdown if T<500° C so do not freeze reactor-coolant salt
- Example: NDHX frozen-salt air-cooled tubes (normal operation ↓)

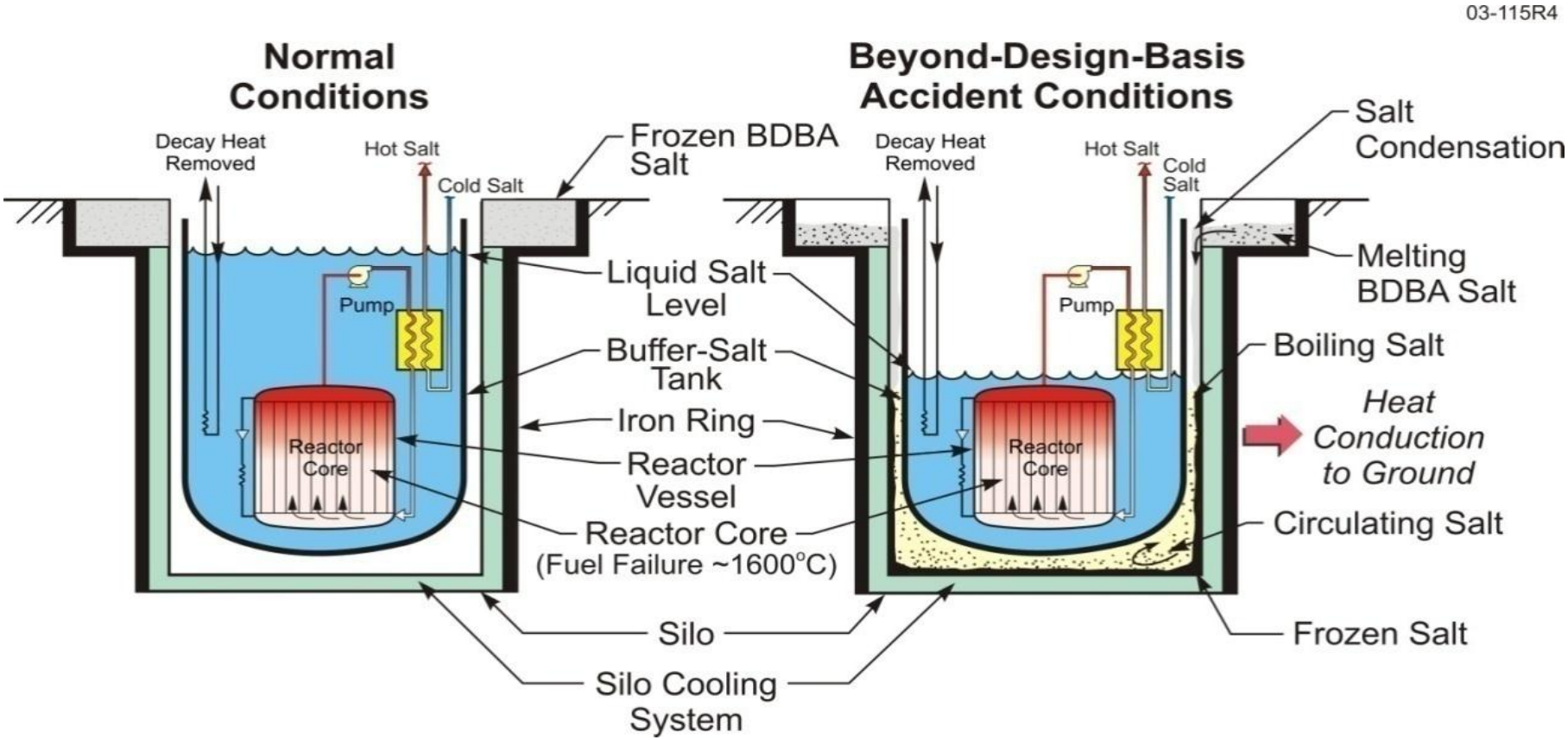




↑ Natural Air Circulation

Potential for Large Reactor That Can Not Have a Catastrophic Accident

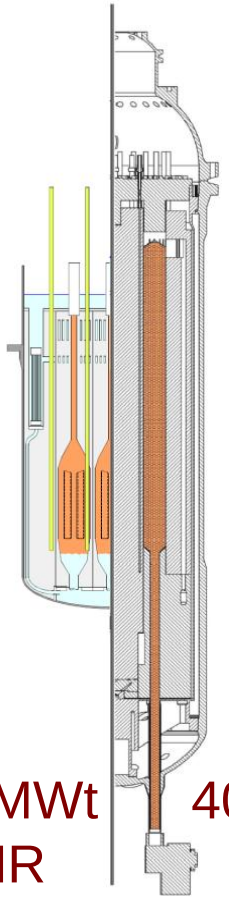
Large Temperature Drop to Conduct Heat To Ground



BDBA Salt Upon Melting Thermally Couples Reactor to Ground

FHR Cost Estimates Lower than Light-Water and Gas-Cooled High-Temperature Reactors

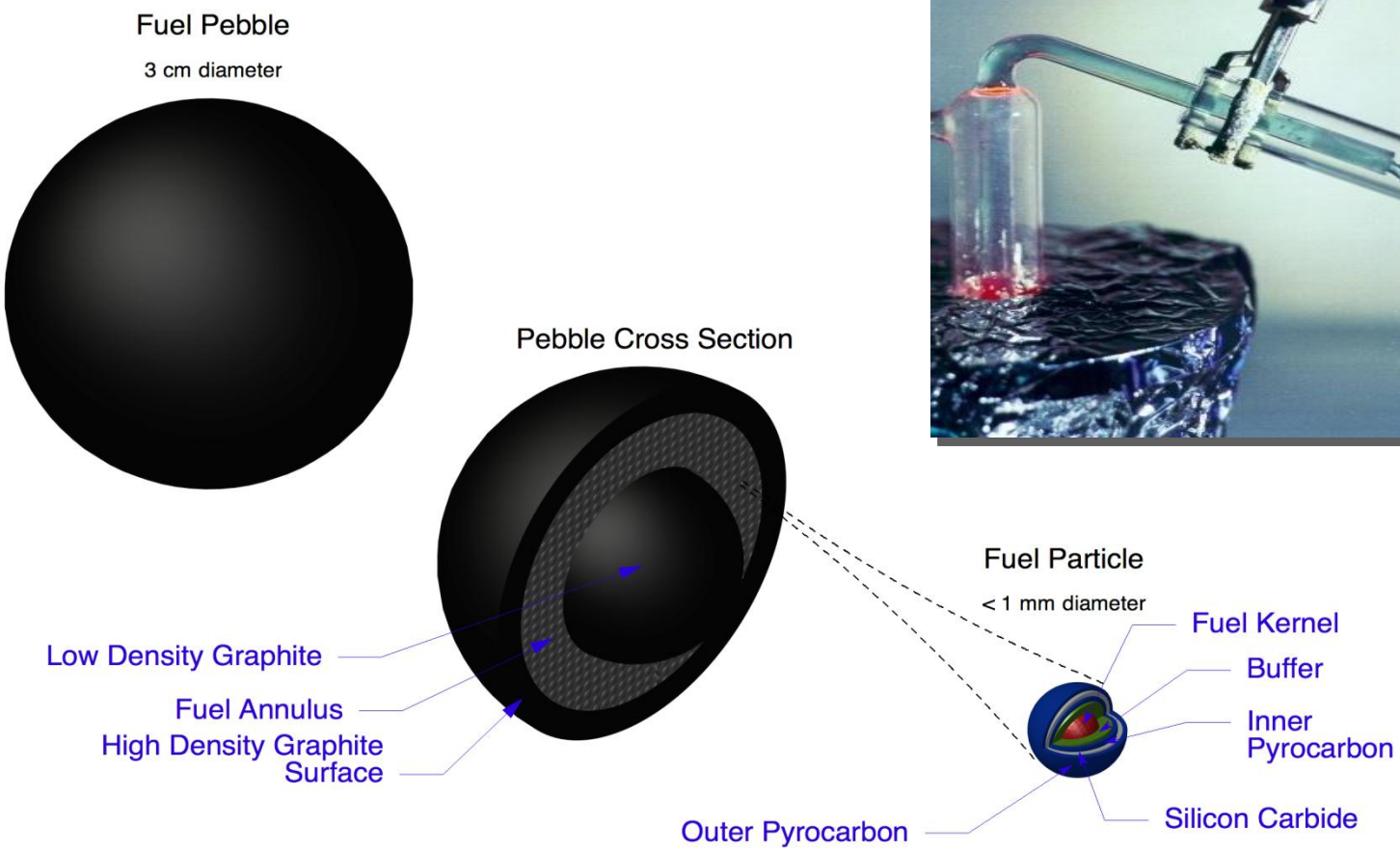
- Lower energy costs than Advanced Light Water Reactors (LWRs)
  - Primary loop components more compact than ALWRs per MWth
  - No stored energy source requiring a large-dry containment
  - Higher plant efficiency (40 to 50%)
  - Unanswered: Does the FHR size need to approach LWRs for superior economics
- Lower construction cost than high-temperature gas-cooled reactors

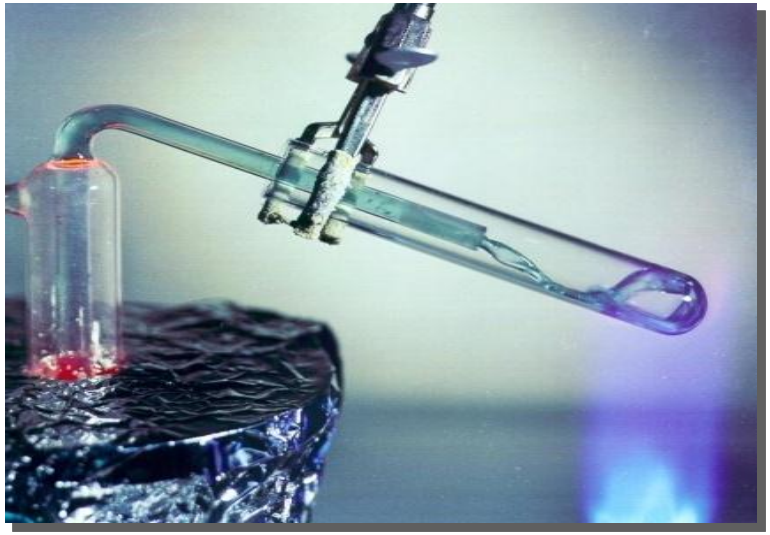


900 MWt FHR

400 MWt HTR

Salt Density Is Greater Than Fuel Density

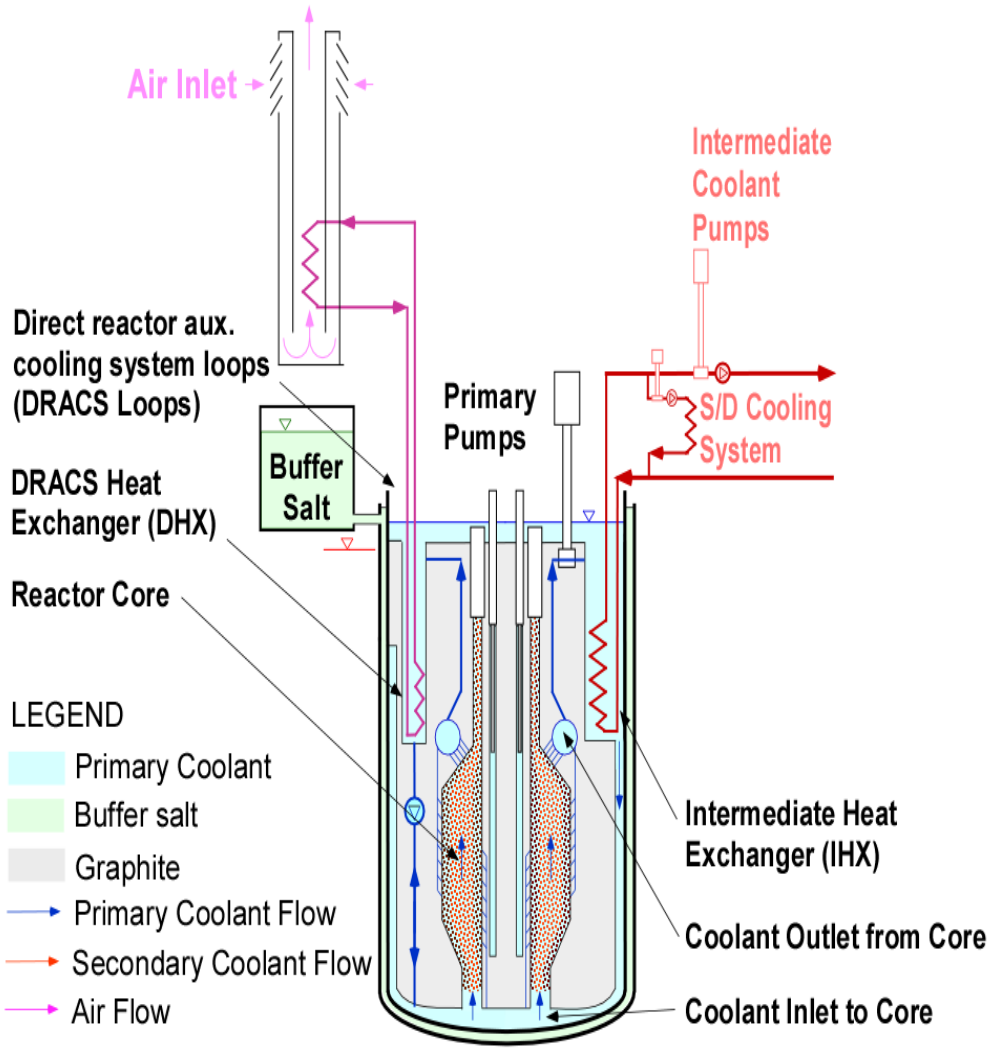




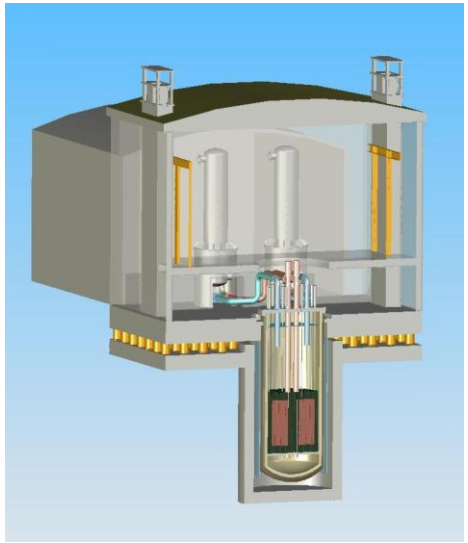
Fuel Floats !

Refueling Pebble Bed FHR

- 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



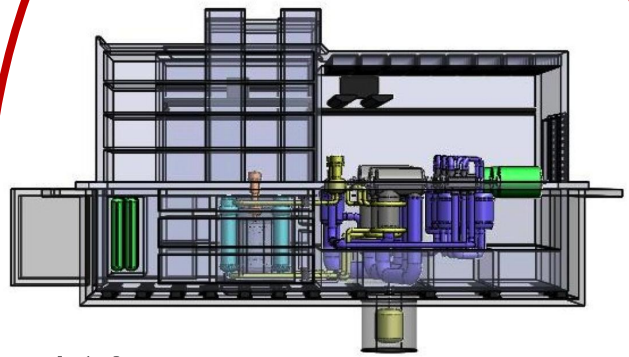
FHR Concepts Span Wide Power Range



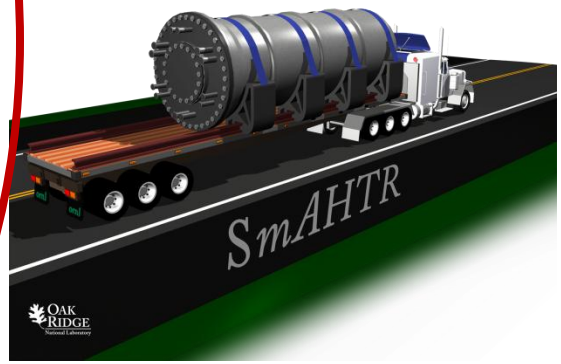
3400 MWt /

1500 MWe

Base Case



410 MWe
900 MWt



125 MWt/50 MWe