Accident Criticality Safety for Fast-Spectrum Molten Salt Reactors

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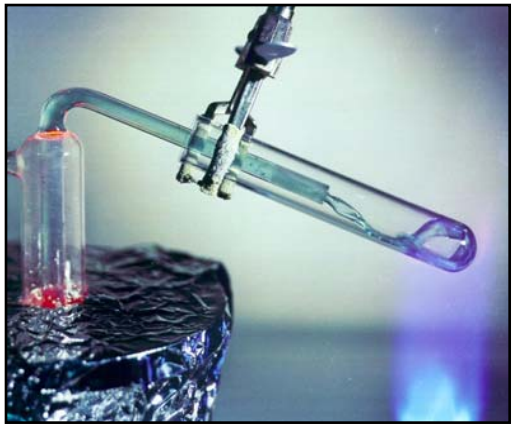
Presentation Outline

- **Salt-cooled reactor systems**
- **Fast spectrum molten salt reactors (FS-MSRs)**
  - **Description**
  - **Accident criticality safety challenges**
- **The Advanced High-Temperature Reactor (AHTR)**
  - **Description**
- **Use of AHTR plant design strategy to address fast-spectrum MSR accident criticality challenges**

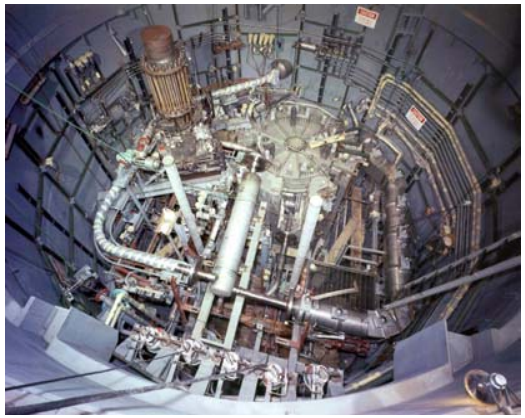
Salt-Cooled Reactor Systems

Molten and Liquid Salts are High-Temperature Coolants

- **Fluoride salts**
  - **Molten: fuel dissolved in the salt**
  - **Liquid: clean salt**
- **Characteristics**
  - **Melting points between 350 and 500ºC**
  - **Boiling points >1200ºC**
  - **Physical properties similar to water**
  - **Transparent**
- **Technology originally developed for the molten salt reactor in the 1950s and 1960s**
- **Only usable in high-temperature systems**

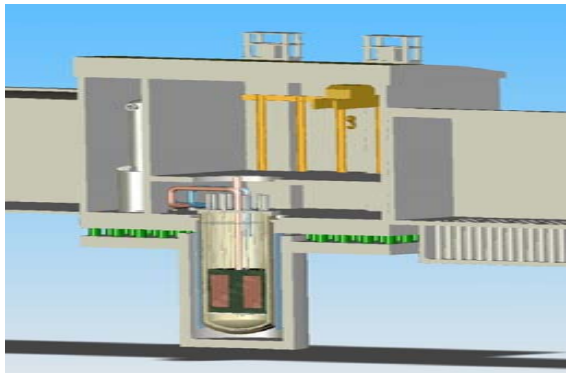


Liquid Fluoride Salt



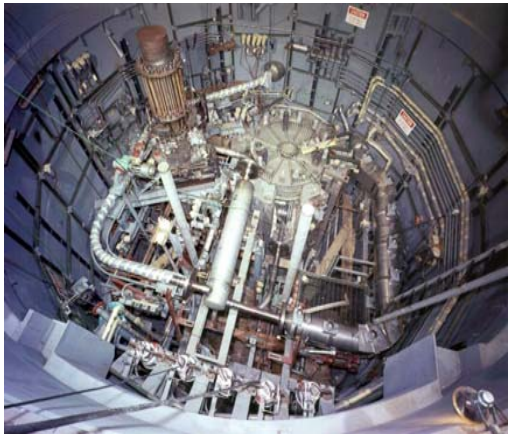
Molten Salt Reactor Experiment

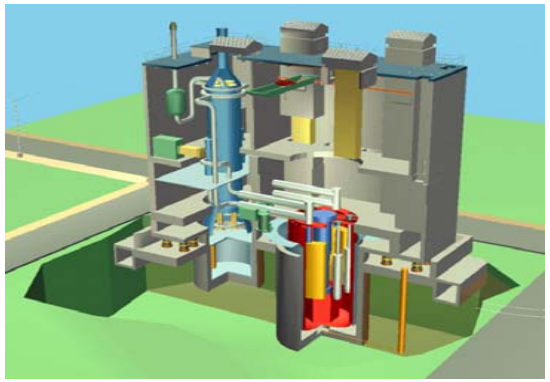
Four Salt-Cooled Reactor Systems are Being Examined



←Advanced High-Temperature Reactor
Graphite Moderated
Solid Fuel

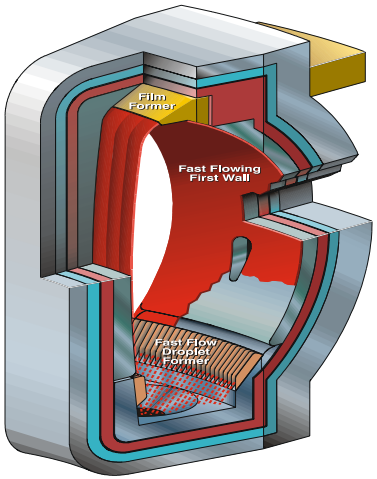
Molten Salt Reactor→
Fuel Dissolved in Salt





←Liquid-Salt-Cooled
Fast Reactor
Metal-Clad Solid Fuel

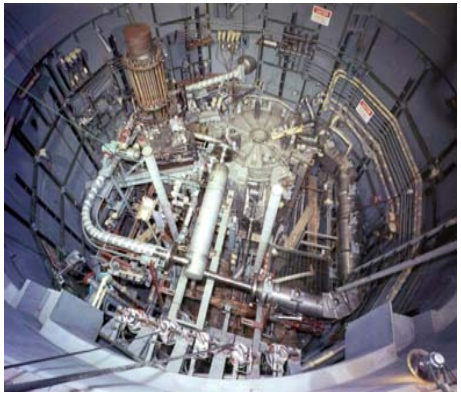
Fusion→
Liquid First Wall



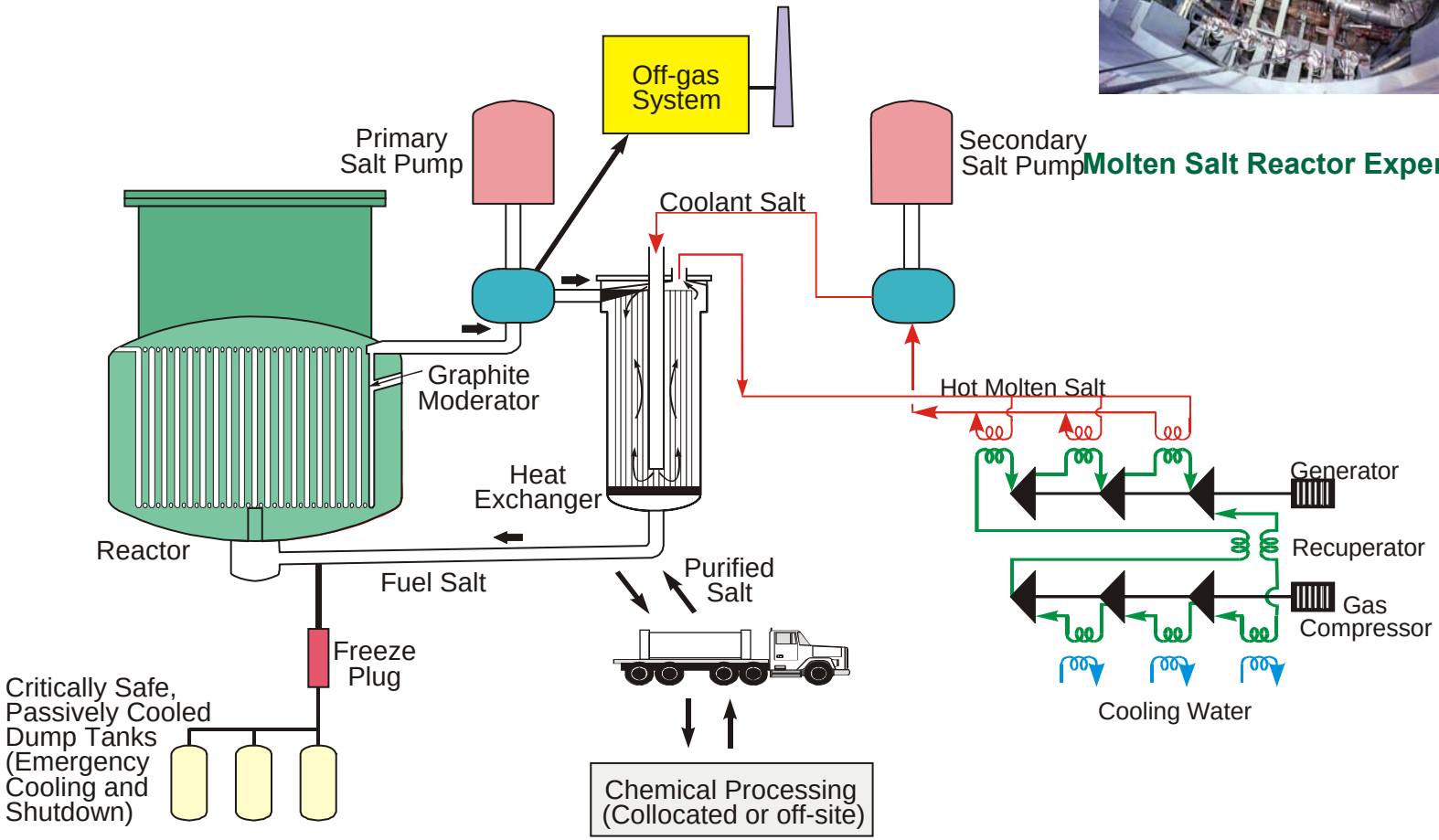
Fast-Spectrum Molten Salt Reactors

Molten Salt Reactor

Fuel Dissolved in the Salt Coolant
Traditional Design with Graphite Moderator and Thermal/Epithermal Neutron Flux



Molten Salt Reactor Experiment



New Missions and New Technology are Creating a FS-MSR

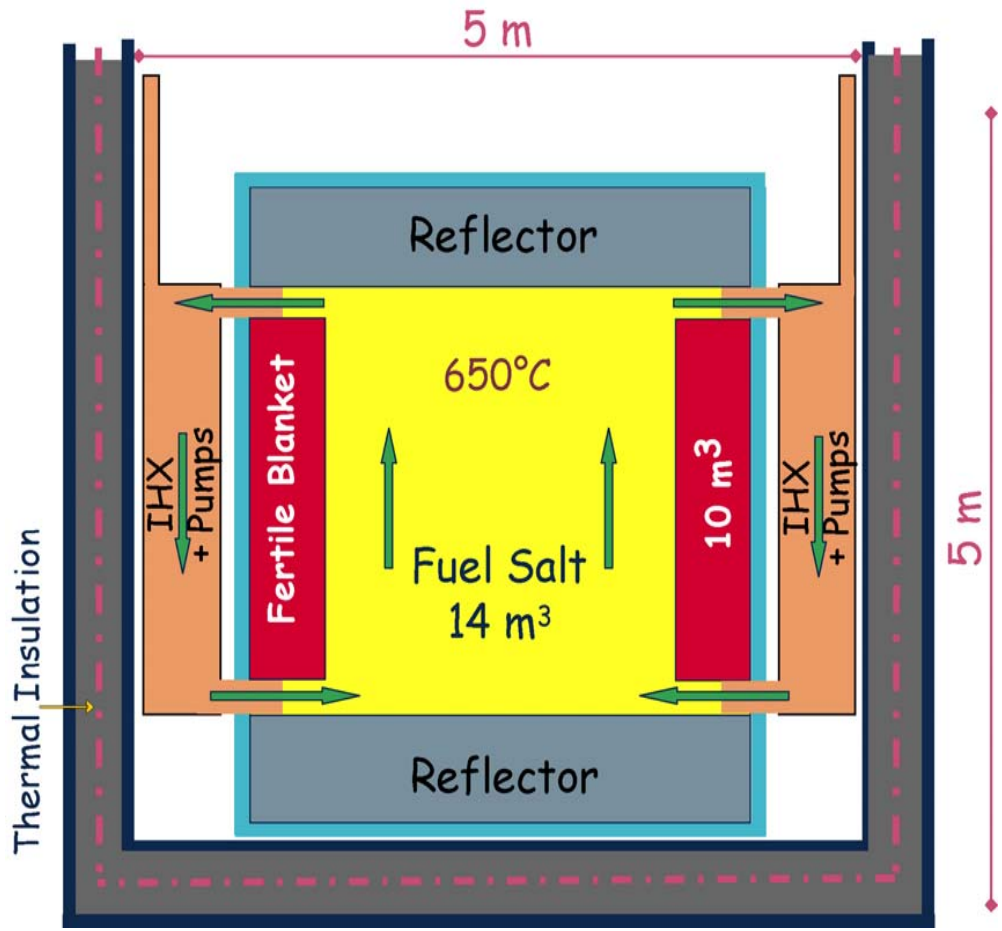
- **Missions**
  - **Sustainable power production**
  - **Actinide burning**
- **Technology**
  - **Thermal neutron spectrum (Traditional)**
  - **Fast spectrum (New development)**
    - **No Graphite**
    - **Modified salt compositions**

Sustainable FS-MSR

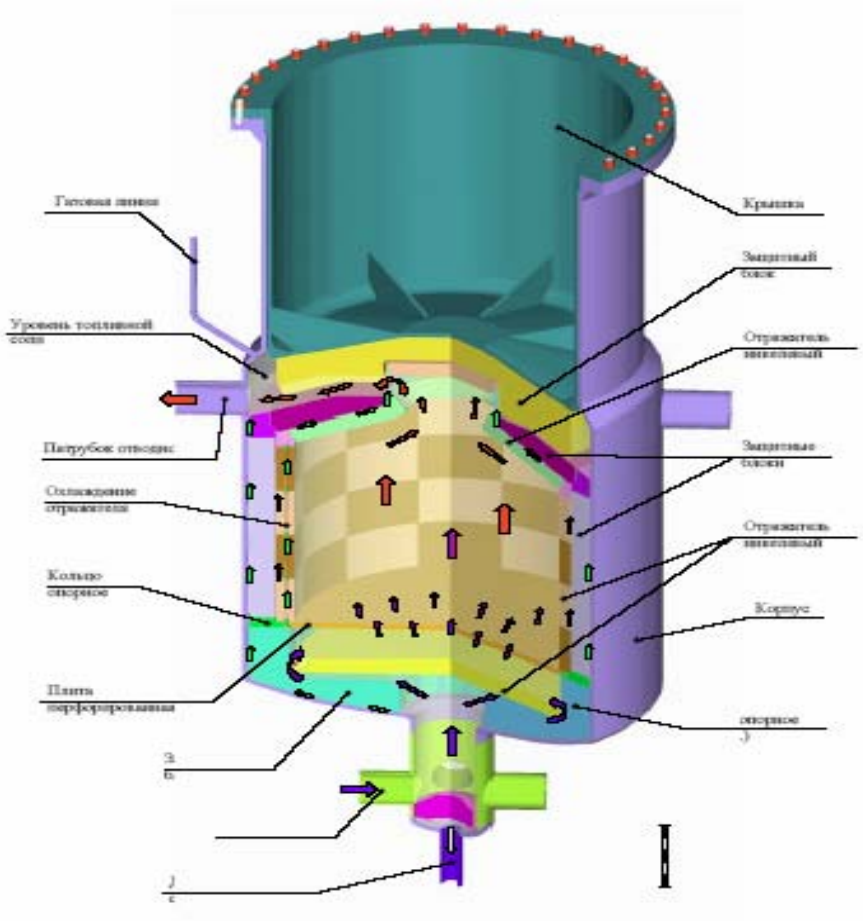
- **Breeder reactor**
  - **French design**
- **New salt compositions**
  - **LiF: 80%**
  - **$(HN)F_4$: 20%**
- **Advantages over solid-fuel fast reactors**
  - **High efficiency**
  - **Negative void and temperature coefficients**

Vertical Representation of the Thorium Molten Salt Reactor (TMSR)

(E. Merle-Lucotte et al, ICAPP 2007, Paper 7186)



MOlten Salt Actinide Recycler Transmuter (MOSART)



- **Transmute Pu and minor actinides without U-Th support**
  - **Russian design**
- **Salt selected for high-actinide solubility**
  - **LiF: 15–17 mole %**
  - **BeF: 25–27 mole %**
  - **NaF: remainder**
- **Design parameters**
  - **2400 MW(t)**
  - **Fission product removal cycle 300 days**
  - **Power density: 43 W/cm^3**
  - **Negative void coefficients**

Nuclear Criticality Accident Safety Challenge

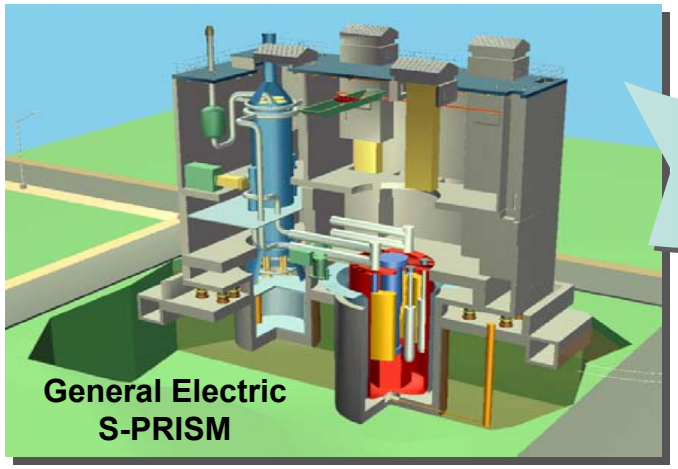
- **High fissile content of a fast-spectrum reactor implies potential criticality in an accident if**
  - **a geometry change**
  - **contact with a neutron moderator**
- **FS-MSRs have liquid fuels that can flow into empty spaces**
- **Many materials in a reactor are moderators (concrete, etc.)**

Advanced High-Temperature Reactors

System Characteristics May Address FS-MSR Accident Criticality Challenge

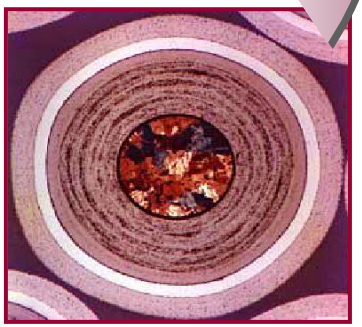
The Advanced High-Temperature Reactor

The Near-Term Option That Combines Four Existing Technologies



Passively Safe Pool-Type Plant Designs

Brayton Power Cycles

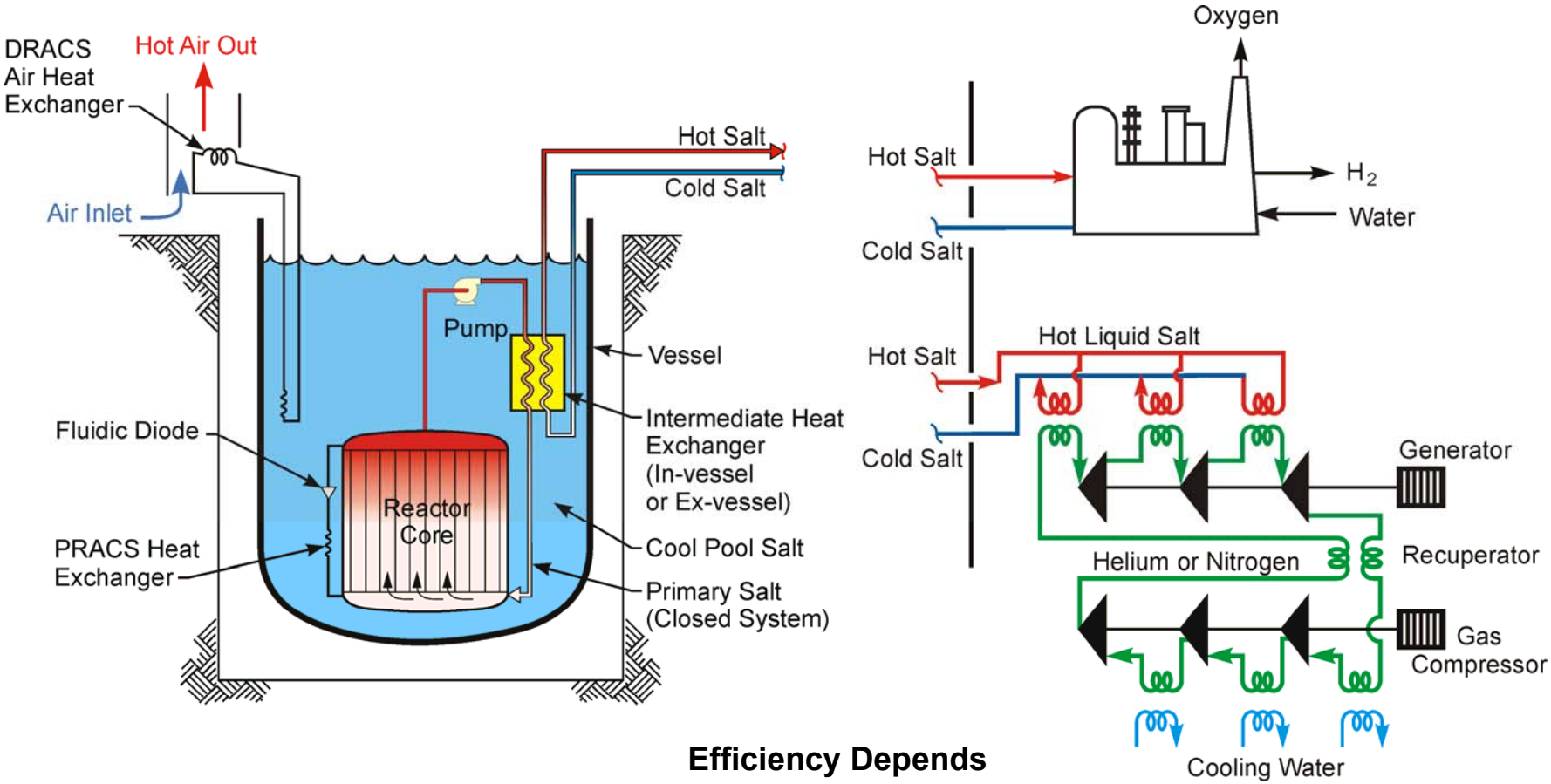


High-Temperature Fuel and Graphite Moderator

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

AHTR Schematic

Passive Decay Heat Removal **Reactor** **Hydrogen/Brayton Electricity Production**

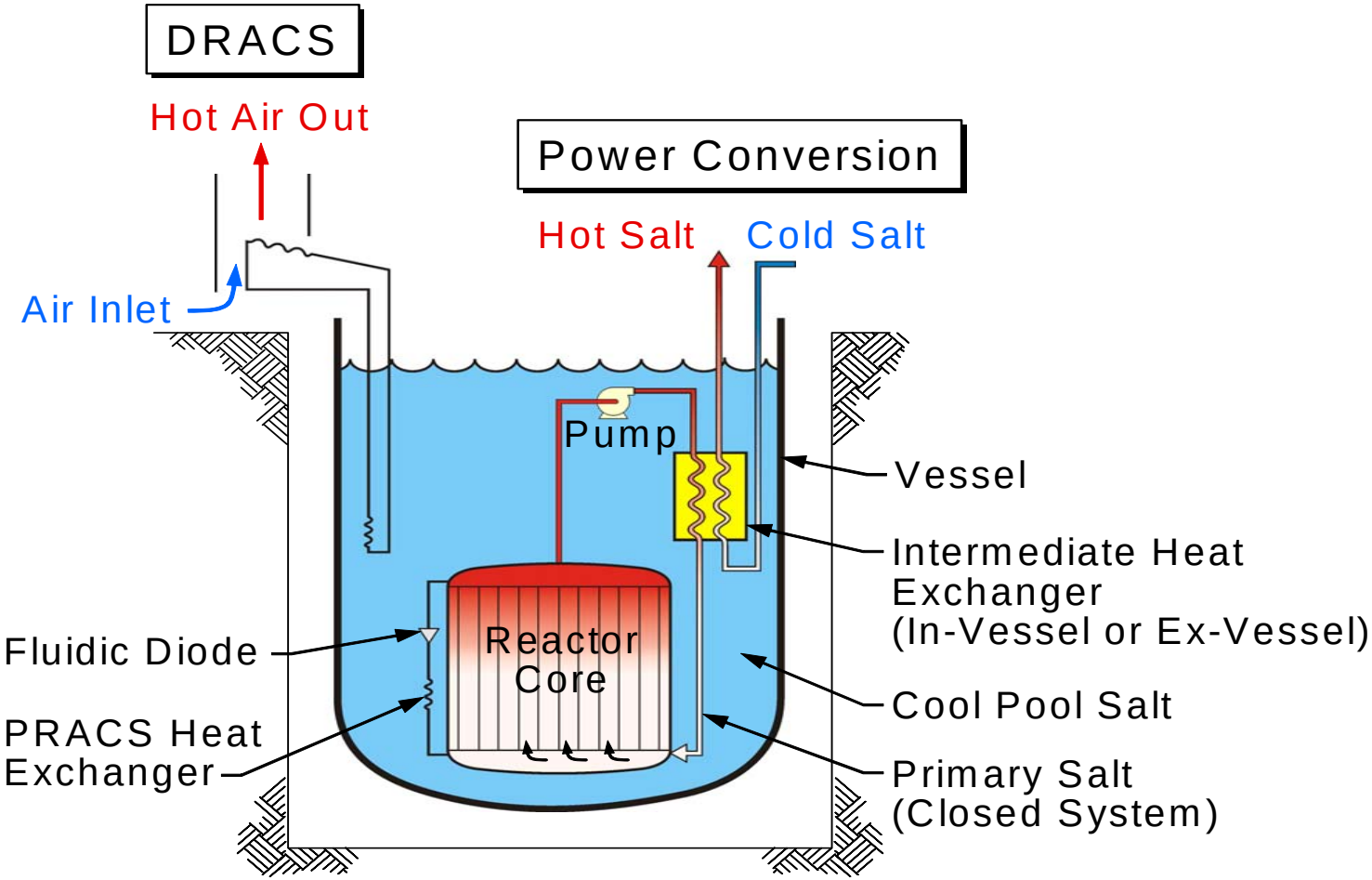


Efficiency Depends upon Temperature:

705ºC: 48.0%
800ºC: 51.5%
1000ºC: 56.6%

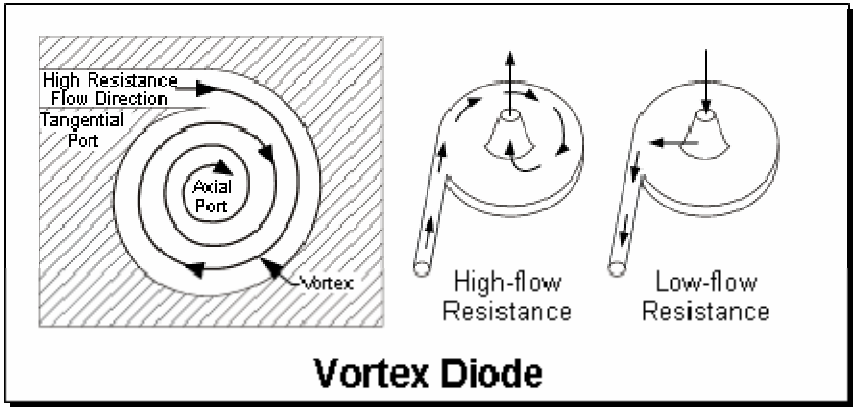
Decay Heat Removal System Enables Passive Safety and High-Power Levels

(Pool Reactor Auxiliary Cooling System: PRACS)

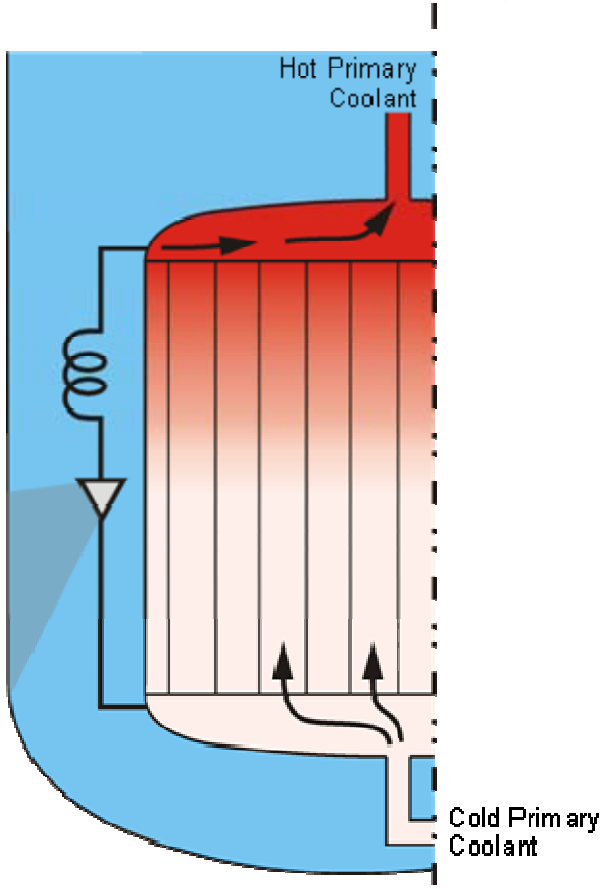


PRACS Heat Exchanger and Valve Dumps Decay Heat to the Pool Salt

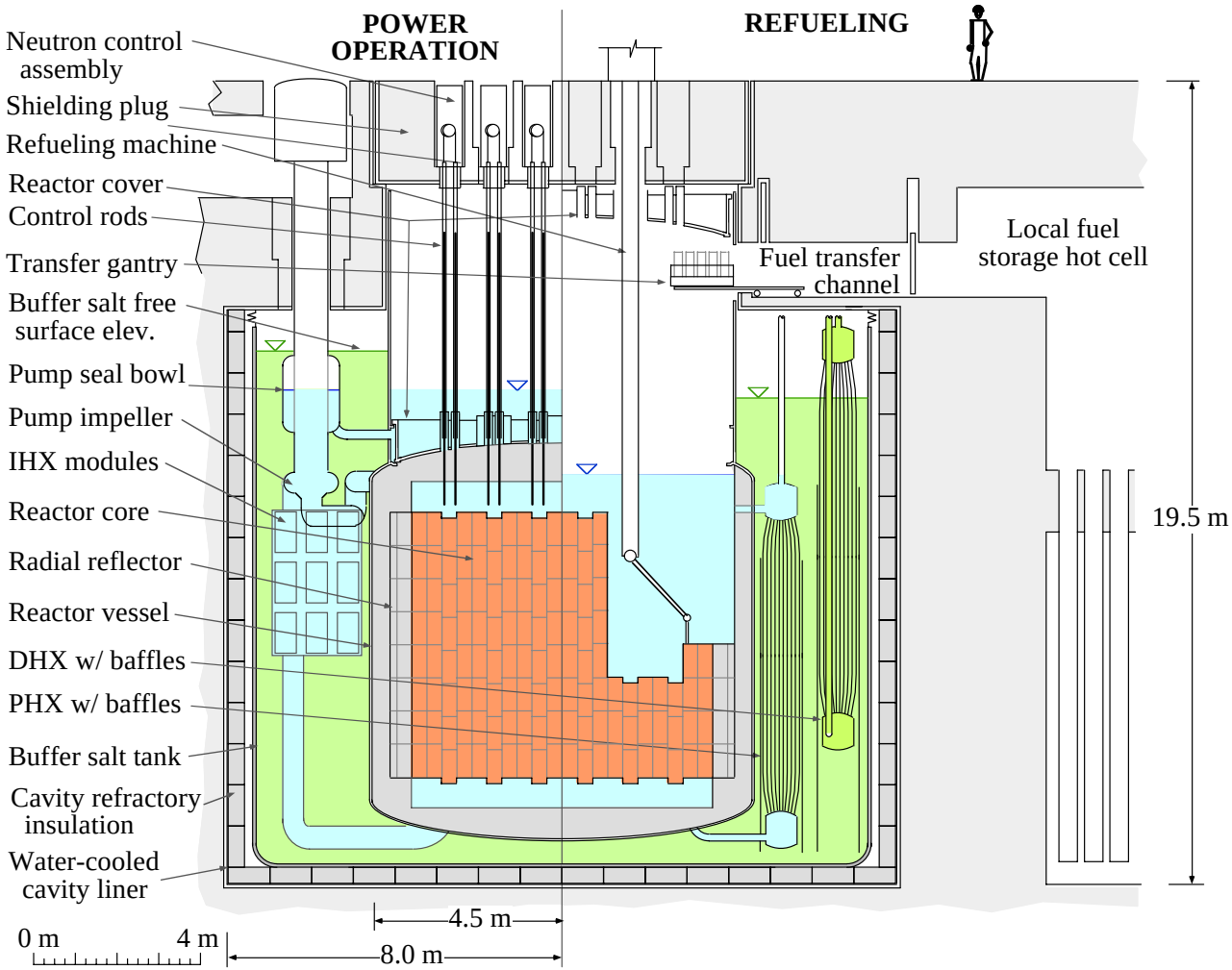
- **Low flow in upward direction during normal operations due to fluidic diode**
- **High flow in reverse direction after pump shutdown and natural-circulation flow startup**
- **Decay heat removal upon flow reversal**



Multiple fluidic valve options

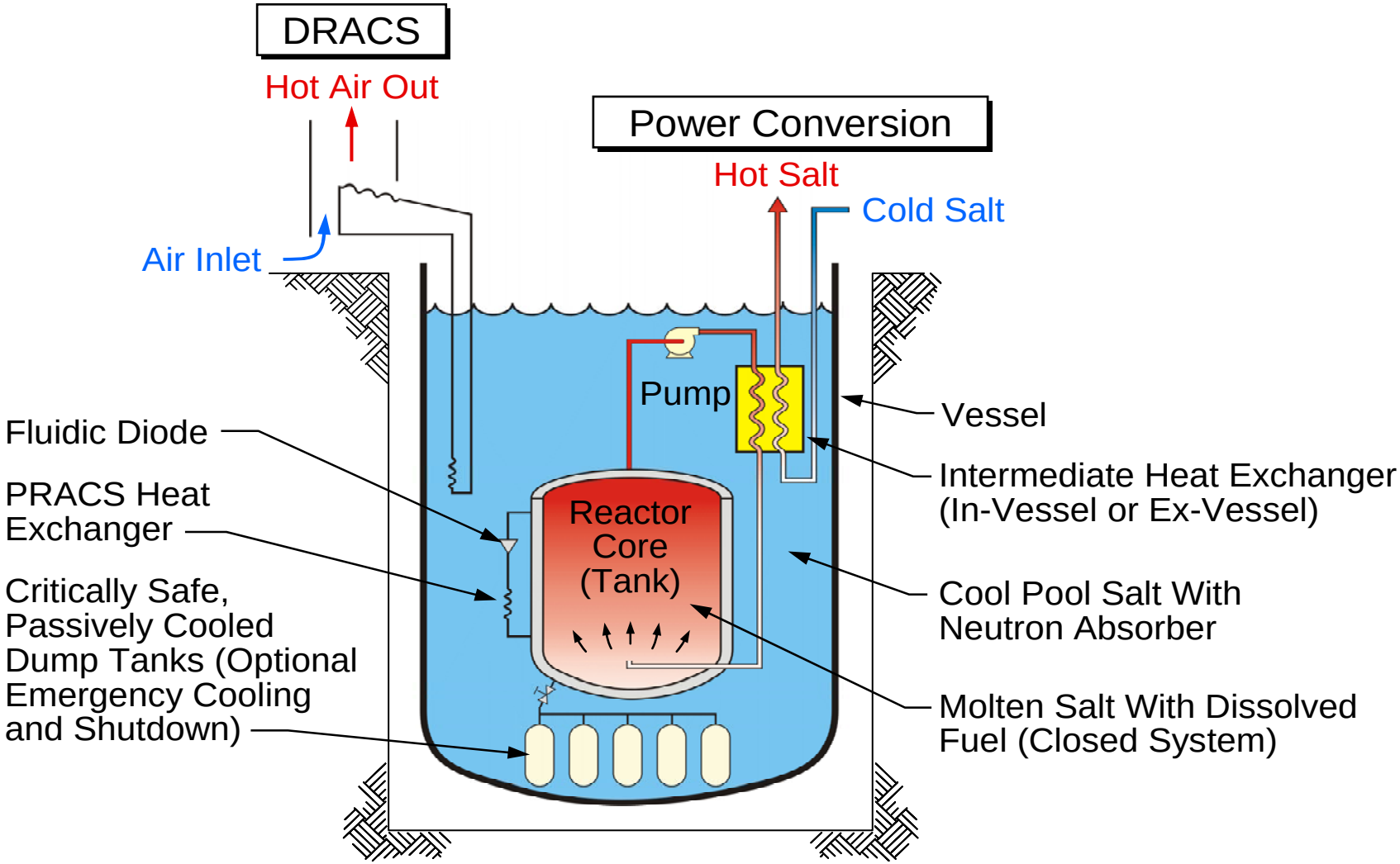


2400 MW(t) AHTR with Prismatic Fuel



Use of AHTR Plant Design to Address the Accident Criticality Challenge of a FS-MSR

FS-MSR with AHTR Two-Salt System



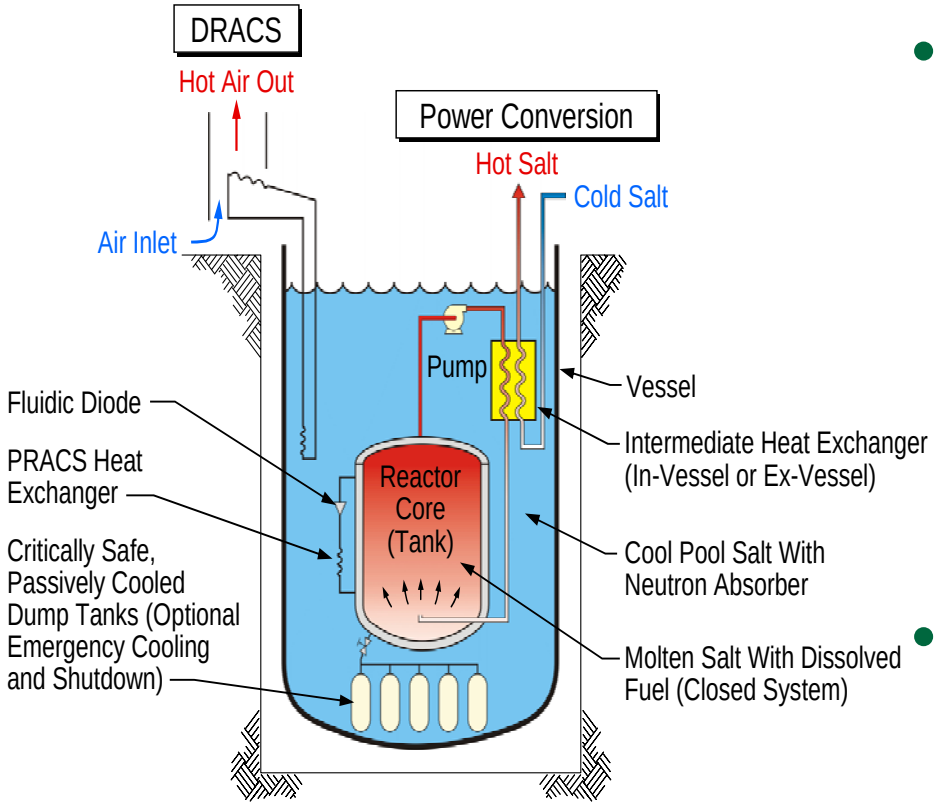
Criticality Safety System Characteristics

- **Secondary salt contains rare-earth absorbers**
  - **Nearly identical chemistry**
  - **If salts mix, no accident mechanisms for separation of fissile materials from rare-earth absorbers**
- **Secondary salt has a lower melting point to assure mixing of any leaking molten salt**
- **Secondary salt volume is much larger than the primary salt volume**
- **Secondary salt volume is sufficient to flood the silo above the core level if there is secondary vessel failure**

Other Benefits of Clean-Salt Pool System

- **Improved containment of radioactivity**
  - **Physical containment (secondary vessel)**
  - **Chemical containment: fission products dissolve in the secondary salt and this prevents their release to the environment under accident conditions**
- **Shielding**
- **Avoid thermal shock to primary system**
- **High-assurance of no freezing of liquid or molten salt**
  - **High heat capacity in secondary-vessel salt**
  - **Limited surface area for heat loss**

Conclusions



- **FS-MSR capabilities**
  - **Sustainable energy production**
  - **Actinide Burning**
- **FS-MSR safety advantages compared to solid-fuel fast reactors**
  - **Negative void coefficients**
  - **Lower fission product inventory (removal of fission products)**
  - **Lower system fissile inventories**
- **Secondary salt-filled vessel with neutron absorber may address FS-MSR accident criticality challenges**
- **Development required**

Biography: Charles Forsberg

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

Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. After working for Bechtel Corporation, he joined the staff of Oak Ridge National Laboratory, where he is presently the Senior Reactor Technical Advisor. Dr. Forsberg has been awarded 10 patents and has published over 200 papers in advanced energy systems, waste management, and hydrogen futures.

Accident Criticality Safety for Fast-Spectrum Molten Salt Reactors

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A new method to ensure criticality safety under accident conditions in fast-spectrum (no moderator) molten salt reactors (FS-MSRs) is proposed. MSRs are liquid-fuel reactors [1] that can be used for producing electricity or hydrogen as well as burning actinides and producing fissile fuels (breeding). Fissile, fertile, and fission products are dissolved in a high-temperature atmospheric-pressure molten fluoride salt. The fuel salt flows through a reactor core, where fission occurs within the flowing salt; through an intermediate heat exchanger; and back to the reactor core. An intermediate heat-transfer loop transports the heat to a turbine hall or to a hydrogen production facility.

FAST-SPECTRUM MOLTEN SALT REACTORS. MSRs are being reexamined today because of their unique fuel cycle and safety characteristics. The fuel-cycle capabilities include online refueling, no fuel fabrication (i.e., use of liquid fuel), and easy online blending of different fissile feedstocks. While the original MSRs were thermal spectrum reactors with graphite in the core as a moderator, today interest exists in FS-MSRs in which the core is a wide pipe in a molten salt circuit. Two concepts are being evaluated. In the actinide burning MSR, the plutonium and minor actinides from LWRs are the feed for an MSR that destroys 99.8% of the actinides. There is no fertile uranium or thorium that breeds fissile materials. This feature minimizes the number of actinide-burning reactors that are required for a fleet of LWRs. In the breeder MSR uses either the plutonium or U-233 with the fertile materials dissolved in the fluoride salt.

CRITICALITY SAFETY. Two reactivity-based safety issues are associated with fast-spectrum reactors: reactor control and criticality safety under accident conditions. Regarding reactor control, unlike solid-fuel fast-spectrum reactors, FS-MSRs have large negative temperature and void coefficients because liquid fuel is expelled from the core if voids are formed or if the temperature increases. The other criticality safety challenge associated with fast reactors is that accidental criticality can occur if the fissile materials are placed near neutron moderators—such as concrete. The critical masses in thermal-neutron environments are much less than those in fast reactors. For FS-MSRs, the challenge is the possible leakage of liquid fuel should a pipe break occur. A conceptual approach to solve this criticality safety challenge has been identified based on the technology being developed for the Advanced High-Temperature Reactor (AHTR).

The AHTR is a high-temperature reactor that uses coated-particle fuel (the same fuel used in gas-cooled high-temperature reactors) and liquid-fluoride-salt coolants. The closed primary reactor system is in a pool of liquid “buffer” salt, such as an inexpensive sodium fluoroborate salt. The primary salt coolant does not mix with the pool buffer salt. Instead, the salt coolant goes through the reactor core, the intermediate heat exchanger, and the primary pumps before returning to the reactor core. The buffer-salt pool is cooled with a direct reactor auxiliary cooling system (DRACS). During normal operation, the buffer salt is at the same temperature as (or a lower temperature than) the coldest primary salt.

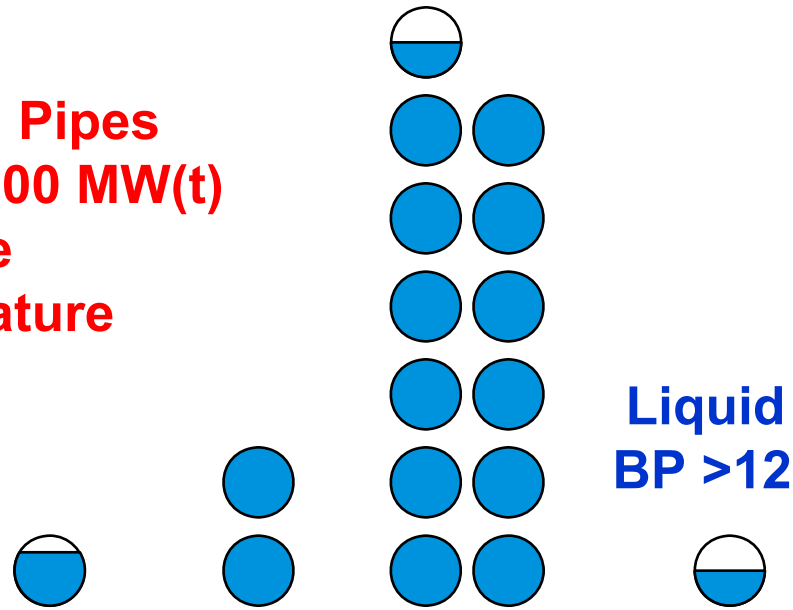
In the AHTR, if the intermediate heat exchangers do not remove the reactor heat, hotter primary coolant exits the heat exchangers and the temperature difference between the primary coolant in uninsulated pipes and the buffer salt dumps decay heat to the pool. Decay-heat removal can be enhanced by a secondary loop containing a fluidic diode and a heat exchanger that is connected between the top and bottom plenums of the reactor core. The fluidic diode allows high primary-system salt-coolant flow in one direction with low pressure drops but low primary-salt flow in the other direction with high pressure drops. If the pump stops, hot salt from near the top of the reactor flows by natural circulation down the loop and through a heat exchanger, dumps its heat to the pool, and enters the bottom of the reactor core plenum.

The use of the same system geometry for an FS-MSR can provide the basis for ensuring accident criticality safety (as well as normal decay heat removal). The FS-MSR would be in a closed system in a pool of buffer salt, which would contain the same salt or another salt with rare earth neutron absorbers. Because plutonium has a chemistry similar to that of the rare earths, the concentration of neutron absorbers in the secondary salt can be the same as or higher than that of the plutonium in the primary fuel salt. If a failure occurs in the reactor vessel or piping, the fuel salt and pool salt mix. However, criticality is avoided by mixing two salts with essentially identical chemistries but different nuclear properties. The similar chemistry ensures that there are no mechanisms to separate the rare earths and plutonium. For the MSR, the buffer tank would likely also include dump tanks under the core to drain the fuel salt to critically-safe, passively cooled tanks during maintenance and under some accident conditions. Significant analysis will be required to validate the strategy and chose the appropriate rare earths.

Salt Coolant Properties can Reduce Equipment Size and Costs

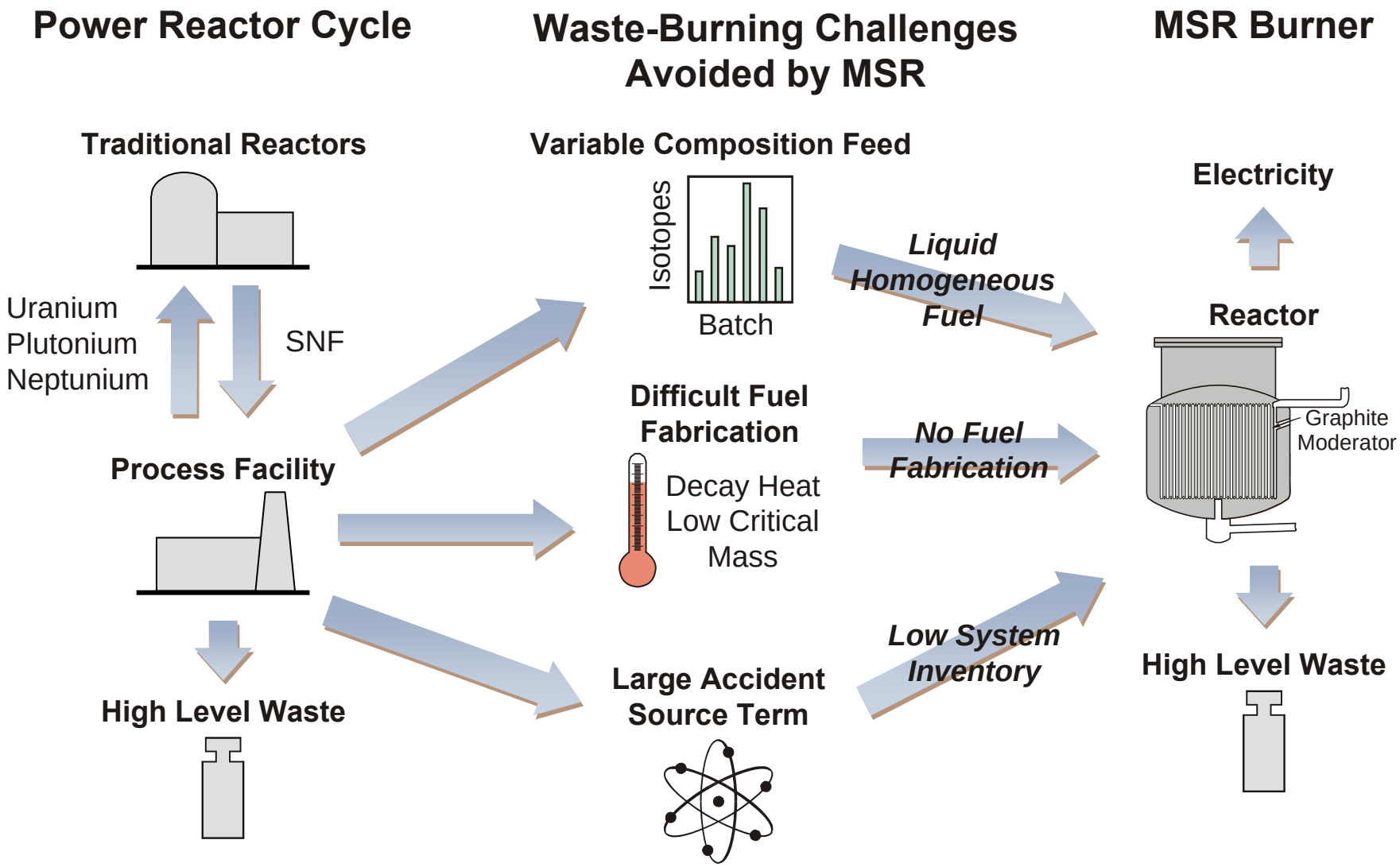
(Determine Pipe, Valve, and Heat Exchanger Sizes)

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

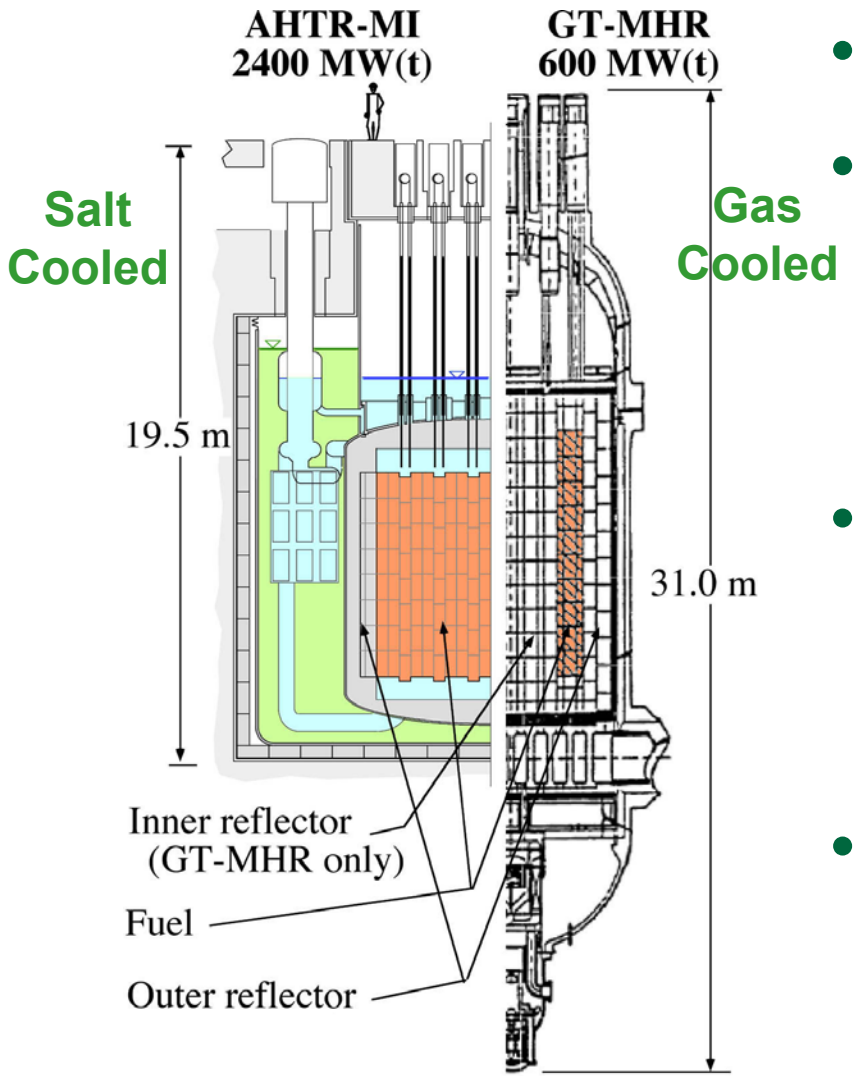


	Water (PWR)	Sodium (LMR)	Helium	Liquid Salt
Pressure (MPa)	15.5	0.69	7.07	0.69
Outlet Temp (ºC)	320	540	1000	1000
Coolant Velocity (m/s)	6	6	75	6

Actinide Burning: MSRs Avoid Several Solid-Fuel-Reactor Challenges



AHTR Characteristics and Status



- **Match modular gas-cooled reactor passive safety**
- **Characteristics**
  - **Low pressure salt coolant**
  - **2400 to 4000 MW(t)**
  - **Peak coolant temperatures**
    - **Electricity: ~750°C**
    - **Hydrogen: up to 950°C**
- **Economics is the primary incentive: Preliminary assessments**
  - **30% less than LWR**
  - **50% less than modular high-temperature reactors**
- **Status**
  - **Longer-term VHTR**
  - **Work at ORNL, U.C.-Berkeley, Areva-NP, and others**

ALWRs will improve with time thus advanced reactor goals must exceed expected ALWR technology in 2025