Molten Salt Reactors: Technology History, Status, and Promise

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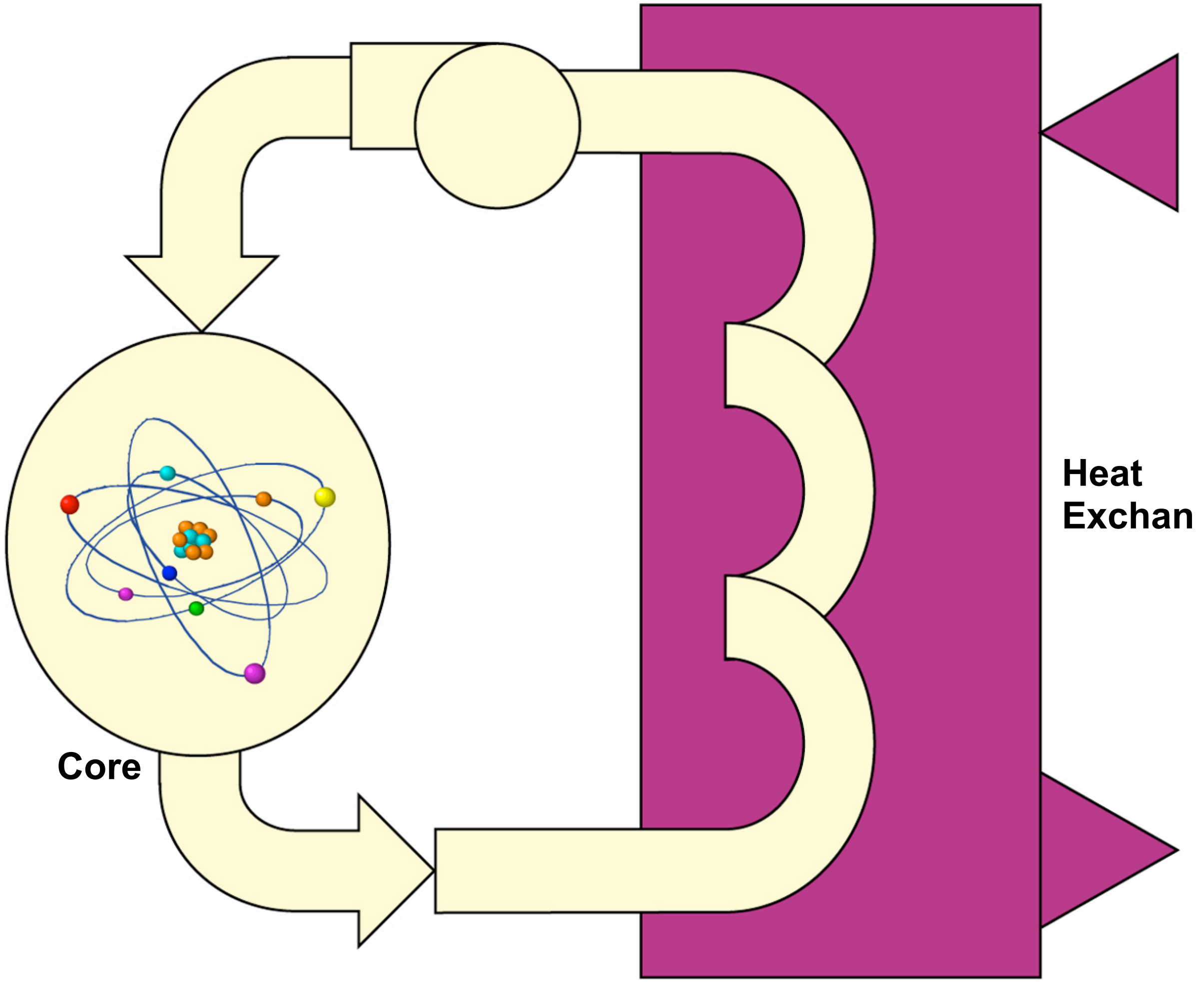
Presentation Overview

- What the heck is a “molten salt” reactor?
- Molten Salt Reactor Development History
- Technology Status & Lessons Learned
- Prospects for Space Applications

Molten Salt Reactors Utilize Circulating Liquid Fluoride Salt/Uranium Mixtures as Integrated Fuel and Heat Transfer Fluid

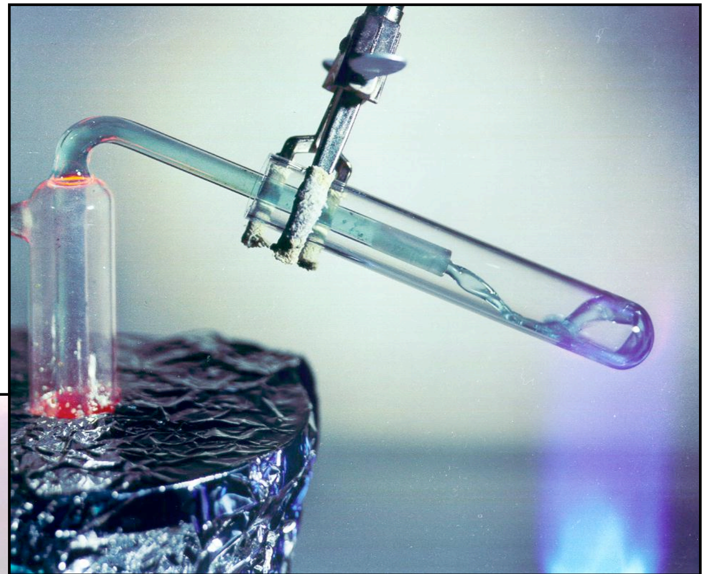


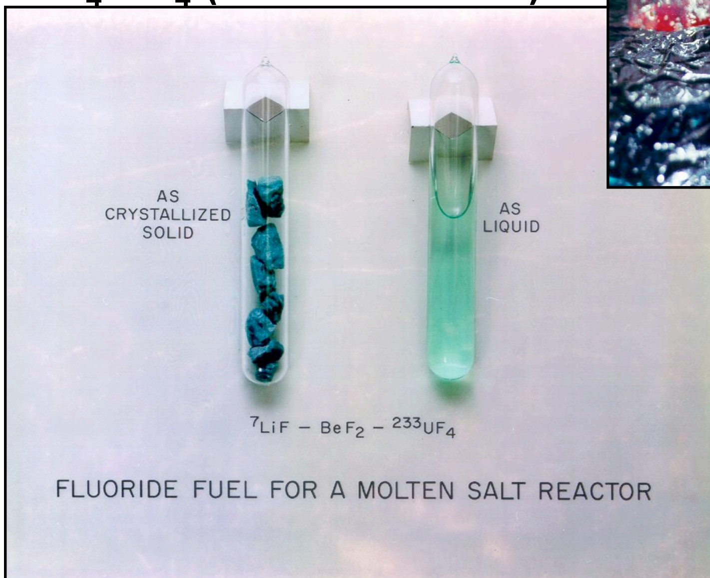
Molten Salt Reactor Technology Has 50-yr Development History at ORNL

- Originally proposed by Ed Bettis and Ray Briant of ORNL in late 1940's
- Aircraft Nuclear Propulsion Program (1946 – 1961)
  - Aircraft Reactor Experiment (1953 – 1954)
  - Aircraft Reactor Test (1954 – 1957)
- Experimental Molten Salt Fuel Power Reactor (1960)
- Molten Salt Reactor Experiment (1960 – 1969)
- Molten Salt Demonstration Reactor
- Molten Salt Breeder Experiment (1970 – 1976)
- Molten Salt Breeder Reactor (1970 – 1976)
- Molten Salt Cooled Reactor (Today)

Several Salt Options Exist

- $NaF-ZrF_4-UF_4$ (ARE & ART)
- $NaF-BeF_2-UF_4$
- $LiF-BeF_2-ZrF_4-UF_4$ (MSRE)
- $LiF-BeF_2-ZrF_4-PuF_3$ (MSRE)
- $NaF-KF-LiF-UF_4$
- $LiF-BeF_2-ThF_4-UF_4$ (MSBE & MSBR)





Molten Salt Systems Have Compelling Inherent Advantages*

- Wide range of uranium and thorium solubility
- Stable thermodynamically
- Do not undergo radiolytic decomposition
- Have very low vapor pressure at operating temperatures
- Do not attack nickel-based alloys used for circulating salt plumbing

*TID-8505 & TID-8507, 1959.

Molten Salt Reactors Offer Many Potential Advantages over More Traditional Reactor Technologies

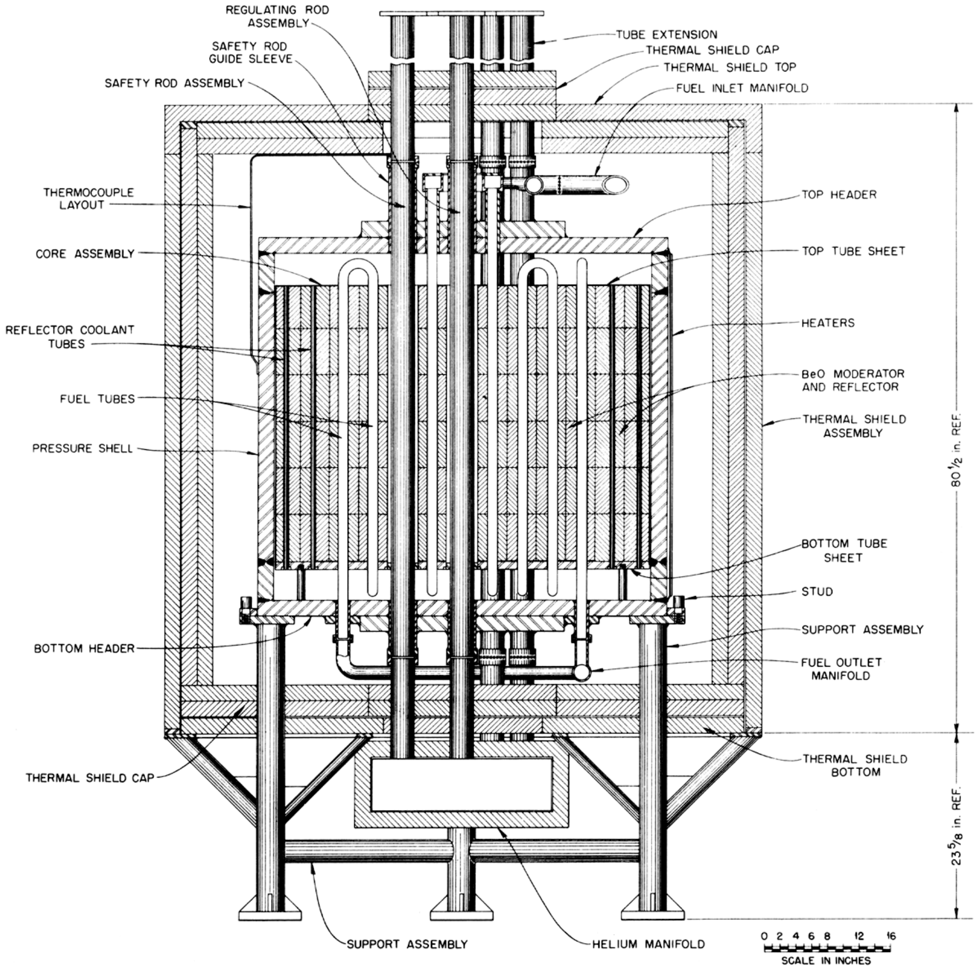
- Capability for very high power densities
  - > 1 MW/L
- Inherent load following and control
  - Large negative temperature coefficients
- Very high conversion ratios / breeding option
- High reliability
  - Design simplicity and ease of control
- Superior scaling potential
  - Simplified & less expensive growth path
- No “fuel fabrication”
  - Enormous reduction in fuel fabrication costs

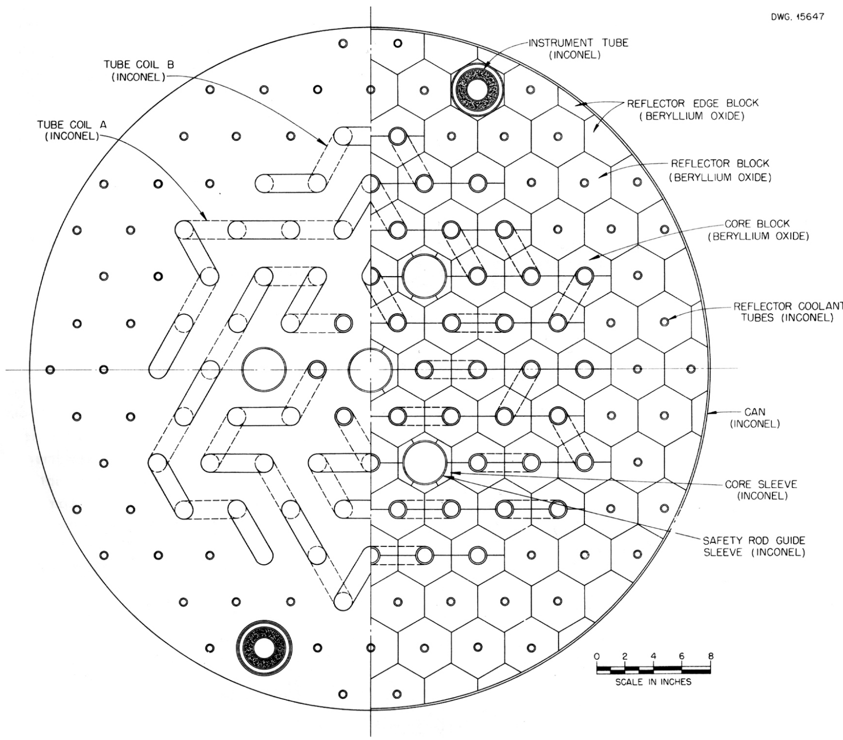
Aircraft Nuclear Propulsion Program Initiated Work on Molten Salt

- 1946 – 1961
- $1B Investment
- Pioneering work
  - ZrH fuels
  - Molten salt fuels
  - Liquid metal heat transfer
  - Light-weight metals
  - Advanced I&C
  - High temperature corrosion resistant materials

- Challenges
  - Changing mission definitions
  - Two customers (Air Force and AEC)

2.5 MWt Aircraft Reactor Experiment (ARE) Successfully Demonstrated Molten Salt Reactor Technology in 1954





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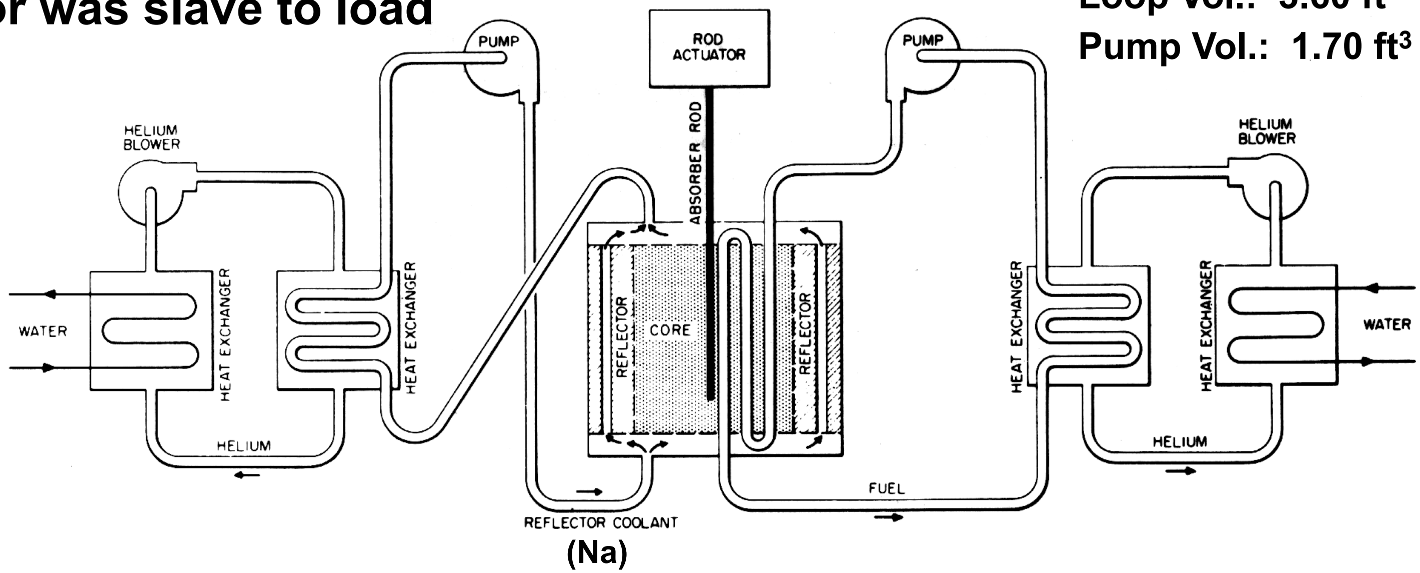
Aircraft Reactor Experiment (ARE) Successfully Demonstrated Molten Salt Reactor Technology in 1954

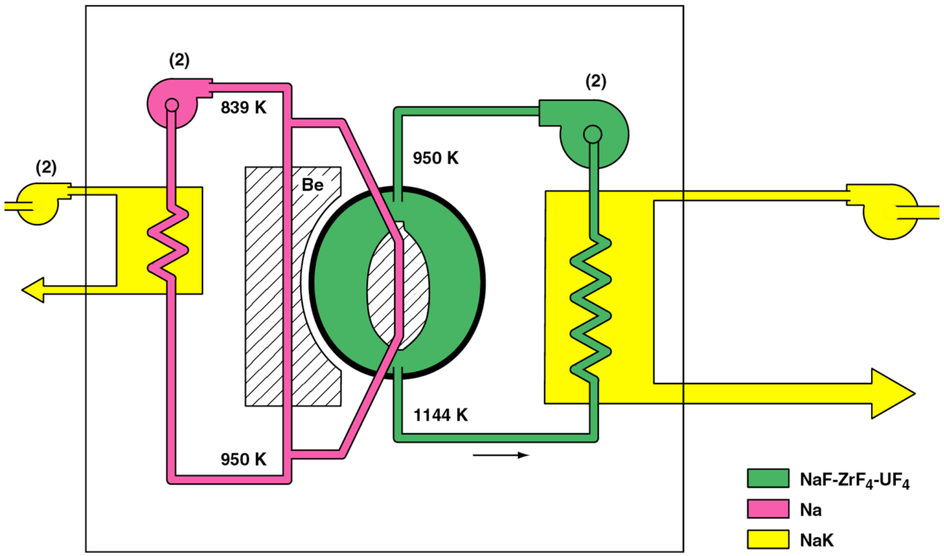
- Evolution of Na-cooled, solid fuel design
- Fuel: $NaF\text{-}ZrF_4\text{-}UF_4$ (53-41-6) (mole%)
- Operated > 100Mw-hr
- Max. fuel temp. 882°C
- Very large neg. temp. coeff (-6.1E-5)
- Reactor was slave to load

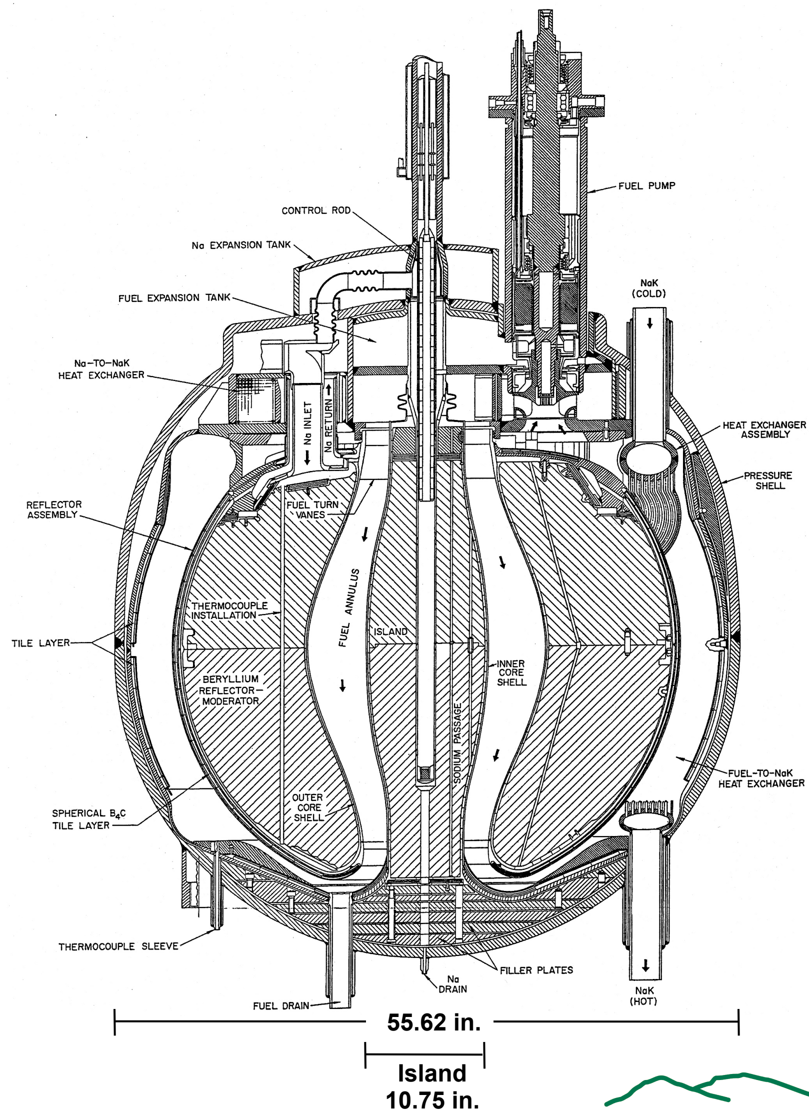
Core Vol.: 1.37 ft^3
Loop Vol.: 3.60 ft^3
Pump Vol.: 1.70 ft^3



60 MWt Aircraft Reactor Test Was Compact, High Power Density, Reflector-Moderated Design

- 1.3 MW/L (max. design)
- 1144K core outlet temp.
- 1500 hr. design life
- 10 ft^3 total fuel volume
- 3.2 ft^3 core fuel volume

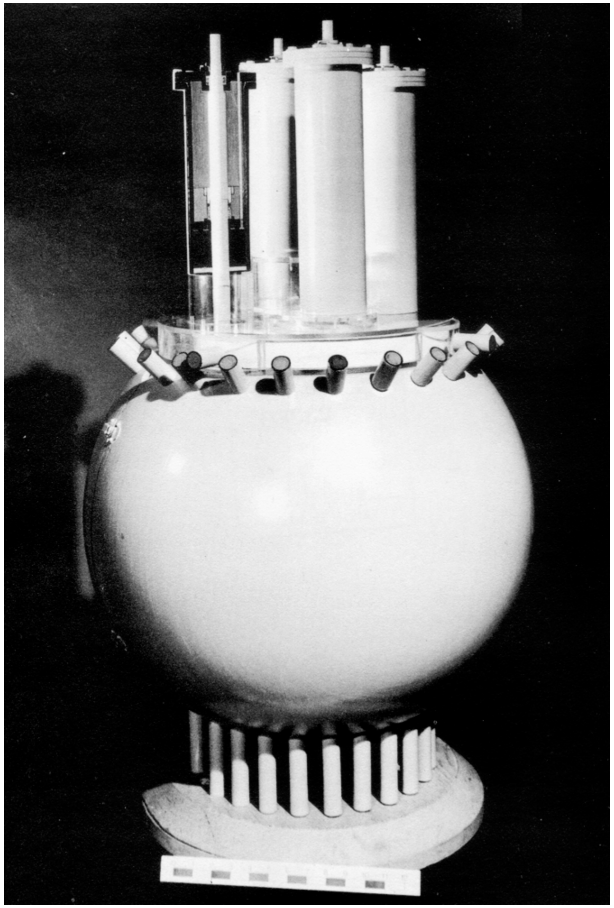




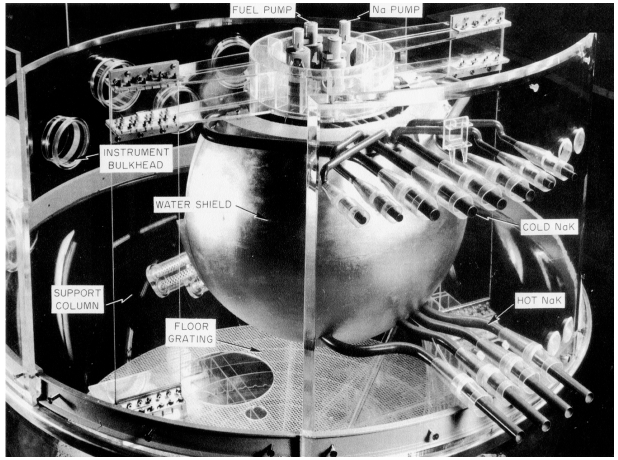
ART Program Included Comprehensive Technology

- Fuel Salt Capsule Irradiations in MTR
- In-pile Circulating Fuel Salt Tests in MTR and LITR
- Major Component Tests
- Engineering Test Unit Fabrication
  - Exact ART clone
  - Circulating non-fuel salt
  - Heated by gas furnaces

ART Facility Construction and ETU Fabrication Were Near Completion When ANP Program Was Cancelled In 1961



Full-Scale ART Model



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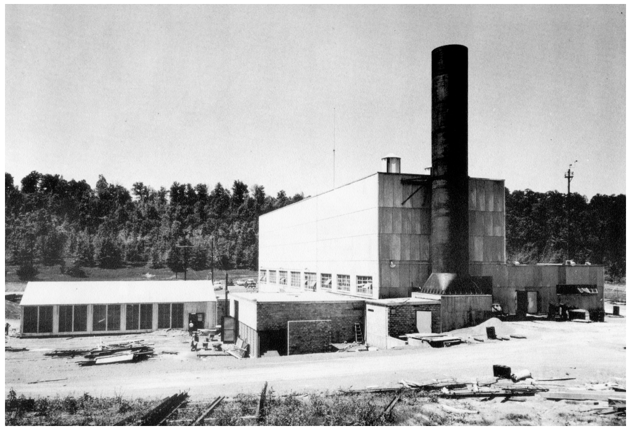

ART Building

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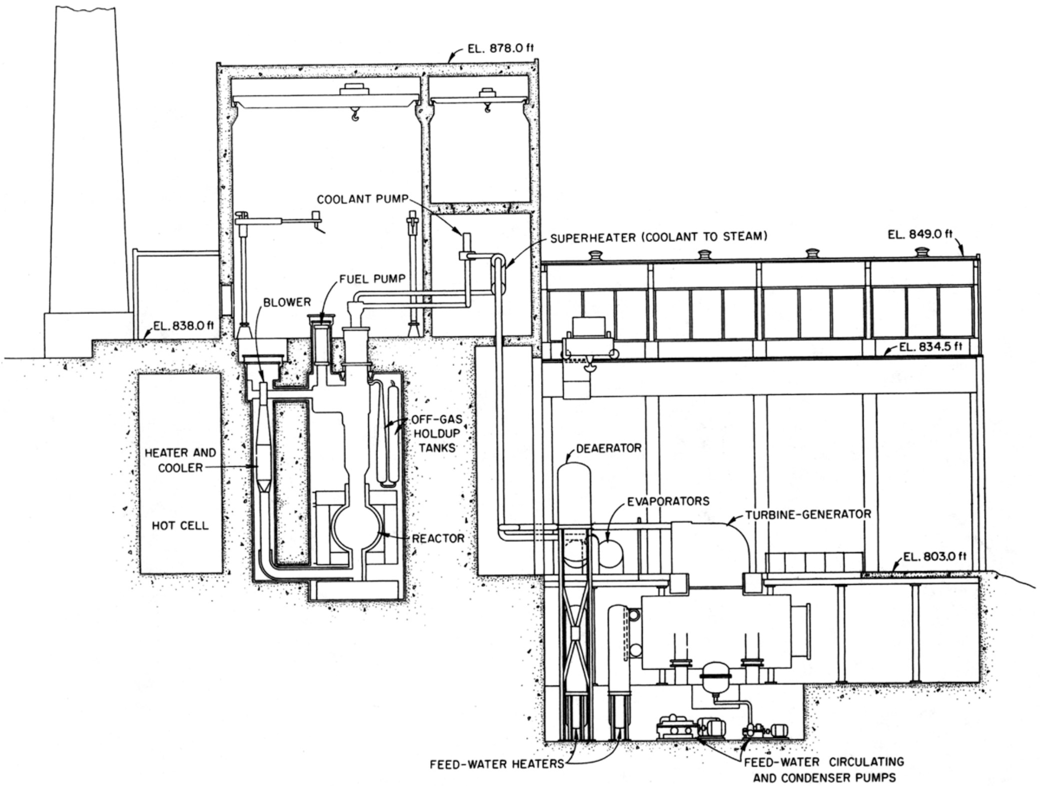
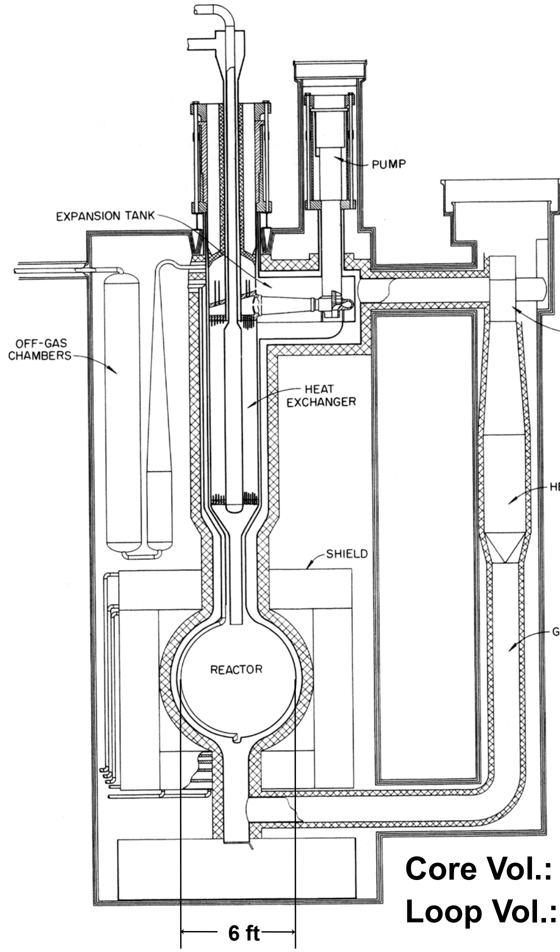
Experimental Molten Salt Power Reactor Design Was 30 MWt/10 MWe Epithermal Prototype Power Station



LiF-BeF_2-UF_4 Fuel



Core Vol.: 113.2 ft^3
Loop Vol.: 57.5 ft^3

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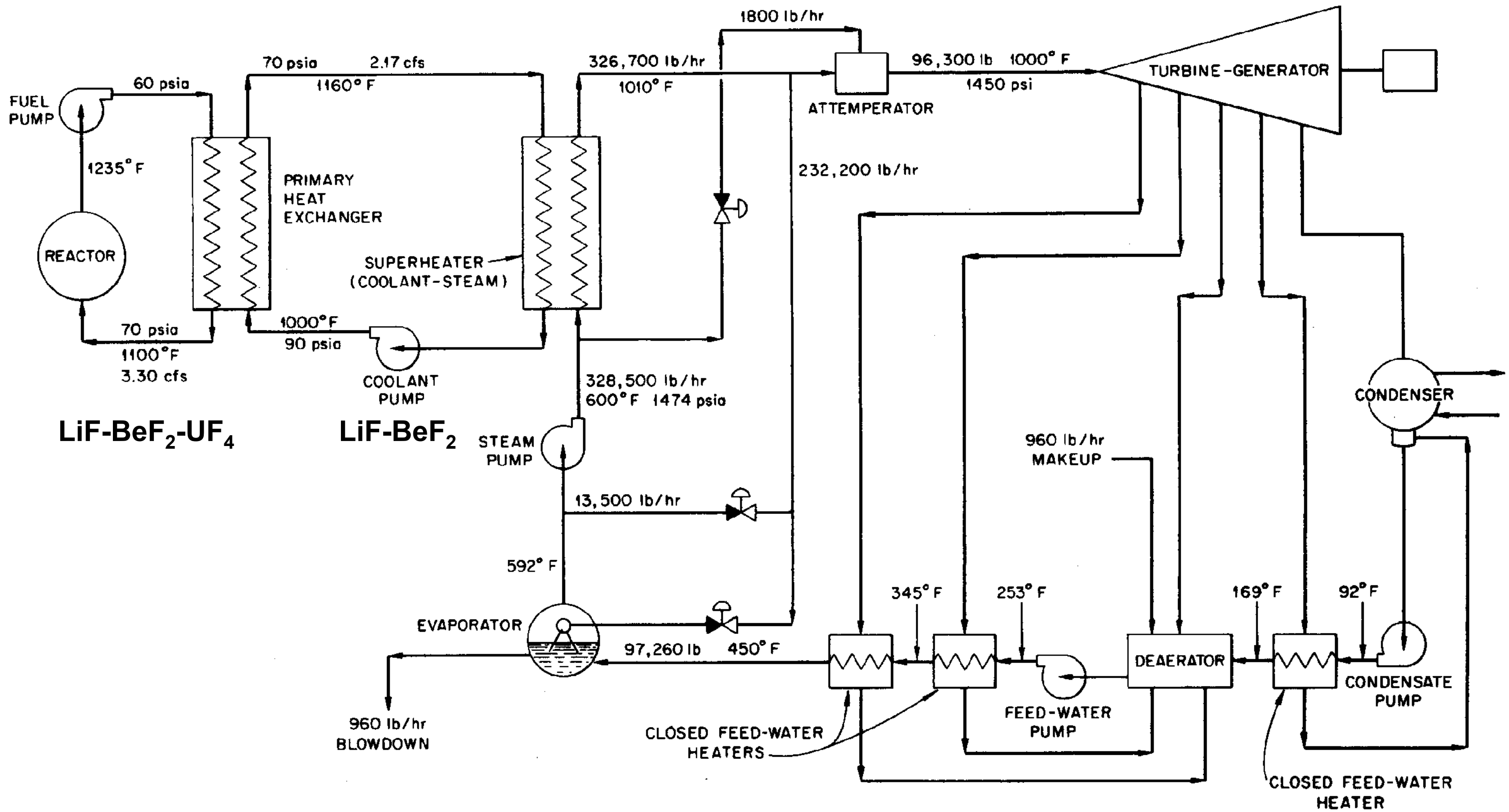
Experimental Molten Salt Power Reactor Design Utilized Loeffler Steam Cycle



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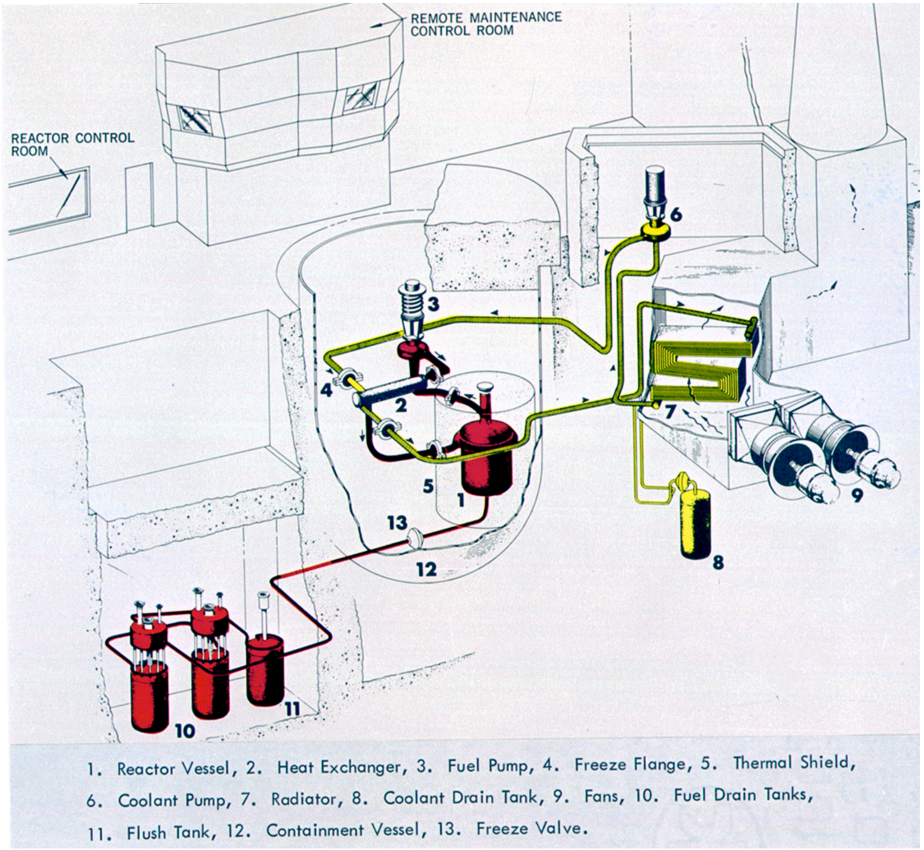
Molten Salt Reactor Experiment (MSRE) Was Extremely Successful Demonstration

- Operated: 1965 – 1969 at ORNL
- Design features:
  - 8 MWt (original design was 10 MWt to facilitate construction on operating funds)
  - Single region core
  - Fuels
    - $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$
    - $LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4\text{-}PuF_3$
- Graphite moderated
- Hastelloy-N vessel and piping
- Achievements
  - First use of U-233 Fuel
  - First use of mixed U/Pu salt fuel
  - On-line refueling
  - >13,000 full power hours



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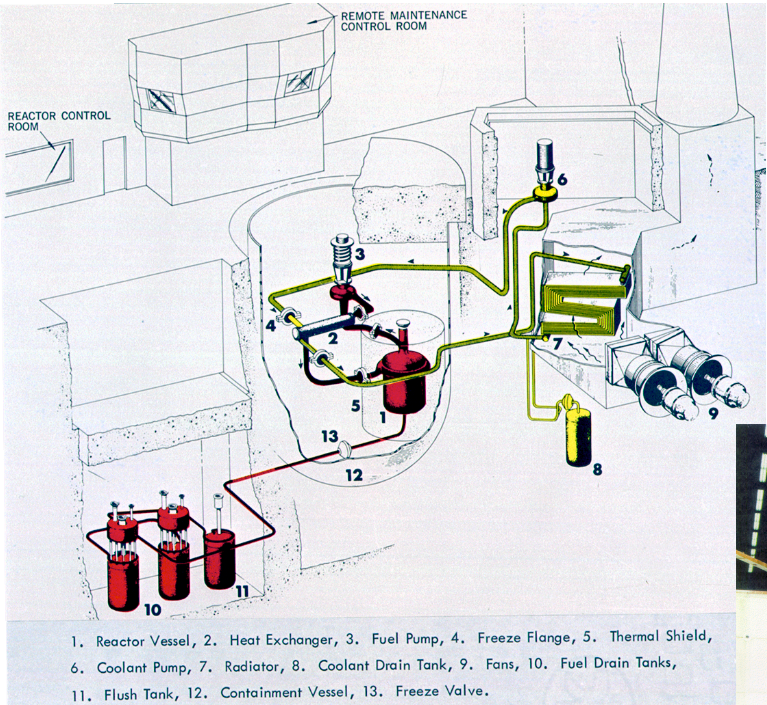

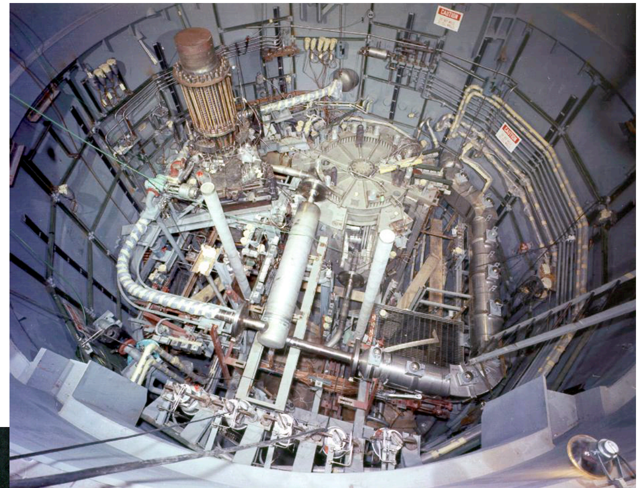

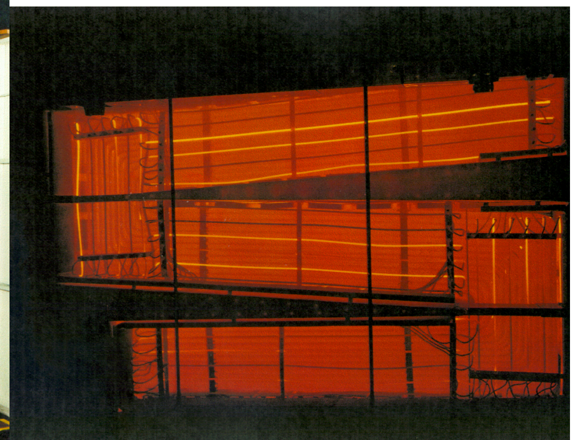

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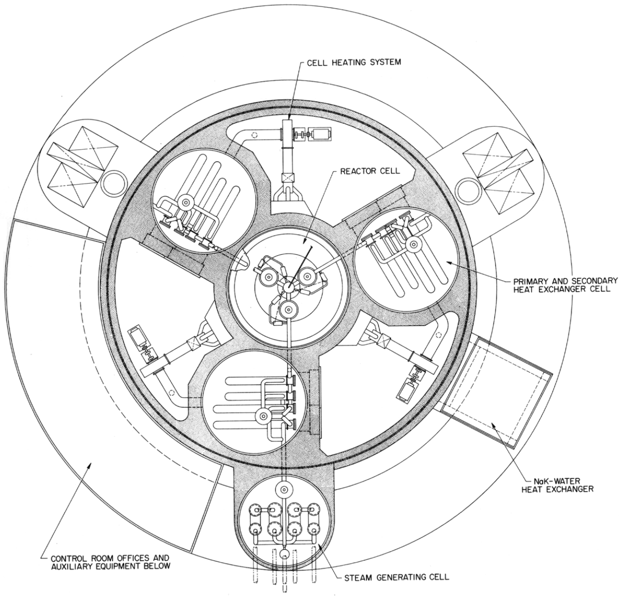
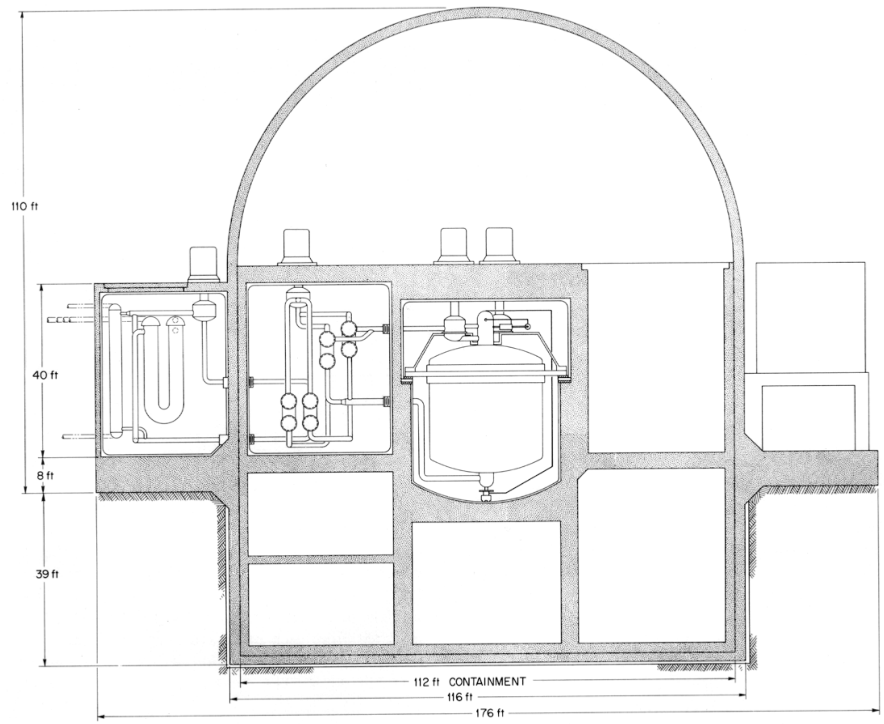
Molten Salt Demonstration Reactor (MSDR) Was Designed for 300 MW(e)

- Low Power Density Converter (breeding ratio = 0.8)
  - 21 ft. x 21 ft. core
  - 2.5 ft. thick annular graphite reflector
- Design Features:
  - 3 fuel-salt circulation loops
  - Tertiary heat exchanger loop to act as tritium trap





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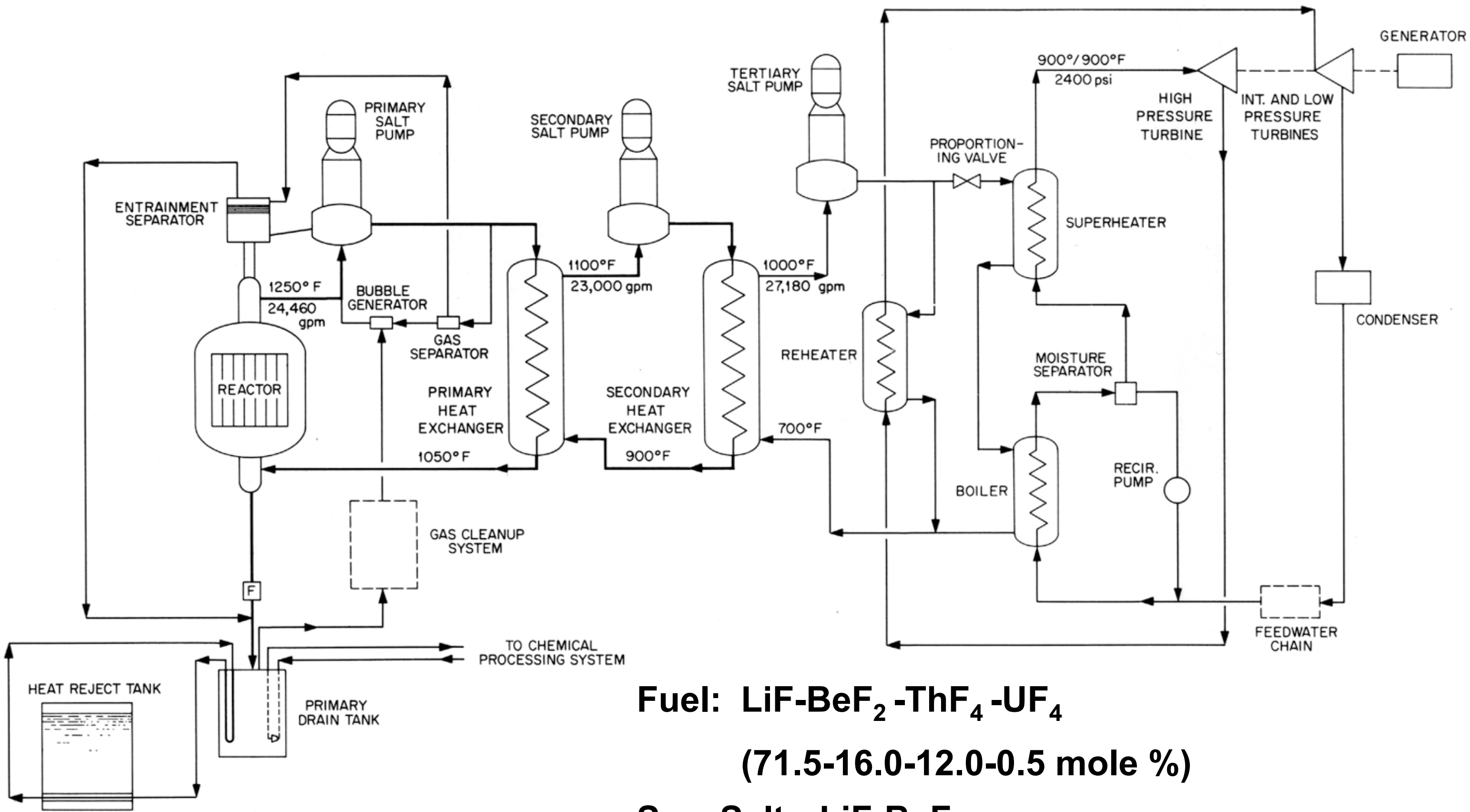
Molten Salt Demonstration Reactor (MSDR) Was Design for 300 MW(e) Prototype Power Station



Fuel: $LiF\text{-}BeF_2\text{-}ThF_4\text{-}UF_4$

(71.5-16.0-12.0-0.5 mole %)

Sec. Salt: $LiF\text{-}BeF_2$

(66-34 mole %, >99.99% ^7Li)

Ter. Salt: $KNO_3\text{-}NaNO_2\text{-}NaNO_3$

(44-49-7 mole %)

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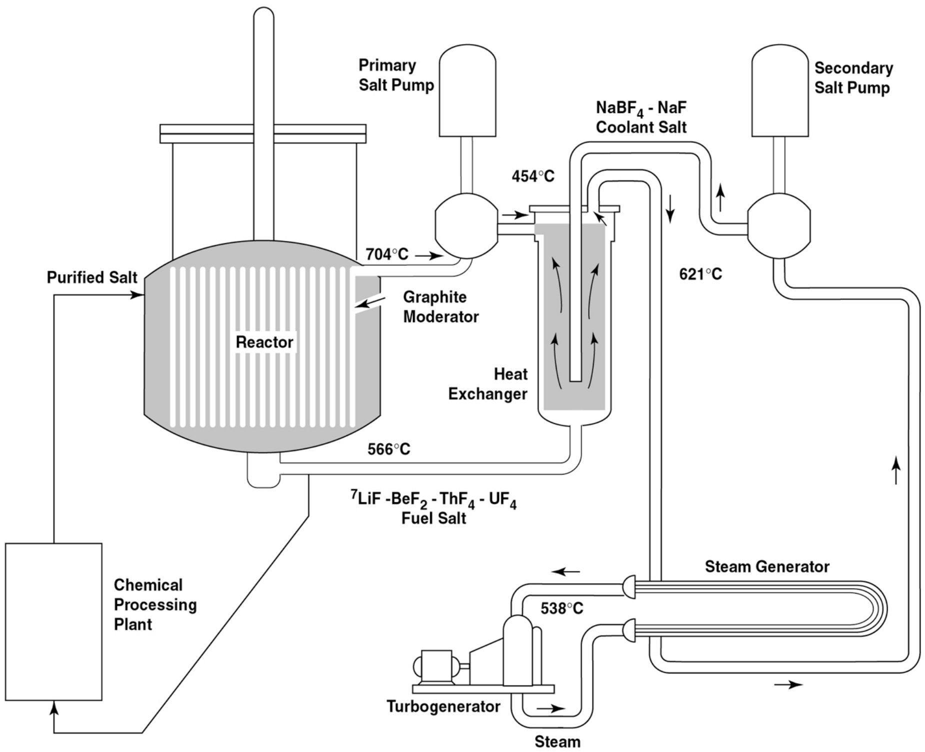
Significant Effort Was Expended on Molten Salt Breeder Reactor Designs In the 1960's

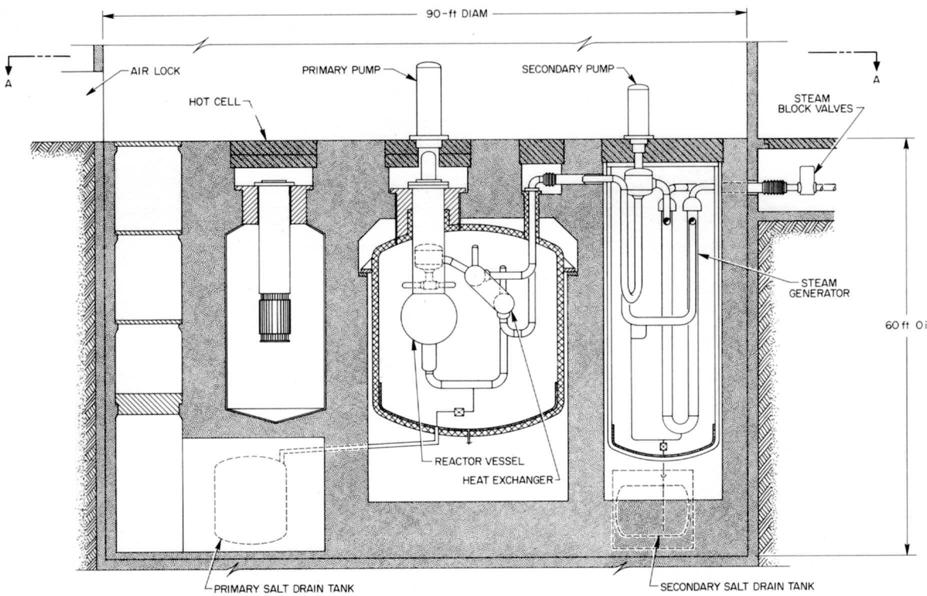
- **Molten Salt Breeder Experiment**
  - 65 MW(e) (150 MWt)
  - Single region – one fluid system
  - Fuel: LiF-BeF_2-ThF_4 -UF_4
- **Molten Salt Breeder Reactor (MSBR)**
  - 1000 Mw(e) (2250 MWt)
  - 2-region-two-fluid system
  - Fuel: Li^7F -BeF_2-UF_4
  - Blanket: Li^7F-ThF_4
  - Breeding ratio: 1.06
  - Four fuel-salt circulation loops
  - Fuel salt separated from blanket salt by graphite tubes

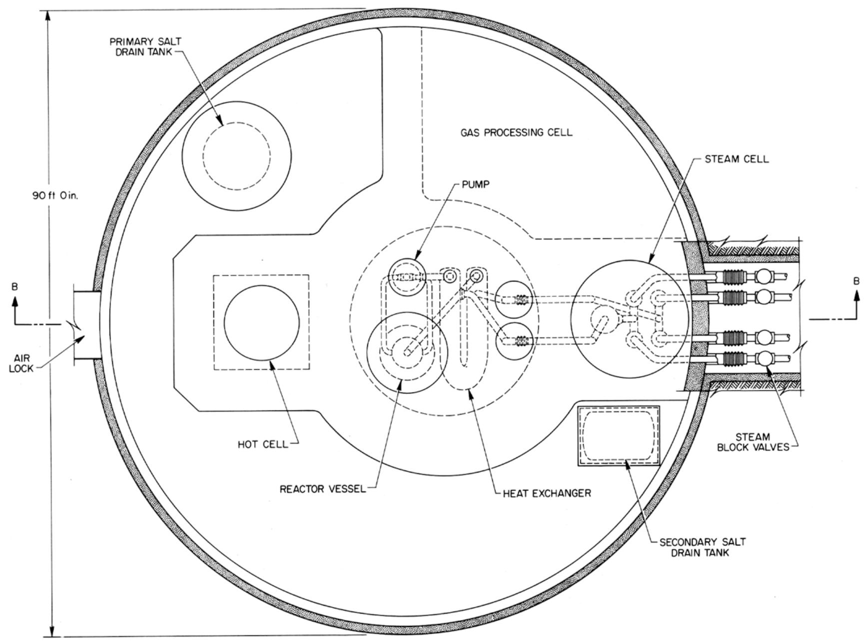


MSBE

150 MWt Molten Salt Breeder Experiment (MSBE) Was Single Fluid Design Activity

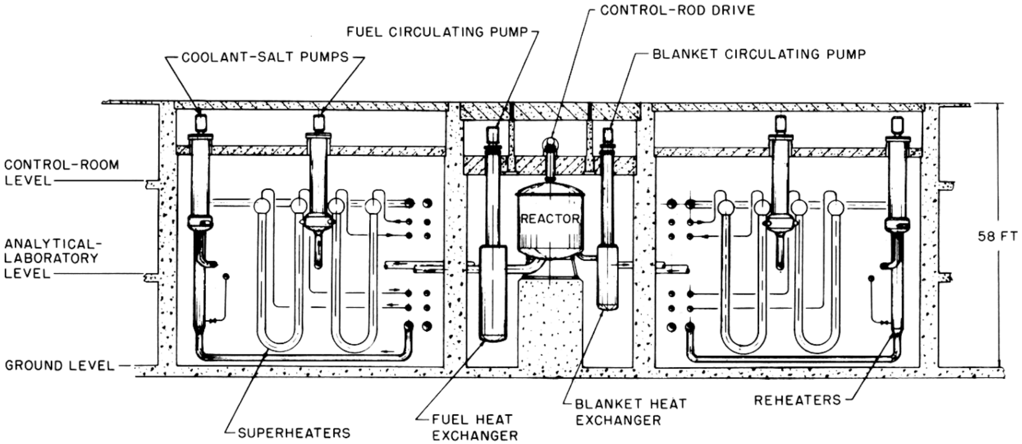
- Breeding ratio = 0.96
- Unreflected reactor
- One fuel-salt circulation loop

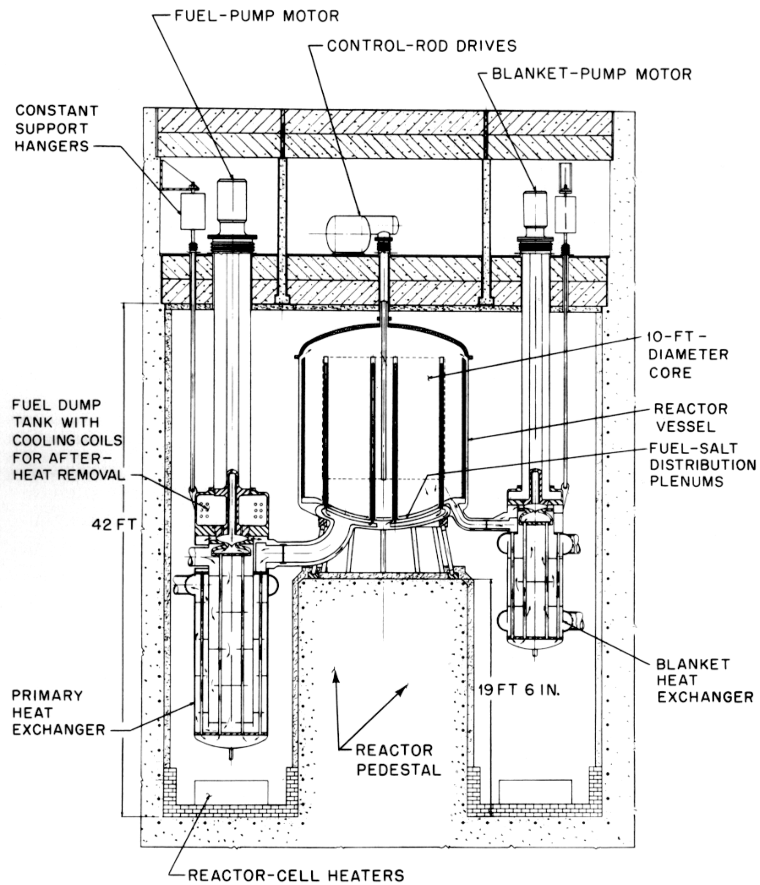




Molten Salt Breeder Reactor (MSBR) Was Two-Region, Two-Fluid Design

- 1000 MW(e)
- Fuel: Li^7F -BeF_2-UF_4
- Blanket: Li^7F-ThF_4
- Continuous on-line fuel processing
- 45% thermal efficiency
- Many fission products removed on-line allowing reactor to operate with less fuel





MSRE, MSBE, and MSBR Shared Common Pedigree

	MSRE	MSBE	MSBR[a]
Reactor power, MW(t)	7.3	150	2250
Breeding ratio		0.96	1.06
Peak power density, w/cc, core including graphite	6.6	14	70
Volume fraction of salt in core	0.225	0.15	0.13
Primary salt			
Composition, mole %			
LiF	65	71.5	71.7
BeF_2	29.1	16	16
ThF_4	None	12	12
UF_4	0.9	0.5	0.3
ZrF_4	5	None	NONE
Liquidus, °F	813	932	932
Density, lb_m/ft^3 at 1100°F	141	211	210
Viscosity, lb ft^{-1} hr^{-1} at 1100°F	19	29	29
Heat capacity, Btu lb_m^{-1} $(°F)^{-1}$	0.47	0.32	0.32
Thermal conductivity, Btu hr^{-1} ft^{-1} $(°F)^{-1}$	0.83	0.71	0.71
Temperature, °F			
Inlet, reactor vessel	1170	1050	1050
Outlet, reactor vessel	1210	1300	1300
Circulating primary salt volume, ft^3	70	266	1720
Inventory, fissile, kg	32[b]	396[b]	1470
Power density, primary salt, circulating, average, W/cc	4	20	46
Number of primary loops	1	1	4
Secondary system salt	LiF-BeF_2	$NaBF_4$-NaF	$NaBF_4$-NaF

[a] *MSR Program Semiannu. Progr. Rep. Feb. 28, 1970*, ORNL-4548, pp. 42-45.
[b] ^{233}U initial.

Why Did U.S. Discontinue Research and Development on

Weinberg to Seaborg

Our problem is not that our idea is a poor one – rather it is different from the main line, and has too chemical a flavor to be fully appreciated by non-chemists.

MacPherson (1985)

1. ***Political and technical support too thin geographically (ORNL only stakeholder)***
2. ***LMFBR program got early start, had major federal funding, and many stakeholders***
3. ***Reduction in uranium demand and need for breeders***

Fifty Years of Molten Salt Reactor Development Have Demonstrated Virtues of Approach

- Well-Mannered Dynamics
- High Temperature Capability
- High Power Density
- High Burn-Up Capability
- Mature Fuel Technology
- Expensive Fuel Fabrication Eliminated
- Compatible Material Systems
- Corrosion Issues Manageable
- High Reliability
- Safe

Are Molten Salt Reactors "Space-Friendly"?

Traditional Reactor Electric System

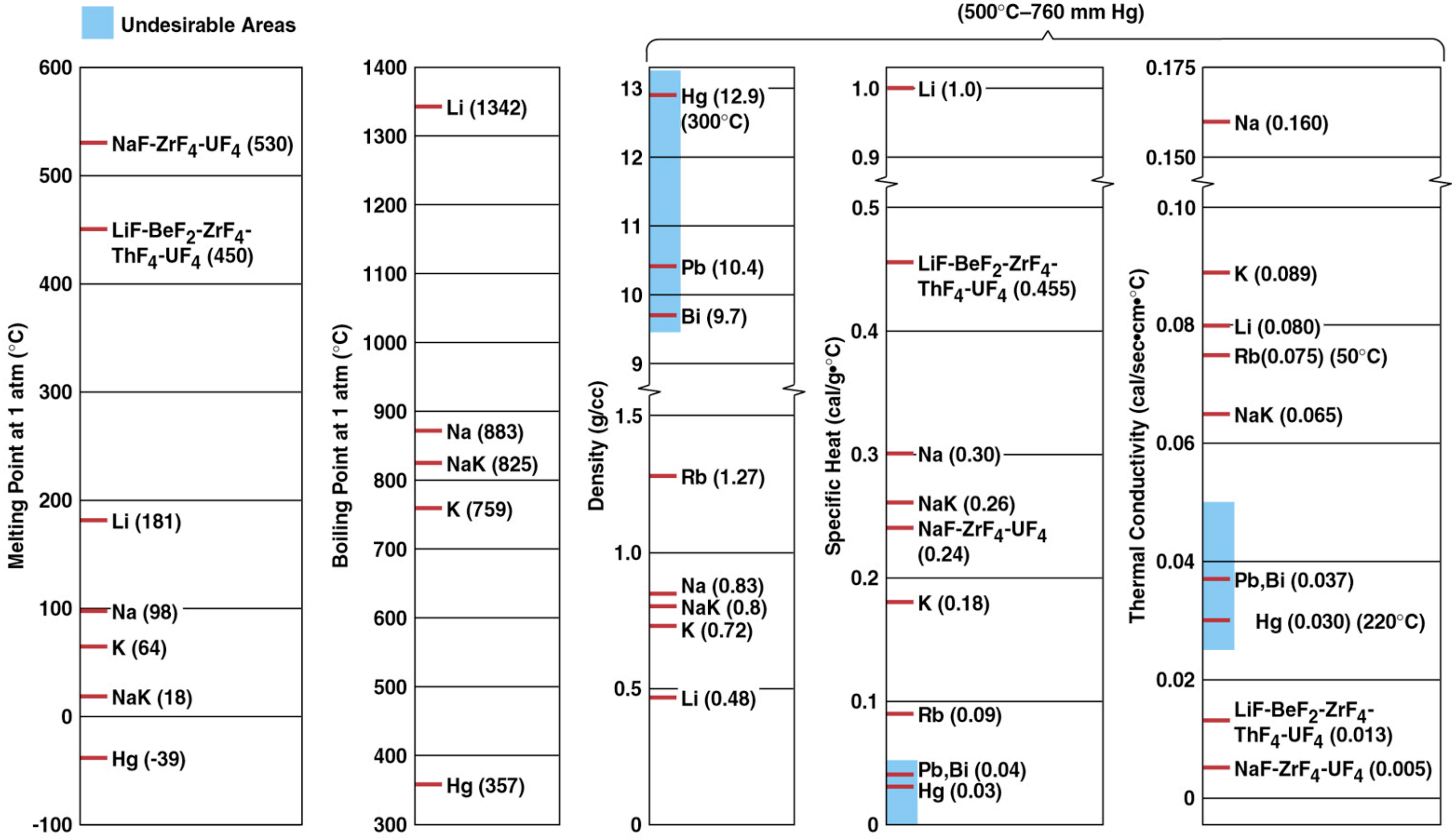
- **Reactor Subsystem**
  - Fuel
  - Clad
  - Working Fluid
  - Reflectors
  - Core Heat Transfer Components
  - Power Control Mechanisms
  - Safety Features
  - Control Instruments
  - Reactor Controller
  - Data Instruments
- **Shielding Subsystem**
  - Gamma Shield
  - Neutron Shield
  - Structure
  - Data Instruments
- **Primary Heat Transport Subsystem**
  - Working Fluid
  - Piping
  - Pumps
  - Heat Pipes
  - Radiative Heat Transfer Surfaces
  - Volume Compensation
  - Expansion Compensation
  - Support/ Structure
  - Thermal Insulation
  - Data Instruments
- **Power Conversion and Processing Subsystem**
  - Power Converters
  - Startup Equipment
  - Structure
  - Power Regulator
  - Power Transport
  - Control Instruments
  - Power Controller
  - Data Instruments
- **Heat Rejection Subsystem**
  - Radiator Surface or Surface Generator
  - Emissivity/ Absorbitivity Coatings
  - Micrometeorite Protection
  - Survival Equipment
  - Secondary Heat Transport
  - Support/ Structure
  - Thermal Insulation
  - Data Instruments

Ref. Space Reactor Electric Systems Subsystem Technology Assessment, ESG -DOE-13398, Rockwell International, 29-Mar-1983

Molten Salt Concepts Warrant Consideration for Multi-Megawatt Space Power Applications

- High power density
- Long life
- Mature fuel technology
- No "fuel fab"
- Demonstrated materials compatibility
- Strong negative temperature coefficient
- Simplified reactor control
- Potential for high conversion ratios
  - Reduced U^{235} mass requirements
  - Reduced ground S&S concerns
- Improved launch safety / reduced probability of inadvertent criticality
- Compatible with variety of power conversion technologies
- Potential for electrically-heated and driven-nuclear testing

Comparison of Molten Salt / Fuel / Coolant Properties



NaF-ZrF_4-UF_4 (54-41-6 mole %)
LiF-BeF_2-ZrF_4-ThF_4-UF_4 (70-23-5-1-1 mole %)
NaK (44% K)

Molten Salt Reactor Space Applications Must Address Additional Issues

- Initial system startup / thaw (fuel expansion)
- System shutdown / freeze / restart / thaw
- Fission gas separation and management in zero-g
- Power conversion cycle selection
- Fuel chemistry control

Summary

- Terrestrial molten salt reactor technology is mature
- Approach has many characteristics which commend its consideration wherever compact, high-power, stable reactors are required
- Technical feasibility of MMW molten salt space fission power systems warrants exploration.