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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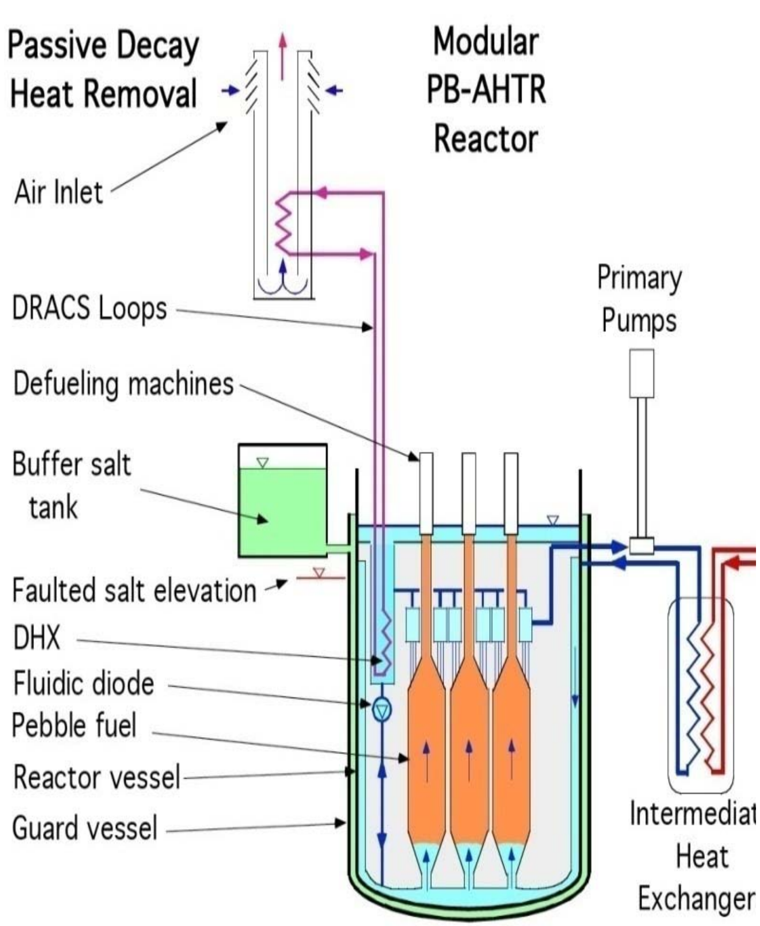
THE UNIVERSITY of WISCONSIN
MADISON

Outline

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

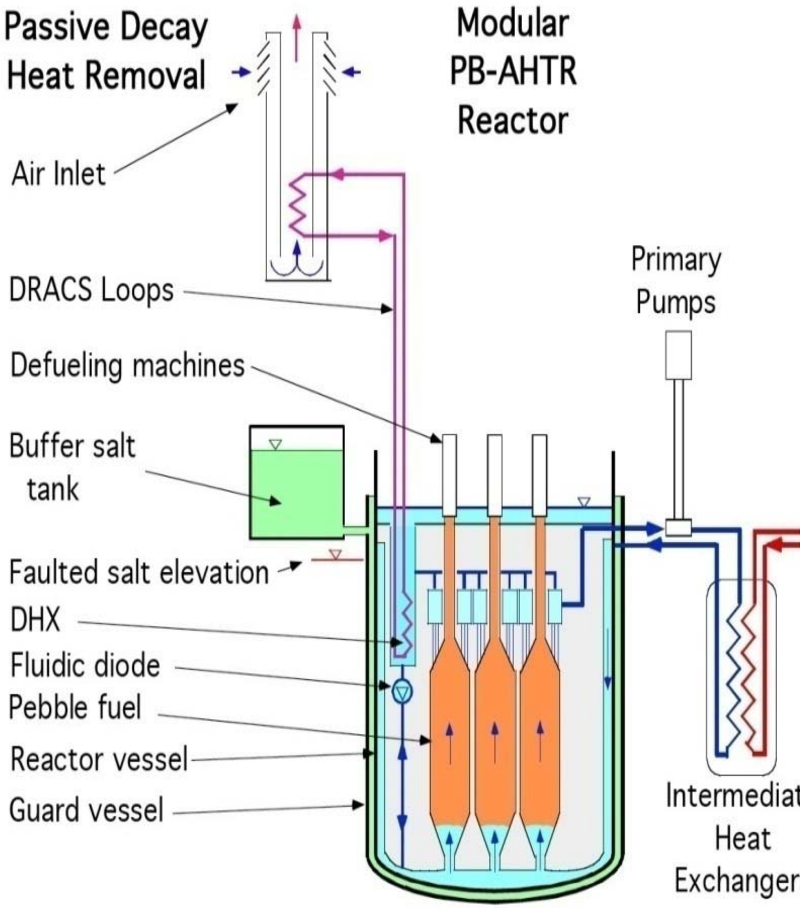
Goals

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)
  - 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

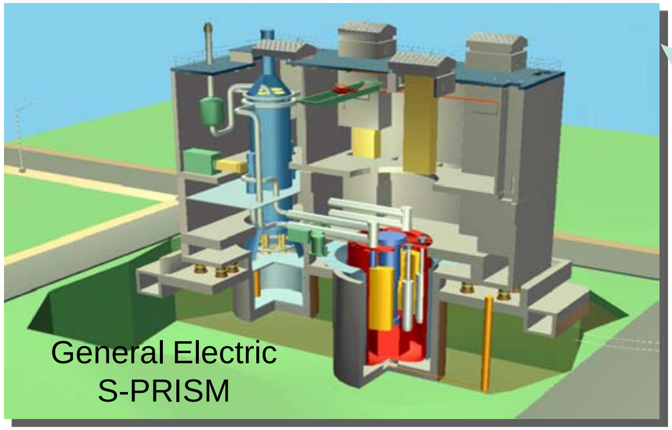


- Sponsor: U.S. Department of Energy
  - $\$7.5 \cdot 10^6$
  - 3-year project
- Project team
  - MIT (lead)
  - U. of California
  - U. of Wisconsin
- Westinghouse advisory role

Fluoride-Salt-Cooled High-Temperature Reactor

Initial Base-Line Design for University Integrated Research Project

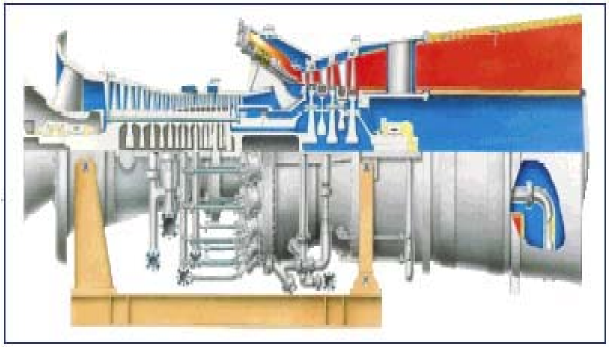
Combining Old Technologies in a New Way



General Electric
S-PRISM

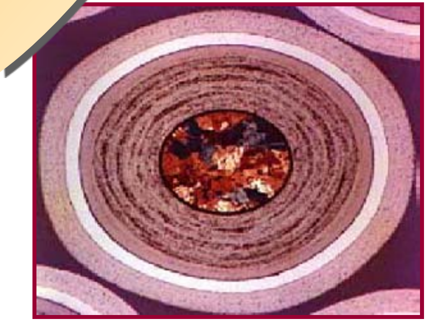
Passively Safe Pool-Type Reactor Designs

Fluoride Salt-Cooled High-Temperature Reactor (FHR)



GE Power Systems MS7001FB

Brayton Power Cycles



High-Temperature Coated-Particle Fuel

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

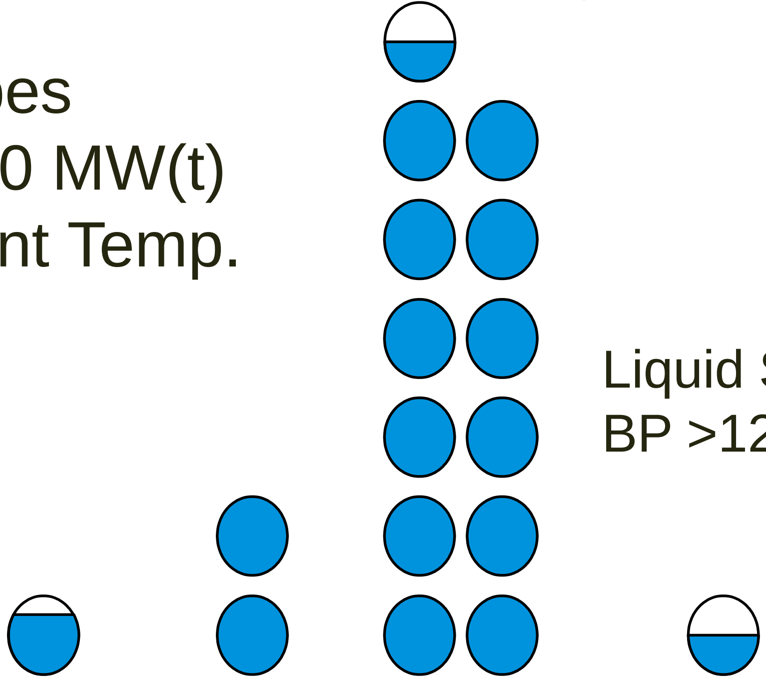
(Transparent)

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 $^7Li_2BeF_4$ (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.

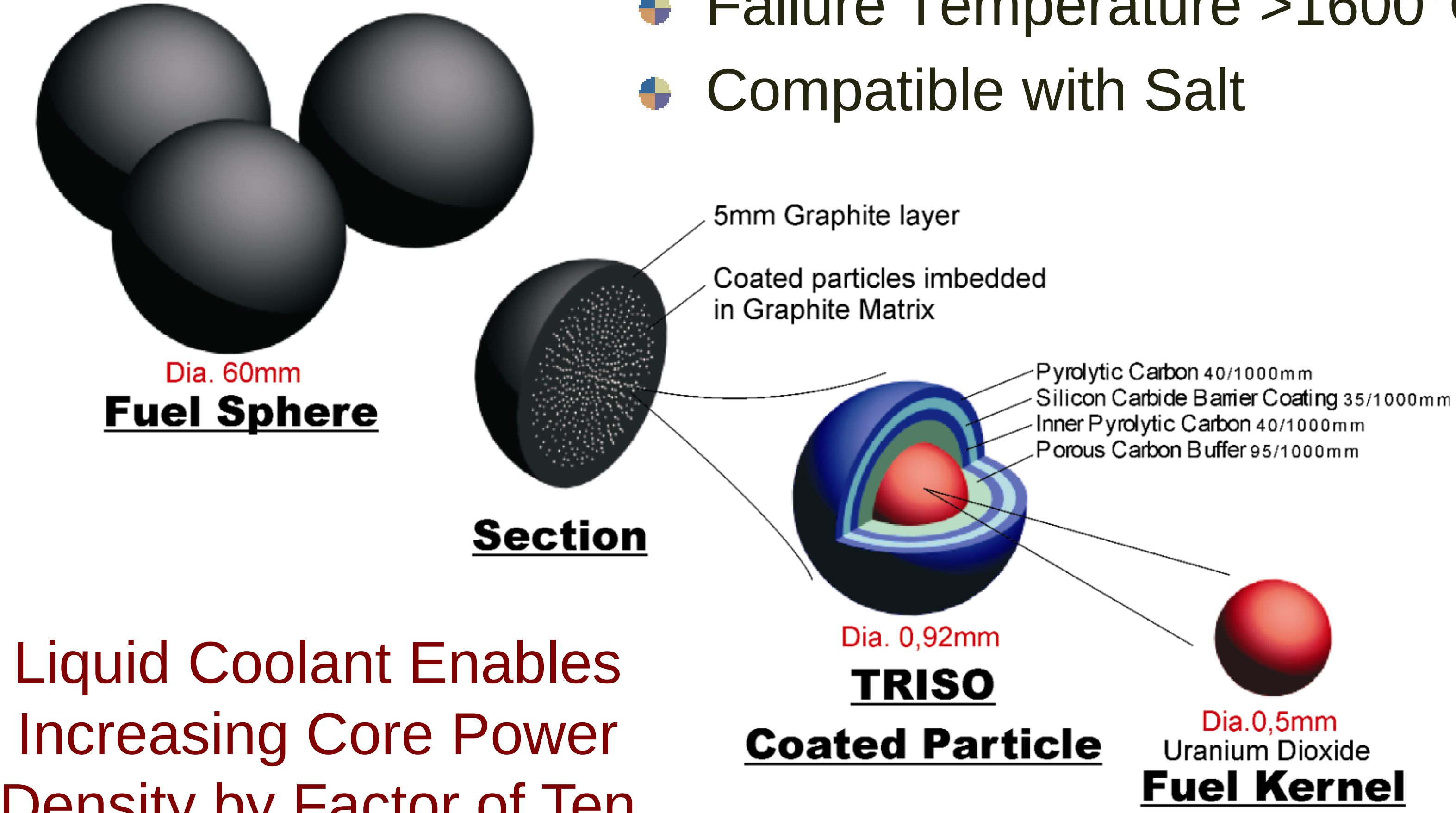
Base Case Salt is $^{7}Li_2BeF_4$ (Flibe)

Basis for Initial Selection

- Advantages
  - Best neutronics including negative void coefficient
  - Experience in molten salt reactor
  - Demonstrated compatible with several metals
  - Demonstrated compatible with graphite
  - Very low activation—no gamma
- Disadvantages
  - Requires isotopically separated lithium-7
  - Some tritium production
  - Chemically toxic
  - Not lowest melting point fluoride salt

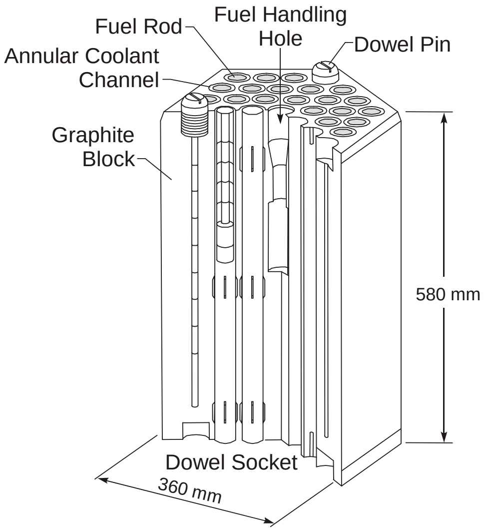
FHR Uses Coated-Particle Fuel

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

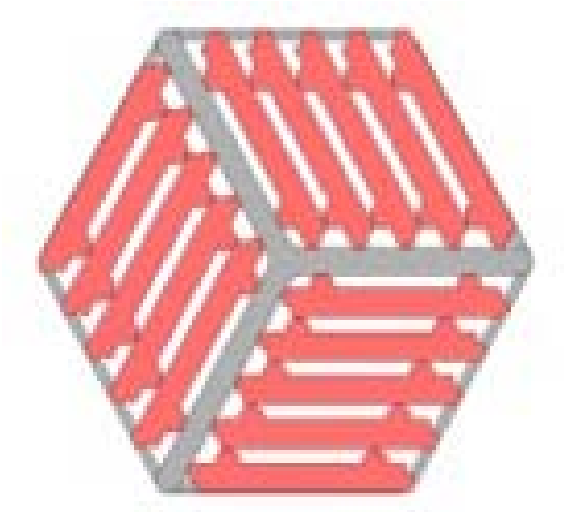


Liquid Coolant Enables Increasing Core Power Density by Factor of Ten

Graphite-Matrix Coated-Particle Fuel Can Take Many Forms

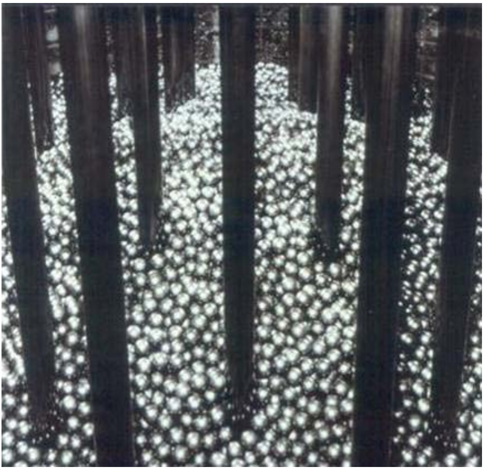


Prismatic Fuel Block



Flat Fuel Plates
in Hex Configuration

Base Case

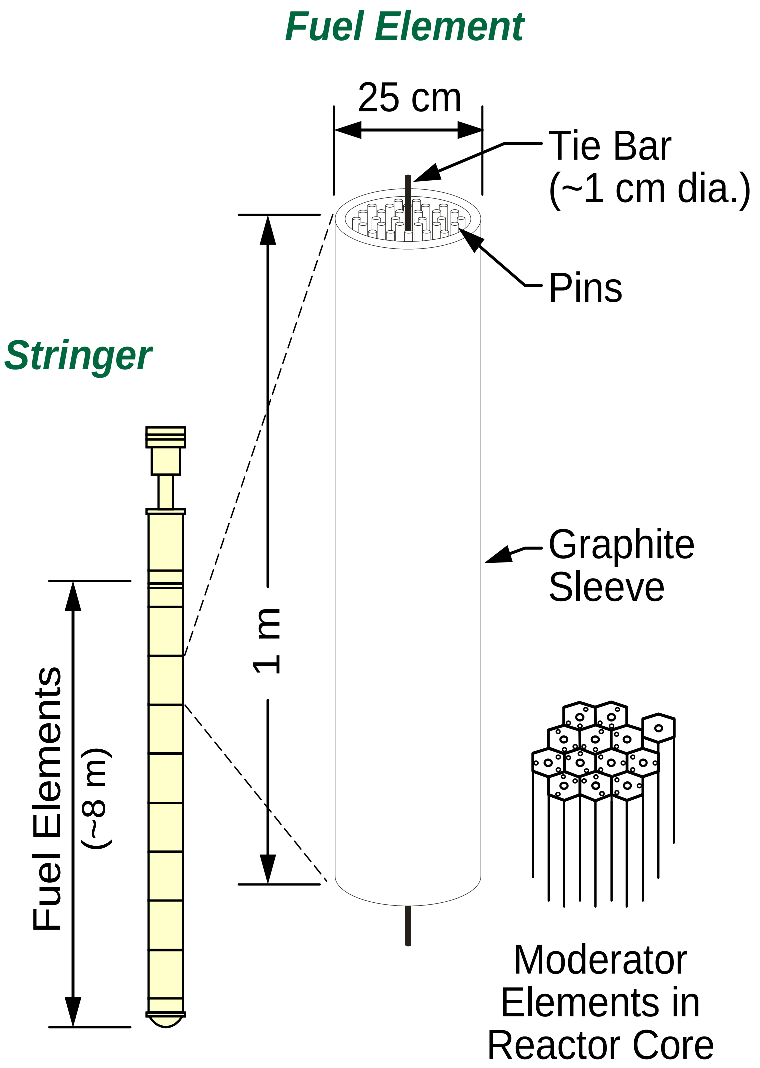


Pebble Bed

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

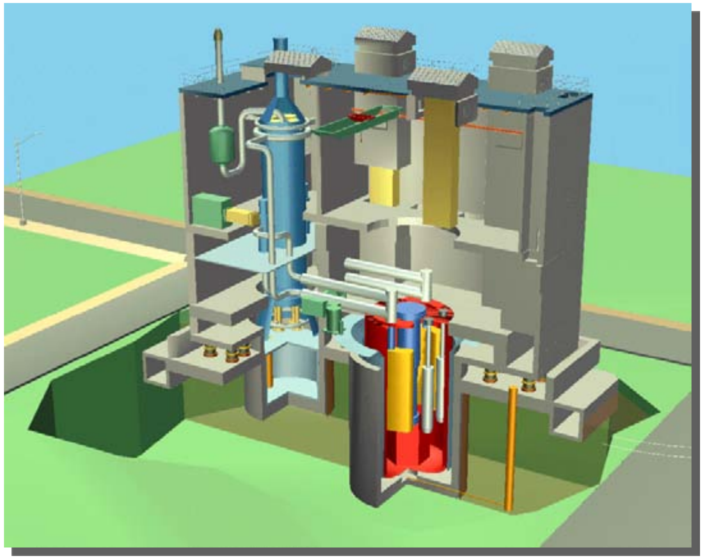
Longer Term FHR Fuel Option: Fuel Element with Pins and Pellets

- Experience →
  - British Advanced Gas-Cooled Reactors: graphite moderated
  - Carbon dioxide cooling
- Advantages
  - Low cost fuel (pellets in rods)
  - Separation of graphite moderator from the fuel
    - Cost advantage
    - Waste management advantage
  - Core-length fuel assemblies
- Disadvantages
  - Requires a new high-temperature clad for salt
  - Major fuel development program



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

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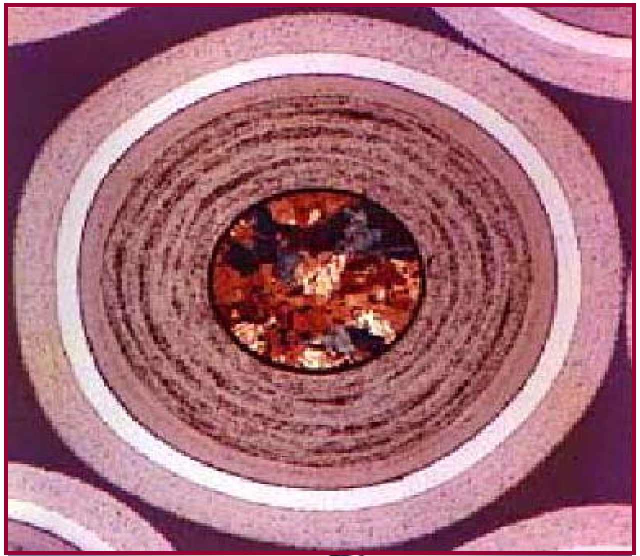
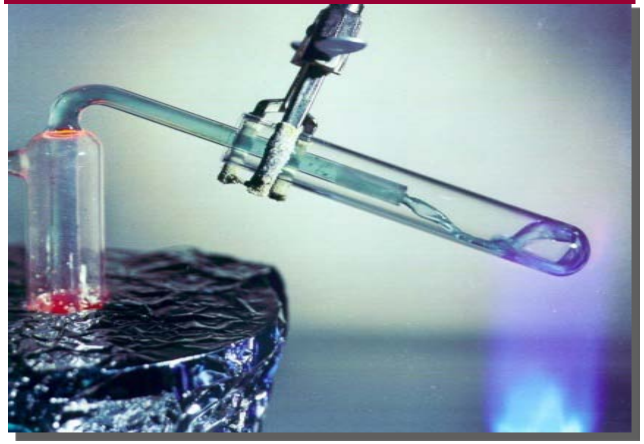
Choice of Fuel and Coolant Enables Enhanced Safety

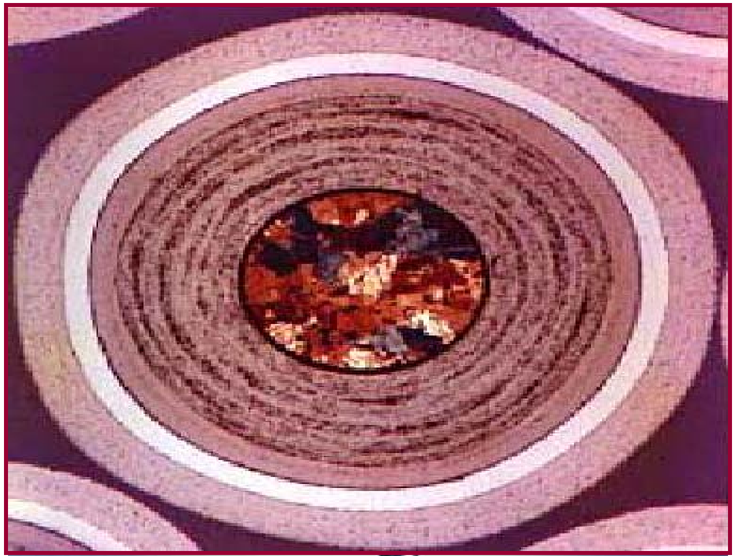


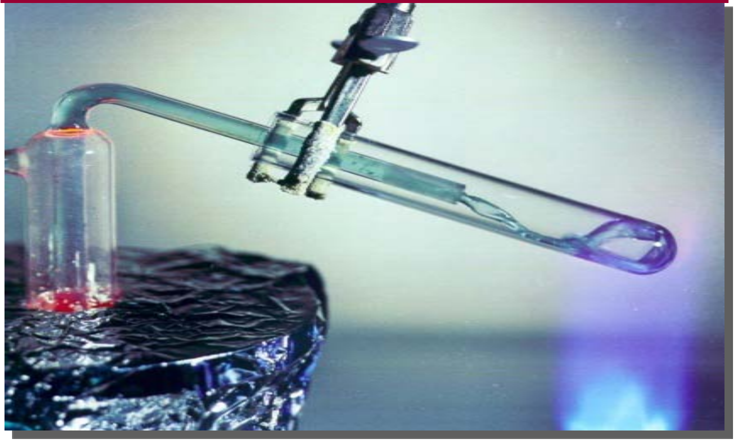


- Coated-particle fuel
  - Failure temperature > 1600ºC
  - Large Doppler shutdown margin
- Liquid salt coolant
  - 700ºC normal peak temp.
  - Boiling point >1400ºC
  - >500ºC margin to boiling
  - Low-pressure that limits accident potential
  - Low corrosion (clean salt)

High-Temperature Fuel and Coolant Alters Safety Limits

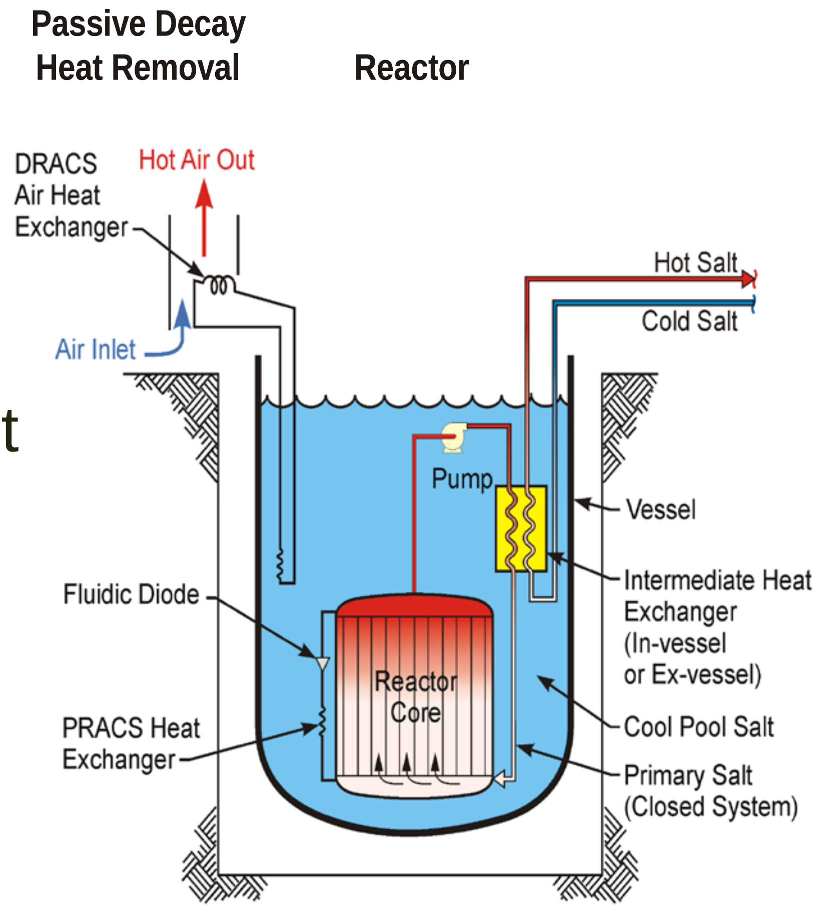
- Safety limit LWR: fuel clad failure from high temperatures
- Safety limit SFR: void coefficient from boiling coolant
- Safety limit HTGR: high temperature fuel failure
- FHR limits not well defined
  - Metal component failure
  - Bulk temperature limit





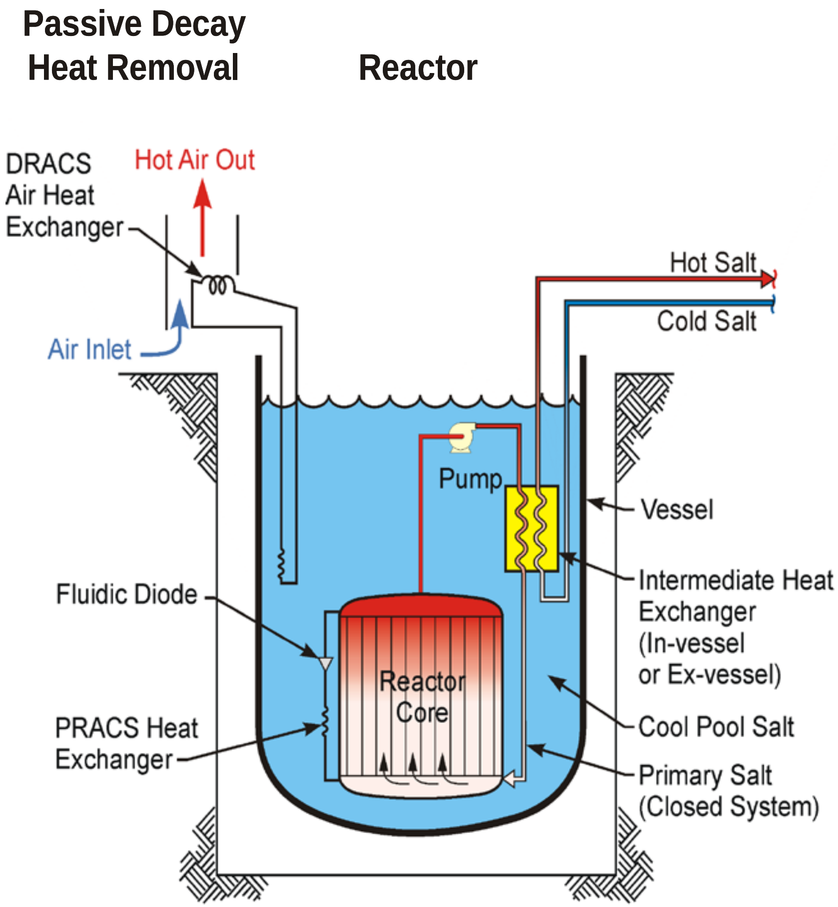
The FHR Primary System is in a Secondary Tank Filled With Salt

- 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



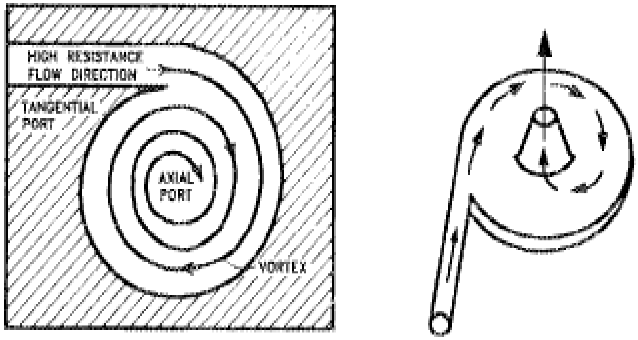
Decay Heat Dumped to Secondary Tank on Pump Trip

- 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



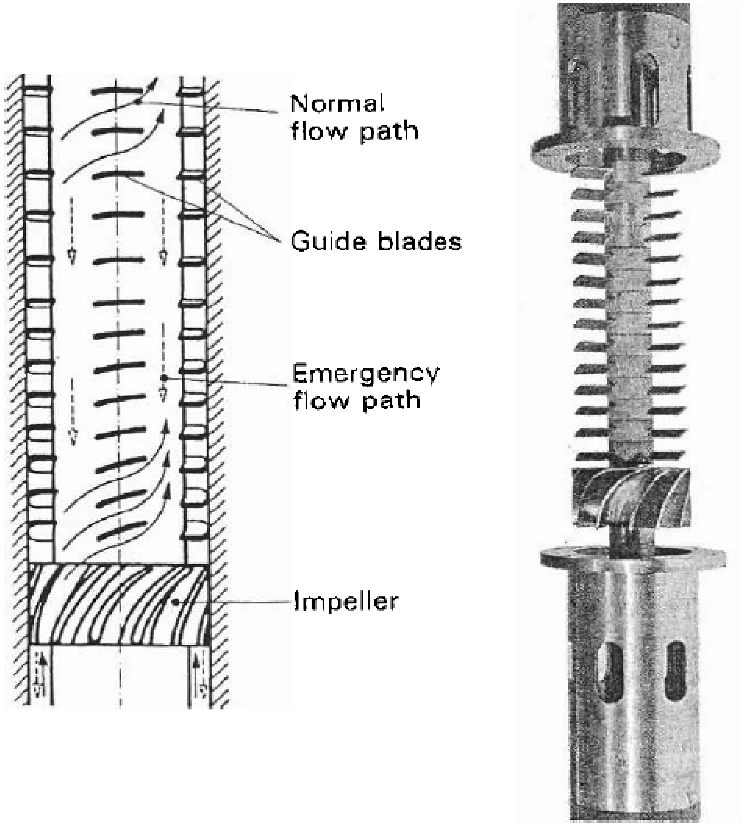
Fluidic Diodes Developed for German Fast Reactor and British Reprocessing Plants

- No moving parts diodes exhibit anisotropic flow resistance
- Substantial nuclear experience available
- Vortex diode chosen as target design



Conventional Vortex Diode

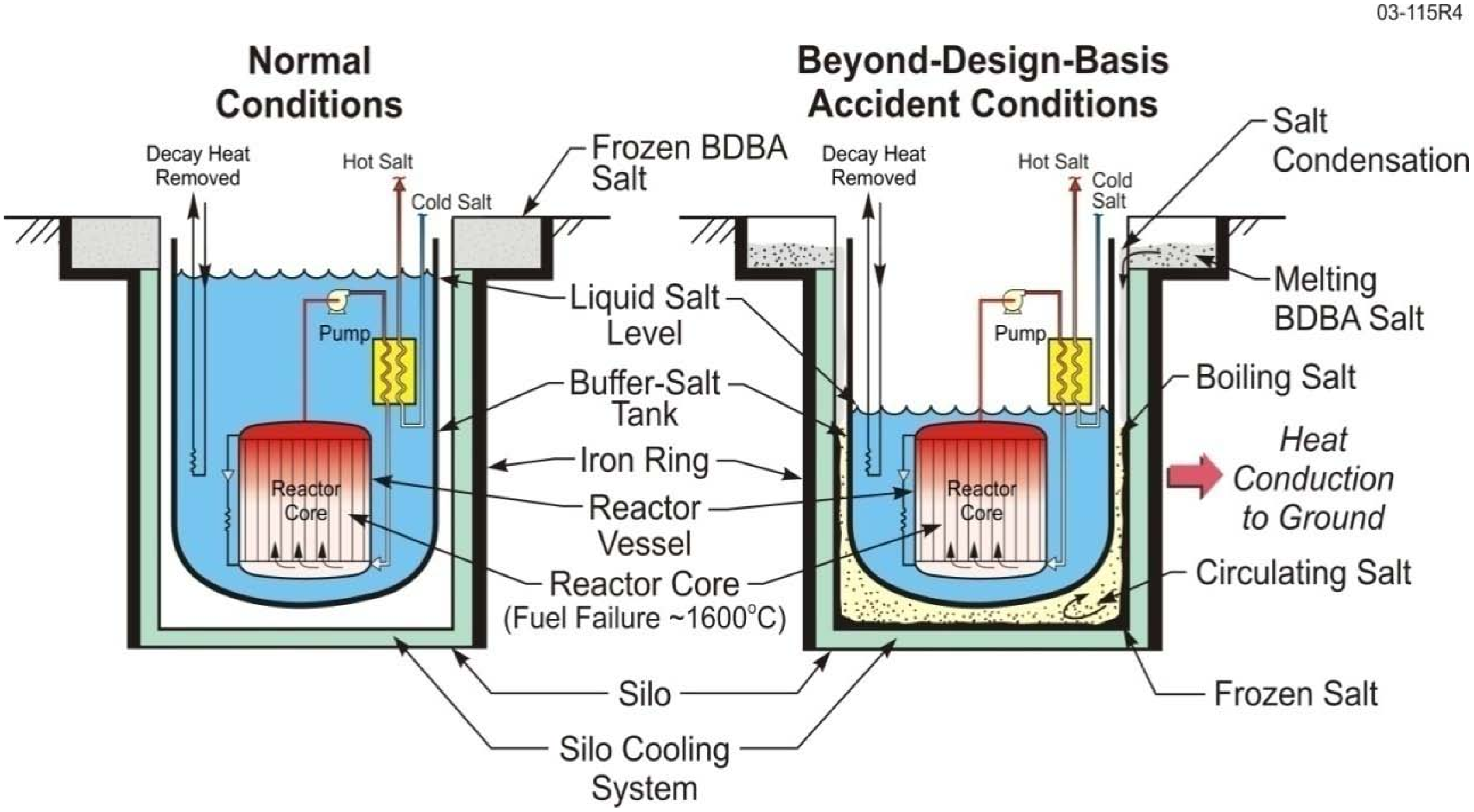
German fluidic diode (Fluid Rectifier Diode)



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

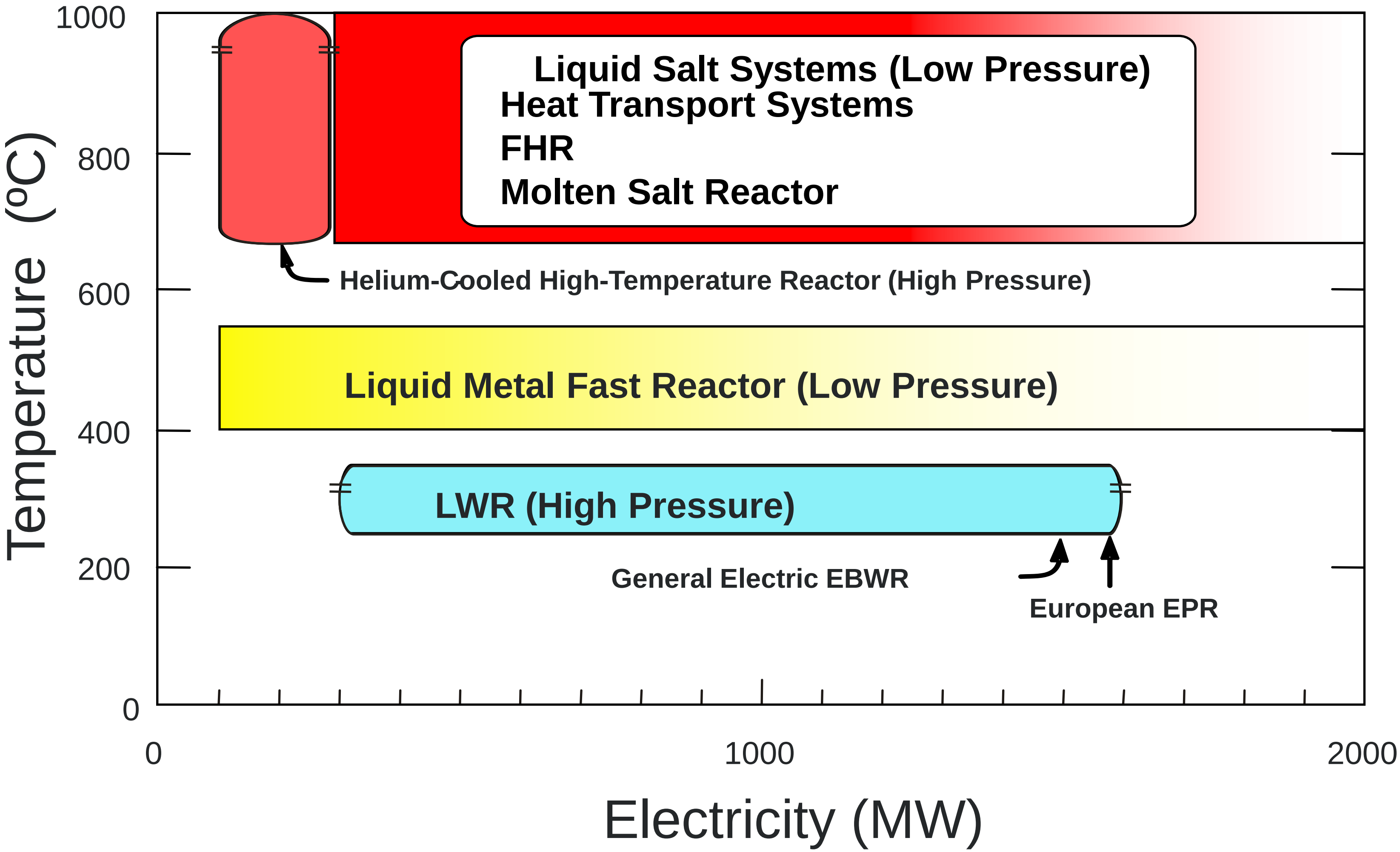


Beyond Design Basis Accident
Long-Term Control Strategy

- High heat capacity system absorbs initial decay heat to provide time for decay heat to decrease
- High-temperature fuel and salt enables large temperature drop to drive heat to environment without fuel failure
- Salt absorbs any fission products that escape fuel from local hot spots—molten salt reactor chemistry
- Silo BDBA salts thermally couple reactor to ground
  - Temperature rise melts salt absorbing decay heat
  - Creates liquid salt heat transfer from outside vessel to silo
  - High melting point of silo secondary salt results in frozen salt on silo—can not loose coolant from system
  - Silo designed for one-time high-temperature transient

Safety System Operates with Major Structural Failures

Salt Coolants Imply High-Temperature High-Efficiency Power Cycles



FHR for Electricity

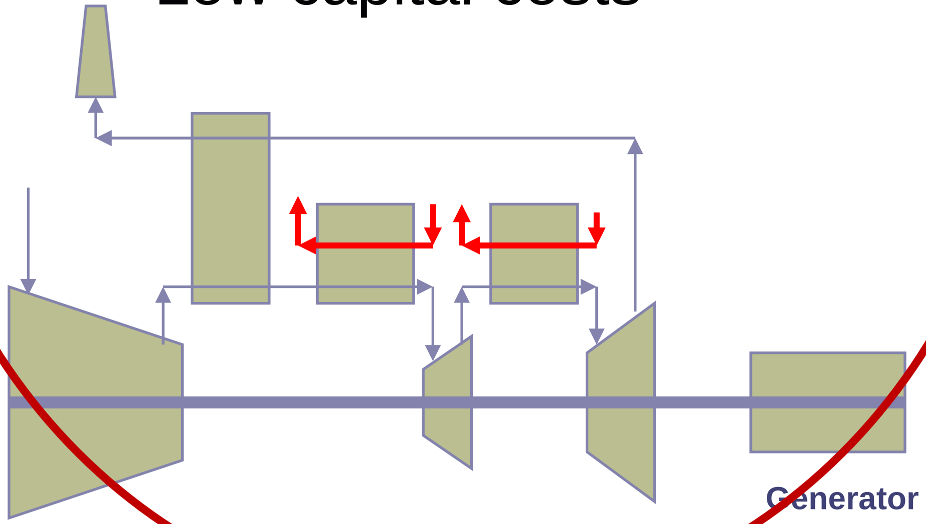
- Deliver heat from 600 to 700ºC
  - Lower temperature above salt melting point
  - Upper temperature within existing materials
- Power cycle options
  - Commercial supercritical water cycle with peak temperature of 650ºC
  - Supercritical carbon dioxide cycle with good temperature match between delivered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

Many Options for Power Cycles

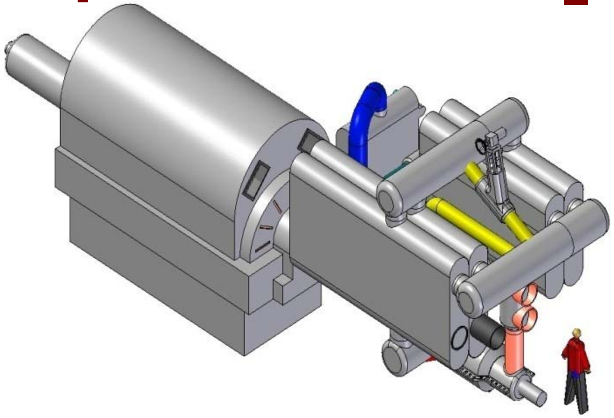
Base Case

Air Brayton Cycle

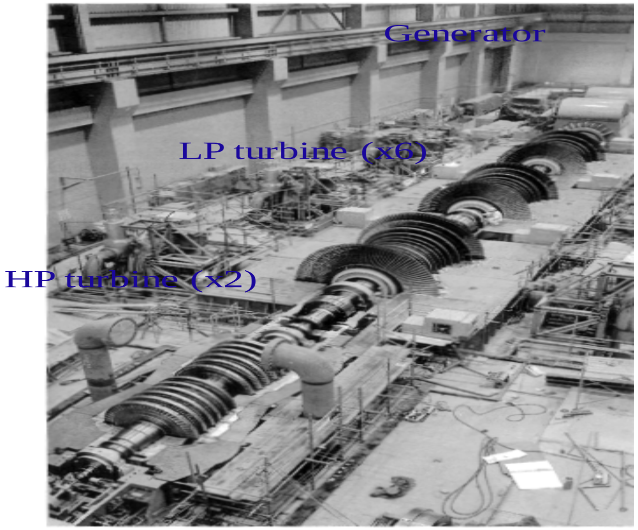
- Air Brayton cycle based on natural gas turbine
- Dry cooling
- Low capital costs



Supercritical CO_2

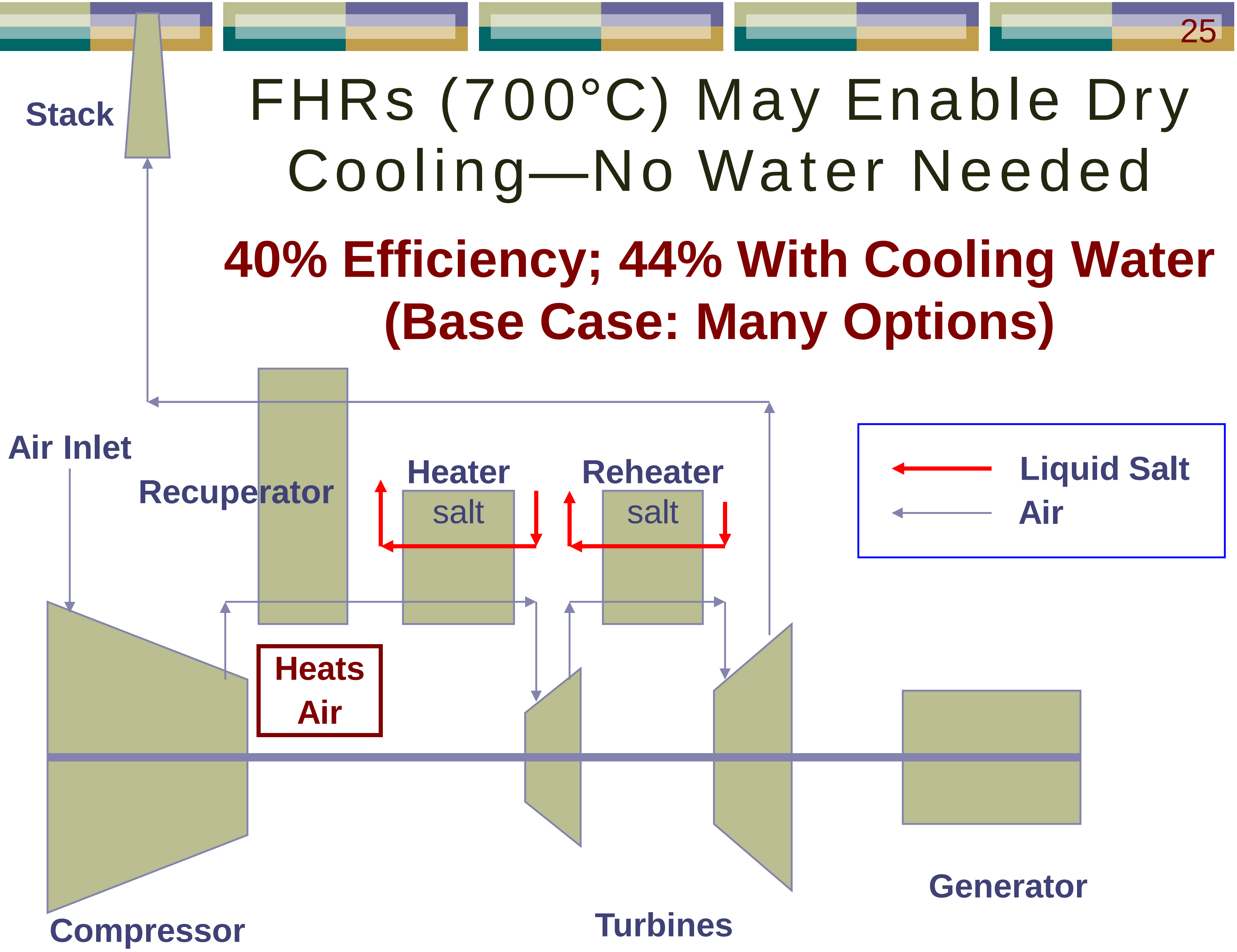


Steam



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

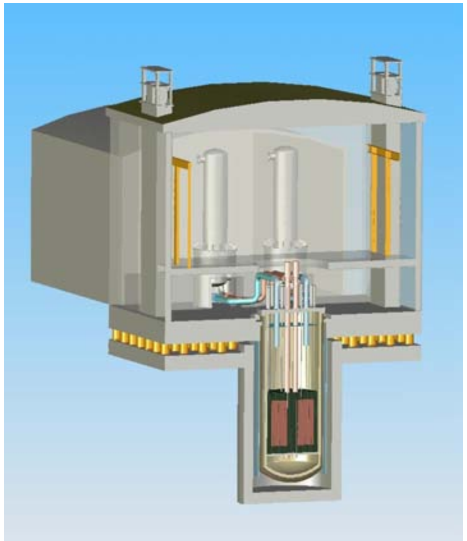
40% Efficiency; 44% With Cooling Water (Base Case: Many Options)



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

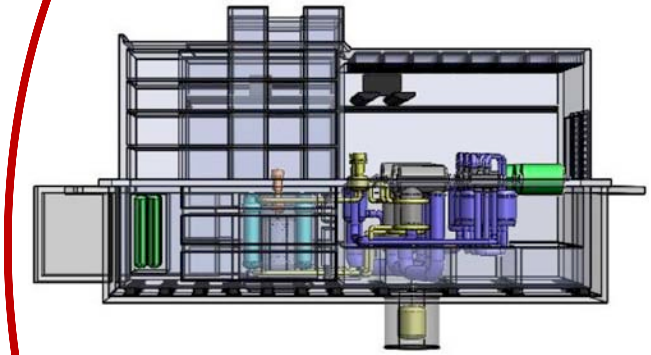
FHR Concepts Span Wide Power Range



3400 MWt /

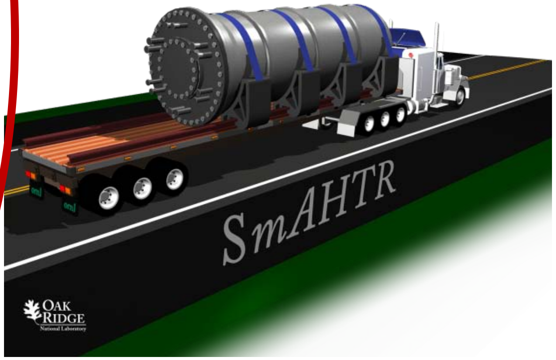
1500 MWe

Base Case



410

MWe

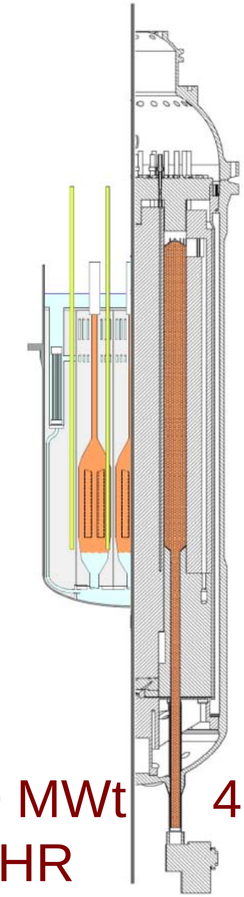


125 MWt/50

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
  - 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


900 MWt FHR

400 MWt HTR

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

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

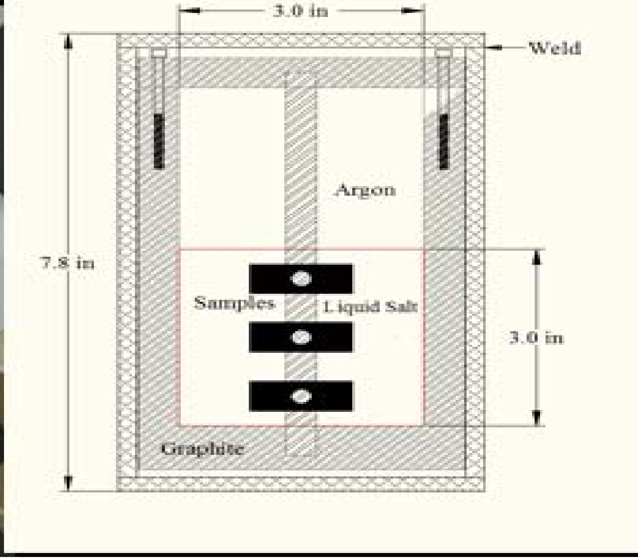
Workshops to Define Current Status and Path Forward

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)

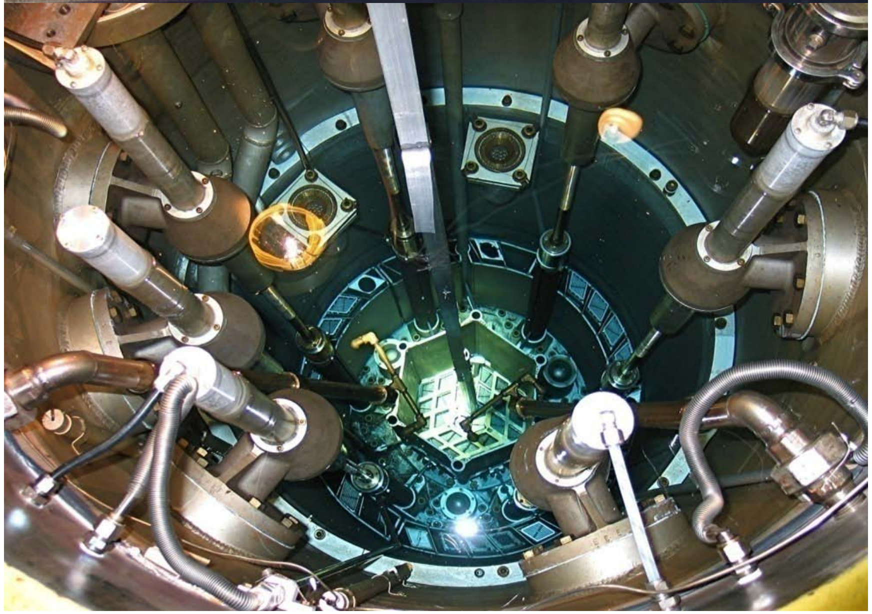
The University of Wisconsin Will Conduct Corrosion Tests

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



MIT To Test 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

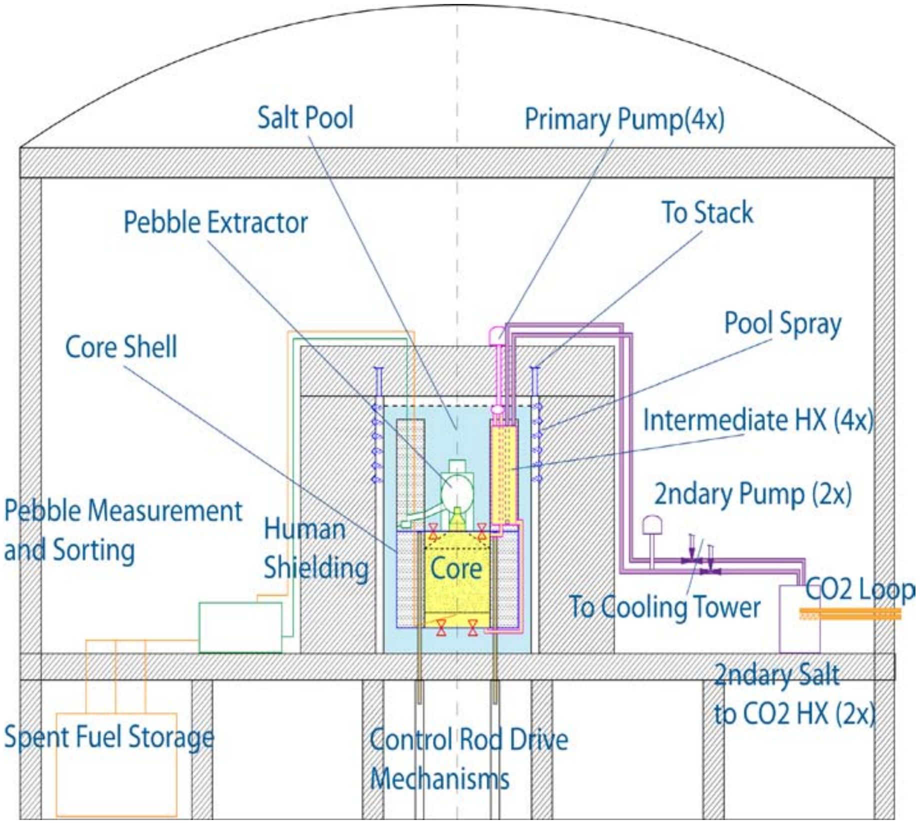


UCB to Conduct Thermal Hydraulics, Safety, and Licensing Tests

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

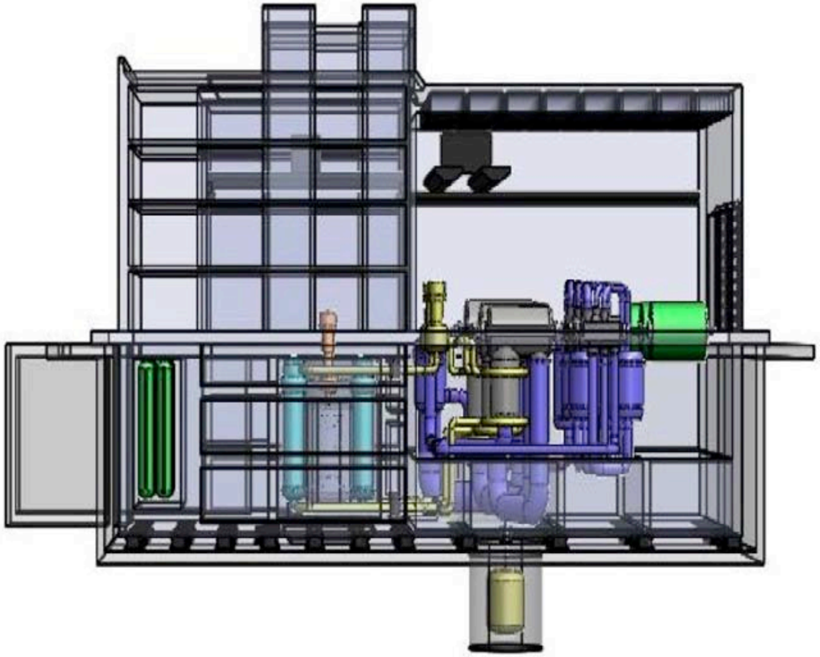
MIT To Develop Pre-Conceptual Test Reactor Design

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

Advisory Panel:
Regis Matzie Chair

- Regis Matzie: Chief Technical Officer Westinghouse (Retired)
- John McGaha: Retired executive from Entergy, retired ANS Board member
- Dr. Dan Mears: President and CEO of Technology Insights
- Jim Rushton: Director of the Nuclear Technology Division at ORNL (Retired)
- Doug Chapin: Previous principal at MPR

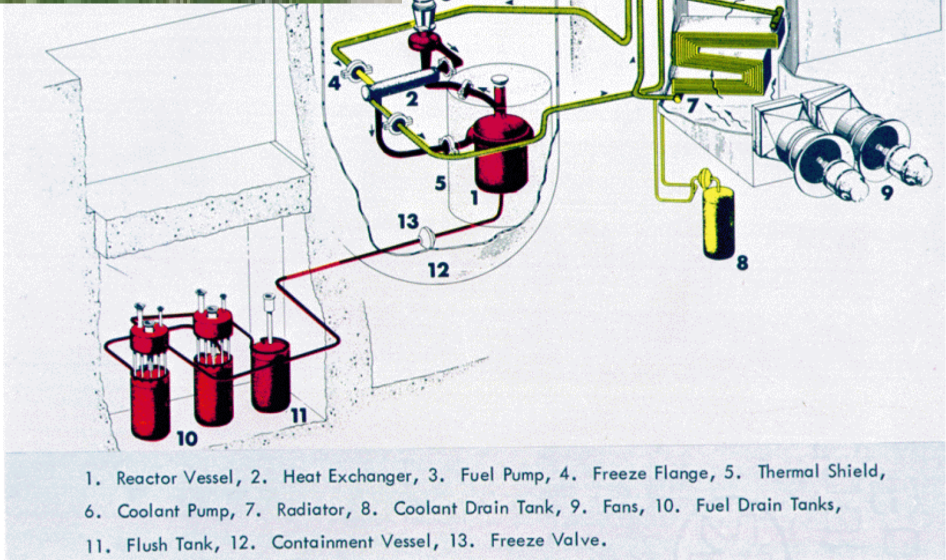
Coupled High-Temperature Salt Technologies

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

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

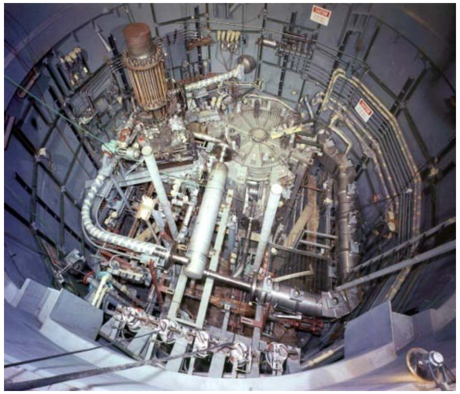
Fuel Dissolved in Salt



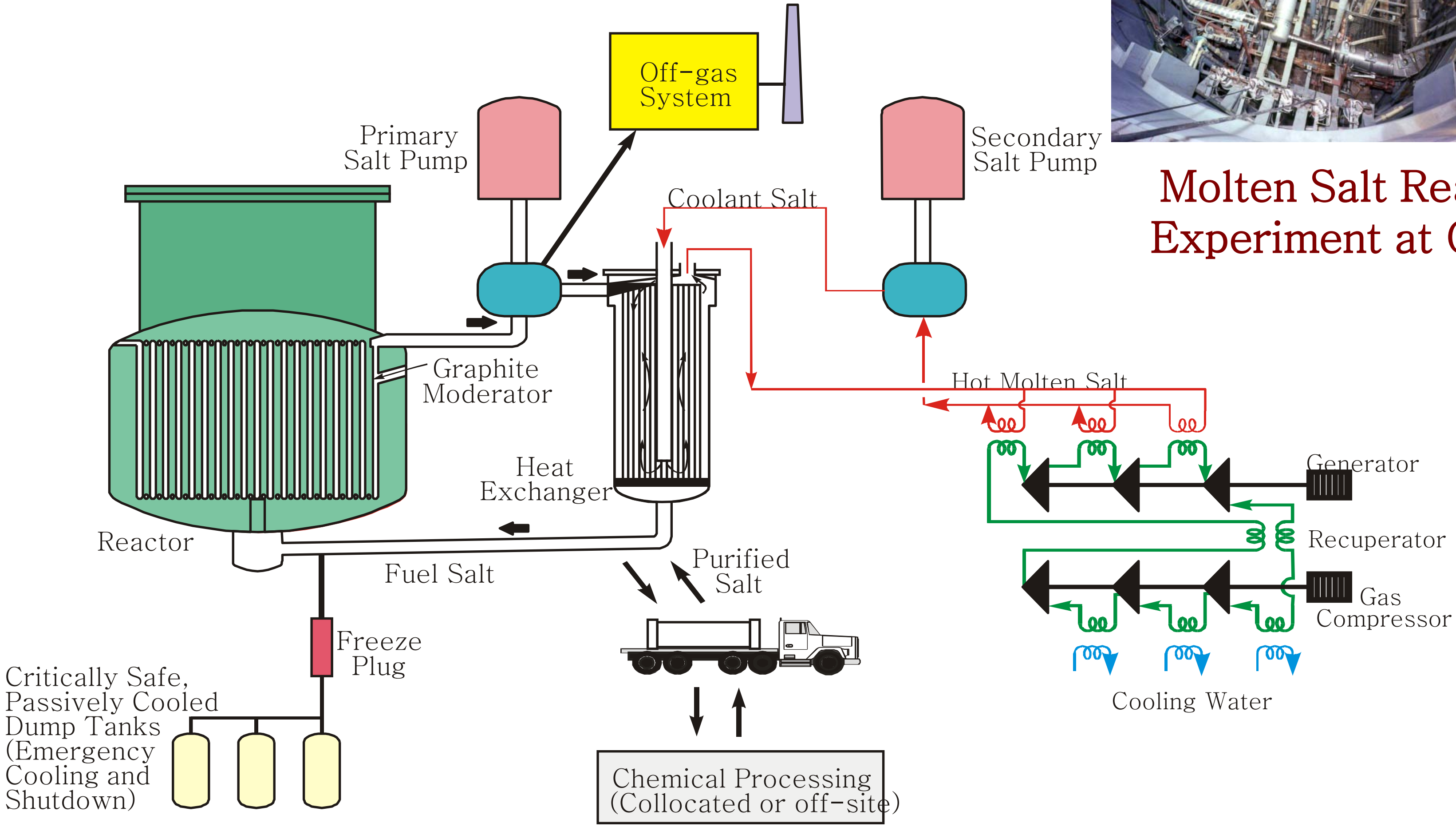
1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

Work Continues on MSR

(Fuel Dissolved in the Salt Coolant)



Molten Salt Reactor Experiment at ORNL



China, France, Russia, Czech Republic, United States

China Program Has Several Hundred People

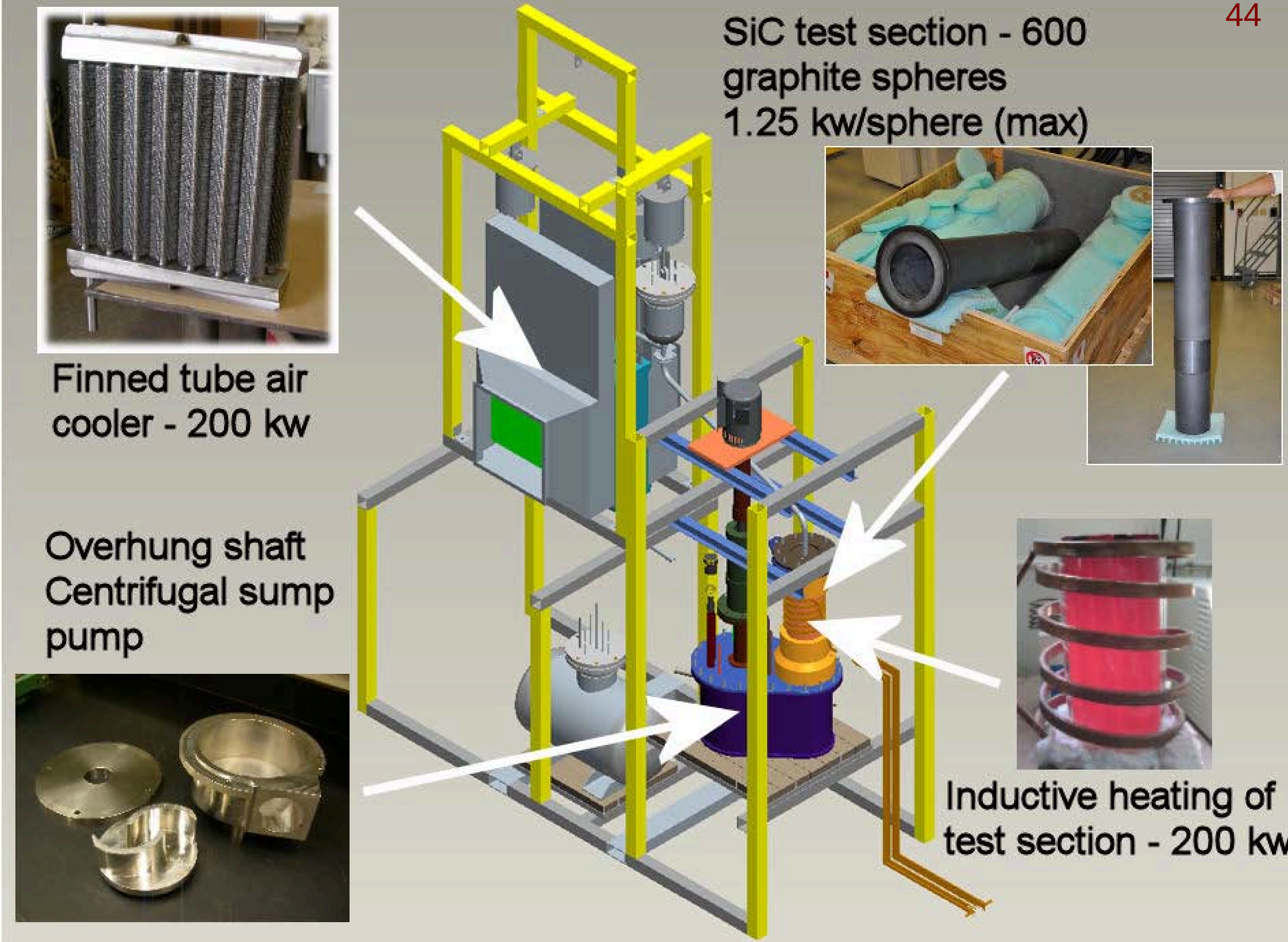
ORNL Starting Salt Heat-Transfer Loop

- Loop Specifications

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

- Initial testing: 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



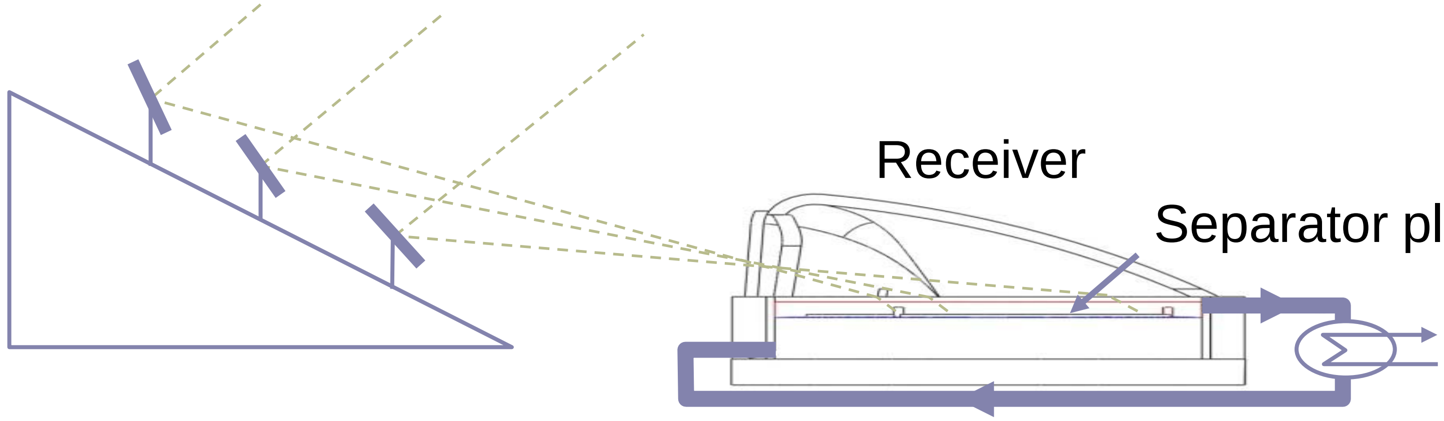
Finned tube air cooler - 200 kw

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

Overhung shaft Centrifugal sump pump

Inductive heating of test section - 200 kw

MIT Concentrated Solar Power on Demand (CSPonD)



Receiver

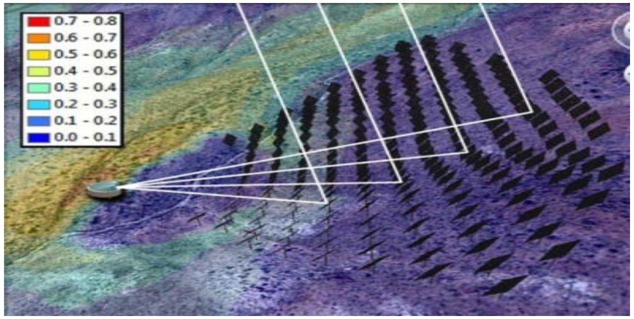
Separator plate

Steam generator

Hillside heliostat field

Molten salt loop

Conventional CSP “Power Tower”

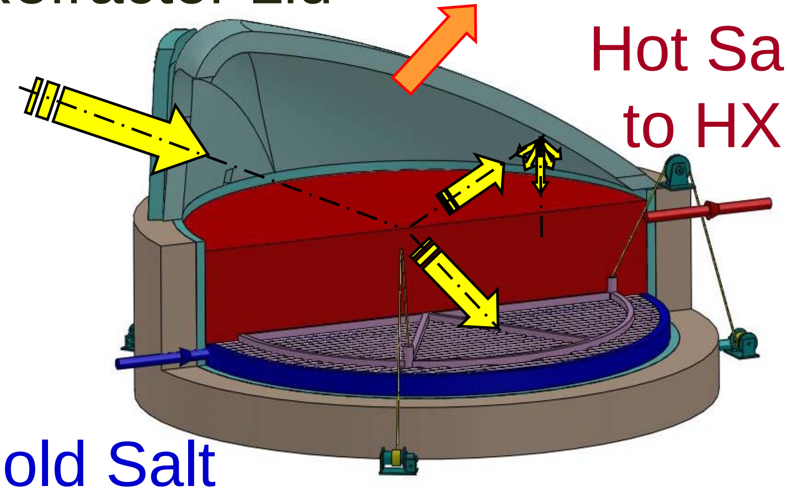


Hillside beam-down: CSPonD

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

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

- Efficient light collection but high solar fluxes—burn through metal collector
- 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



Non-Imaging Refractor Lid

Lid Heat Extraction

Hot Salt to HX

Cold Salt from HX

Light Collected Inside Insulated Building With Open Window

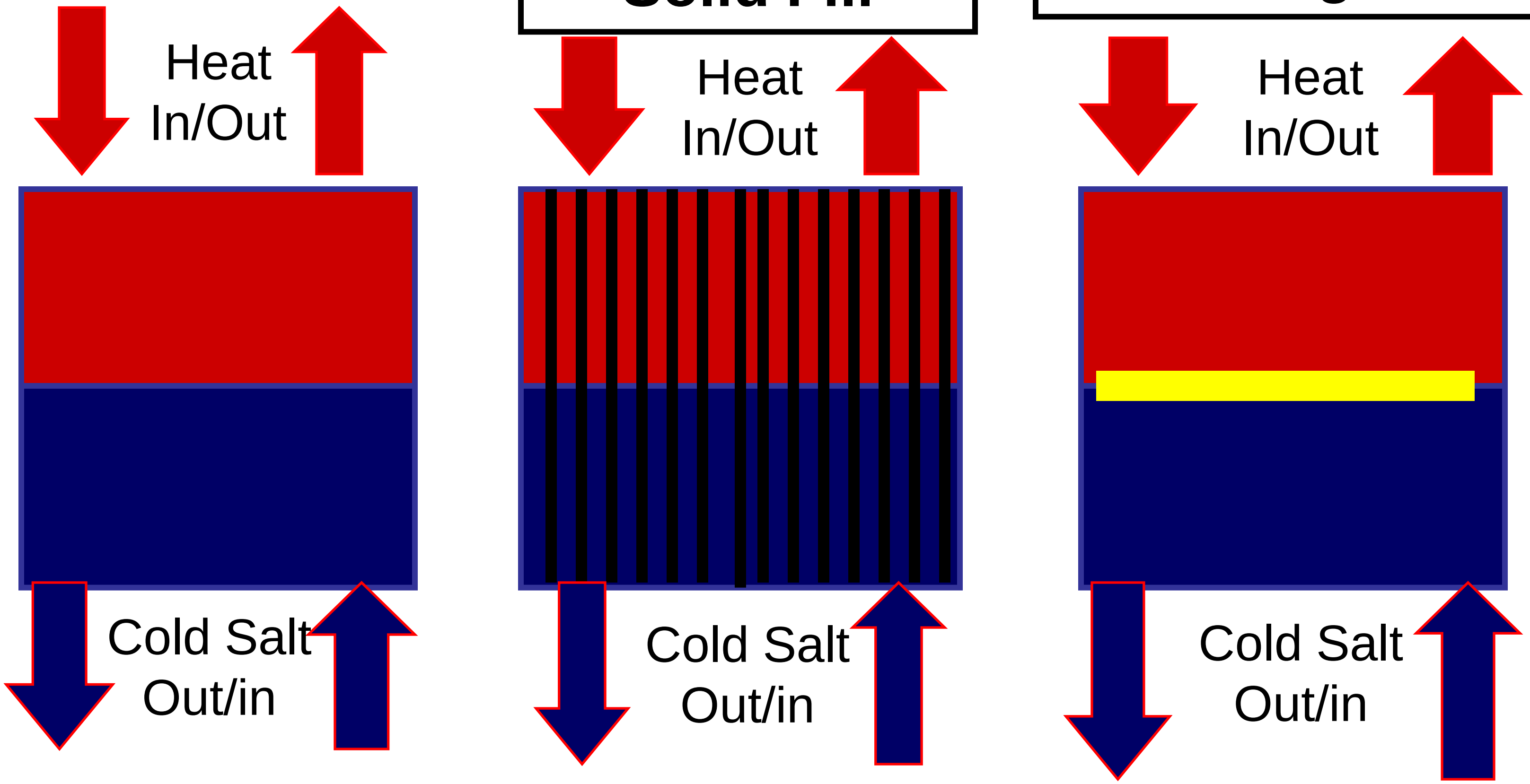
High-Temperature Heat Storage

Ongoing R&D for Nuclear and Solar Applications

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 Floating Plate



Heat In/Out

Cold Salt Out/in

Heat In/Out

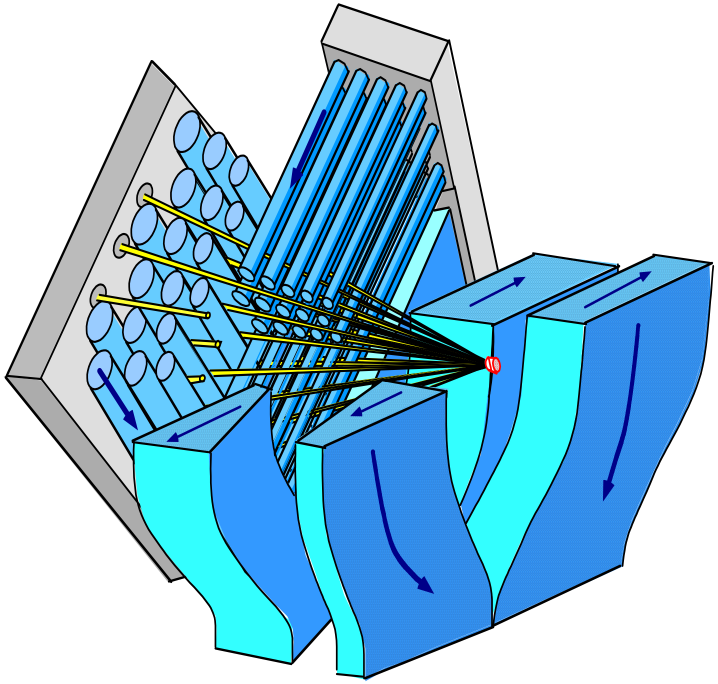
Cold Salt Out/in

Heat In/Out

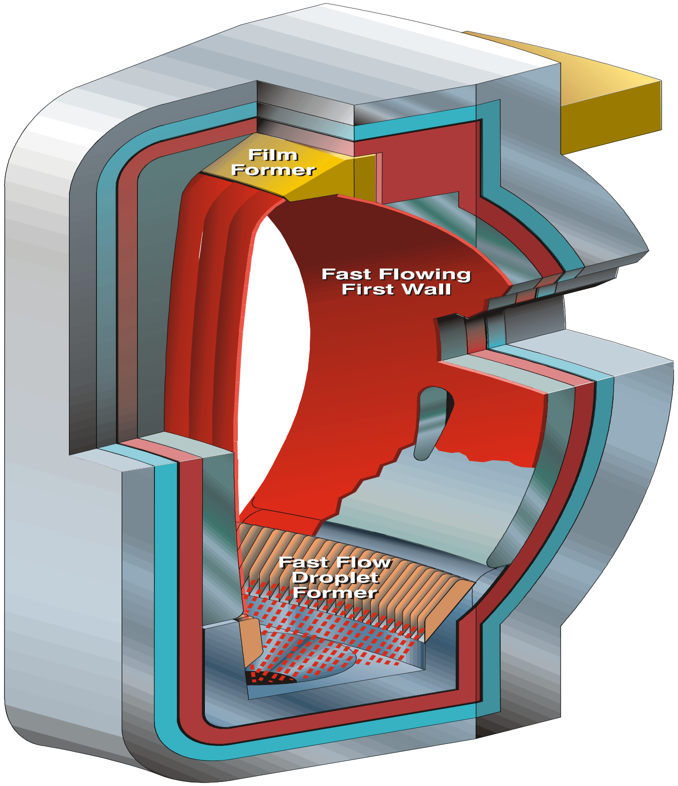
Cold Salt Out/in

Liquid Salt Wall Fusion Machines

Higher-Power Densities and Less Radiation Damage



Heavy-Ion Inertial Fusion

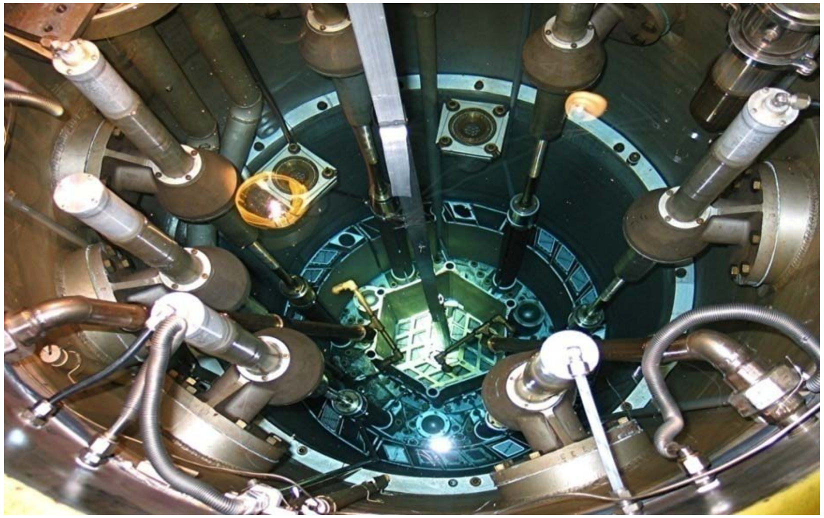


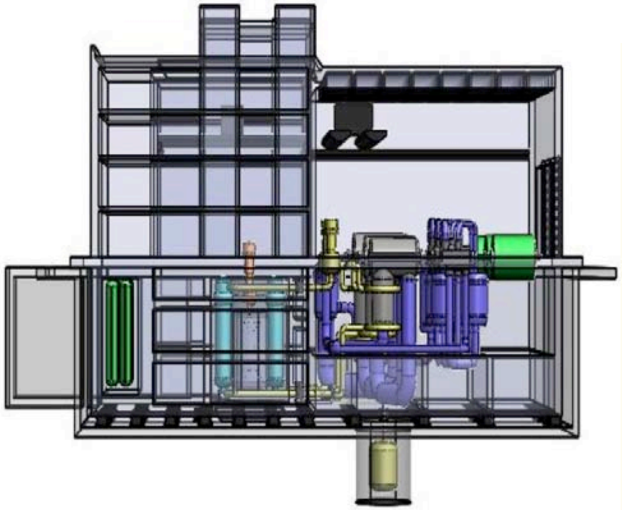
Magnet Fusion Tokamak

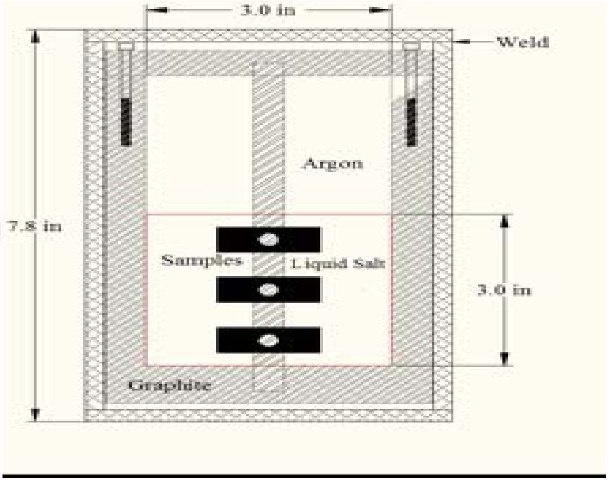
Conclusions

- 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

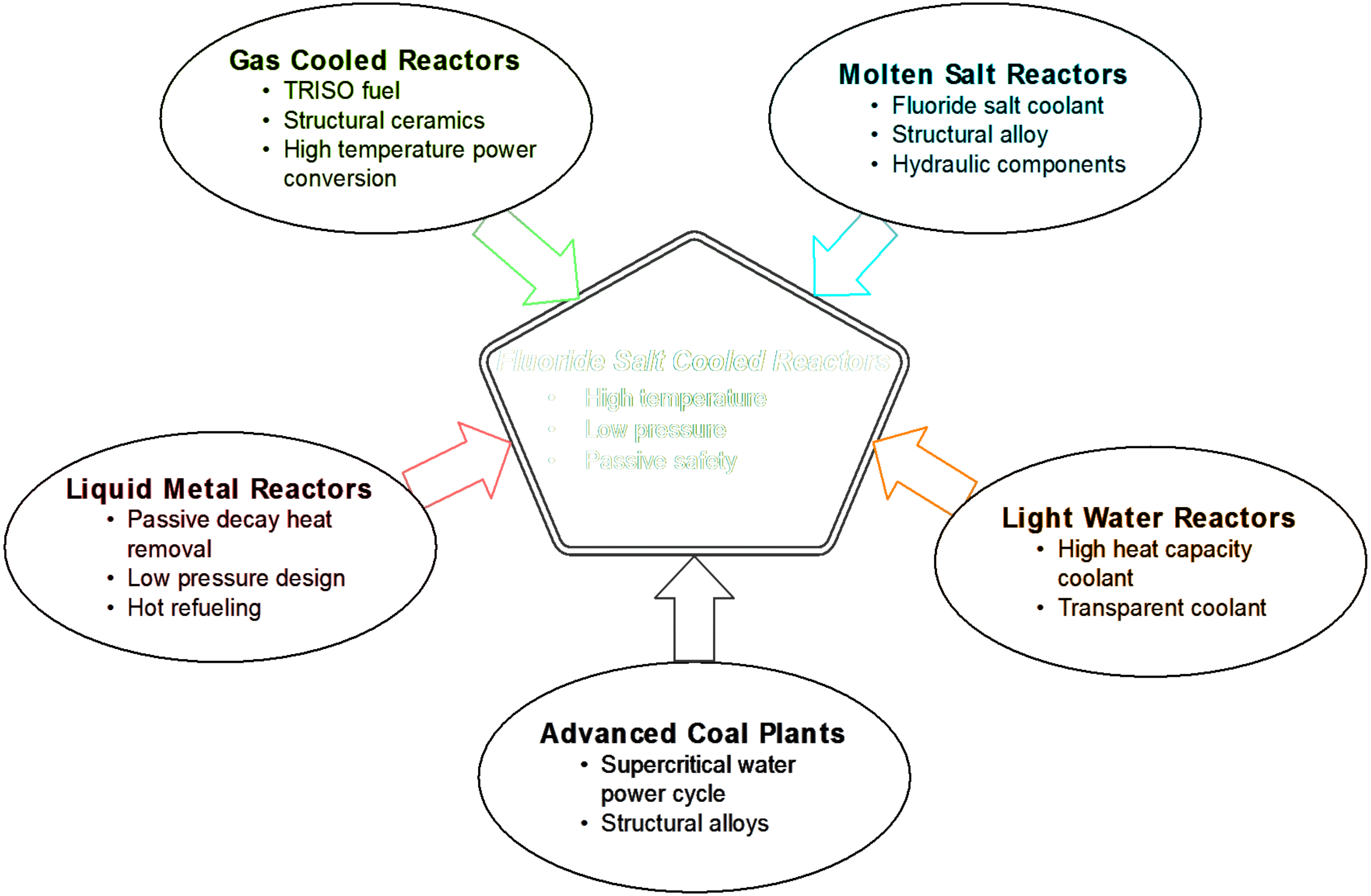
Dr. Charles Forsberg is the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study, Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project, and University Lead for Idaho National Laboratory Institute for Nuclear Energy and Science (INEST)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

The U.S. Has a Competitive Advantage with FHR

- Developed and currently leads in FHR R&D
- Experience with MSR including 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

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

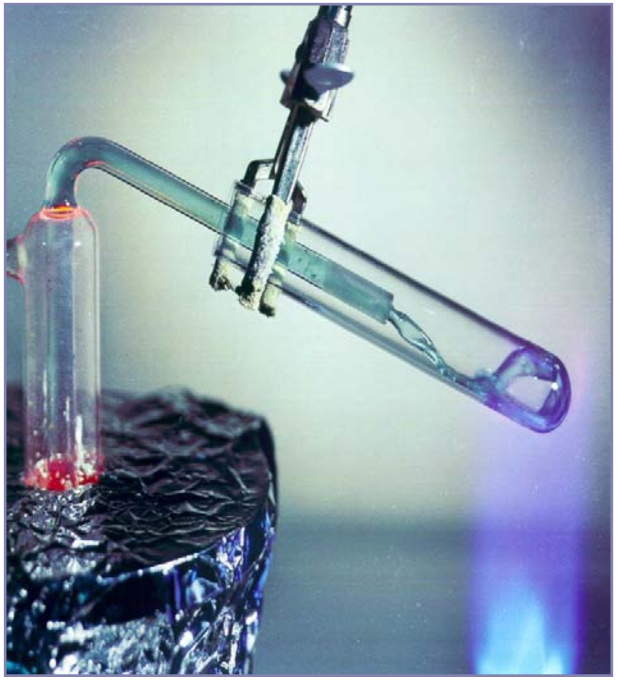
No grid connection requirement for process heat

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

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

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

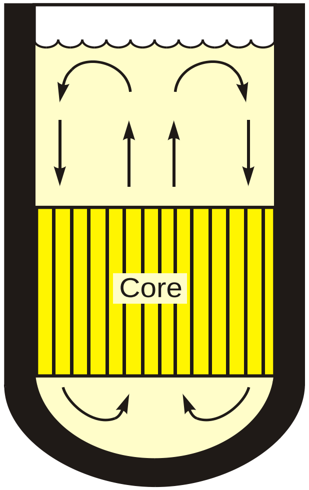
Passive Decay
Heat Removal

Reactor

Hydrogen/Brayton Electricity
Production

Liquid Cooling Allows Large Reactors with Passive Decay Heat Removal

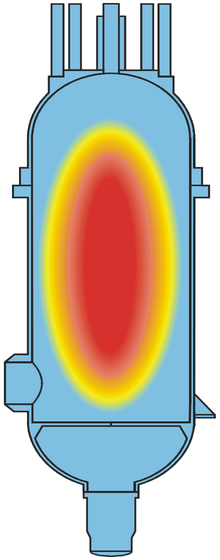
Liquid
[1000s of MW(t)]



Decay Heat Removal Limited by Convective Cooling

(Added benefit of full use of internal heat capacity)

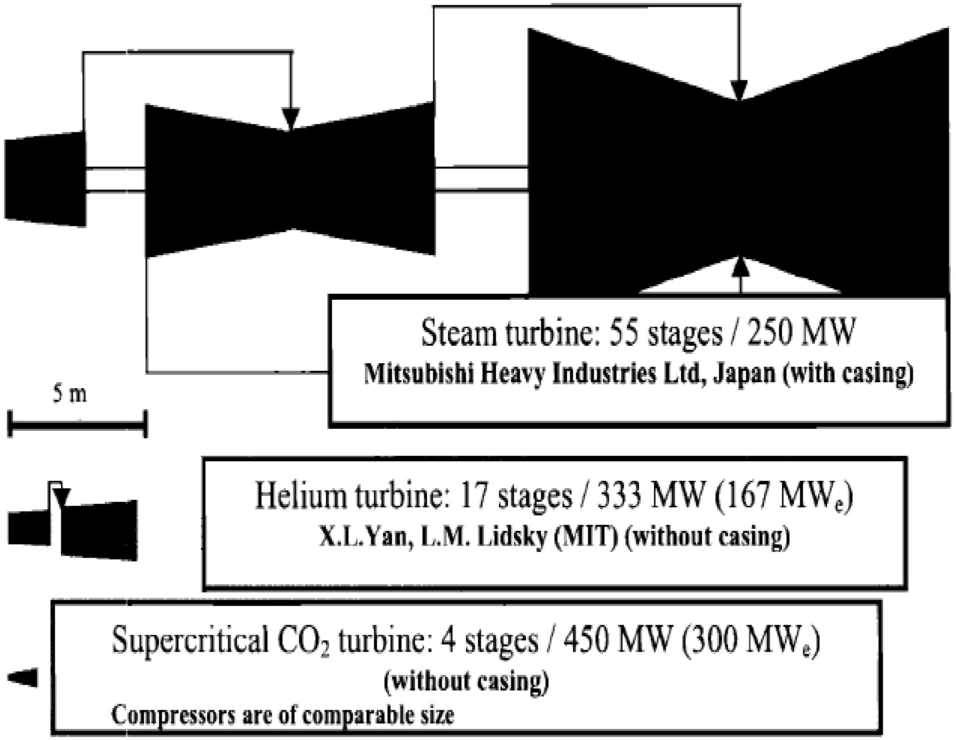
Gas
[~600 MW(t)]



Decay Heat Removal Limited by Conduction Cooling

Supercritical CO_2 Cycles Projected to be Low-Cost Efficient Power System

However, Early in Development Cycle

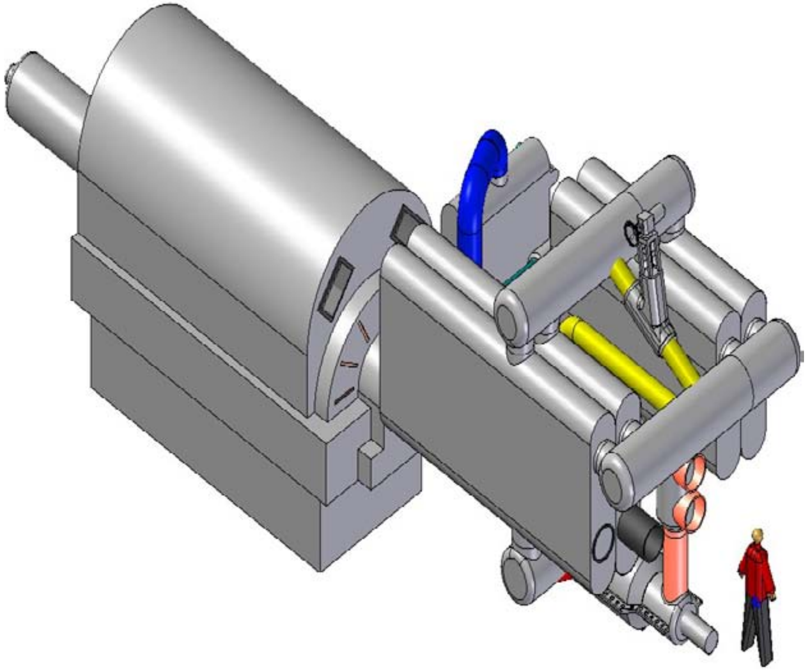


Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries Ltd, Japan (with casing)

Helium turbine: 17 stages / 333 MW (167 MW_e)
X.L.Yan, L.M. Lidsky (MIT) (without casing)

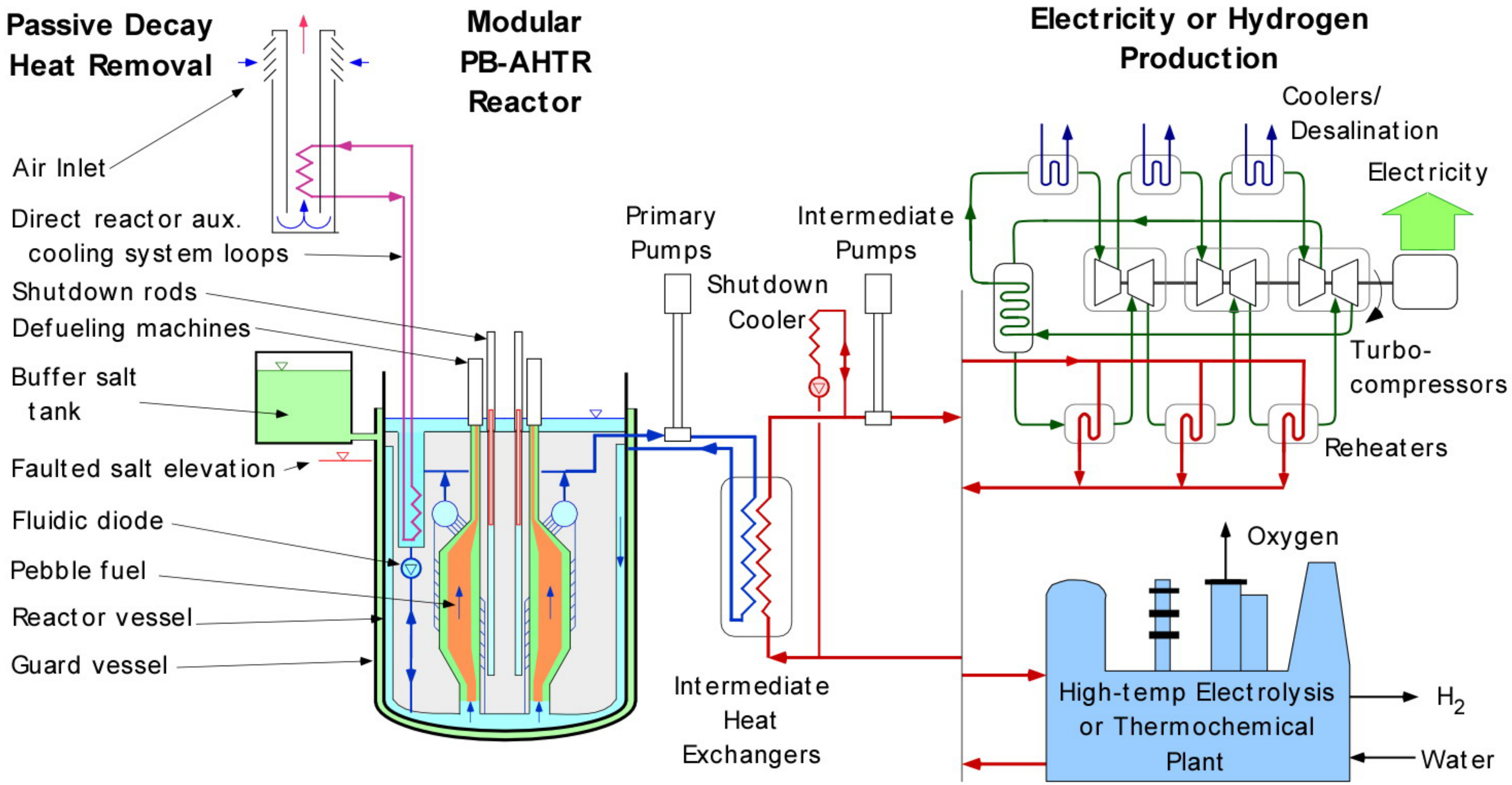
Supercritical CO_2 turbine: 4 stages / 450 MW (300 MW_e)
(without casing)
Compressors are of comparable size

[Dostal, MIT thesis, 2004]



50-MWe Super-Critical Carbon Dioxide Power Conversion Unit

The modular PB-FHR passive decay heat removal relies on a passive flow diode



Fluidic diode minimizes bypass through DHX under forced circulation, but still allows for high flow through DHX under natural circulation

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)	k (W/m°C)	$v \cdot 10^6$ (m^2/s)
Li_2BeF_4 (Flibe)	459	1430	1940	2.42	4670	1.0	2.9
59.5NaF-40.5ZrF_4	500	1290	3140	1.17	3670	0.49	2.6
26LiF-37NaF-37ZrF_4	436		2790	1.25	3500	0.53	
31LiF-31NaF-38BeF_2	315	1400	2000	2.04	4080	1.0	2.5
8NaF-92$NaBF_4$	385	700	1750	1.51	2640	0.5	0.5
Sodium	97.8	883	820	1.27	1040	62	0.12
Lead	328	1750	10540	0.16	1700	16	0.13
Helium (7.5 MPa)			3.8	5.2	20	0.29	11.0
Water (7.5 MPa)	0	290	732	5.5	4040	0.56	0.13

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. Sodium properties are at 550ºC. Pressurized water data are shown at 290°C for comparison. Nomenclature used: ρ is density; C_p is specific heat; k is thermal conductivity; v is viscosity.

FHR Couples to Hybrid Nuclear-Renewable Systems

Base-Load Nuclear Plant For Variable Electricity and Process Heat

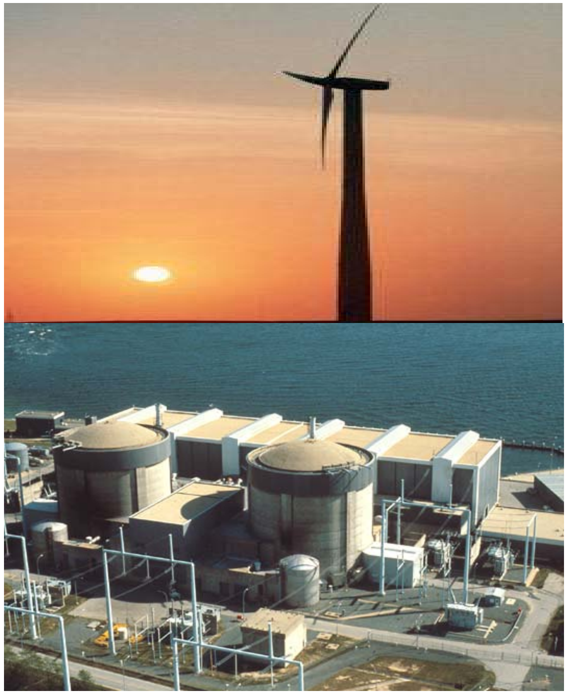
Maximize Capacity Factors of Capital Intensive Power Systems

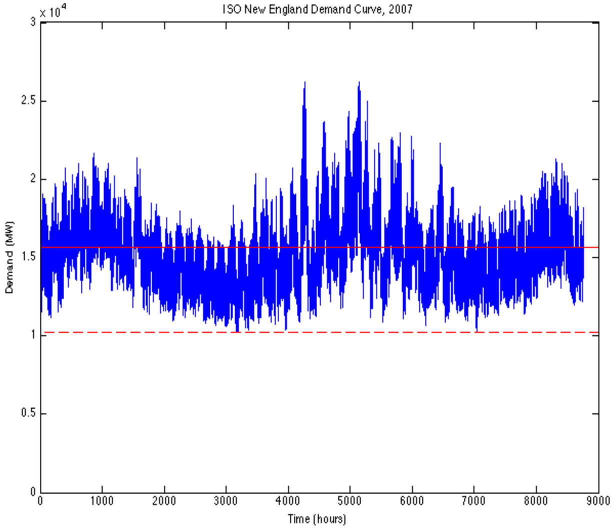
=

Meet Electricity Demand

+

Efficient Use of “Excess” Energy for Fuels Sector



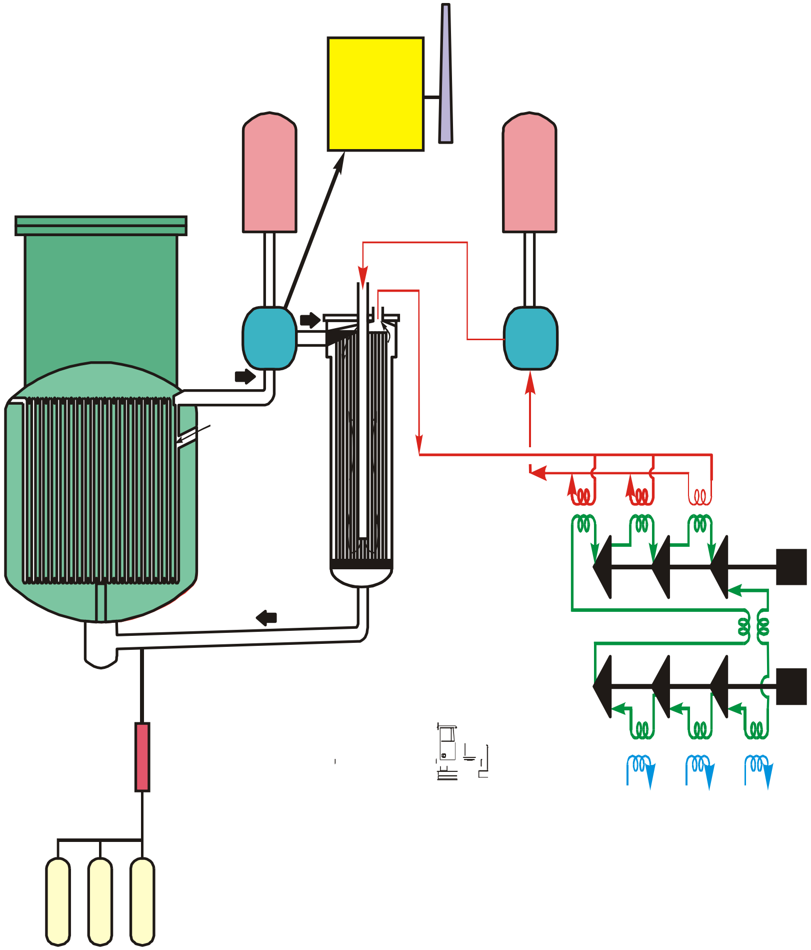


- Biofuels
- Oil shale
- Refineries
- Hydrogen

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

Work on MSR: Implications for FHR

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



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
  - η + $^{6}Li \rightarrow$ ^{3}H (tritium) + ^{4}He (helium)