Molten Salt Reactors (MSRs)

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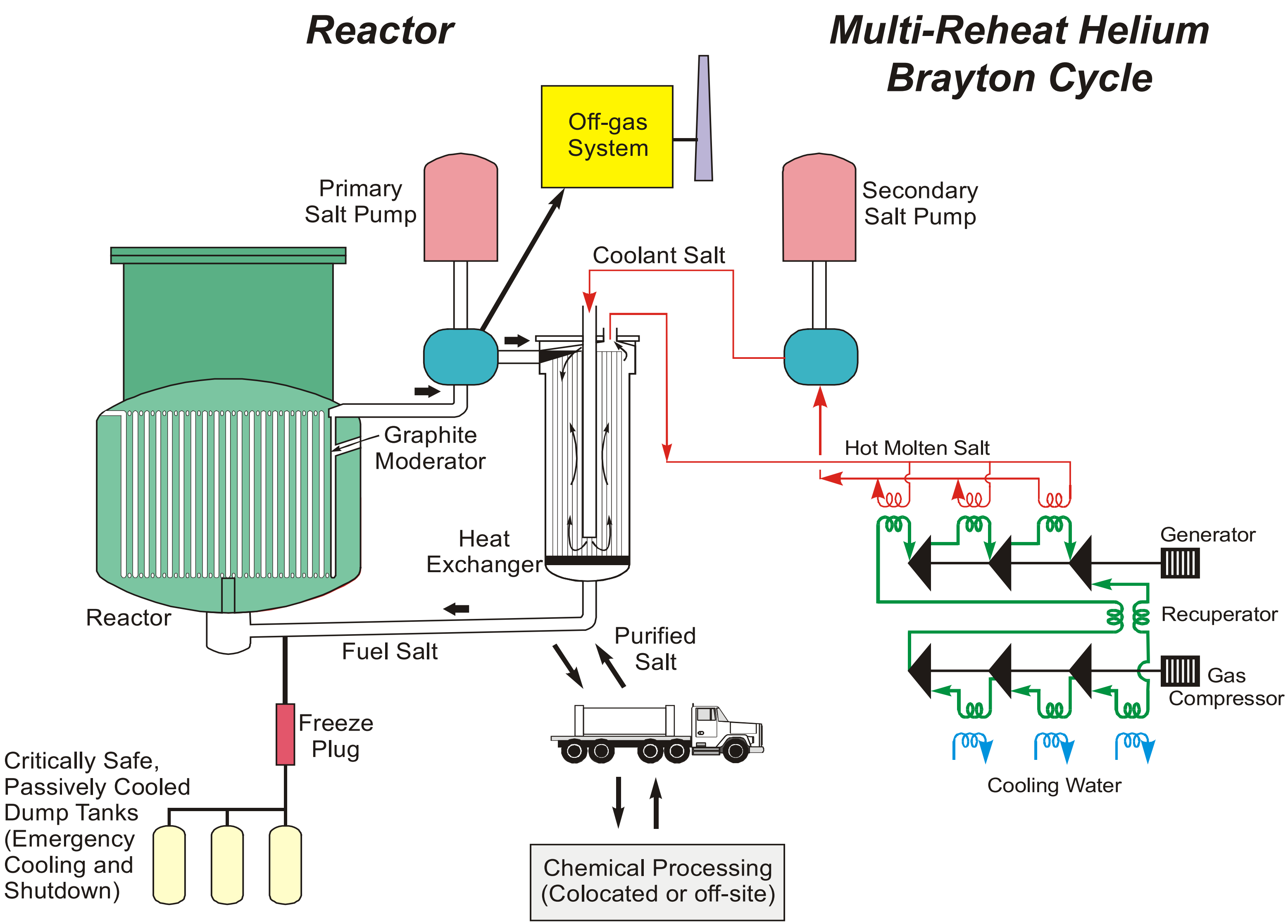
Molten Salt Reactors (MSRs) Use a Molten Salt Coolant Containing Dissolved Fuel

- Thermal Neutron Reactor
  - Molten fluoride salt
  - Fuel and fission products dissolved in fluoride salt
  - Graphite moderator
- Two earlier development programs
  - Aircraft Nuclear Propulsion Program (1950s)
  - Molten Salt Breeder Reactor Program (1960s)
- Current interests (GenIV)
  - Waste (actinide) burning
  - Efficient electricity production
  - Hydrogen production (long term)
  - Fissile production (very long term)

Molten Salt Reactor



Two Molten Salt Reactors (with Different Goals) Were Successfully Operated

- Aircraft Reactor Experiment (ARE)
  - Program goal: military jet engine
  - Power: 2.5 MW(t)
  - Temperature out: 815°C
  - Salt composition: $NaF/ZrF_4/UF_4$
- Molten Salt Reactor Experiment (MSRE)
  - Program goal: breeder reactor
  - Power: 8 MW(t)
  - Temperature out: 650°C
  - Salt: $^7LiF/BeF_2/ThF_4/UF_4$

The Molten Salt Reactor Experiment Demonstrated the Concept

Hours critical	**17,655**
Circulating fuel loop time hours	**21,788**
Equiv. full power hrs w/ ^{235}U fuel	**9,005**
Equiv. full power hrs w/ ^{233}U fuel	**4,167**

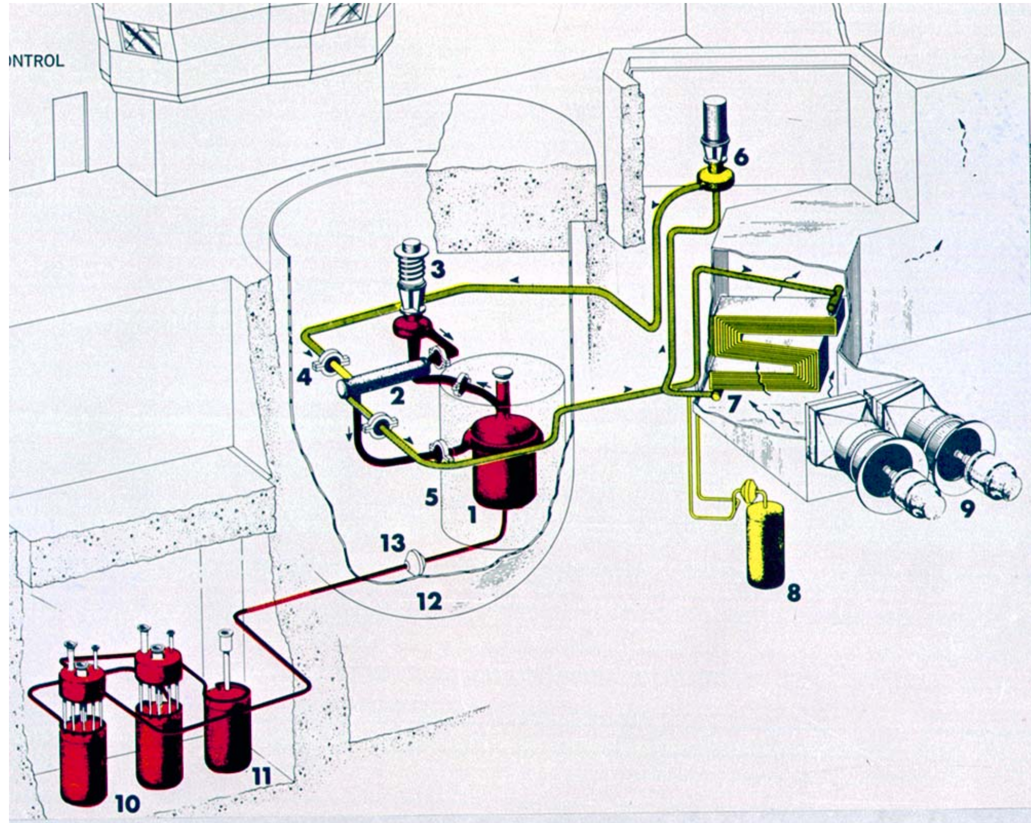
U-235 fuel operation

- Critical — June 1, 1965
- Full power — May 23, 1966
- End operation — Mar 26, 1968

U-233 fuel operation

- Critical — Oct 2, 1968
- Full power — Jan 28, 1969
- Reactor shutdown — Dec 12, 1969

Plutonium feed

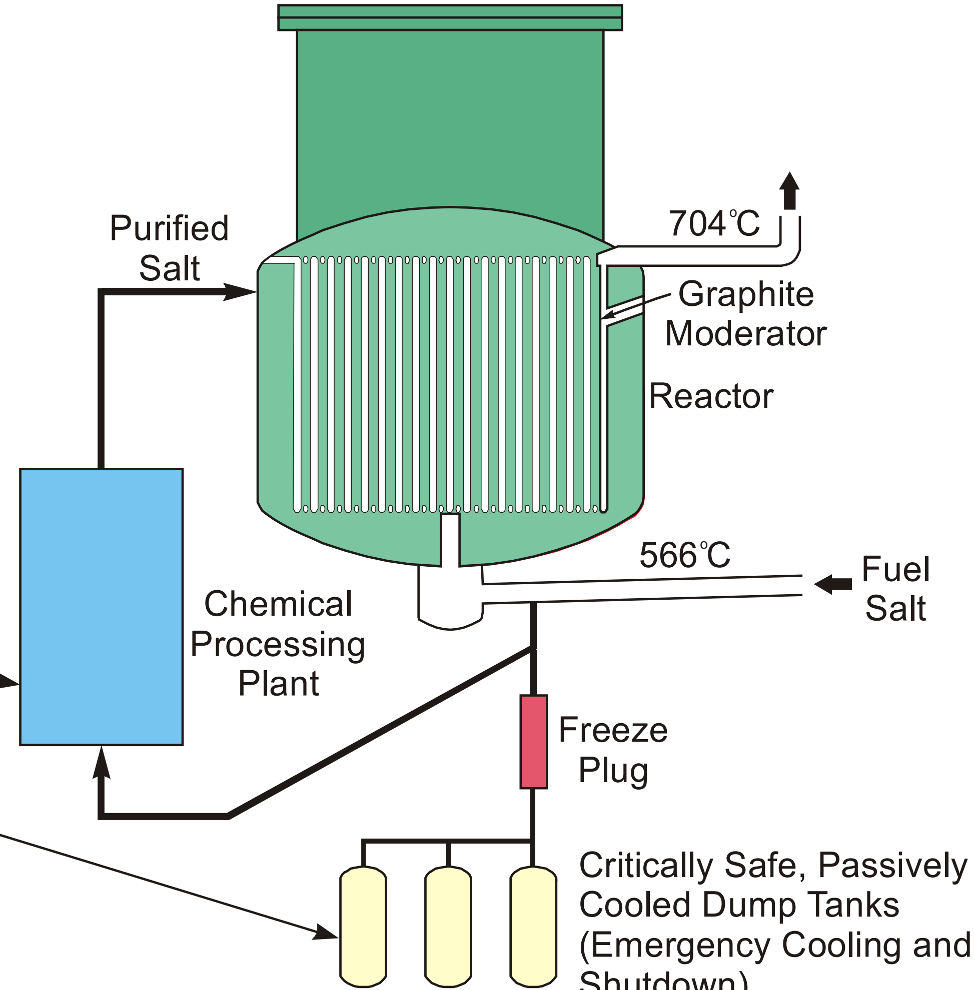


1. Reactor Vessel, 2. Heat Exchanger, 3. Fuel Pump, 4. Freeze Flange, 5. Thermal Shield, 6. Coolant Pump, 7. Radiator, 8. Coolant Drain Tank, 9. Fans, 10. Fuel Drain Tanks, 11. Flush Tank, 12. Containment Vessel, 13. Freeze Valve.

MSRE power = 8 MW(t)
Core volume <2 cubic meters

Molten Salt Reactors Have a Different Safety Approach that Allows Passive Safety in Large Reactors

- **Low pressure (molten salt boiling point ~1400°C)**
- **Low chemical reactivity**
- **Low accident source term with continuous removal of mobile fission products**
- **Passive cooling by dumping fuel to cooled tanks**



Multiple Fuel Cycle Options Exist
(Process and Preferred Salt May Differ)

Fuel Cycle	On-line Processing	Molten Salt
Actinide burning	Optional	NaF, ZrF_4, other
Once-through	Optional	NaF, ZrF_4, other
Denatured (^{238}U)	Limited	NaF, ZrF_4, other
^{233}Th-^{233}U Breeder	Required	^{7}LiF, BeF_2

The Major Interest in MSRs Is for Burning Actinides and Long-Lived Fission Products

Ongoing Molten Salt Transmutation Programs

Russia

EC (CEA-France)

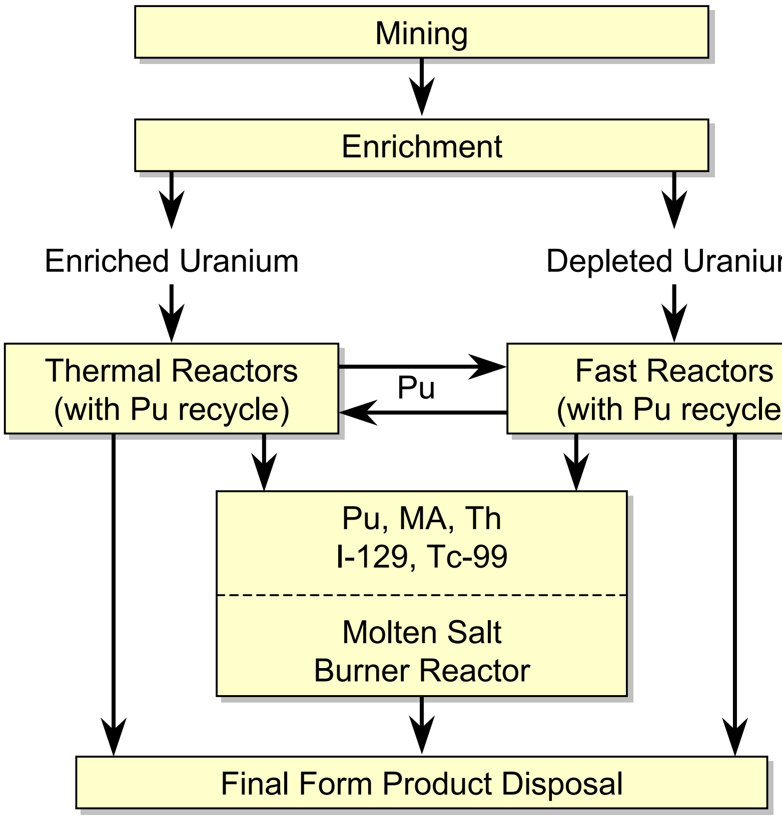
EdF (France)

Korea

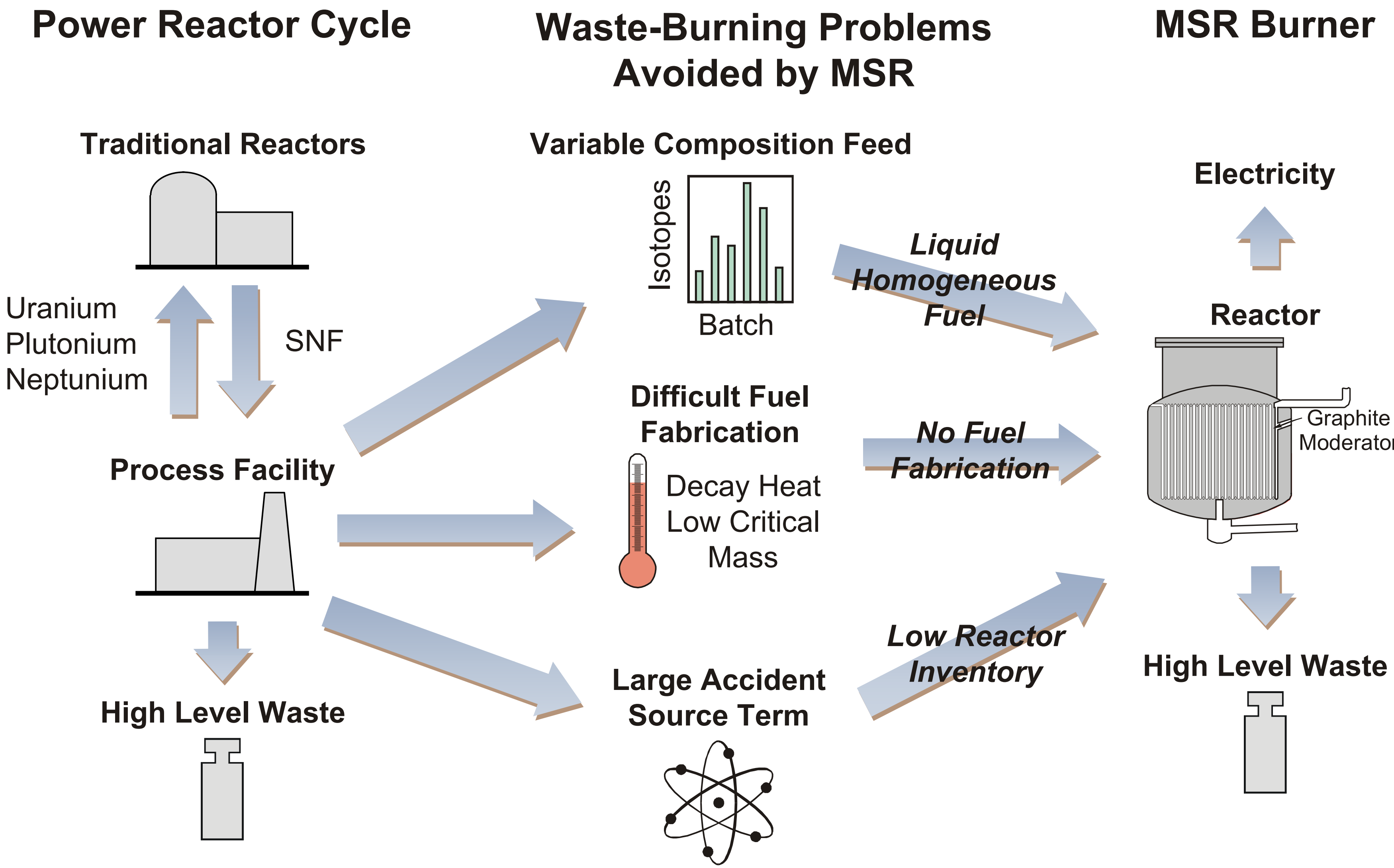
Czech Republic

U.S. (Academic)

Fuel Cycle Advocated in Kurchatov Study

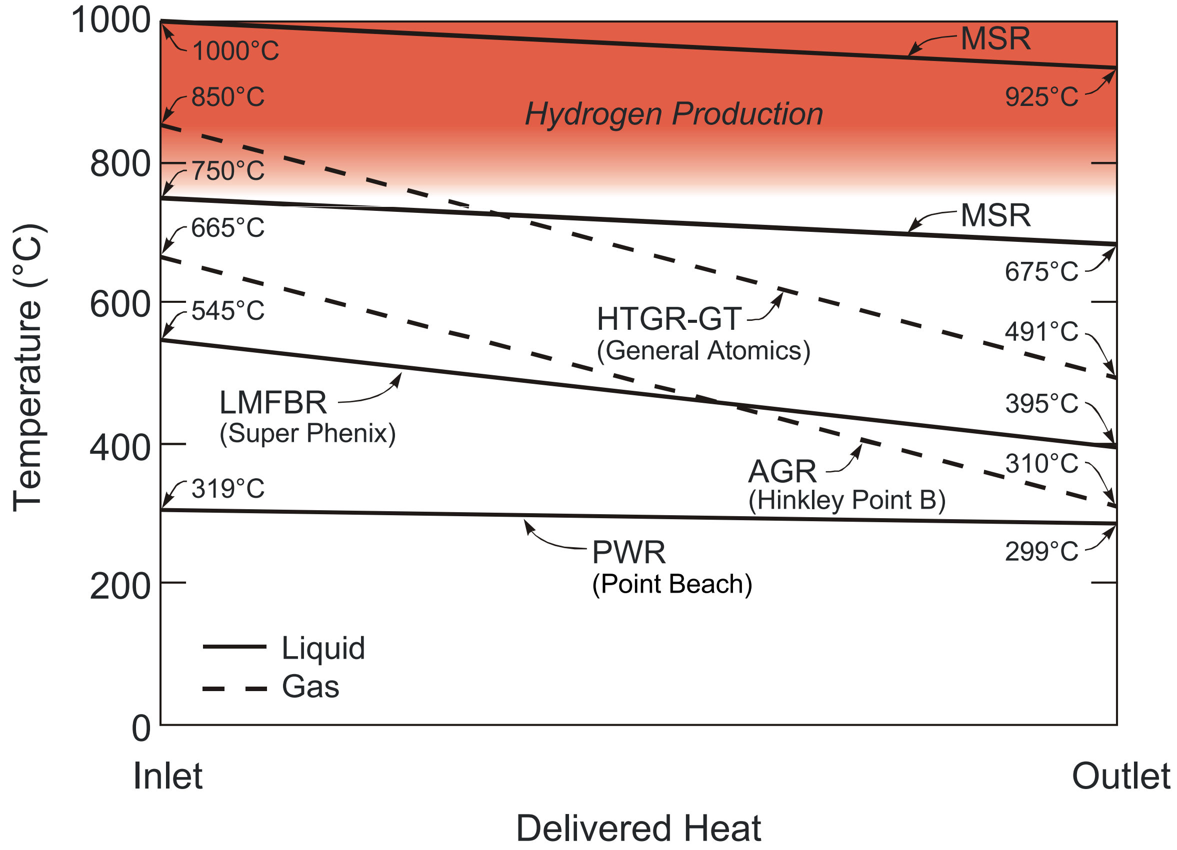


MSRs Avoid Several Solid-Fuel-Reactor Problems with Burning Wastes (High-Burnup Pu, Am, Cm)

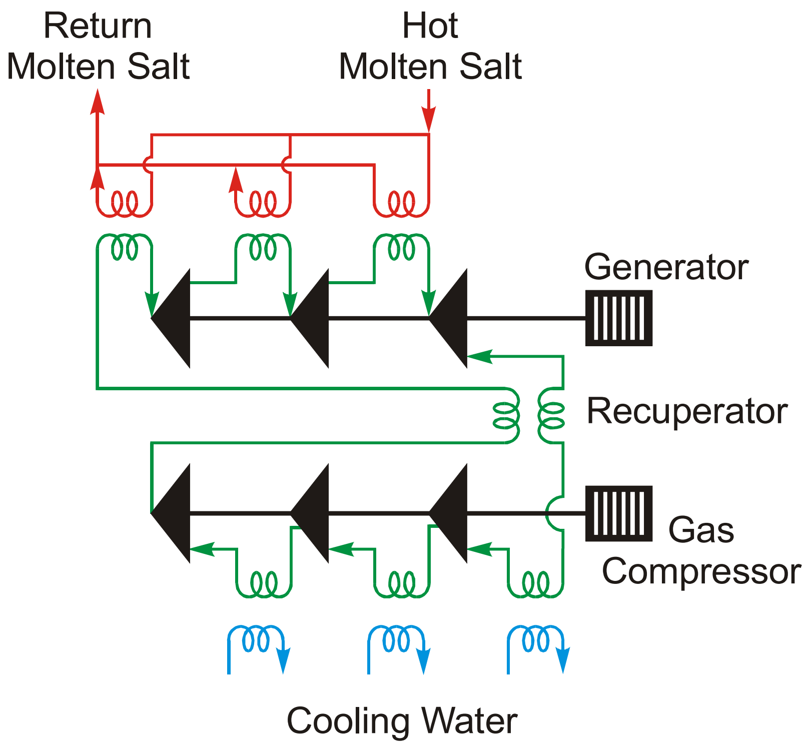


Liquid-Cooled MSRs Deliver High-Temperature Heat over a Small Temperature Range

(Meets Electricity and Hydrogen Production Requirements)

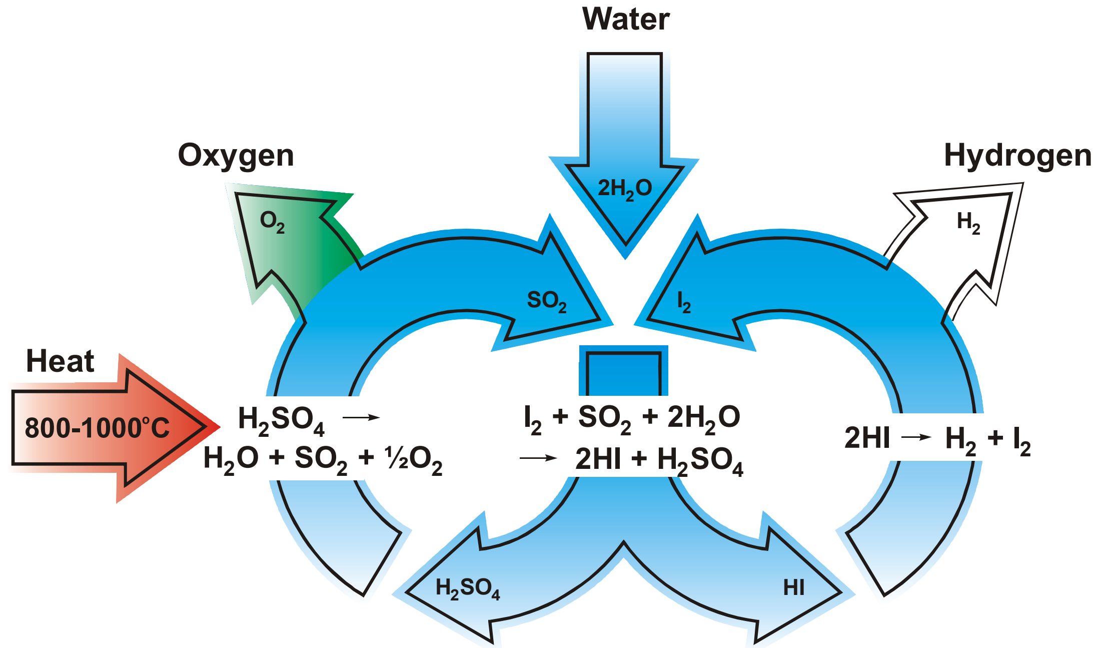


Delivering Heat at Nearly Constant High Temperature Allows Use of Advanced Electric Power Cycles



- **Multi-reheat helium Brayton cycle**
- **Cycle requirements**
  - **High temperature**
  - **All heat delivered at a high temperature**
- **Electrical efficiencies**
  - **705°C yields 45.5% (1970s reactor design exit temperature)**
  - **1000°C yields 60%**

MSRs Have the Longer-Term Potential for Thermochemical Hydrogen Production



- Hydrogen production requirements: (1) heat delivered at high temperature and (2) low pressure
- Requirements similar to those for the first MSR: the Aircraft Reactor Experiment

Extended Molten Salt Reactor Family

Molten Salt Fueled

- Aircraft Nuclear Propulsion Program (1950s)
- Molten Salt Breeder Reactor Program (1960s)
- Waste burner (Russia, France, etc.)
- Molten salt space reactor: Multimegawatt (United States)

Molten Salt Cooled

- Advanced High-Temperature Reactor (hydrogen or electricity)
- Fusion reactors (tritium production with ^{6}Li)
  - Inertial
  - Magnetic

Areas for R&D

- Actinide burning
  - Preferred salt composition for this mission
  - Choice of fuel salt for high actinide content
- Materials (particularly for hydrogen production)
- Disposition of noble metal fission products
- Engineering design
  - Update design (last detailed engineering design in early 1970s)
  - Adopt regulatory structure to liquid fuels
  - Modernize strategy for remote operations (required for MSR)

Conclusions

- Molten salt test reactors built in the 1950s and 1960s
- GenIV International Forum interest in molten-salt-fueled reactors
  - Waste burners (primary interest)
  - Efficient power production
- Growing programs in Europe and Russia
- Base technology used by multiple programs
- R&D issues reasonably well understood

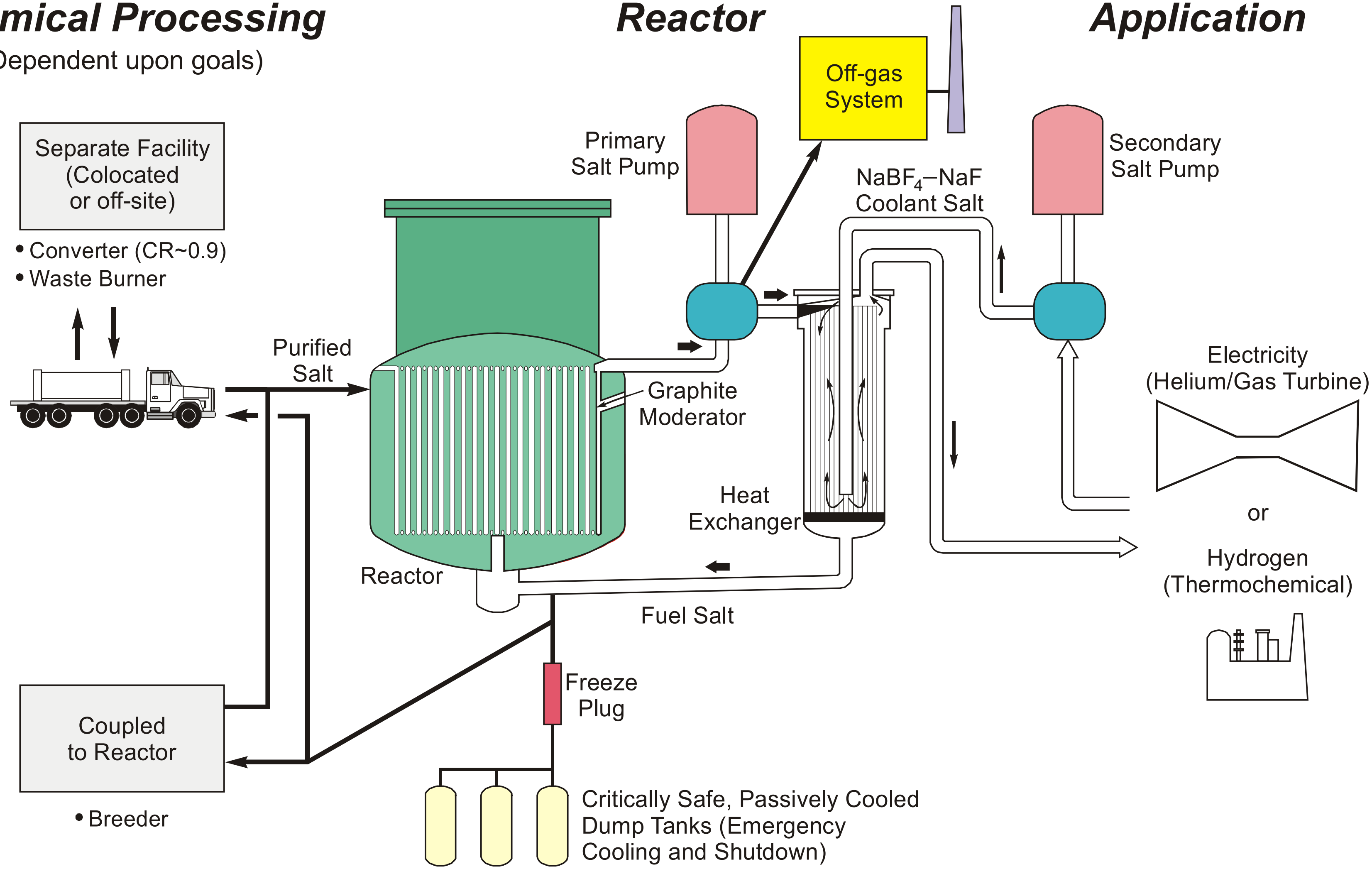
Backup Information

On-line Fuel Processing Is Required Only for Efficient Fuel Production

- Breeding reaction
  - $^{232}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$
- Protactinium characteristics
  - Moderately high absorption cross section
  - Half-life = 27.4 days
- Efficient breeding requires on-line removal of ^{233}Pa from reactor to allow decay to ^{233}U without parasitic neutron capture

Molten Salt Reactor

Chemical Processing (Dependent upon goals) ***Reactor*** ***Application***



Molten Salt Characteristics

- **Molten fluoride salts preferred over chlorides**
  - Low nuclear cross section
  - Excellent chemical stability
  - No troublesome long-lived activation products
- **Choice of salt depends upon mission**
  - Breeder (low absorption cross section: lithium and beryllium fluorides
  - Waste burner (high solubility for all actinides)
  - Hydrogen production (low tritium production: zirconium, sodium, and other fluorides)
- **Extensive industrial experience**
  - Aluminum metal made by electrolysis in a graphite-lined, molten-fluoride salt bath

Rationale for Using MSRs for Waste Burning Is Based on Engineering, Cost, and Operational Issues

- Recycle and fabrication of minor-actinide solid fuels are very expensive and difficult
- Waste burning has large impacts on conventional reactors
  - Complicates operations
  - High actinide inventory to destruction rate with added safety system requirements
- Molten Salt Reactors
  - Add actinides to salt
  - Actinides remain in salt until full burnout with lower actinide inventory than in other reactors
  - Fission products removed from salt
  - For waste burner applications, ~10% of nuclear electricity from MSRs ensures waste destruction
- R&D is required to define the best waste burning strategy

MSR Fuel Cycles

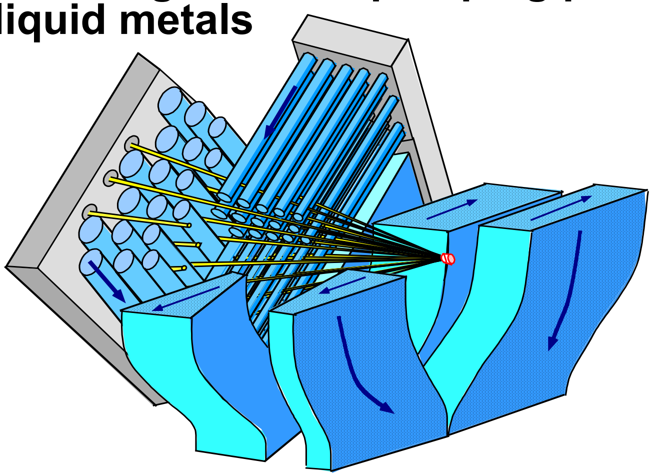
- Actinide burning
  - Intrinsic to ^{233}U/Th breeder cycle
  - Special-purpose reactor to burn actinides (high-burnup plutonium, Am and Cm) from other reactors
- Denatured once-through fuel cycle
- Denatured low-conversion breeder reactor
- High-efficiency thermal neutron (^{233}U/Th) breeder reactor

The Proliferation-Resistant Characteristics of the MSR Are Different from Those of Other Systems

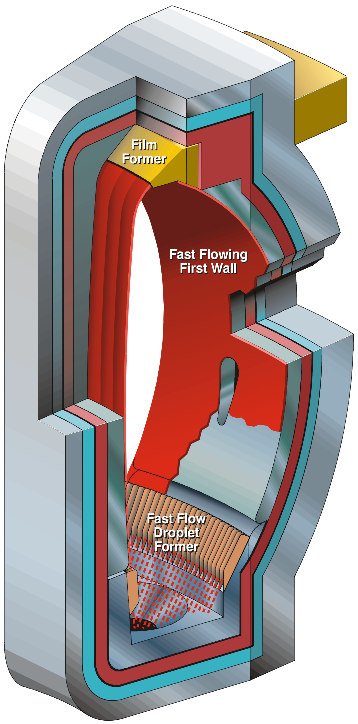
- Total fissile inventory is low
- With added ^{238}U, the ^{233}U and ^{235}U are made non weapons usable
- Plutonium isotopics are very poor (primarily ^{242}Pu)

United States Fusion Research has Major Efforts Focused on Molten Salt Coolants

- **Molten salts have unique advantages for fusion blanket coolants**
  - Breed tritium fuel (enrich ^{6}Li) and shield fusion neutrons
  - Low vapor pressure allows direct contact with fusion plasma
- **Magnet fusion (APEX program)**
  - Molten salts are dielectric and unaffected by magnetic fields
- **Inertial fusion (iCREST program)**
  - Molten salts give lower pumping power than liquid metals



Heavy-ion Inertial Fusion



Magnet Fusion Tokamak

Efficient Brayton Helium Multi-Reheat Cycle for Production of Electricity