Molten Salt Reactor Technology for Thorium-Fueled Small Reactors

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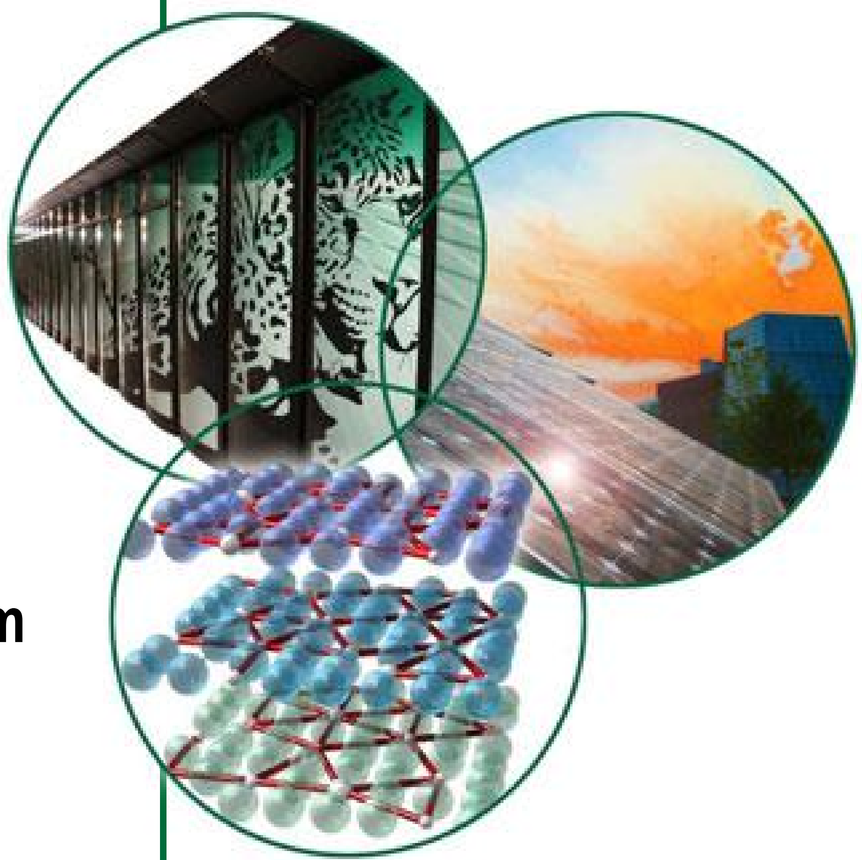

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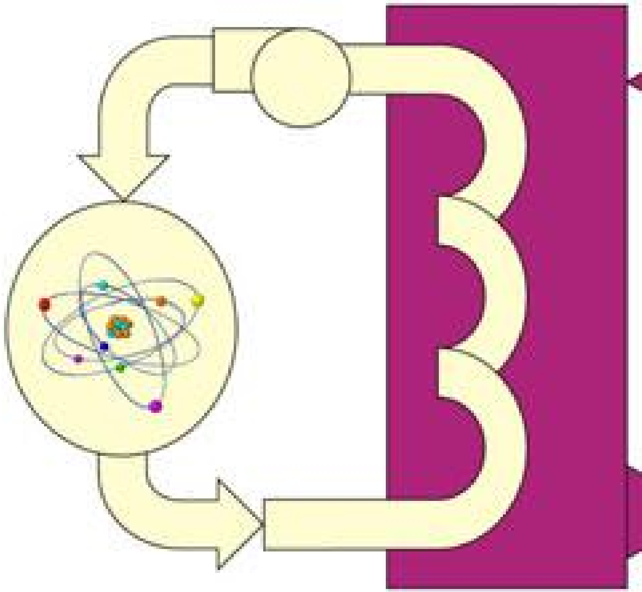
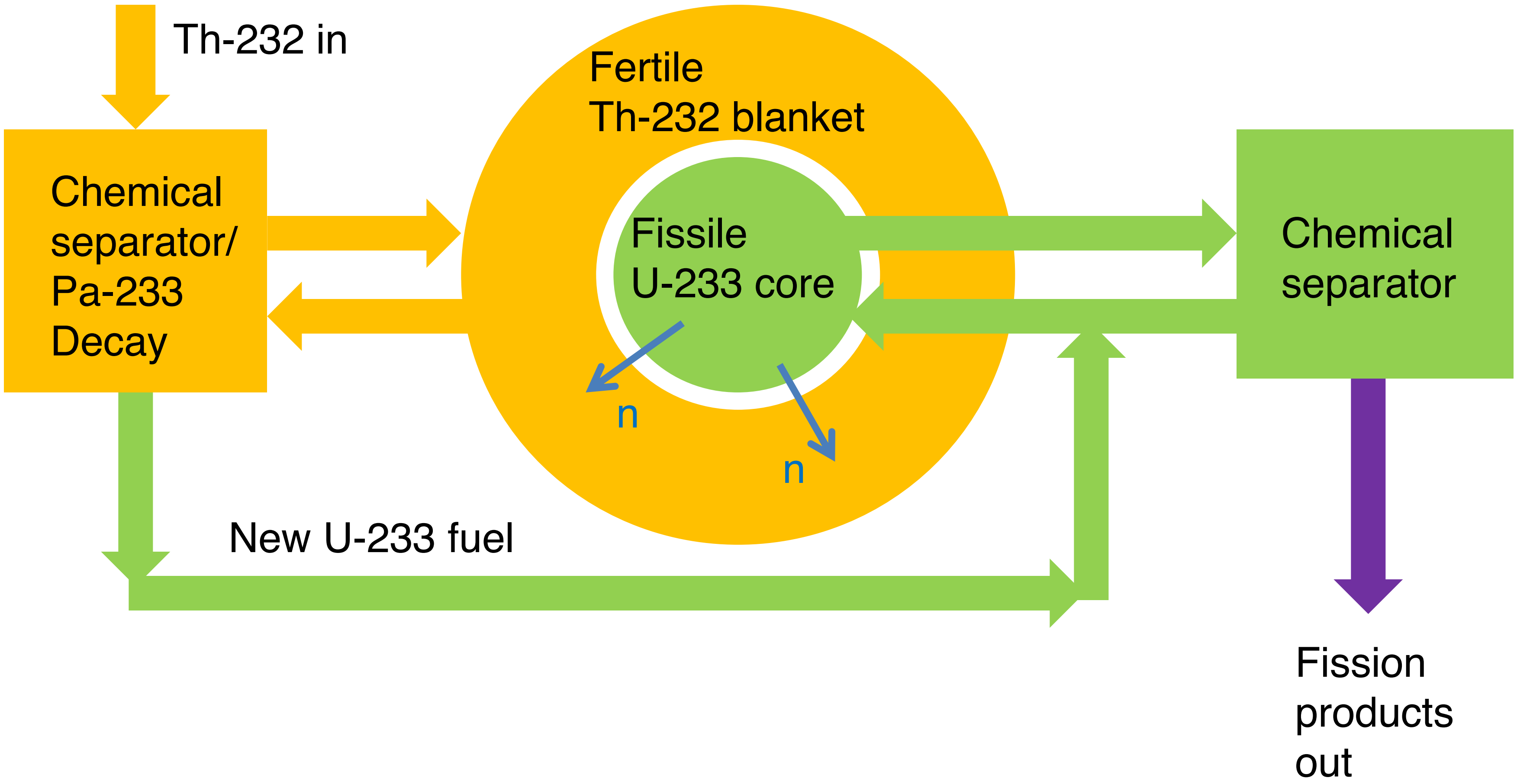
Basic Concept

- Molten salts are a class of homogeneous reactors in which the fuel is dissolved in the coolant.
  - Coolant/Fuel is critical in the core region and produces heat
  - Coolant/Fuel circulates through a heat exchanger
- This provides many advantages:
  - Core design is very simple
  - Online refueling and reactivity control
  - No fuel fabrication
  - Passive safety as the fuel can be be placed in a subcritical configuration
  - Can perform chemical processing of the coolant salt online (an highly integrated fuel cycle!)
- But, it also has several challenges:
  - Radioactive fuel distributed throughout the system
  - Potential for chemical interactions with structural materials
  - Coolant freezing



On-line Chemical Processing of Blanket and Core (Two Fluid Design)



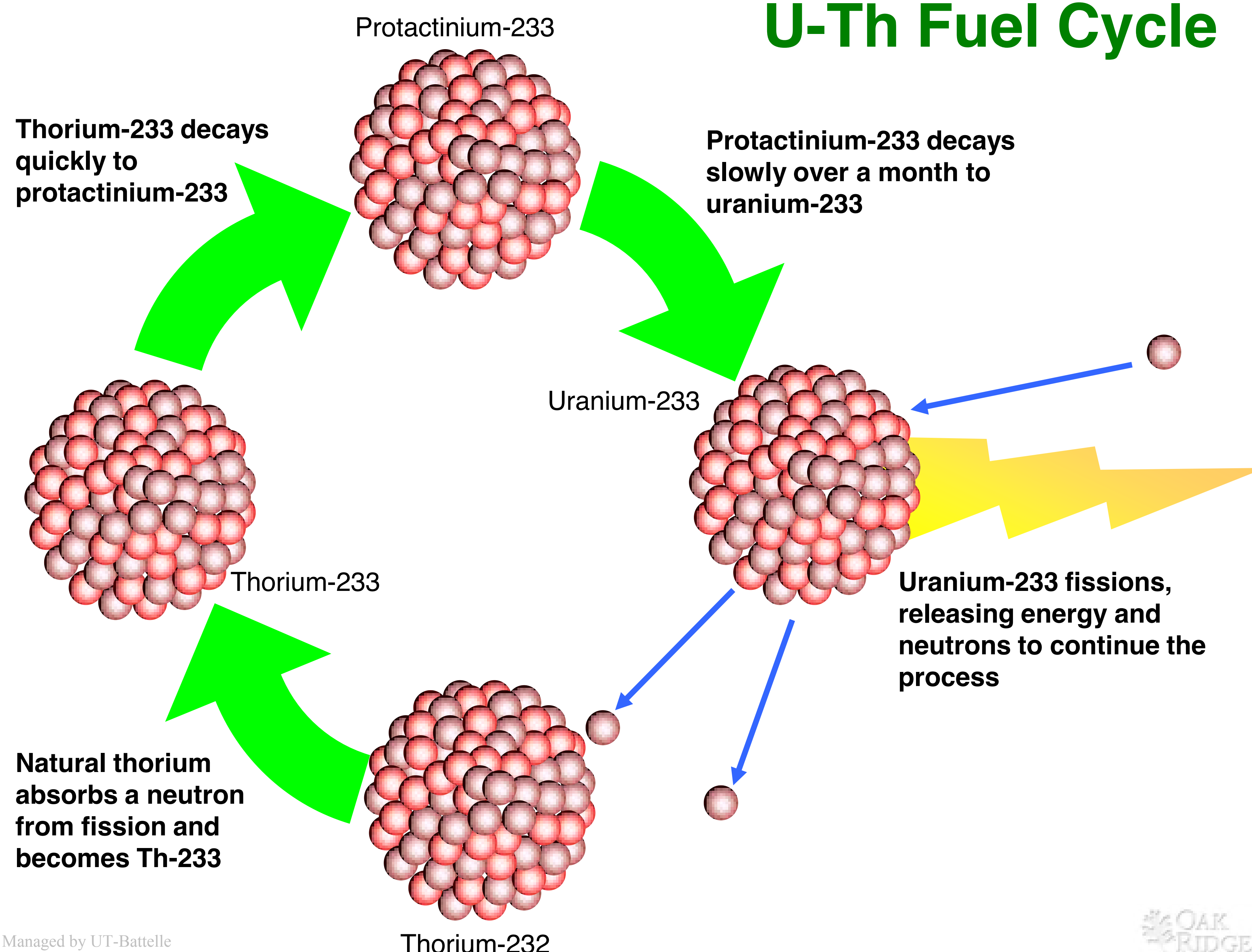
MSRs Are Flexible

- Molten salt reactors can operate on a variety of fuels
  - Traditionally designed as a thorium/uranium breeder
  - Have operated on U-233, U-235, and Pu-239
  - Designs considered as used fuel transmuters with MA fuels
- Molten salt reactors can operate as thermal-neutron, epi-thermal or fast-neutron reactors
- They can support a variety of missions:
  - Electricity generation
  - High-temperature process heat
  - Fuel cycle management
  - Nuclear propulsion (can be very compact)
- They are scalable in size from very small to large

MSRs Were Developed as Optimal Thermal-Spectrum Breeders

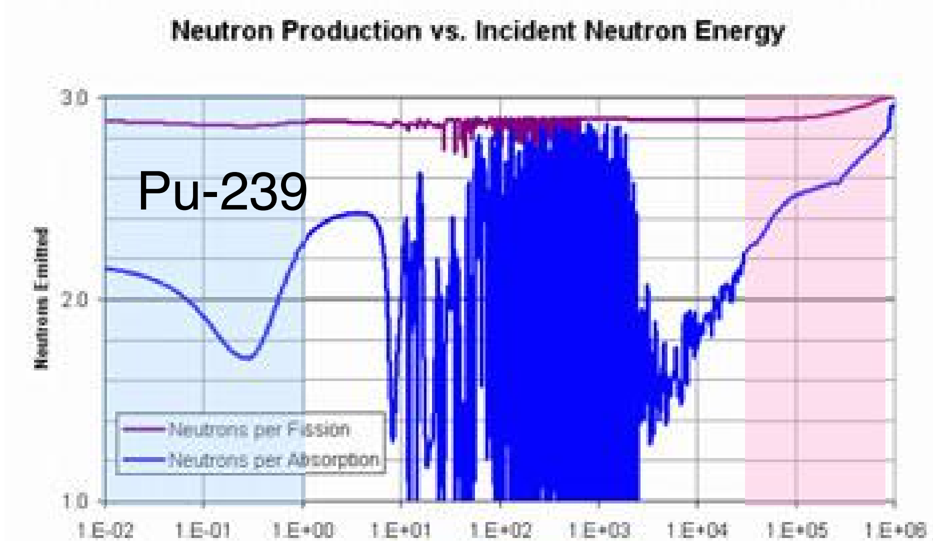
- A major concept alternative to liquid metal fast breeder reactors (U/Pu) developed at ANL.
- Design utilized Th/U fuel cycle which can support breeding in a thermal environment.
- Can achieve similar breeding performance in terms of fuel doubling time as LMFBR U/Pu cycles
  - Thermal system has much lower breeding ratio (1.08 vs 1.2-1.3 of LMFBR)
  - However, thermal system requires a much lower fissile loading (< 1 MT/GWe vs >10 MT/GWe for LMFBR)
  - Net result is doubling times in the range of 20 years for both systems.

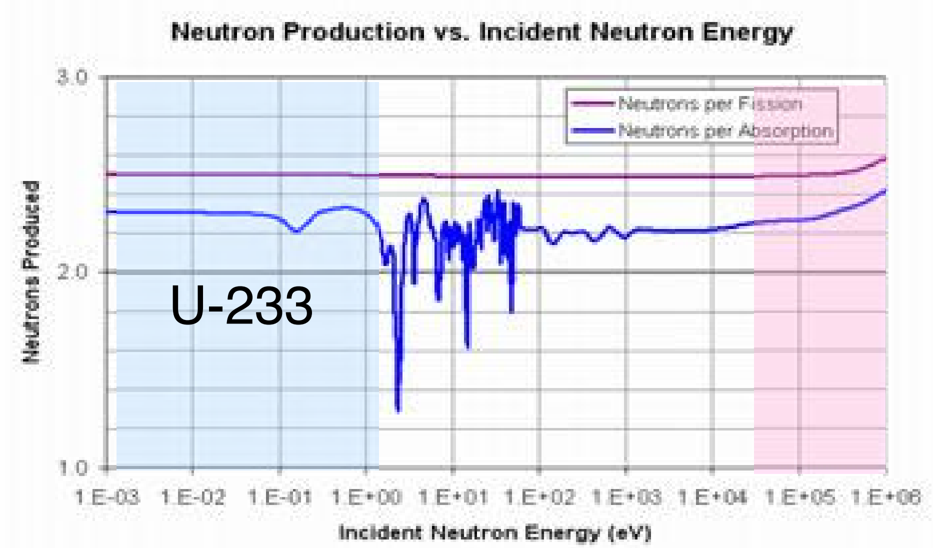
U-Th Fuel Cycle



Nuclear Physics: Why Thorium Can Breed in a Thermal Neutron Spectrum

- Breeding requires excess neutrons to convert fertile to fissile
- Fissile material must have large number of neutrons produced per absorbed (η>2)
  - 1 neutron to continue chain reaction
  - 1 neutron to convert fissile to fertile
  - Addition neutrons for non fission and non conversion reactions
- Pu-239 η too low in thermal range – but good for a fast-spectrum breeder
- U-233 can breed in fast and thermal ranges





What is so special about salts (vs water, liquid metals, gas?)

- 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
- Highly compatible with chemical processing
- No reactions with air/water
- Excellent thermal properties
- Transparent
- Very high boiling points

The Potential Benefits of Salts Stem Directly From *Fundamental* Materials Characteristics

Physical Properties of Coolants[a]

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)	$\nu \cdot 10^6$ (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

[a]Salt compositions are shown in mole percent. Salt properties are measured at 700°C 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 550°C. Pressurized water data are shown at 290°C for comparison. Nomenclature used: ρ is density, C_p is specific heat, k is thermal conductivity, ν is viscosity.

Fluorine Chemistry is the Key to Simplicity in this Design

- The UF4 and in the blanket salt can be easily separated by fluorinating the blanket salt to obtain the U-233
- The blanket salt is removed from the reactor, Pa-233 allowed to decay and then the breed U-233 is removed:
  - UF4 (in solution) + F2 → UF6 (gaseous)
- Bred uranium-233 could be easily removed from a thorium fluoride mixture using this approach and then put into the core region

Fission products are also removed from the system

- Gaseous fission products (including Xenon) removed by helium sparging
- Vacuum distillation used for remainder of fission products
- Actinides continue to cycle within the salt
- The waste stream consists of fission products along with the small system losses

Technology Summary: MSR combines several unique technologies to provide an innovative Reactor System

- Thermal spectrum thorium-uranium breeding for sustainable energy production
- Fluid fuel allows optimal neutron economy by removing parasitic absorbers
- Fluid fuel avoids parasitic losses of Pa-233 by continuous removal from the reactor and decay
- Several desirable safety aspects:
  – Strongly negative temperature coefficients
  – LOCA not possible
  – Drain tanks with decay heat
  – Atmospheric-pressure system

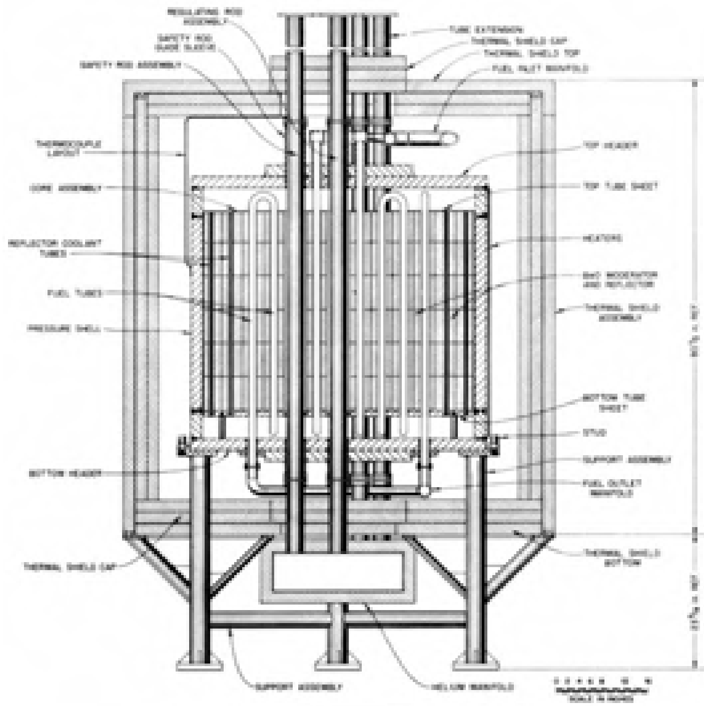
However, there are some challenges for MSR that must be factored into design

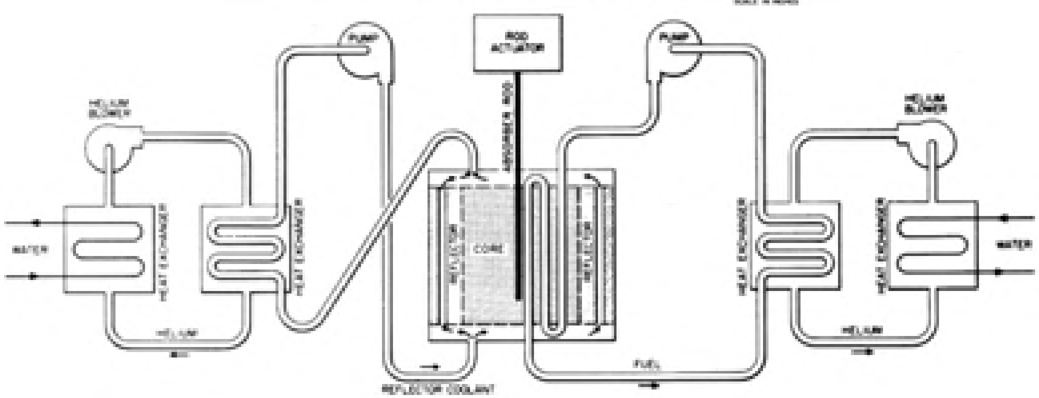
- Must keep system at high temperature to avoid salt freezing
- Lifetime of components (graphite)
- Chemical interactions with structural materials
- The salt of choice (F-Li-Be) produces tritium during operation and requires Li enrichment
- Complexity of a combined reactor and fuel processing system

HISTORY: 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)
- Denatured Molten Salt Reactor (1976-1980)
- Liquid Salt Cooled Reactor (Today)

The First MSR: The Aircraft Reactor Experiment (ARE) – Very Small (2.5 MWt)



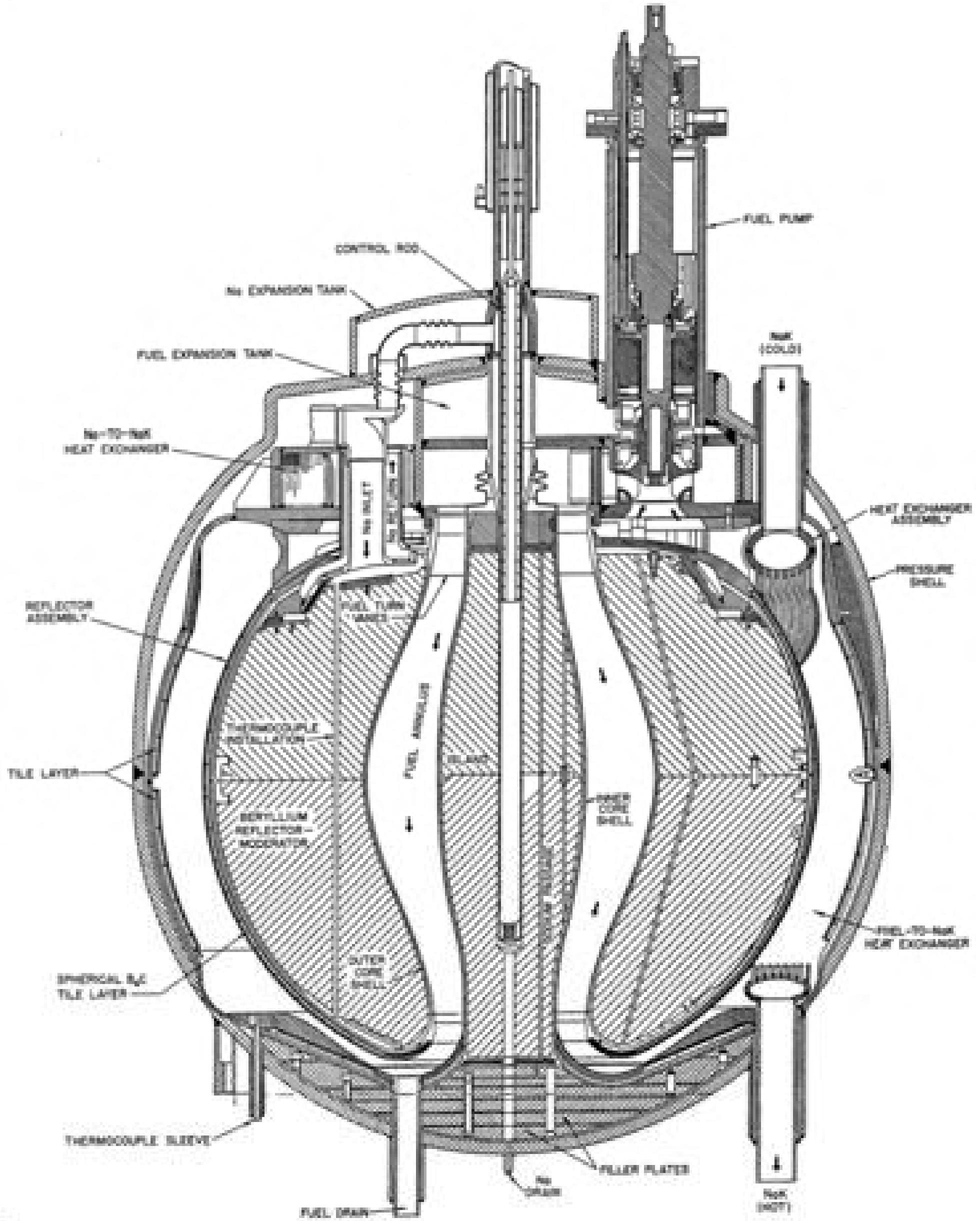


In order to test the liquid-fluoride reactor concept, a solid-core, sodium-cooled reactor was hastily converted into a proof-of-concept liquid-fluoride reactor.

The Aircraft Reactor Experiment ran for 100 hours at the highest temperatures then achieved by a nuclear reactor (860 C).

- Operated from 11/03/54 to 11/12/54
- Liquid-fluoride salt circulated through beryllium reflector in Inconel tubes
- $^{235}UF_4$ dissolved in NaF-ZrF_4
- Produced 2.5 MW of thermal power
- Gaseous fission products were removed naturally through pumping action
- Very stable operation due to high negative reactivity coefficient
- Demonstrated load-following operation without control rods

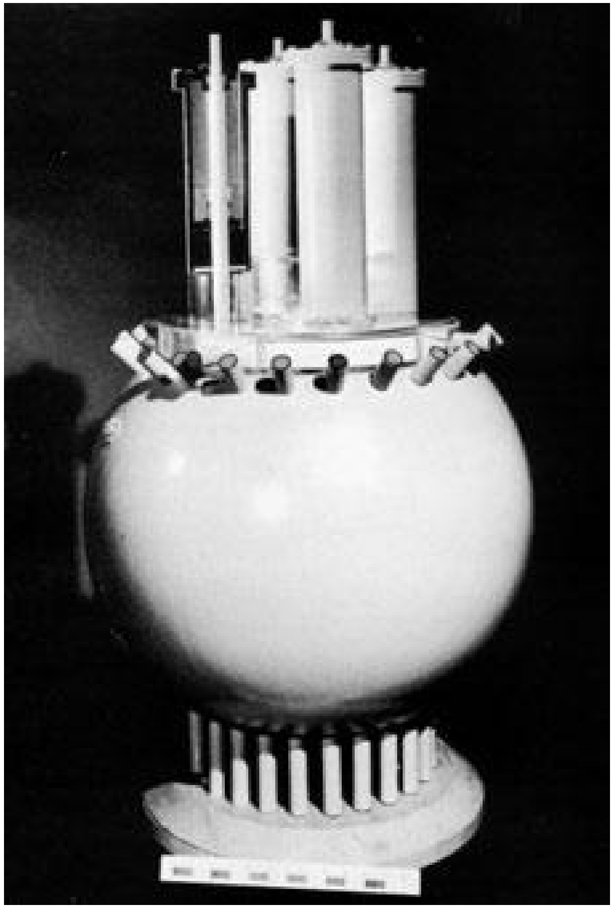
The "Fireball" - Small (60 MWt)



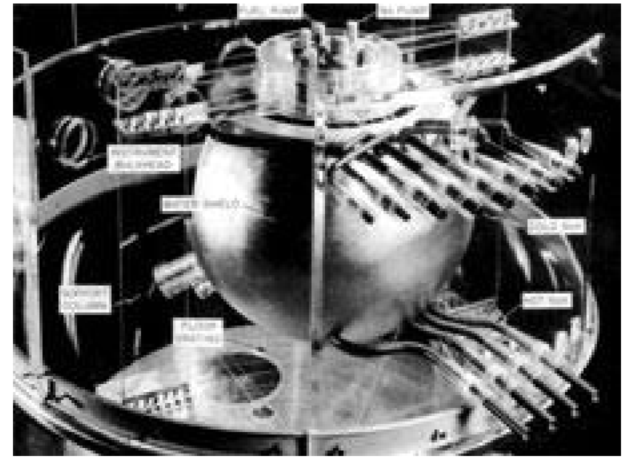
The "Fireball", or Aircraft Reactor Test, was the culmination of the ANP effort at ORNL.

- $^{235}UF_4$ dissolved in NaF-ZrF_4
- Designed to produce 60 MW of thermal power
- Core power density was 1.3 MW/L
- NaK used to transport heat to jet engines at 1150 K
- 1500 hours (63 days) design life
- 500 hours (21 days) at max power
- The "Fireball" pressure shell was only 1.4 meters in diameter!
  - Contained core, reflector, and primary heat exchanger inside

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



Full-Scale ART Model



Full-Scale ART Model

ART Building

ORNL 2001-1656C EFG

The MSR Program Included Development of Civilian Power Reactors as Well

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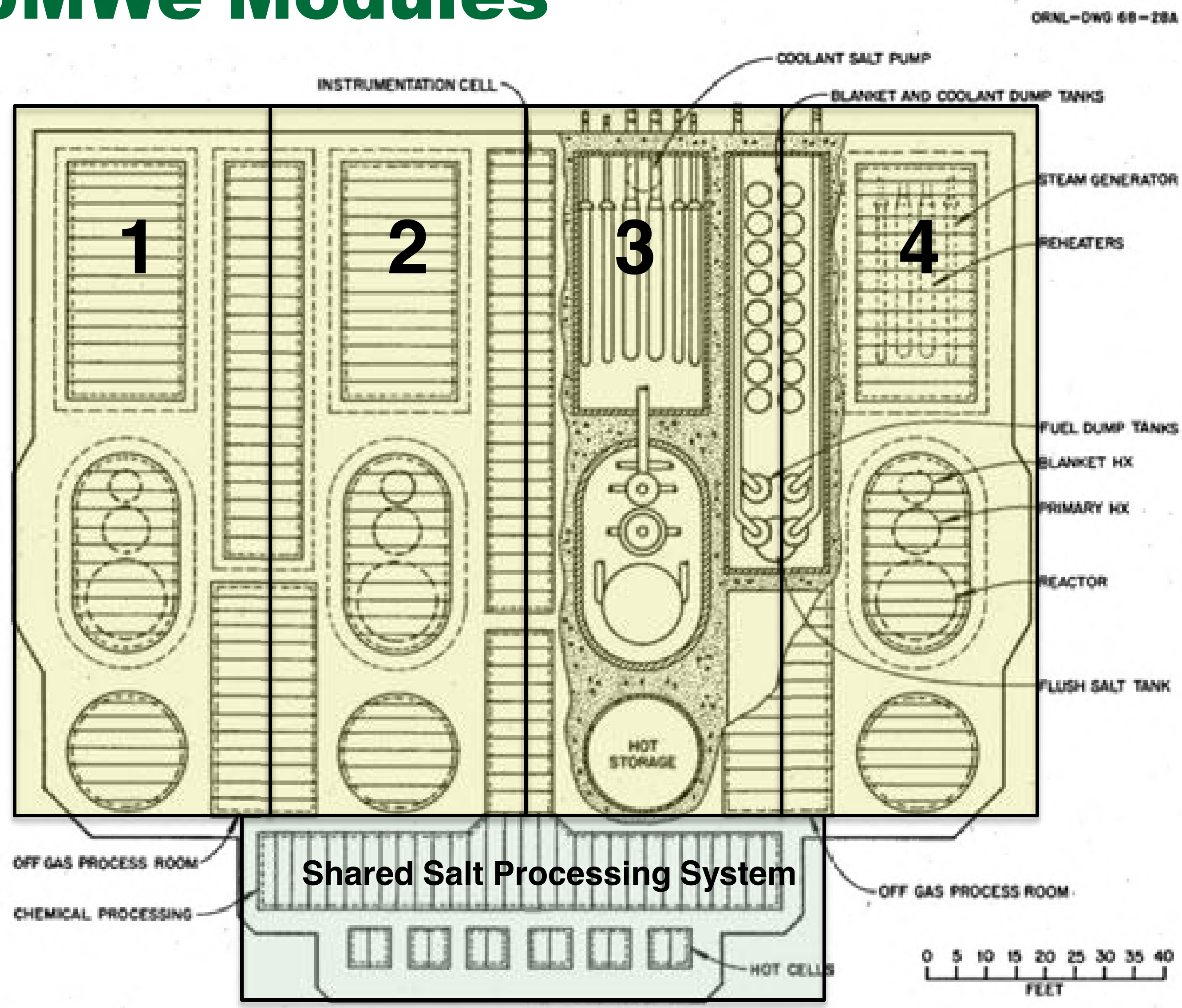
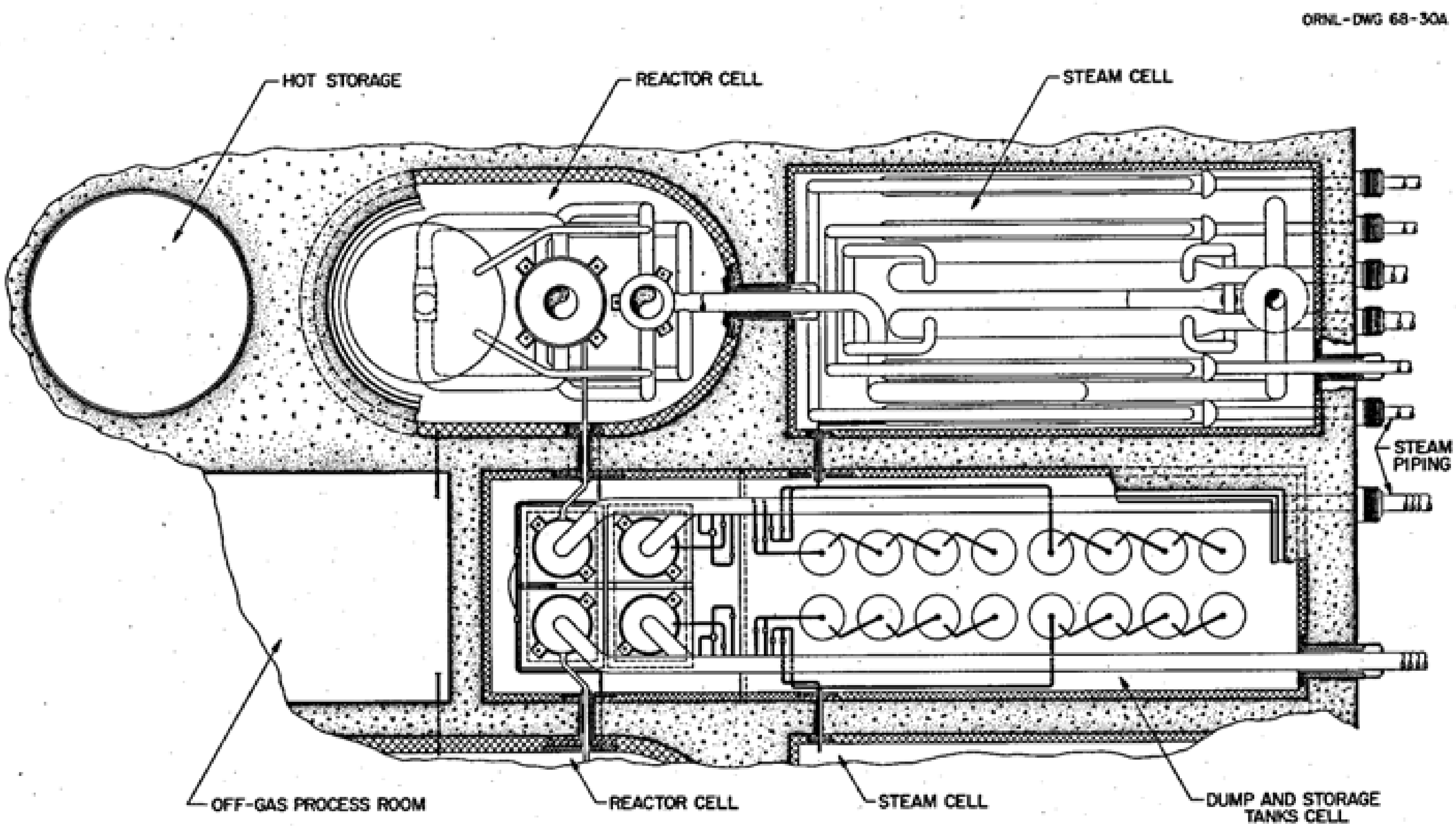
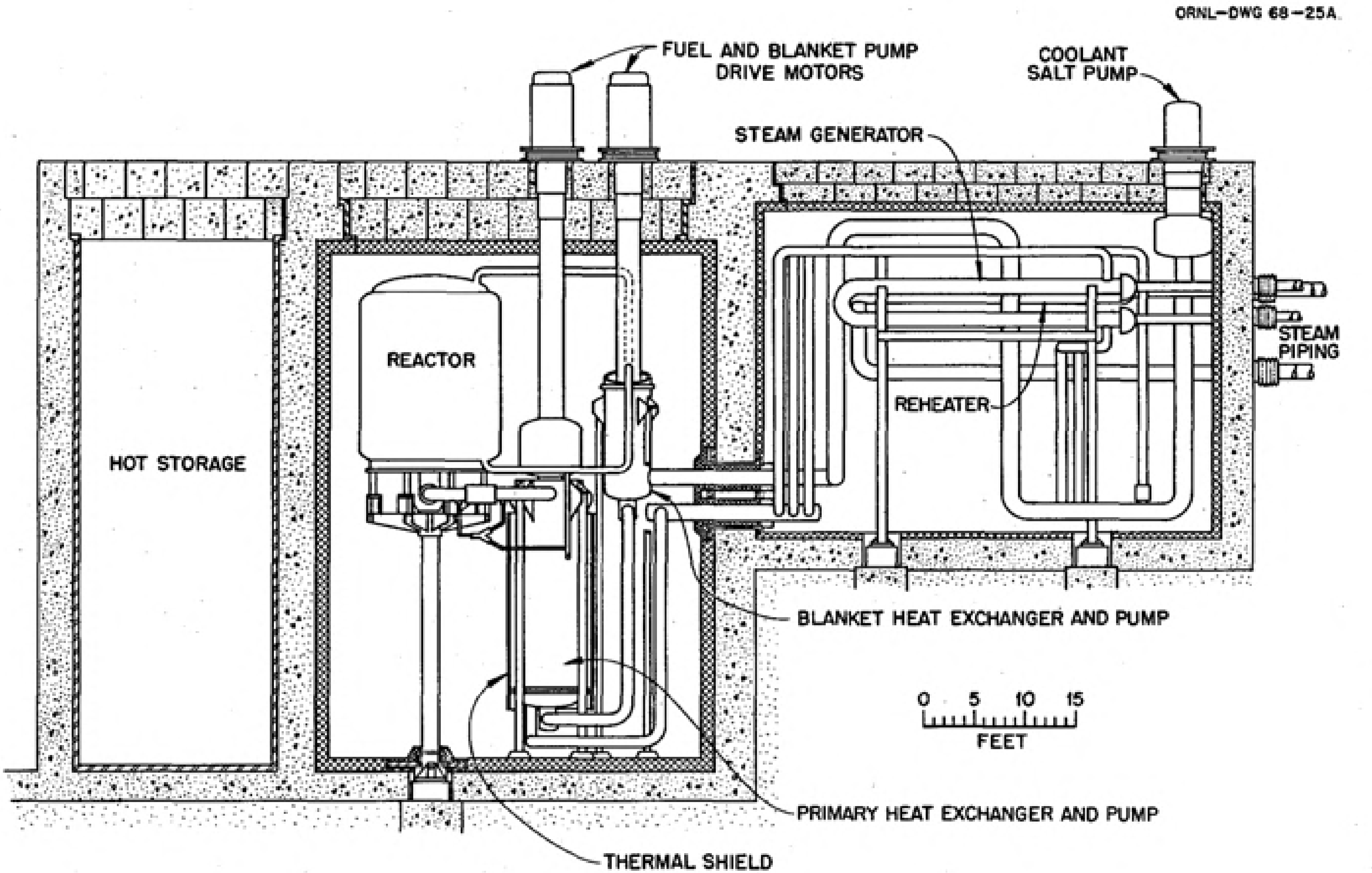
An MSR-SMR: Plant Design with 4x250MWe Modules



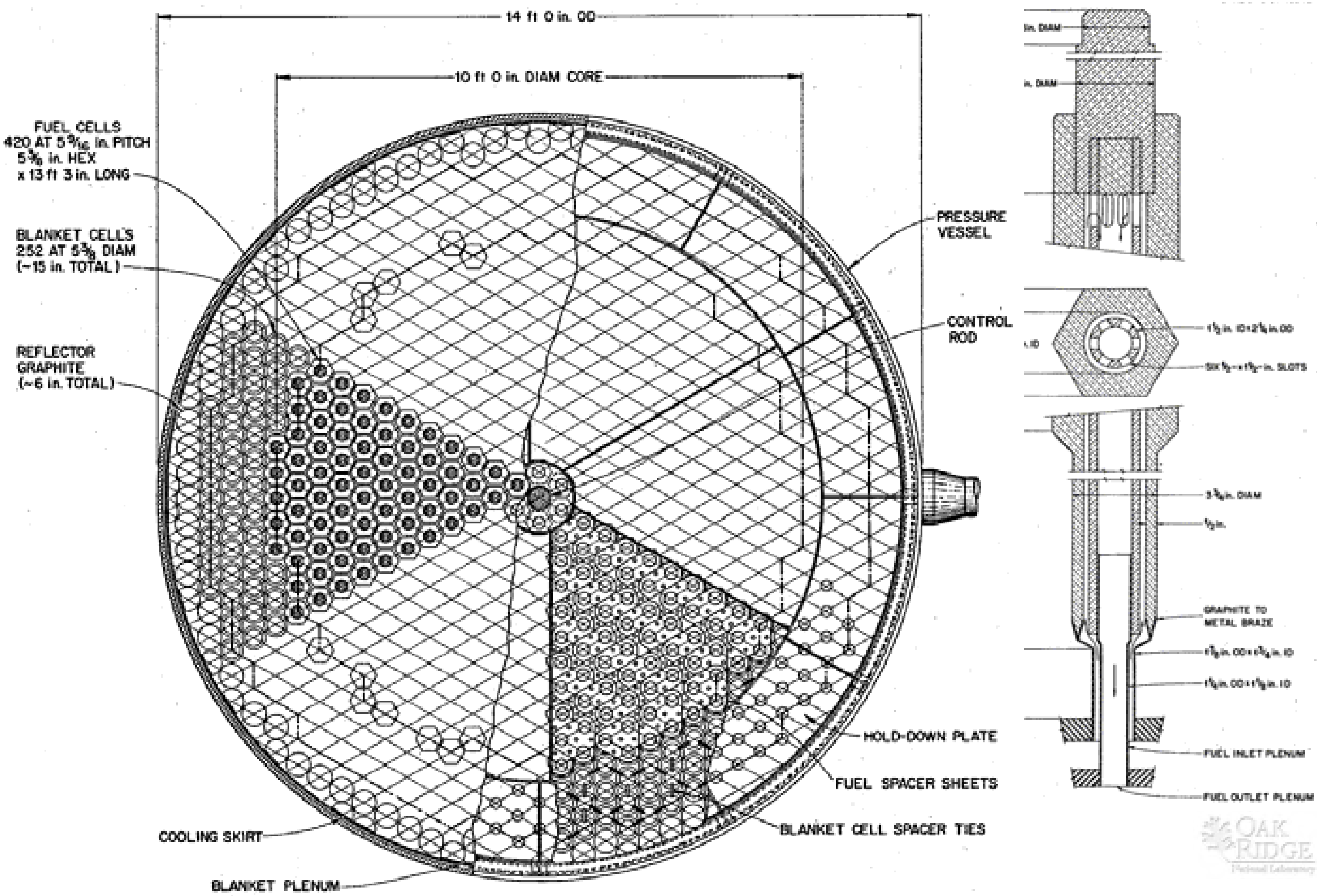
250-MWe MSBR Module Design Detail
Plan View of Steam Generator and Drain Tank Cells



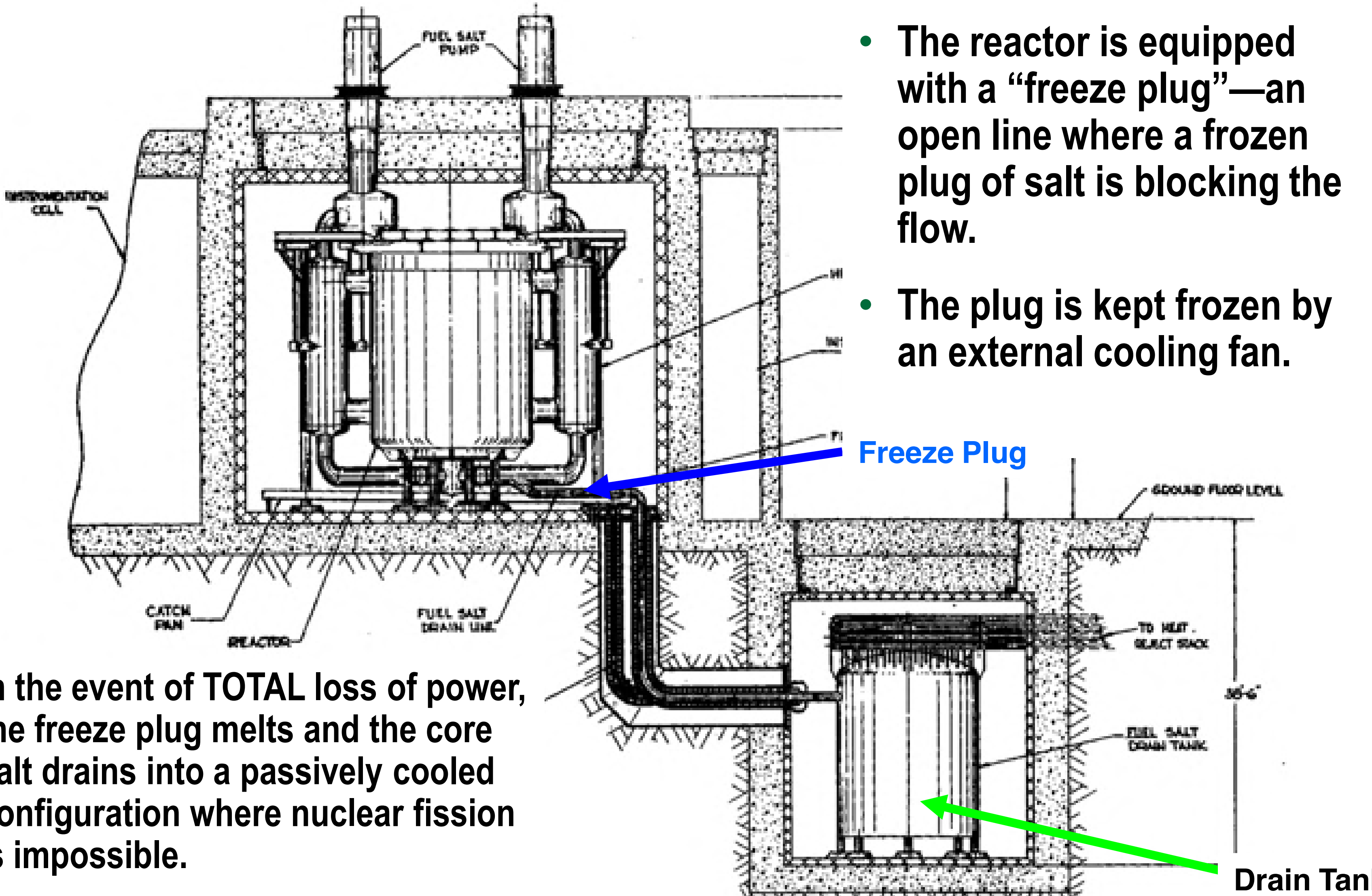
250-MWe MSBR Module: Sectional Elevation of Reactor Cell



Two-Fluid 250-MWe MSBR: Core Design

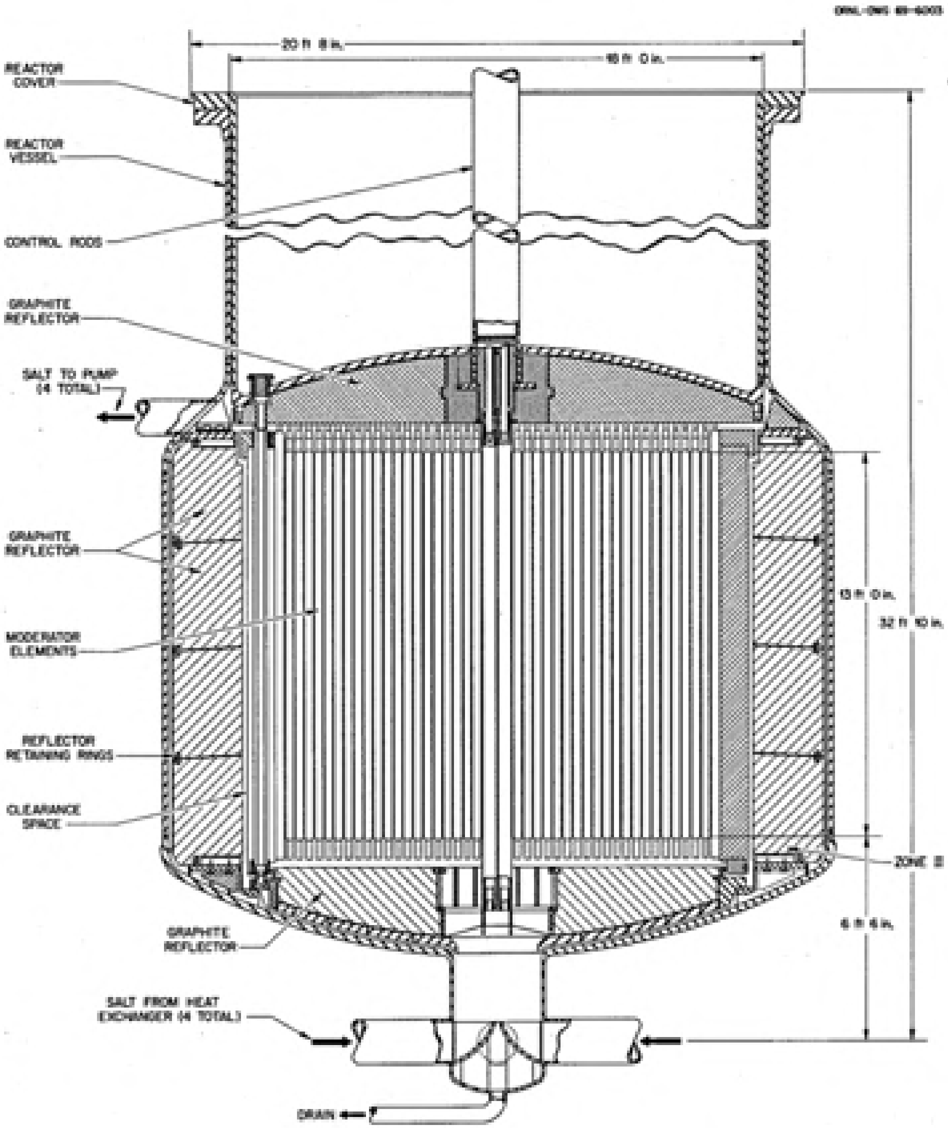


MSR passive safety: The freeze plug



- The reactor is equipped with a “freeze plug”—an open line where a frozen plug of salt is blocking the flow.
- The plug is kept frozen by an external cooling fan.
- In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear fission is impossible.

By the way: MSRs can also be large: One-Fluid 1000-MWe MSBR (1972):



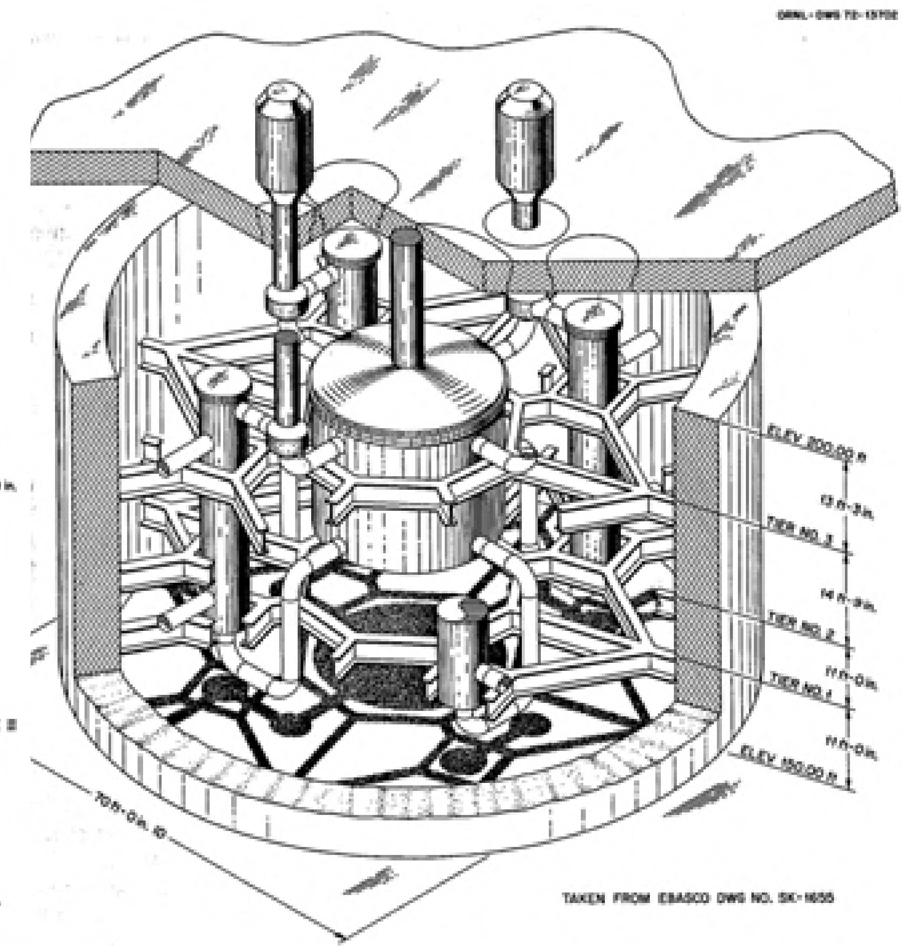
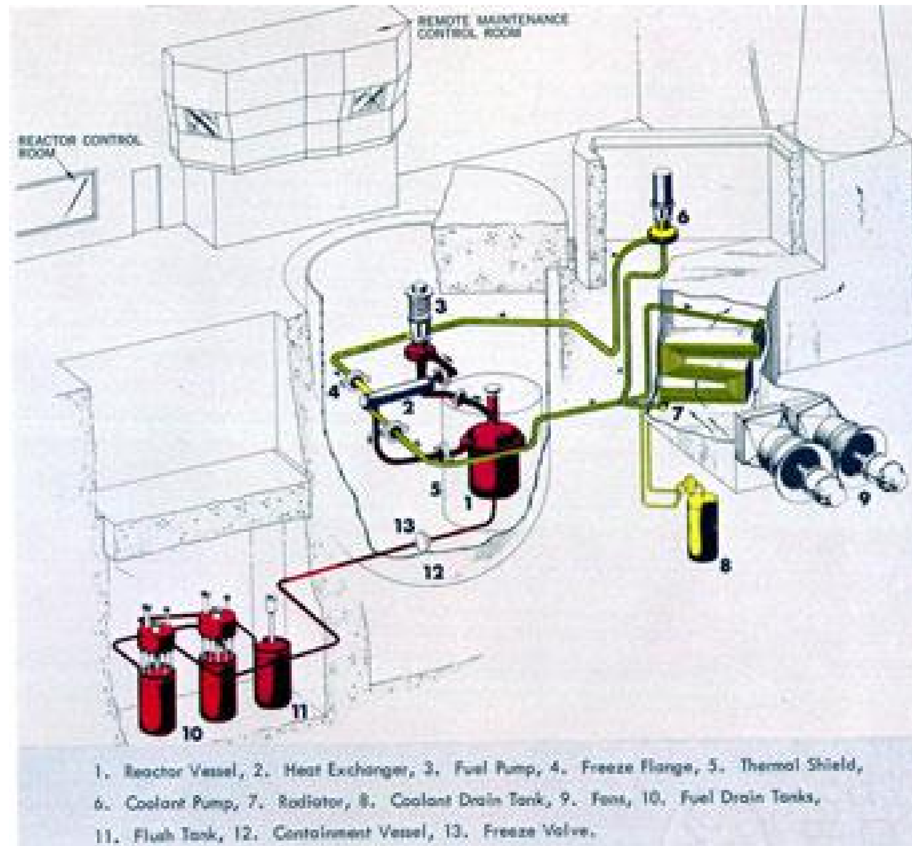


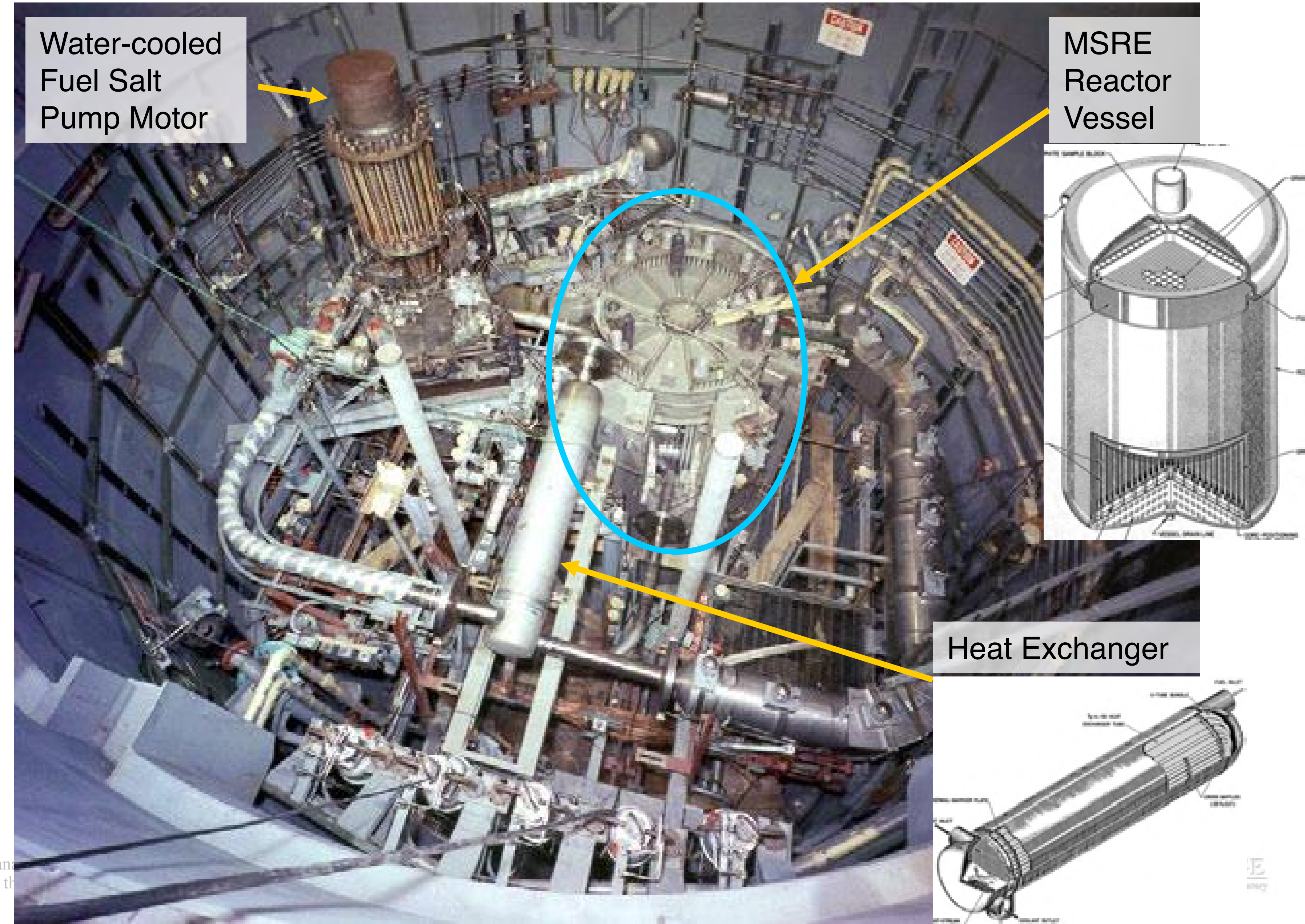
Fig. 1.3. Design study of MSBR cell.

Operating Experience: Molten Salt Reactor Experiment (MSRE) Was an Extremely Successful Demonstration

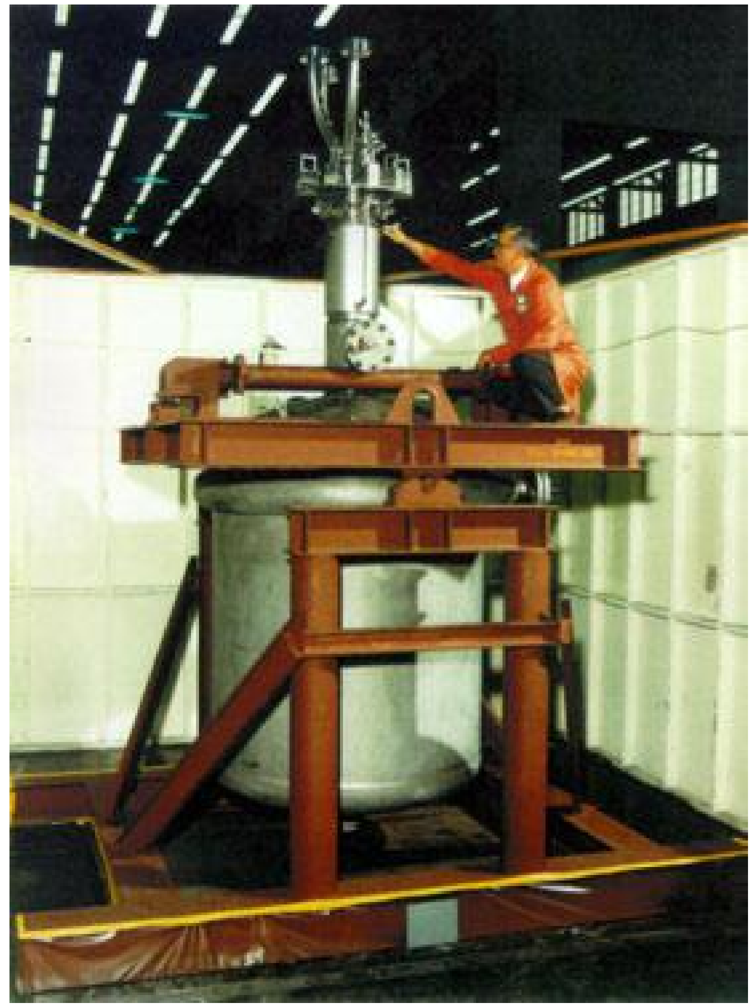
- Operated: 1965 – 1969 at ORNL
- Design features:
  - 8 MWt (original design was 10 MWt to facilitate construction on operating funds)
  - Single region core
  - Fuels
    - LiF-BeF_2- ZrF_4-UF_4
    - LiF-BeF_2- ZrF_4 -UF_4 -PuF_3
- Graphite moderated
- Hastelloy-N vessel and piping
- Achievements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



View inside the MSRE test cell



MSRE Graphite Moderator and Core Assembly



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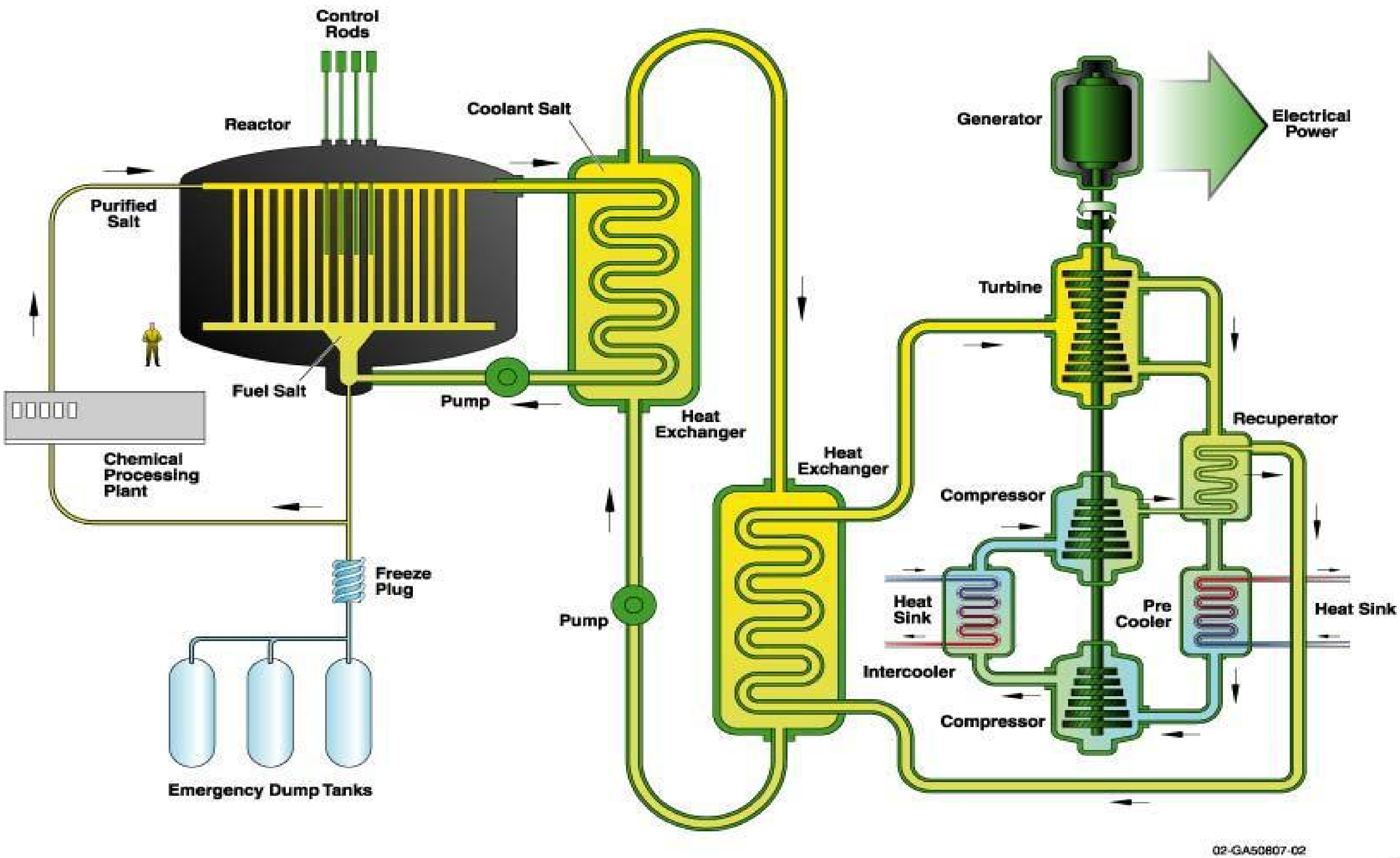
MSR lives on as a Gen-IV Concept with International Interest



An MSR-SMR Concept...

- Thermal spectrum – low fuel inventories and therefore low startup fissile costs
- Compact, modular design sharing common infrastructure with other modules (e.g. salt processing and cleanup)
- Simplified salt processing perhaps only removing key fission products (greatly simplified over optimized breeder and no separated fissile materials)
- On-line refueling and salt processing provides for minimal down time (only for maintenance)
- High temperature system an support high efficiency electricity generation (via SCO2 or He Brayton cycle) and process heat applications
- Passive safety features, low pressure system
- Integral vessel designs could be considered over previous loop designs (for example, SmAHTR but with liquid fuel)

Summary/Conclusions

- The development of the MSR was a key historical achievement of ORNL
- MSRs have been demonstrated at ORNL in the 1950s and 1960s and have shown good performance
- The MSR technology can scale from very small to large plant size
- MSRs have attractive features for advanced SMRs
  - Compact configuration
  - Passive safety/low-pressure system
  - Long-term operation through online fueling
  - Can support high efficiency electricity generation and/or high temperature heat applications.

For More Information

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- www.EnergyFromThorium.com - blog, discussion forum, and large collection of ORNL and other reports on MSRs.
- Presentations from recent salt-cooled reactor workshop: http://www.ornl.gov/fhr