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Molten Salt Nuclear Reactors

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Outline

- *Motivation for Molten Salt Reactors*
- *Molten Salt Reactor Designs*
- *Molten Salt Research*

The (almost) Nuclear Plane XB-70 Valkyrie

The Nuclear Jet Engine

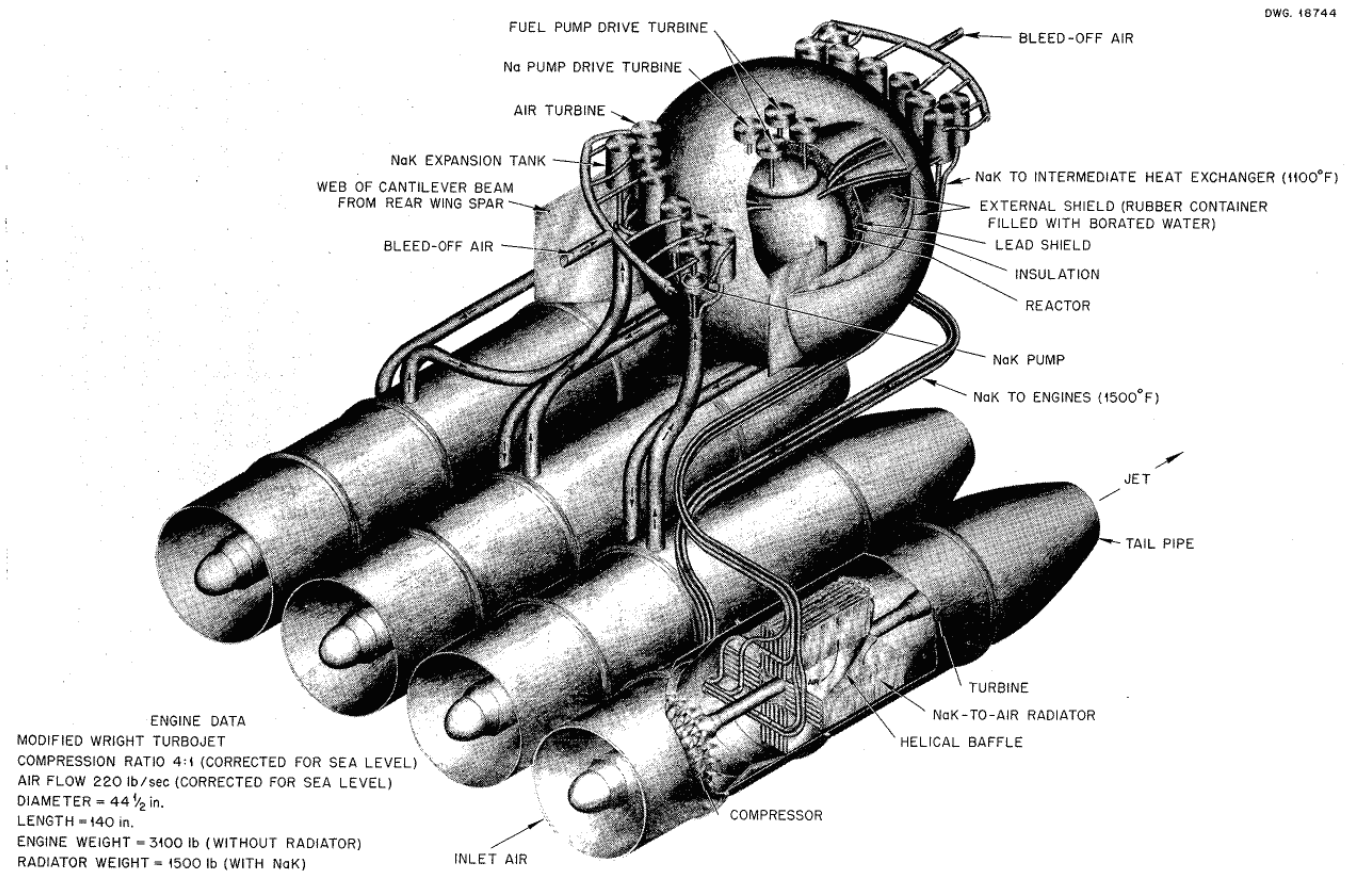
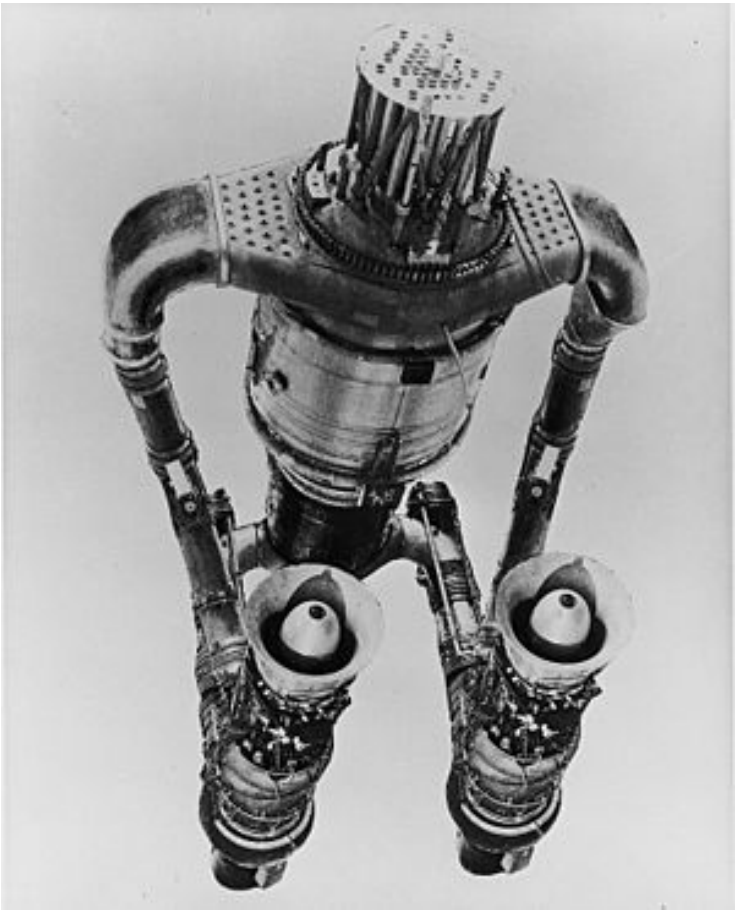


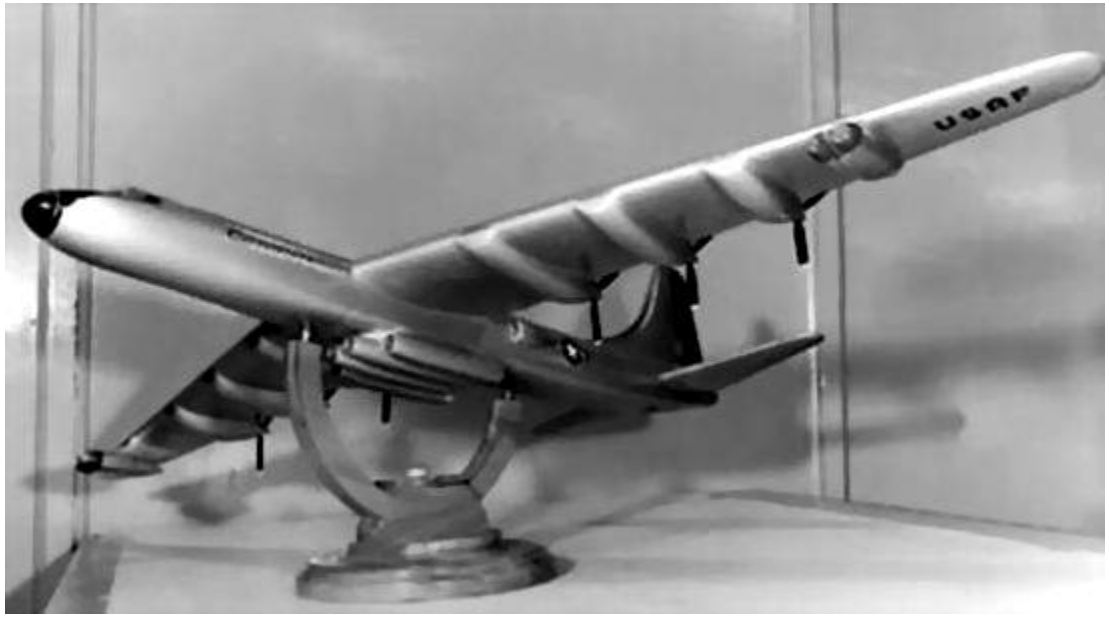
Fig. 4.33. Aircraft Power Plant (200 Megawatt).

The Nuclear Jet Engine

HTRE-3 Reactor:



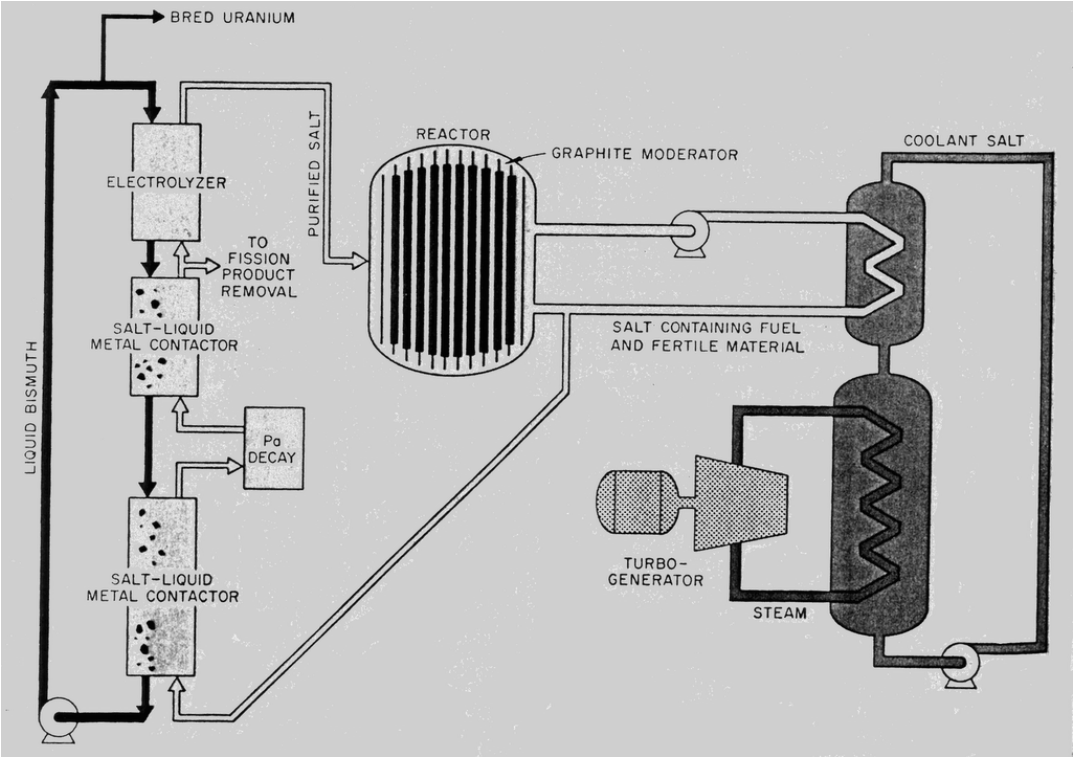
MX-1589 Project



The Nuclear Plane

MSBR70 Reactor (ORNL) 1965-1969

Operated with the main 3 fissile fuels: U-233, U235 and Pu-239



High-Temperature Reactors

Applications

Hydrogen Production
Future fuel

Electricity generation
Better Efficiency

Desalination
Lower temperature use

Desirables

Thorium
Proliferation Resistance

Safety
-ve reactivity coefficients

Higher Burnup

Moderator	Graphite or BeO
Inert Coolant	He, Pb-Bi eutectic, Molten Salt (2FLi-BeF2)
Fuel	TRISO coated particle Form

High-Temperature Reactors

Requirement: Process heat applications

Process temperature	**Up to 700°C**	**Up to 900°C**	**Up to 950°C**
Electricity production	Rankine (steam) cycle	Brayton (direct) cycle	
Utility applications	Desalination	H_2 via steam reforming of methane	Thermochemical H_2 production
Oil and chemical industry	Tar/oil sands and heavy oil recovery, Syncrude, Refinery and petrochemical	Syngas for ammonia and methanol	Thermochemical H_2 production

http://www.world-nuclear.org/info/inf116_processheat.html

Historic Overview of MSR

1950s • Aircraft Reactor Experiment (ARE)*

1960s • Molten Salt Reactor Experiment (MSRE)*

1970s • Molten Salt Breeder Reactor (MSBR)*

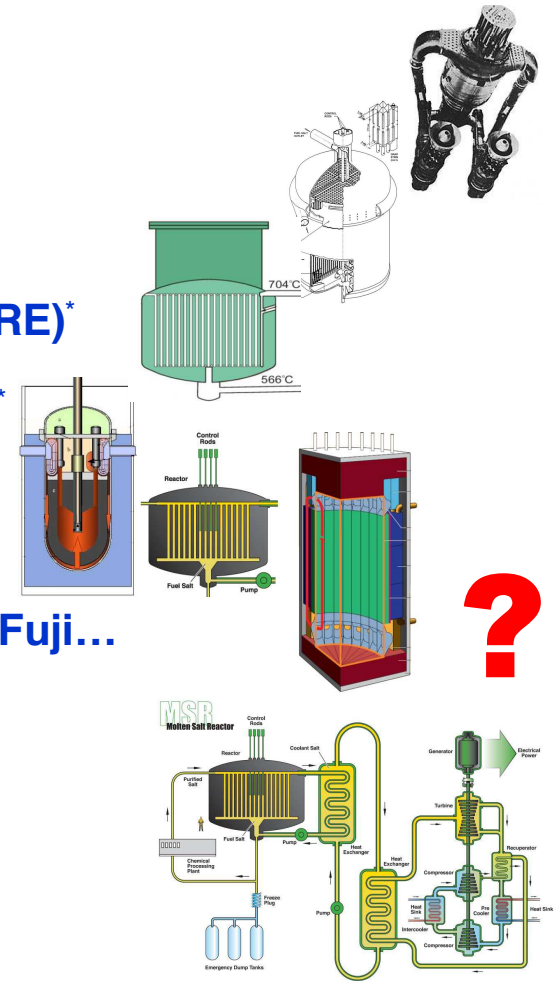
1990s • Accelerator-driven transmutation of Nuclear Waste (ATW)**

2000s • Generation IV, Amster, Sphinx, Tier, Fuji…

2010s • MSFR, Mosart…

Future • U-Th breeding, transmutation of Actinides, H_2 production … ?

* ORNL, ** LANL



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MSR: One of the GEN-IV Designs

1) VHTR *Very-High Temperature Reactor*

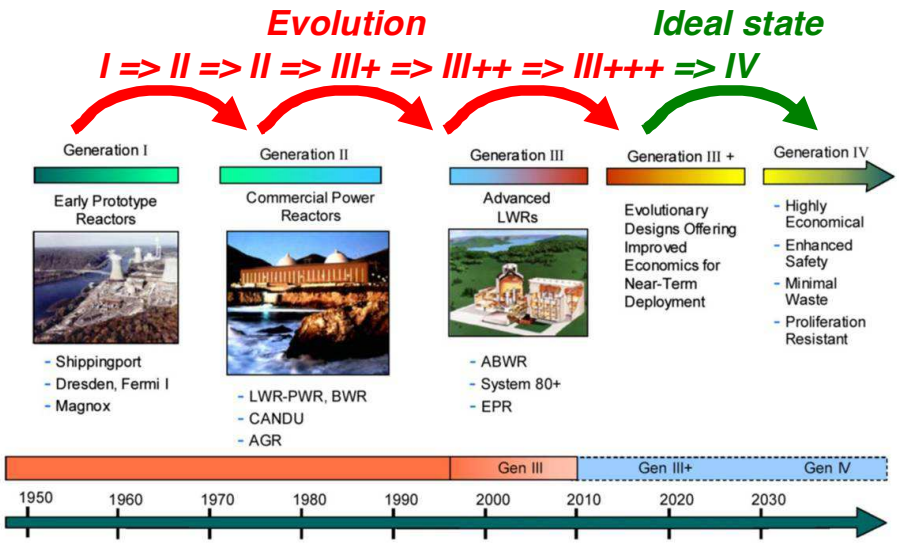
2) SCWR *Supercritical-Water-Cooled Reactor*

3) GFR *Gas-Cooled Fast Reactor*

4) LFR *Lead-Cooled Fast Reactor*

5) MSR *Molten Salt Reactor*

6) SFR *Sodium-Cooled Fast Reactor*



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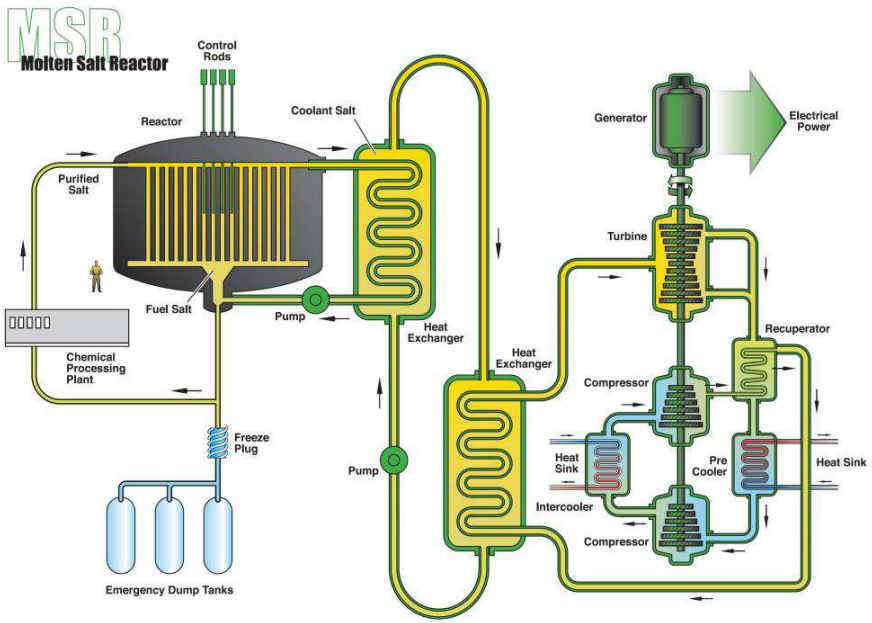
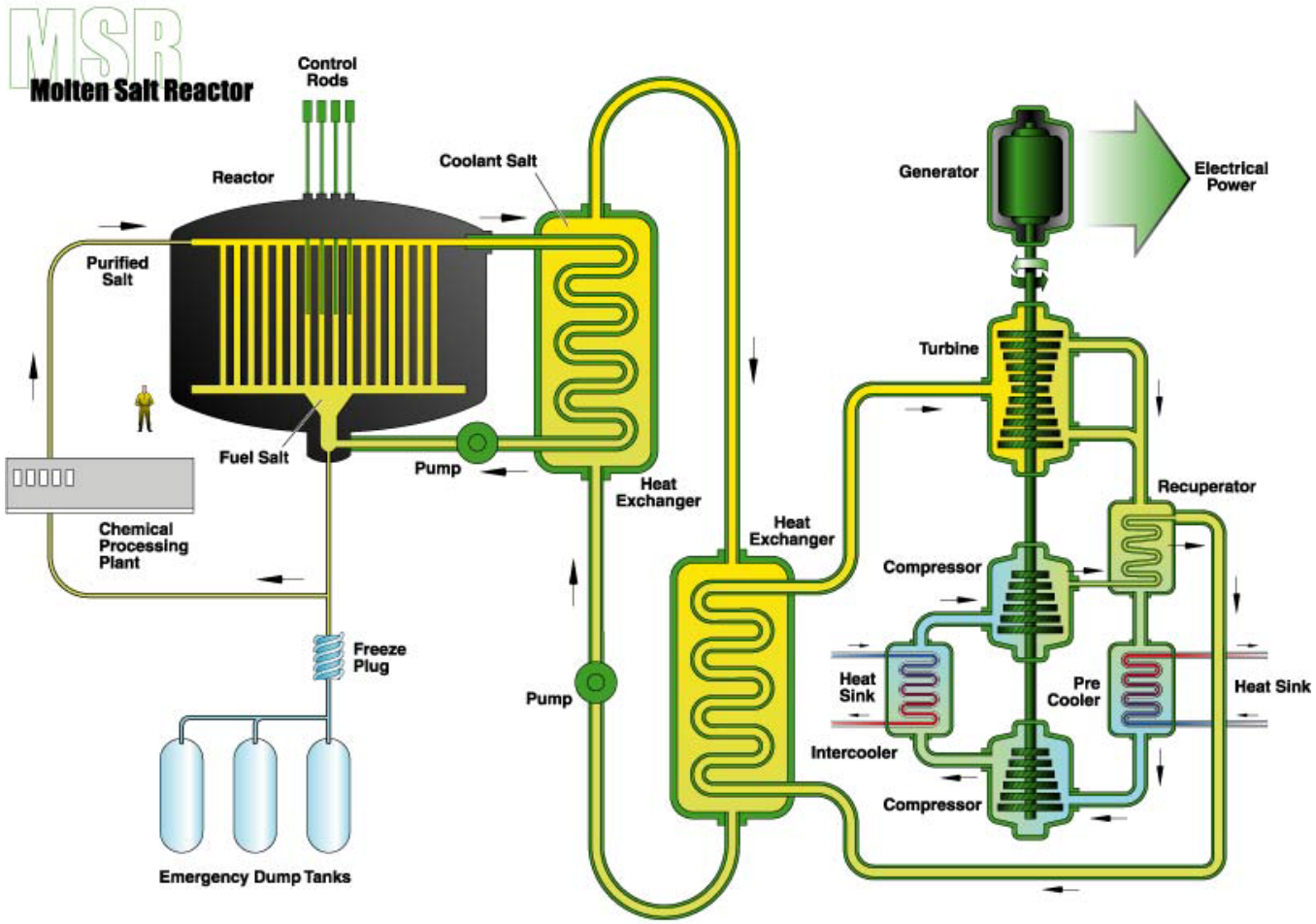
Gen-IV MSR

1) **VHTR** *Very-High Temperature Reactor*
2) **SCWR** *Supercritical-Water-Cooled Reactor*
3) **GFR** *Gas-Cooled Fast Reactor*
4) **LFR** *Lead-Cooled Fast Reactor*
5) **MSR** *Molten Salt Reactor*
6) **SFR** *Sodium-Cooled Fast Reactor*



- **Inherent safety**
  (fail-safe drainage, passive cooling, low inventory of volatile fission products, and negative temperature feedbacks)
- **Excellent neutron economy**
  (high availability, low inventory, breeding, burning)
- **Liquid fuel**
  (online refueling, reprocessing, volatile fission products removal, no fabrication)

Gen-IV MSR


MSR
Molten Salt Reactor
Control Rods
Reactor
Coolant Salt
Purified Salt
Fuel Salt
Pump
Heat Exchanger
Chemical Processing Plant
Freeze Plug
Emergency Dump Tanks
Pump
Heat Exchanger
Generator
Electrical Power
Turbine
Recuperator
Compressor
Heat Sink
Pre Cooler
Heat Sink
Intercooler
Compressor

Uses of Molten Salts in Nuclear Technology

Molten Salt as Liquid Coolant

High Temperature Reactors

Molten Salt as Liquid Fuel

MSRE at ORNL from 1965-69

Molten Salt as Process Medium

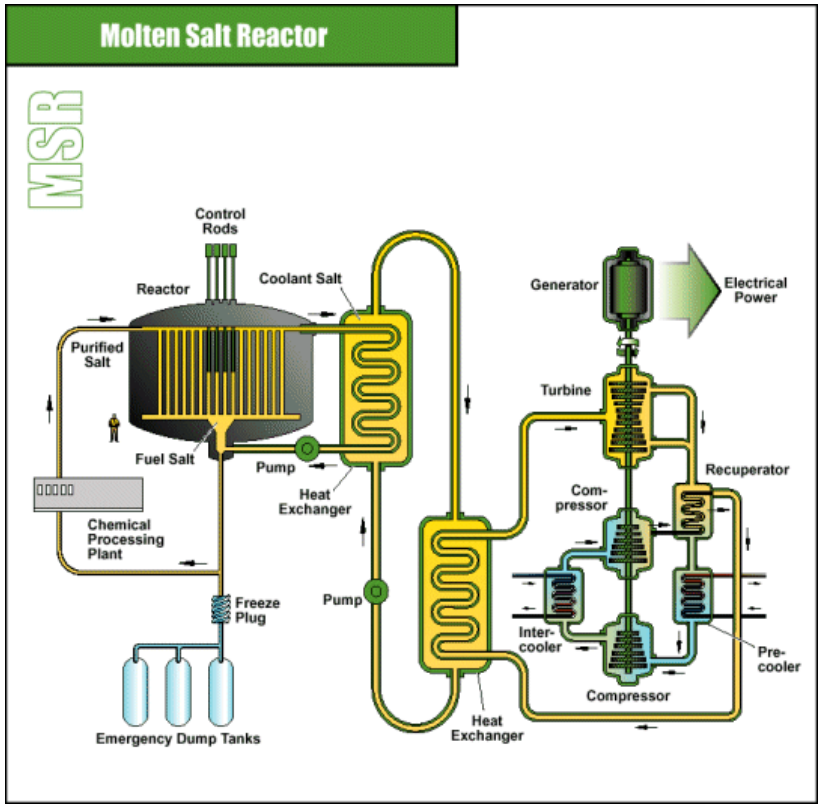
Advanced Partitioning Processes based on Pyro-processing of Spent Nuclear Fuel

MSR – A Non-Classic Reactor Type

Specific features of MSR comes out from the use of liquid (molten-salt) fuel circulating in the primary circuit.

MSR can be operated either as thorium breeder (in thermal or fast/resonance spectrum) within the ^{232}Th – ^{233}U fuel cycle or as actinide transmuter (in resonance/epithermal spectrum) incinerating transuranium fuel.

Typical fuel: fluorides of actinides dissolved in fluoride carrier salt.



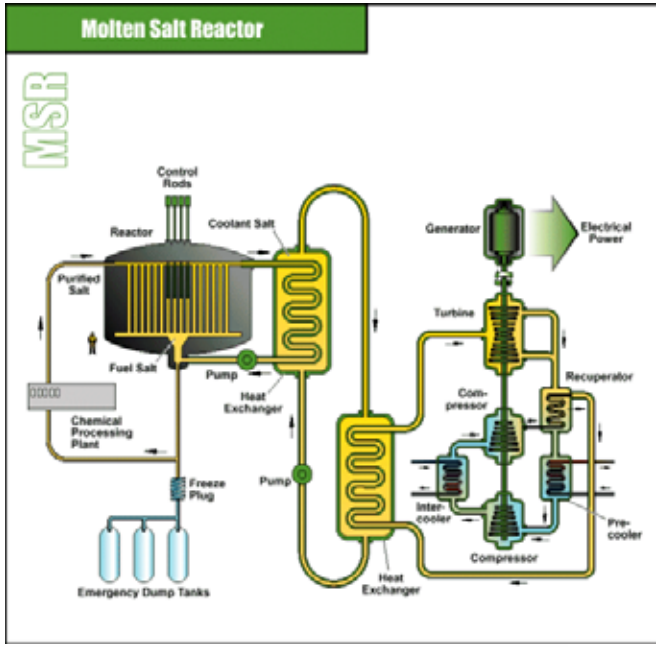
MSR – Thorium Breeder

MSR is the only reactor system from the GEN IV reactor family for which the thorium fuel is considered.

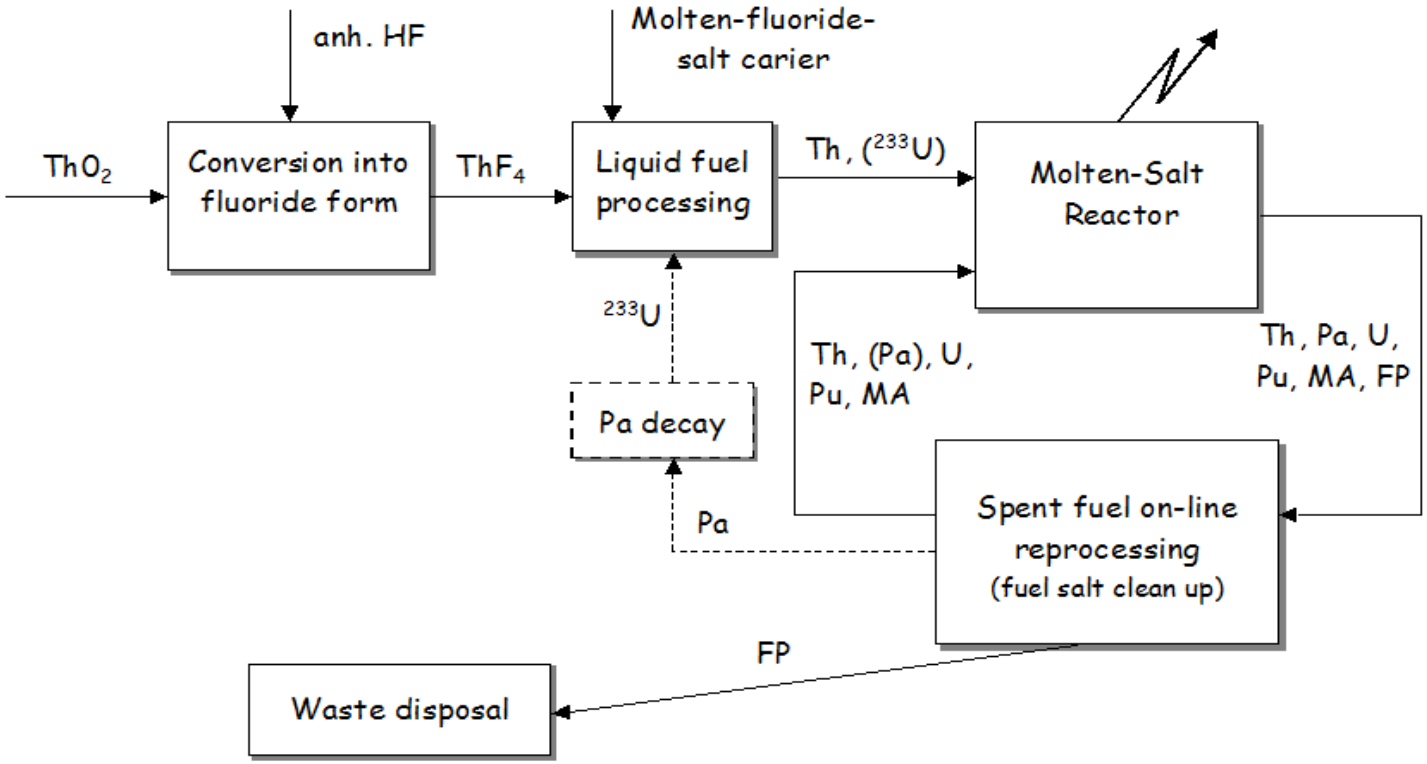
^{233}U is the only fissile material in the thorium – uranium fuel cycle

MSR – Th breeder with higher breeding cannot be operated without the on-line reprocessing

Typical fuel: ThF_4 and UF_4 dissolved in ^{7}LiF – BeF_2 carrier molten salt.



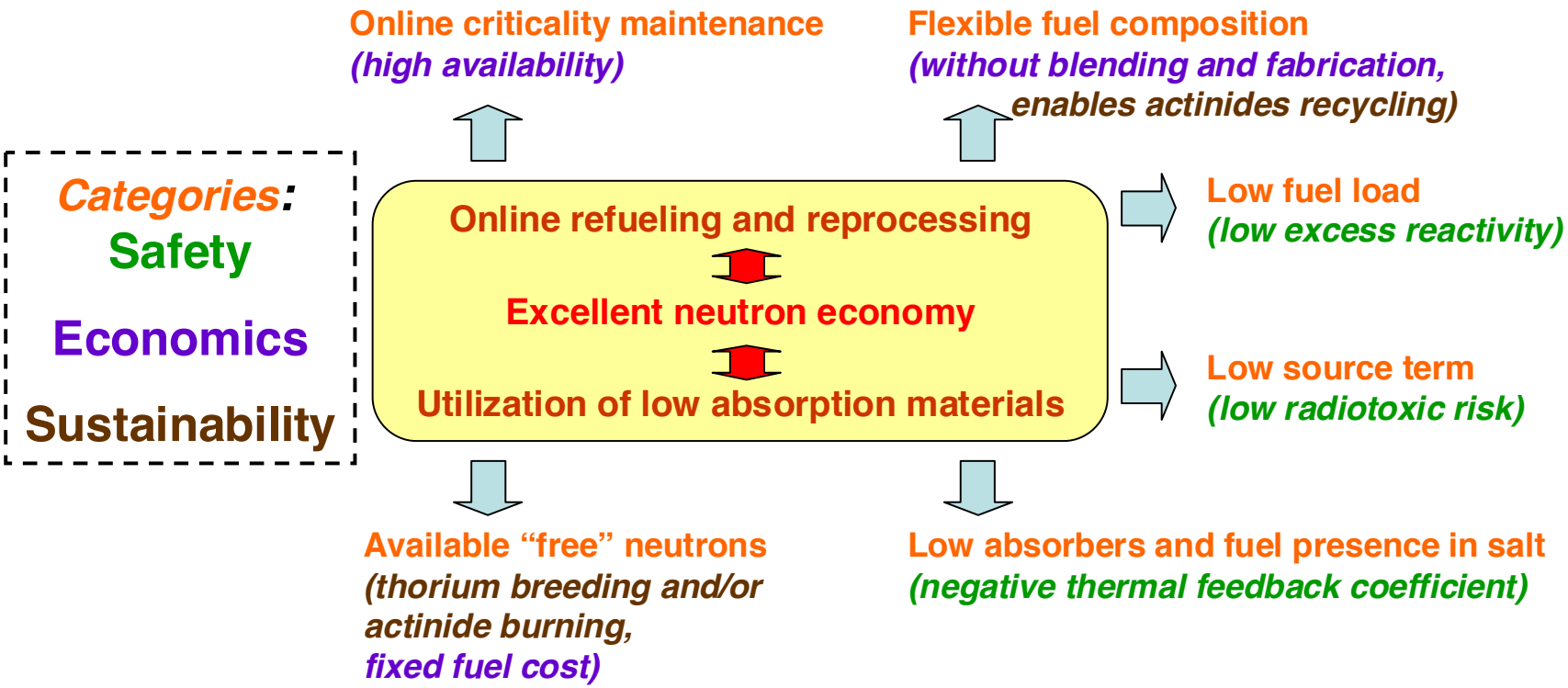
Fuel Cycle Technology on MSR System



Advantages of MSR

- Safety
  - Inherent safety, understandable to the public
  - Hard to even imagine accidents hazardous to the public
- Reduced Capital Cost
  - Low pressure, high thermal efficiency and far superior coolants (smaller pumps, heat exchangers)
- Long Lived Waste Profile
  - Even converter designs can have closed cycles that see almost no transuranics going to waste
  - Ideal system for consuming existing transuranic wastes
- Resource Sustainability and Low Fuel Cycle Cost
  - Thorium breeders obvious but MSR converters also extremely efficient on uranium use

Neutronics Characteristics of MSR



Molten Salt Features and Characteristics

Categories:

Safety

Economics

Sustainability

molten fluoride salts for MSR are transparent

Chemically inert substance
(no rapid reaction with water no fire or explosion hazard)

Radiation resistant substance
(unlimited use only with purification)

Freezing is inherent and passive
(dispersion and freezing after leakage)

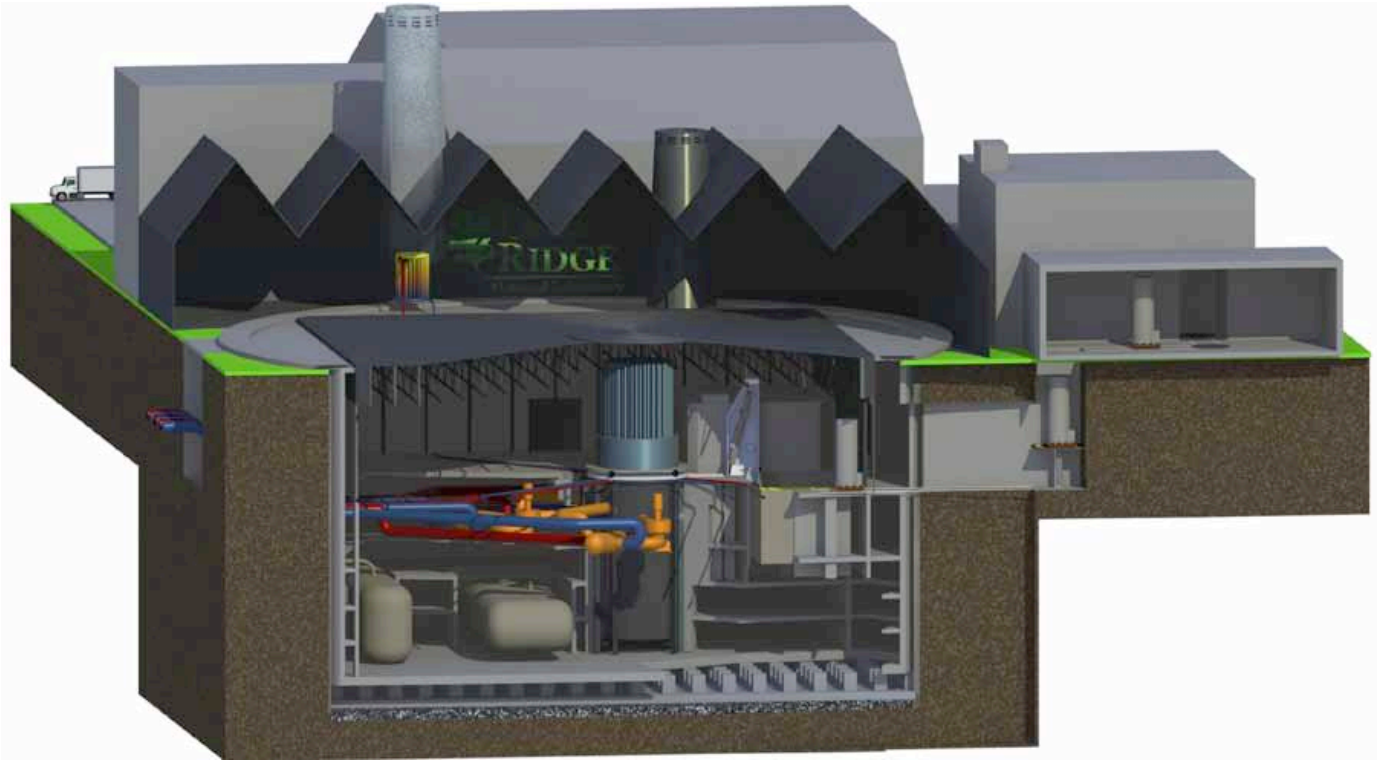
freezing < 500°C ***1400°C < boiling***

High-temperature operation
(potential for hydrogen production)

Low vapor pressure of fluoride salts
(reduced stresses on vessel and piping)

Fuel is molten and in liquid state
(it can be drained, no melting accidents)

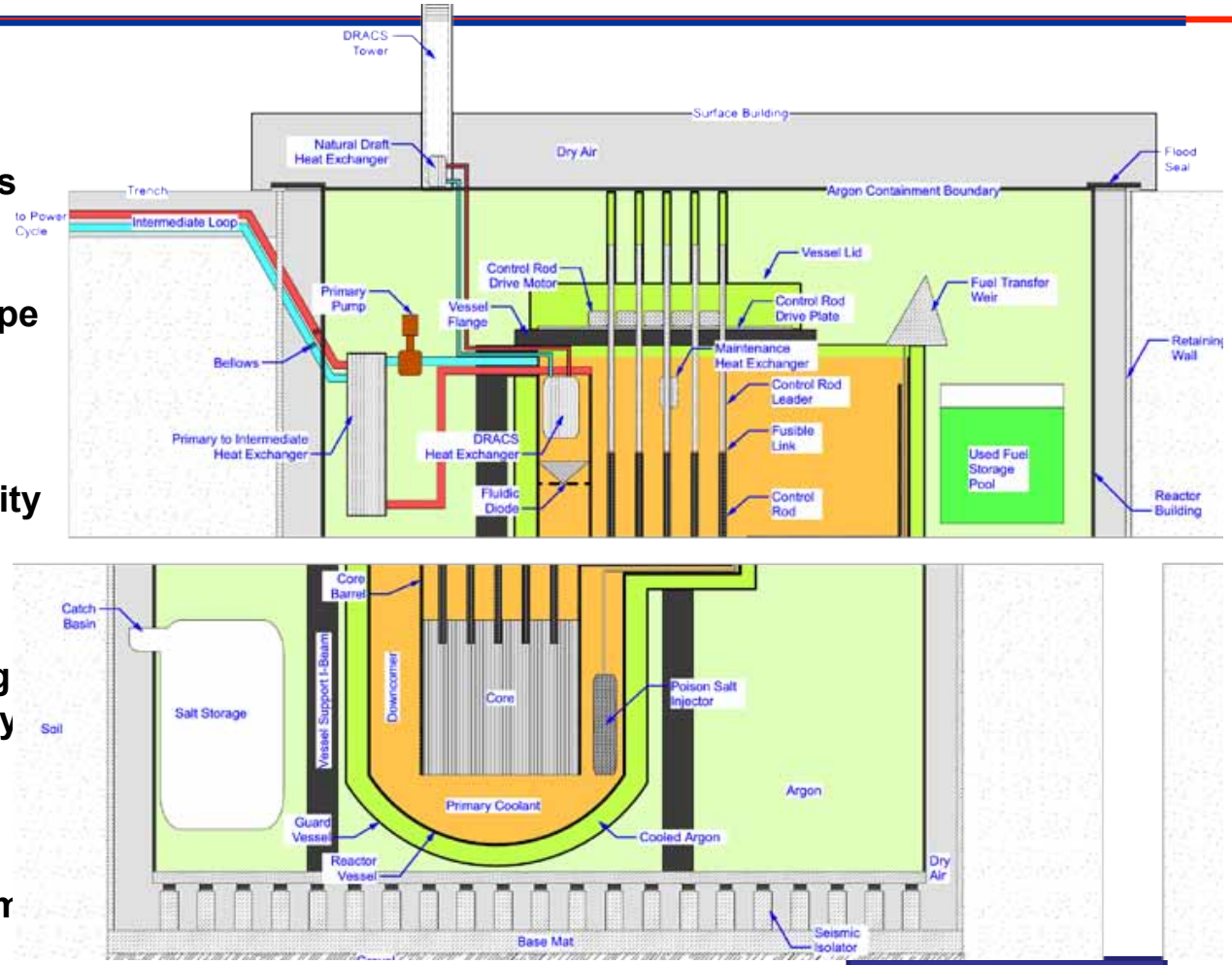
AHTR (ORNL)



ORNL/TM-2012/320 - AHTR Mechanical, Structural, And Neutronic Preconceptual Design

AHTR (ORNL)

- Advanced High Temperature Reactor (AHTR) is ORNL's design concept for a central station type (1500 MW_e) FHR
- Objective is to demonstrate the technical feasibility of FHRs as low-cost, large-size power producers while maintaining full passive safety
- Focus on developing a functional, self-consistent system



AHTR Schematic

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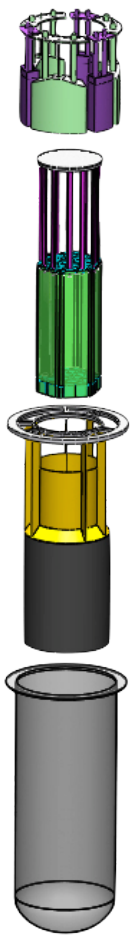
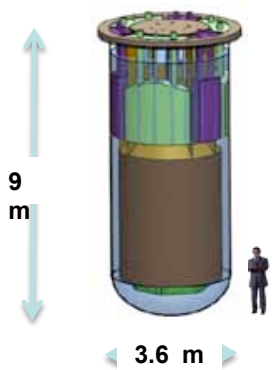
SmAHTR

Small, modular Advanced High Temperature reactor (SmAHTR) has been designed for modular, factory fabrication, and truck transport

- 125 MW_{th}
- Plate assembly fuel
- Cartridge core
- Integral primary heat exchangers

Technology development requirements for small and large FHRs is virtually identical





What defines an HFR?

The general characteristics of a Fluoride Salt Cooled High Temperature Reactor (FHR) are:

- Use of coated particle ceramic fuel
- Use of fluoride salt as primary coolant
- Use of a low-pressure, pool type primary system configuration
- Delivery of heat at temperatures greater than 600°C
- Strong passive safety features

No requirement for active response to avoid core damage or large off-site release following even severe accidents

Relevance of HFRs

Large FHRs have transformational potential to provide lower cost, high efficiency, large scale electrical power

- May be cheaper than LWRs due to higher thermal efficiency and low-pressure, and passive safety

Small, modular FHRs can be cost effective, local process heat sources

- High temperature, liquid cooling enables efficient hydrogen production
- Domestic oil shale based gasoline production requires large-scale, distributed process heat

FHRs have a high degree of inherent passive safety

- No requirement for offsite power or cooling water
- Low-pressure primary and intermediate loops

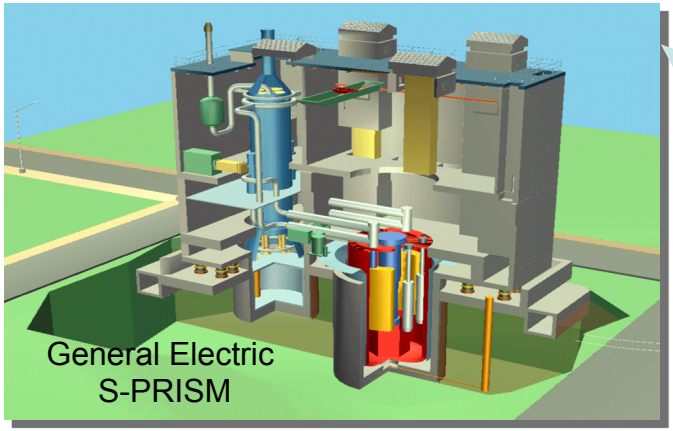
Plant concept and technologies must be matured significantly before the potential for FHRs can be realized

- Lithium isotope separation technology must be reindustrialized
- Tritium capture technology must be developed and demonstrated
- Structural ceramics must become safety grade engineering material
- Safety and licensing approach must be developed and demonstrated
- Layered TRISO fuel manufacturing technology must be demonstrated

US FHR Project

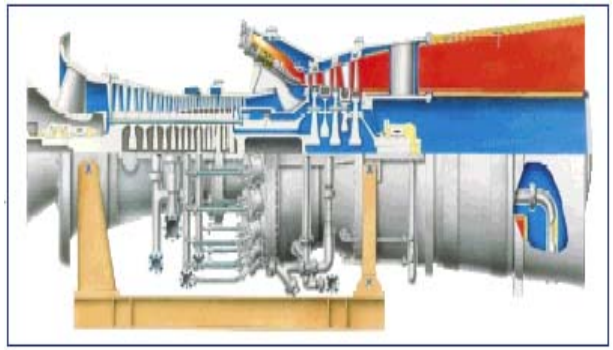
- MIT
- University of California Berkley
- University of Wisconsin
- Oak Ridge National Laboratory
- Idaho National Laboratory

FHR Combines Existing Technologies



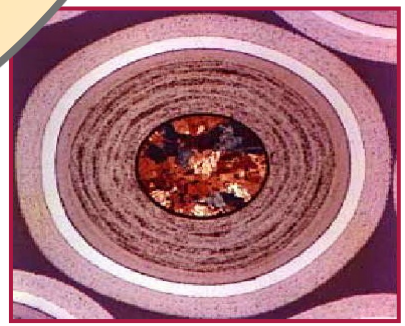
Passively-Safe Pool-Type Reactor

Fluoride Salt-Cooled High-Temperature Reactor (FHR)

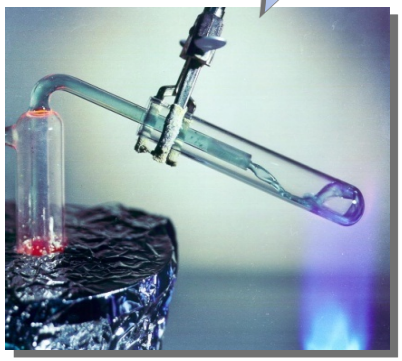


GE Power Systems MS7001FB

Brayton Power Cycles



High-Temperature Coated-Particle Fuel

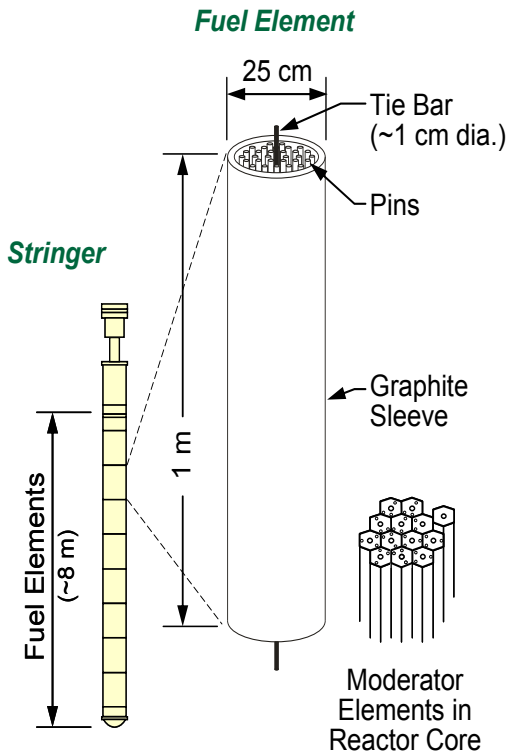


High-Temp., Low-Pressure Liquid-Salt Coolant

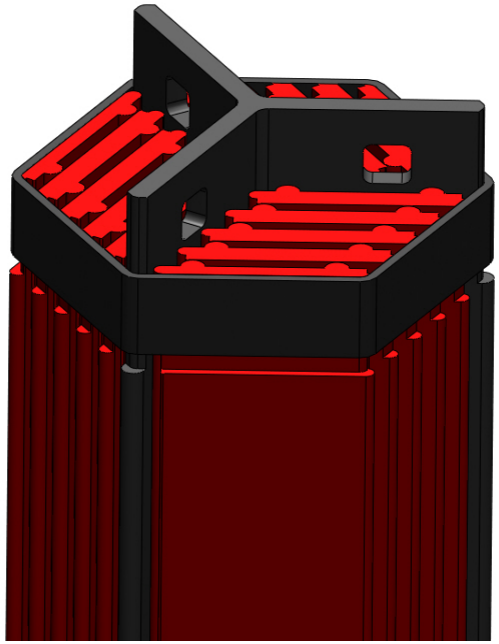
(Transparent)

Many Fuel Options

Mostly Graphite-Matrix Coated-Particle Fuels

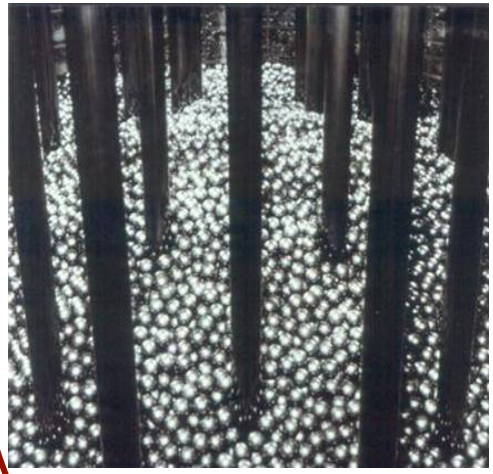


Pin Assembly in Graphite Pile



Flat Fuel Planks in Hex Configuration

Base Case

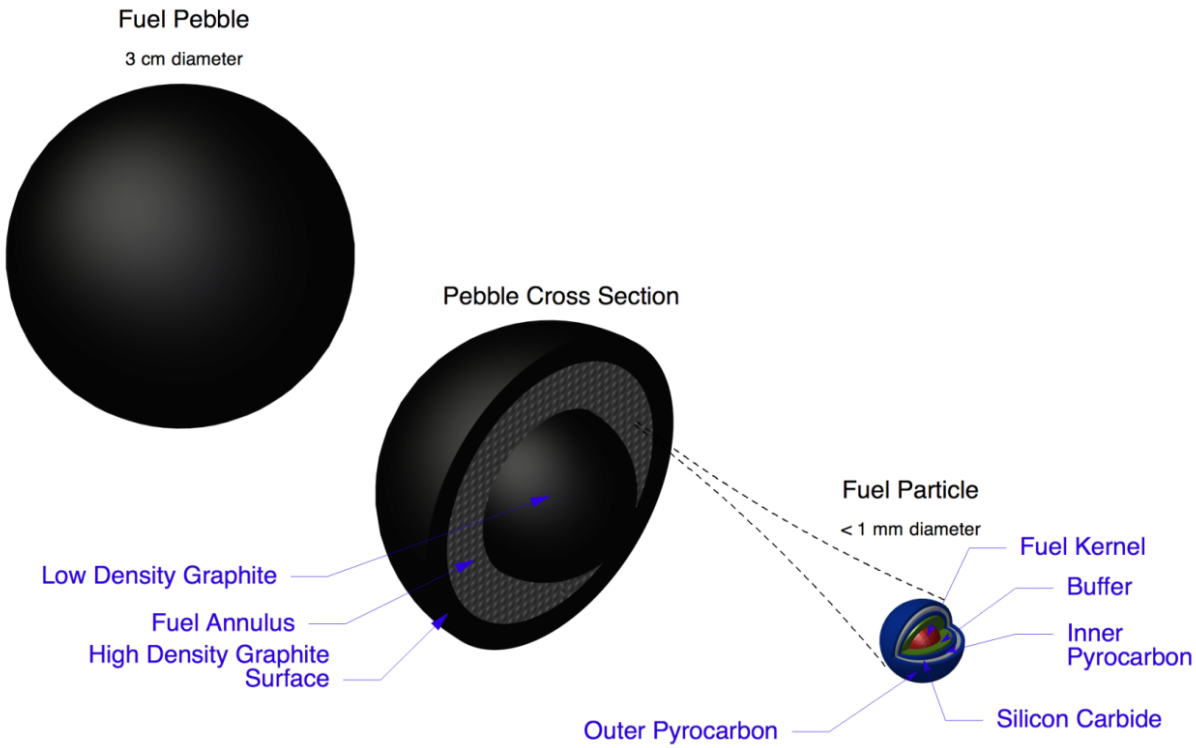


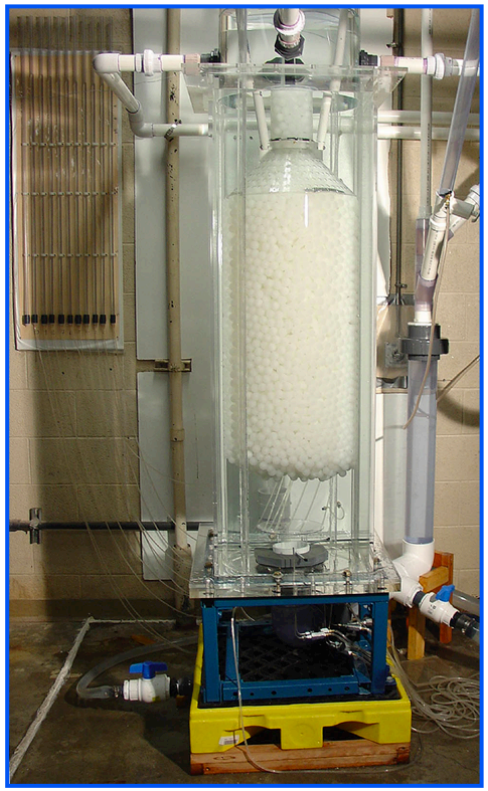
Pebble Bed

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

FHR-Pebble Bed Uses Coated-Particle Fuel

Same Fuel: High-Temperature Gas-Cooled Reactors





UCB Pebble Recirculation Experiment

Pebbles 3-cm Diameter
Higher Power Density than HTGR

FHR uses Fluoride Salts Coolants

- Low-pressure high-temperature coolant
- Base-line salt Flibe (Li_2BeF_4)
  - Melting point: 460°C
  - Boiling point: >1400°C
- **Heat delivered to power cycle between 600 and 700C**
  - **Avoid freezing salt**
  - **Limits of current materials**

Base Case Salt is FLIBE ($^7Li_2BeF_4$)

There Are Alternative Coolant Salts

Coolant	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m³)	ρC_p (kJ/m³ °C)
$^7Li_2BeF_4$ (Flibe)	**459**	**1430**	**1940**	**4670**
59.5 NaF-40.5 ZrF_4	500	1290	3140	3670
26 ^{7}LiF-37 NaF-37 ZrF_4	436		2790	3500
51^7 LiF-49 ZrF_4	509		3090	3750
Water (7.5 MPa)	0	290	732	4040

Salt compositions are shown in mole percent. Salt properties at 700ºC and 1 atm. Sodium-zirconium fluoride salt conductivity is estimated—not measured. Pressurized water data are shown at 290°C for comparison.

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FHR Status

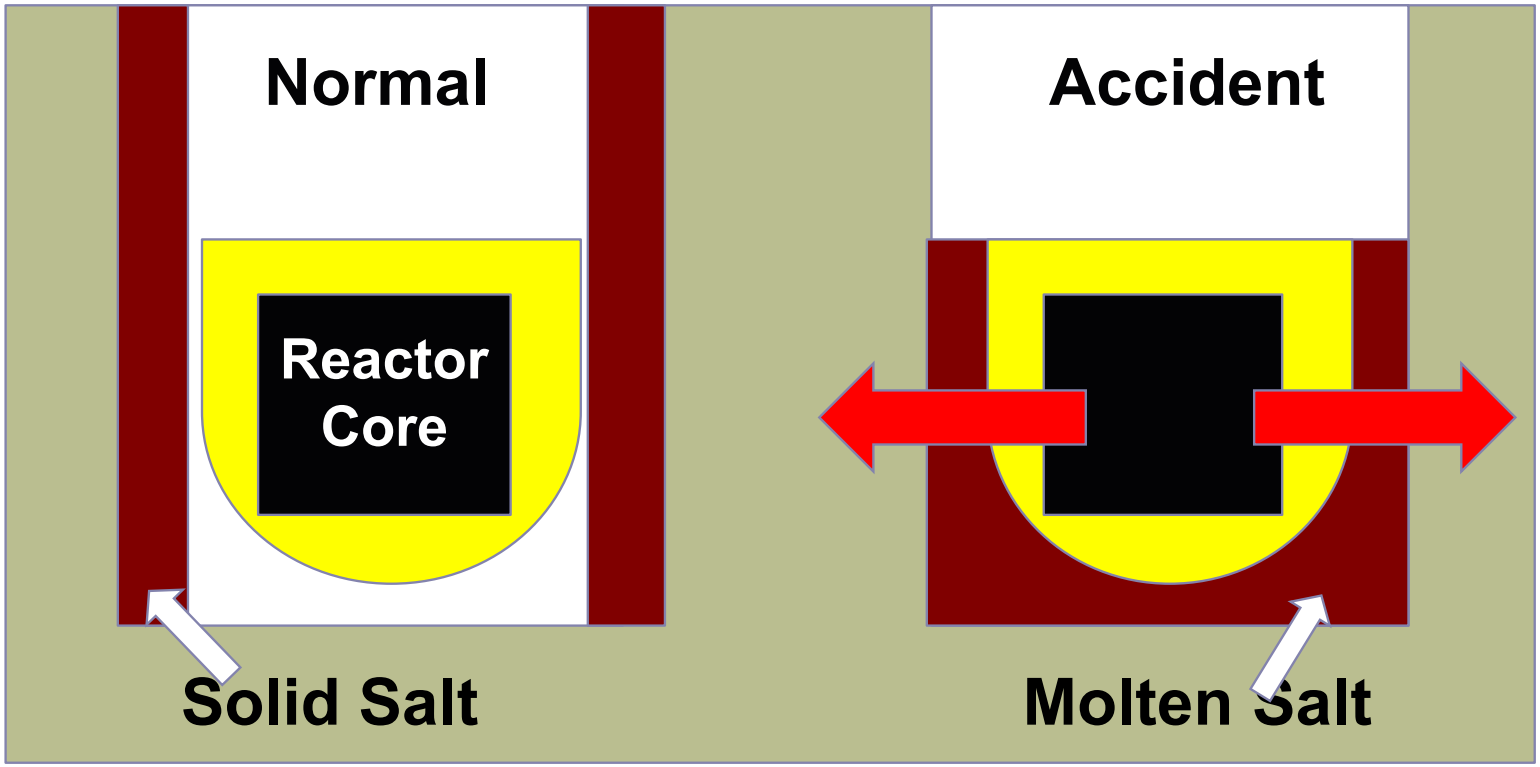
- No FHR has been built: new concept
- United States activities
  - MIT, University of California at Berkeley (UCB), University of Wisconsin (UW), Westinghouse Consortium[1]
  - Oak Ridge National Laboratory
  - Idaho National Laboratory
- Chinese Academy of Science
  - Small 2-MWt test reactor by 2017
  - Use pebble bed fuel from Chinese high-temperature gas-cooled reactor program

FHR is in Different Reactor Design Space

Coolant Temperature	System Pressure Low	System Pressure High
Low		Light-Water Reactor
Medium	Sodium Fast Reactor	
High	**FHR** High Inlet Temperature	High-Temperature Gas-Cooled Reactor Low Inlet Temperature

Severe Accident Strategy

If Major Failures, Conduct Heat to Ground
Keep T_{fuel} below $T_{failure}$



Summary

- Active research on MSR being pursued in the world: USA, EU, China, India….
- Great potential for combined & flexible power generation grids
- Molten Salts also being considered for solar applications