# Module 6: Systems and Components

**Presentation on Molten Salt Reactor Technology by:**

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**Presentation for:**
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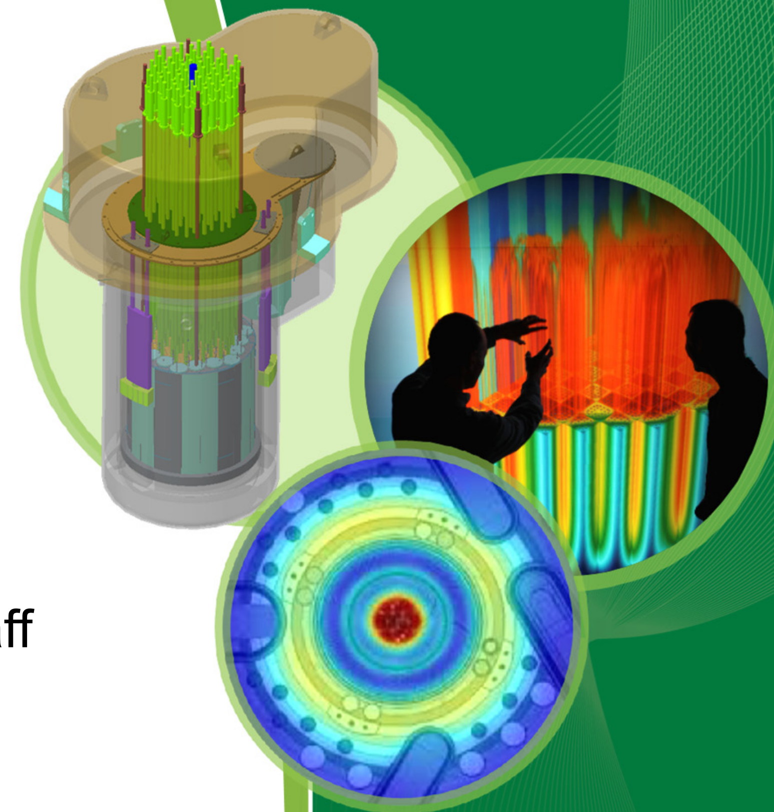

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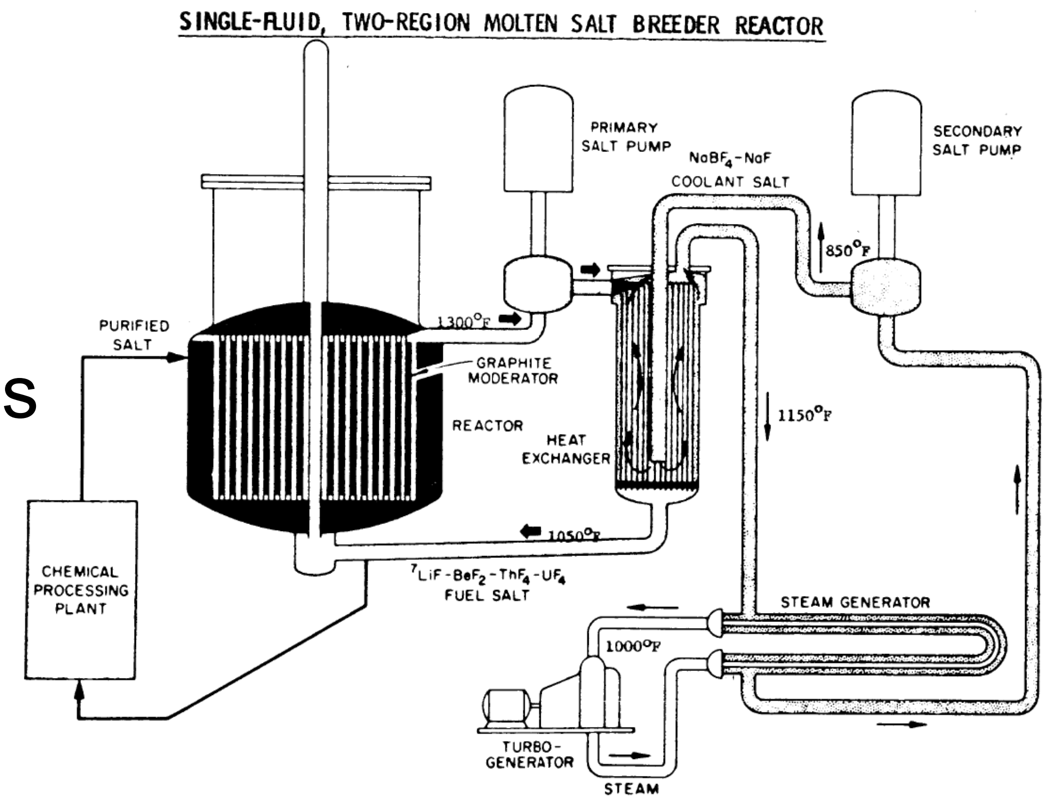
# Module Outline

- Overview
- Nuclear Heat Supply
  - MSRE
- Heat Transport
- Major Support Systems
- Power Units
- Balance of Plant
- Other Issues
- Fast Spectrum MSRs



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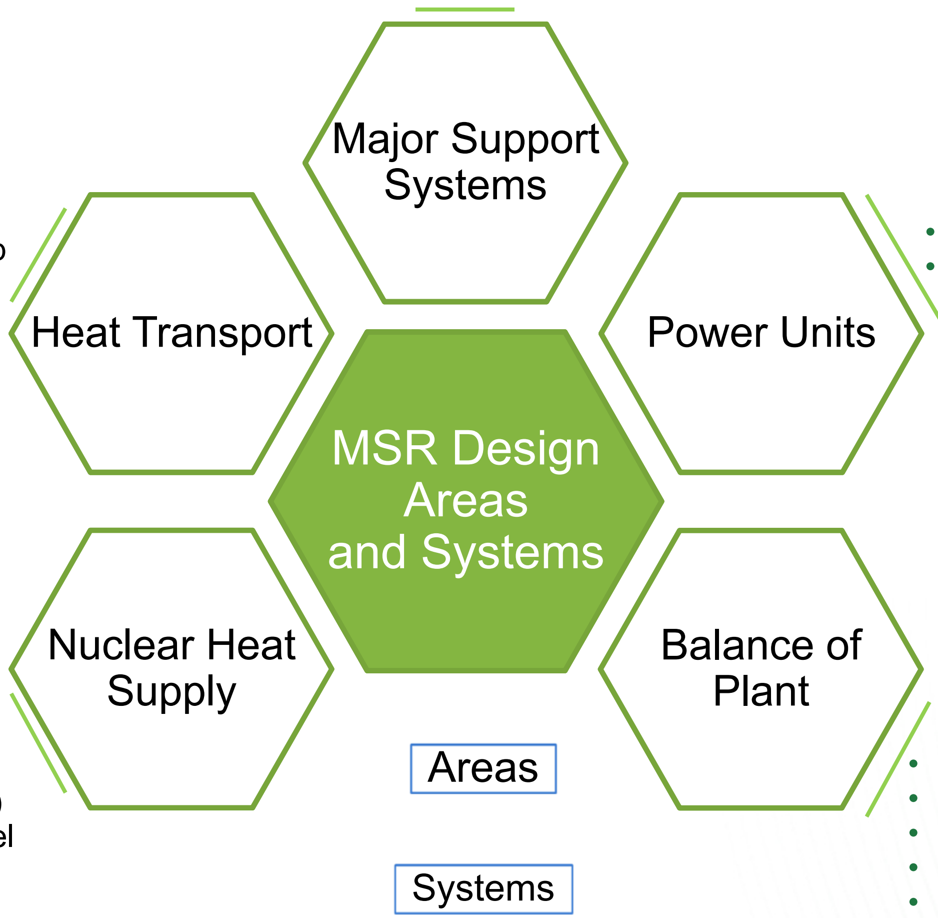
# General Design Areas and Systems

- Chemistry and inventory
- Cover gas
- Fuel handling and storage
- I&C




- Coolant salt loop

- Power conversion
- Process heat

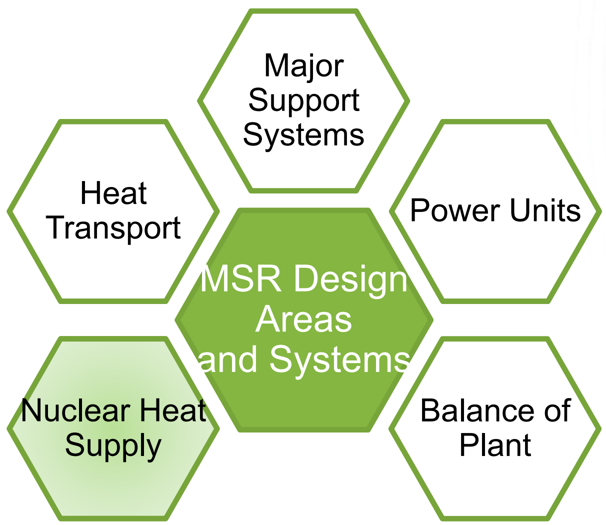
- Reactor
- Reactivity control
- Direct reactor auxiliary cooling system (DRACS)
- Vessel and vessel cavity

- Electric
- Fire protection
- Cooling and service water
- Waste handling
- Control room
- HVAC

Source:
FHR Subsystems Definition, Functional Requirement Definition, and Licensing Basis Event Identification White Paper UCBTH-12-001

# Nuclear Heat Supply

- Reactor
- Reactivity Control
- Decay Heat Removal
- Reactor Vessel and Reactor Cavity

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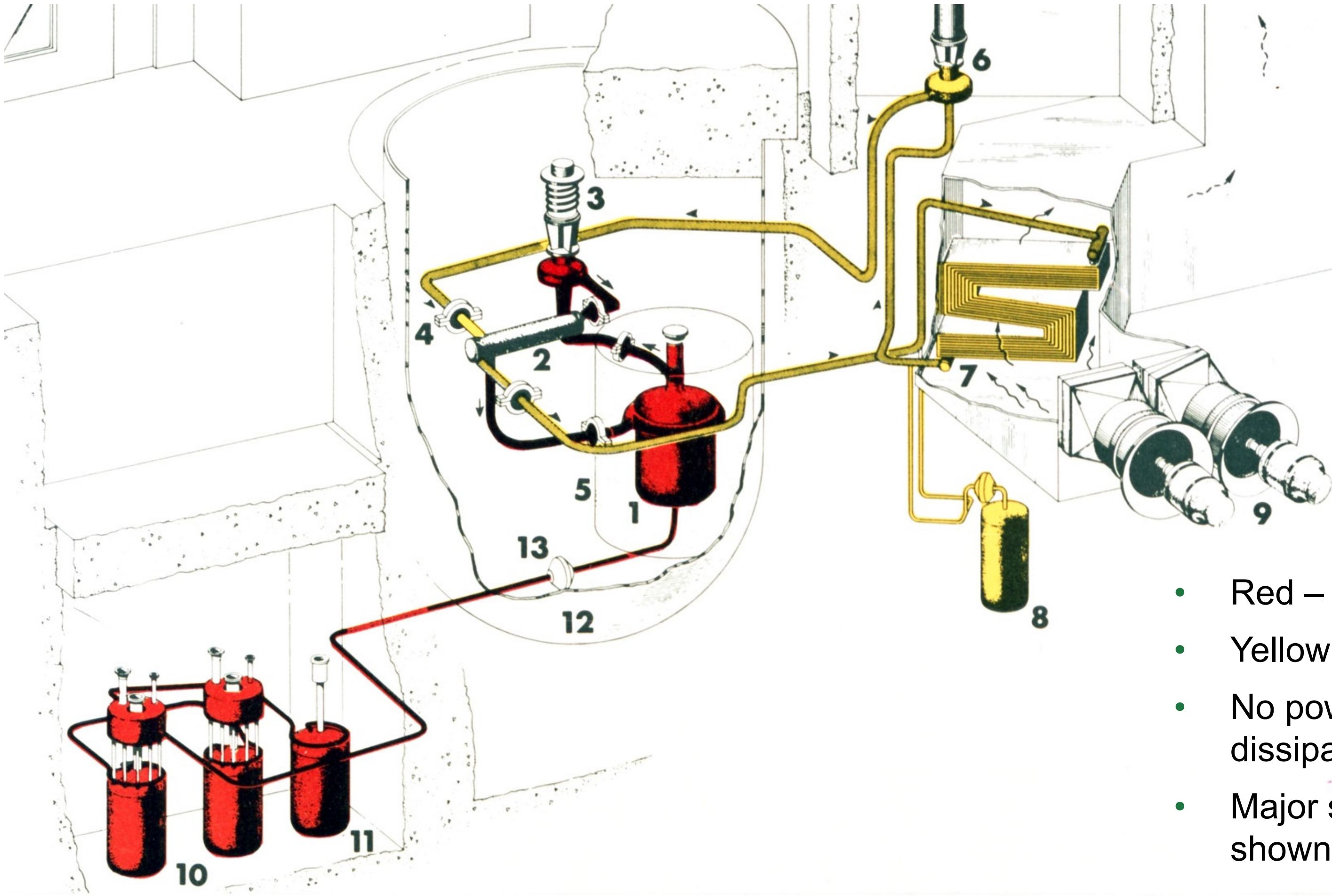
# A Look at the 8 MWt MSR Experiment (MSRE) Reactor




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.

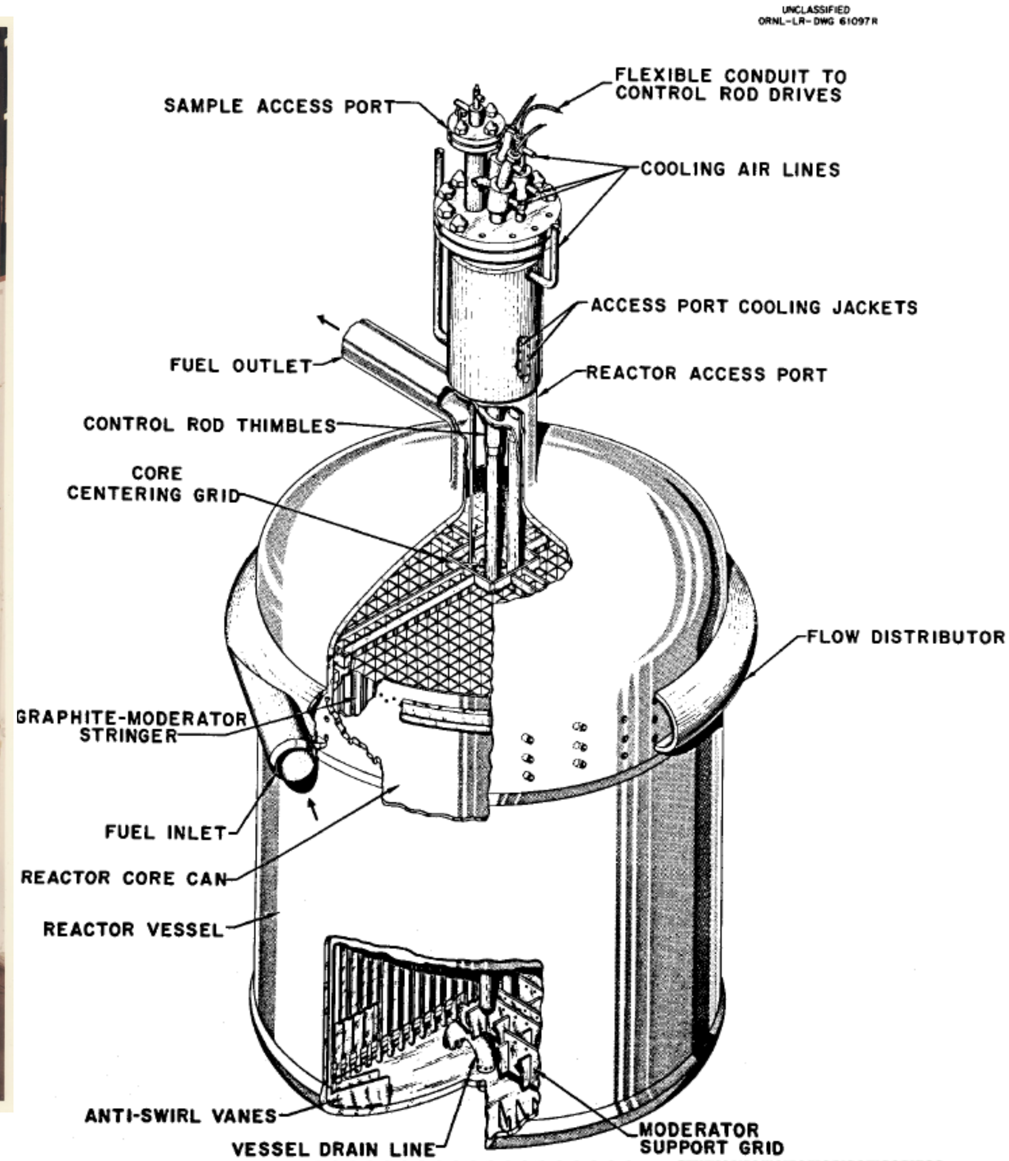
- Red – fuel salt flow
- Yellow – coolant salt flow
- No power conversion – heat dissipated to atmosphere
- Major system components shown

Source: ORNL-TM-728

# MSRE Reactor Vessel is Compact

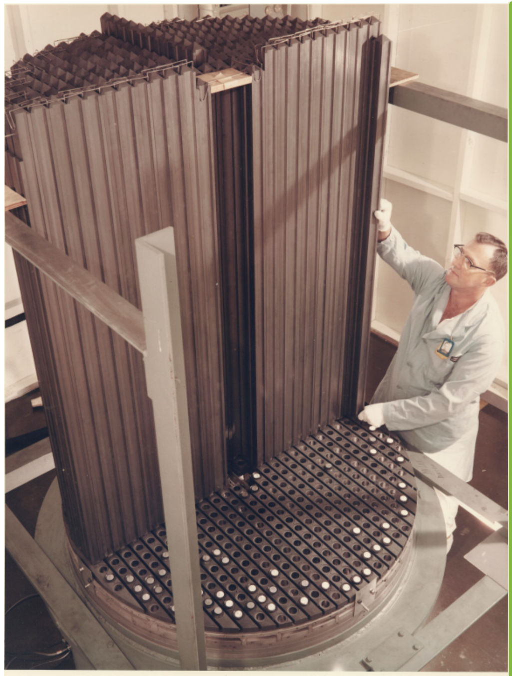
ORNL Photo 71114

**MSRE Vessel: 5 ft diameter, 8 ft tall**



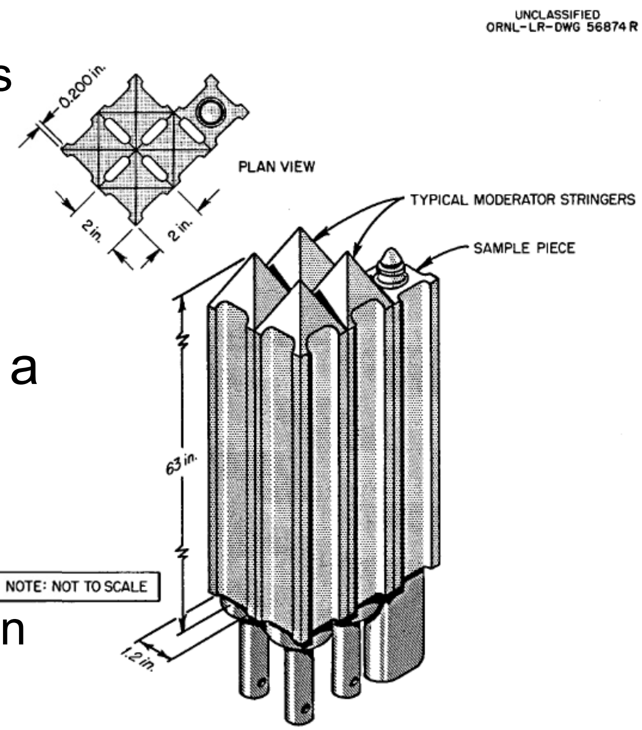

Source: ORNL-TM-728

# The MSRE Graphite Moderator is Key…



MSRE Graphite Moderator
55 in. diameter, 64 in. tall

- The reactor core is formed of 513 2-in. × 2-in. graphite stringers
  - 104 fractional-sized blocks at the periphery
  - Upper horizontal surfaces of each stringer are tapered to prevent salt pooling after a reactor drain down
- Stringers are mounted in a vertical, close-packed array
  - Half-channel salt flow passages are machined in the four faces of each stringer




Typical Stringer Arrangement

Source: ORNL-TM-728

# Comparison of MSRE and PWR Reactor Vessels

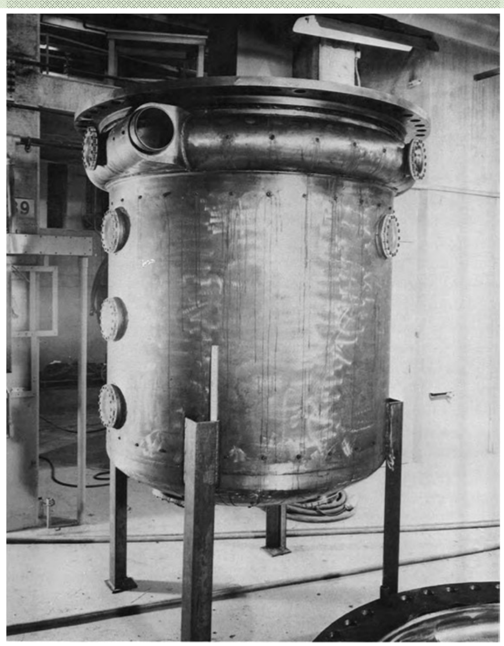
**MSRE Reactor**

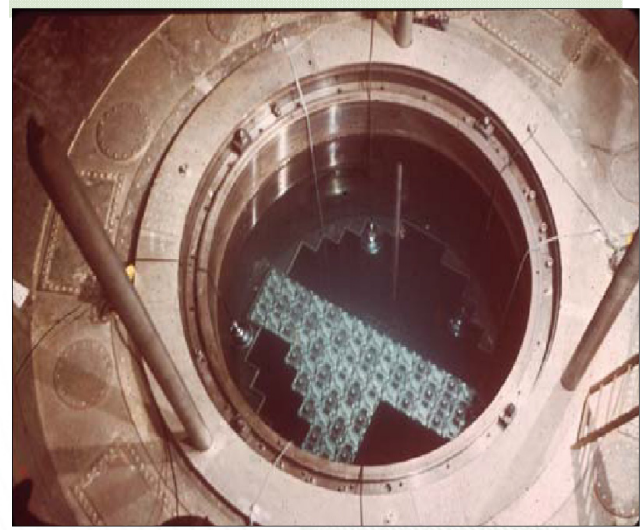
The nominal MSRE core volume is 90 ft$^3$: 20 ft$^3$ is fuel salt and 70 ft$^3$ is graphite.

Three control rods help control temperature. Rapid insertion is not required because complete reactor shutdown is provided by draining the fuel salt.

Sources:
ORNL-TM-728,
ORNL-2780,
NRC Technology Course on SFRs,
NRC Reactor Concepts Manual

| MSRE | PWR |
|---|---|
| INOR-8 alloy (nickel-based; Hastelloy N) | Stainless steel clad manganese moly steel |
| 58 in. ID, 7 ft 10 in. high (1.5 m ID, 2.4 m high) | 153 in. ID, 35 ft high (3.9 m ID, 10.7 m high) |
| 9/16 in. thick | 12 in. thick |
| No guard vessel (water-cooled thermal shield) | No guard vessel |







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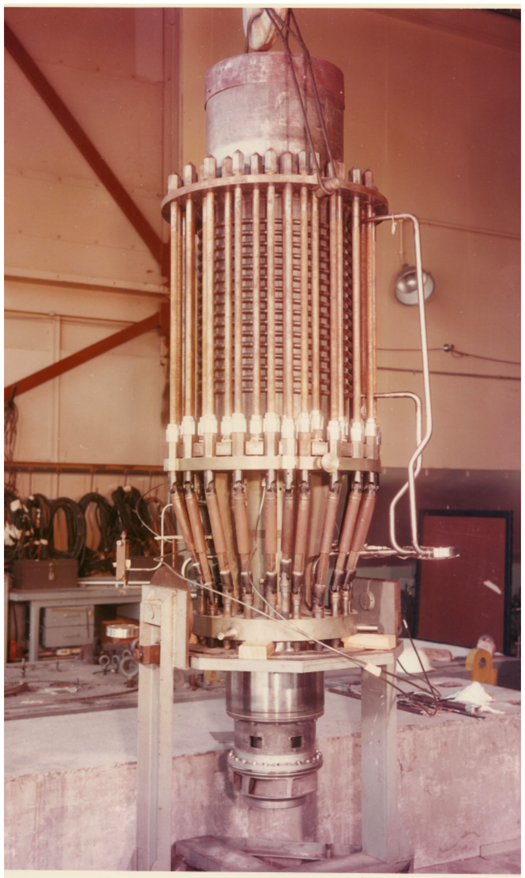
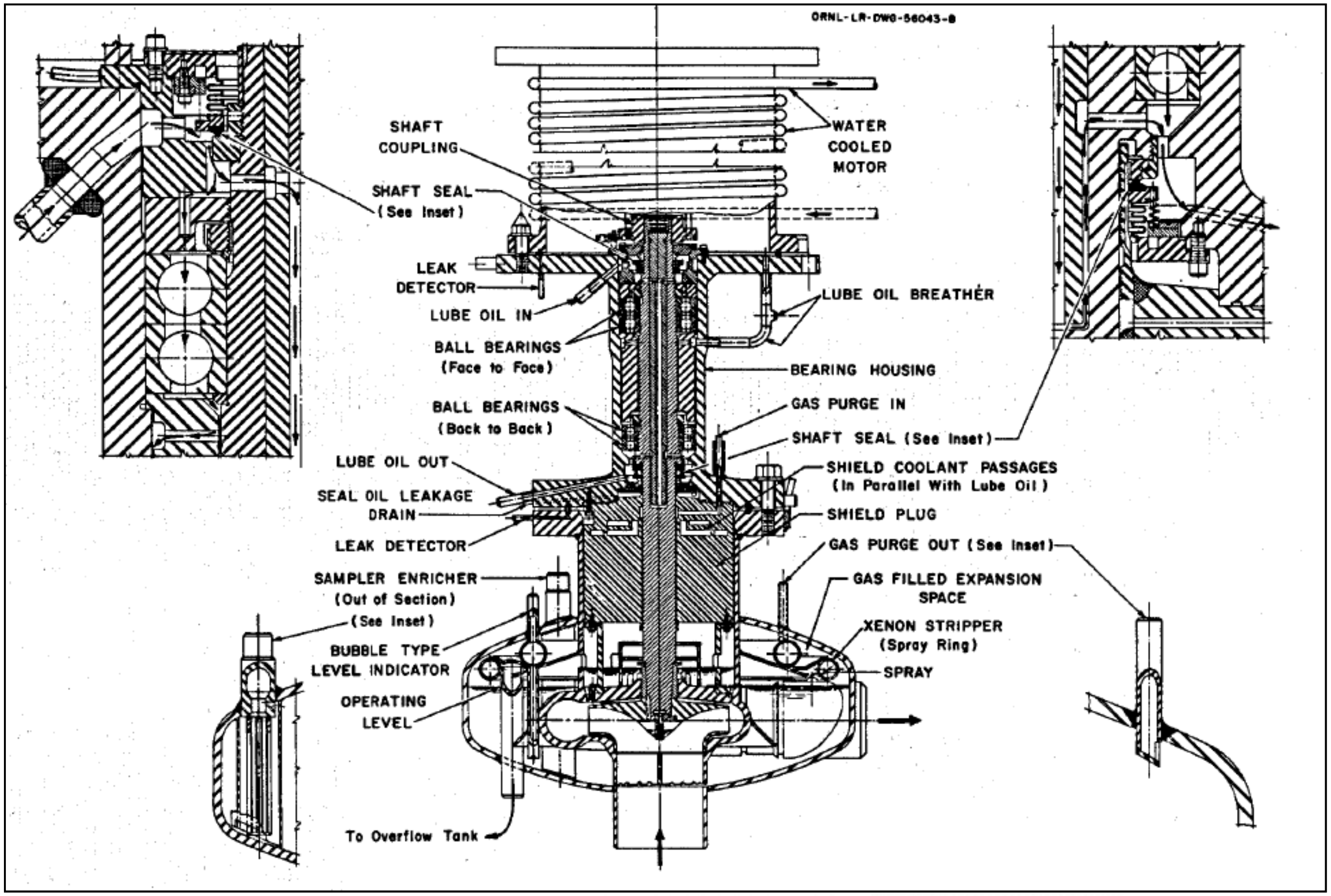
# MSRE Fuel Pump Operated with Some Issues





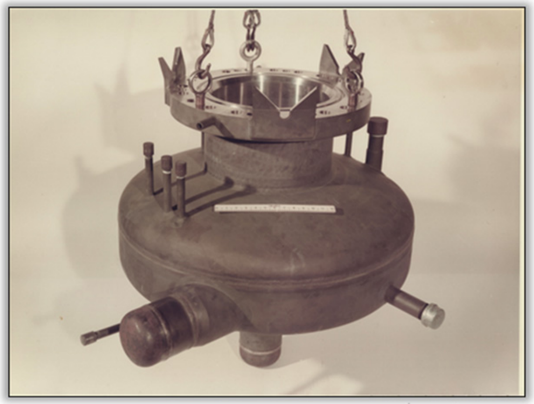

- 75 hp water-cooled electric motor, 480 Vac
- 1200 gpm
- Sampling and fuel addition possible through bowl
- Bowl: 36 in. diameter; 15 in. high
- Pump and motor: 8.6 ft high
- 21,788 cumulative hours operating at temperature
- Experienced lubricating oil leaks and offgas line plugging

Sources:
ORNL-TM-728
ORNL-TM-2987

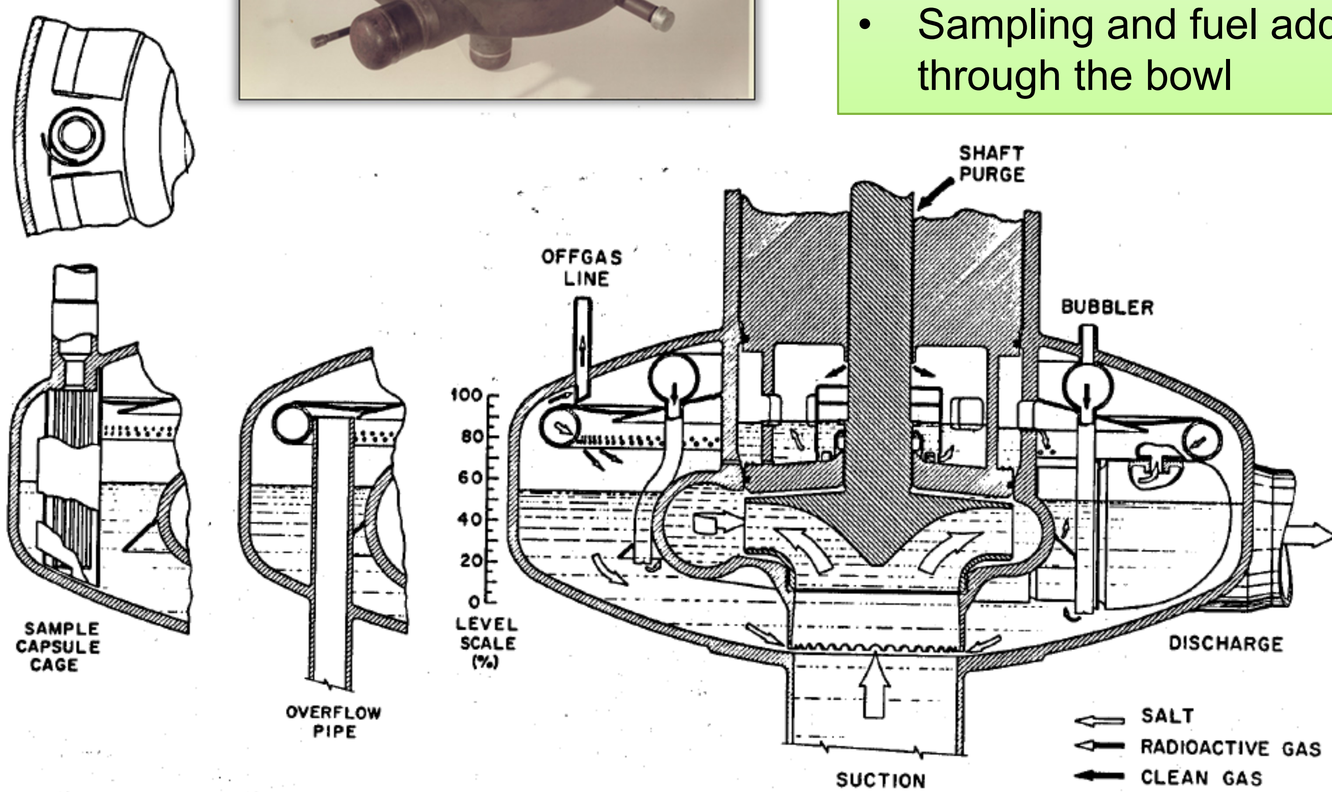
# Modern MSR Pumps May Incorporate These Features

- Long shaft versus short shaft
  - Reduces issues associated with high radiation fields and high temperatures on pump motors and motor maintenance activities
- Possible use of a flywheel
  - Enhances longer coast down of the pumps for loss of power events
- Modern bearings
- Gas seals
  - Address issues associated with lubricating oil leaks and associated plugging

# The MSRE Pump Bowl Provides Multiple Functions



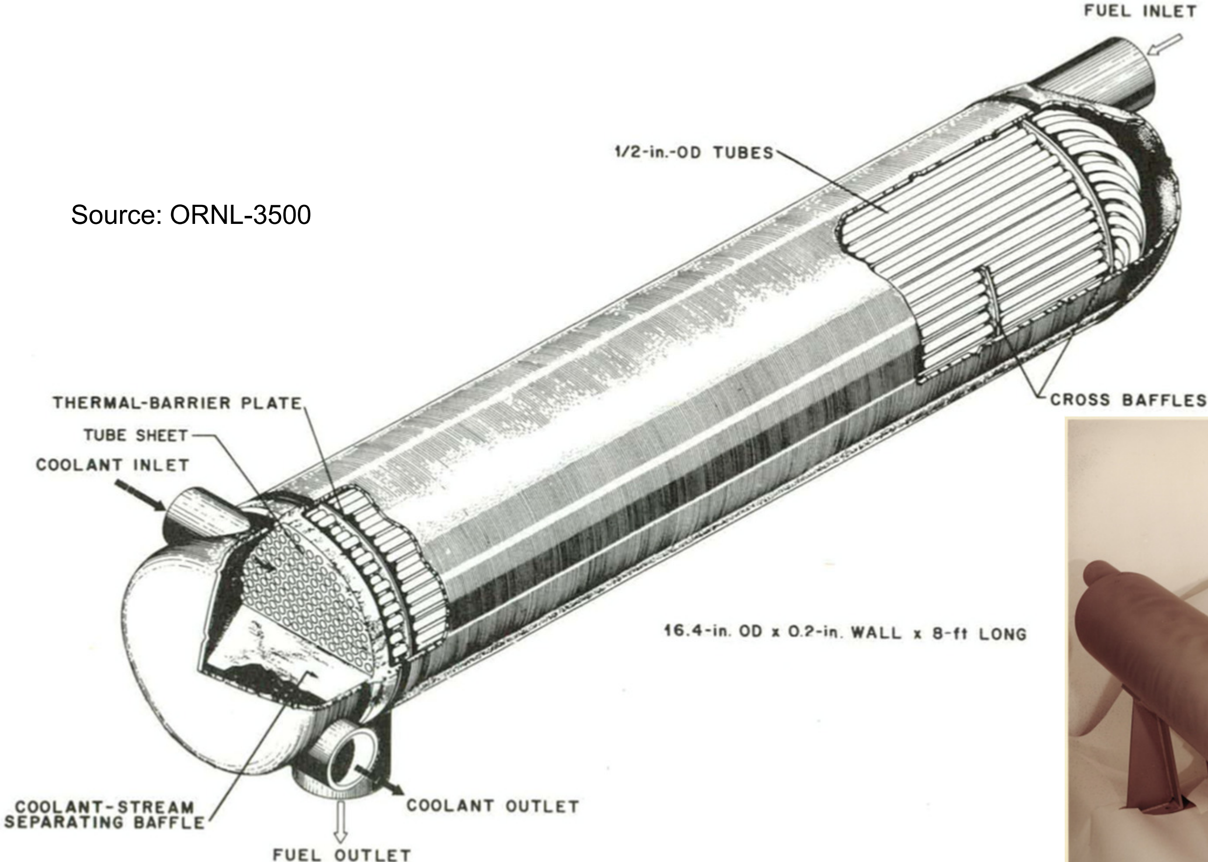
- Helium flows through the gas space in the bowl to sweep xenon and krypton to the offgas disposal system
  - Removes neutron poison and prevents bubbles from going through the core
  - Protects seal from fission gases, salt mist, and tritium
- Sampling and fuel addition are possible through the bowl

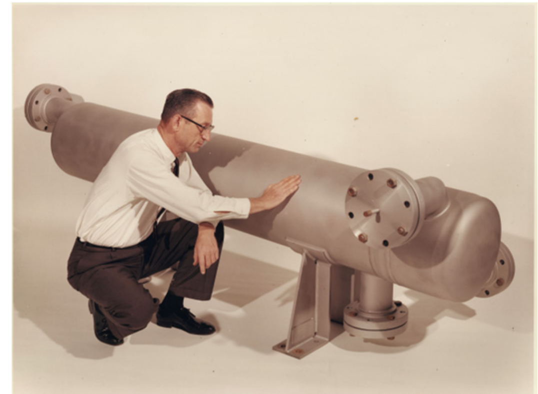



Source: ORNL-TM-3039

# Fuel Pump Discharges to MSRE Heat Exchanger

Source: ORNL-3500



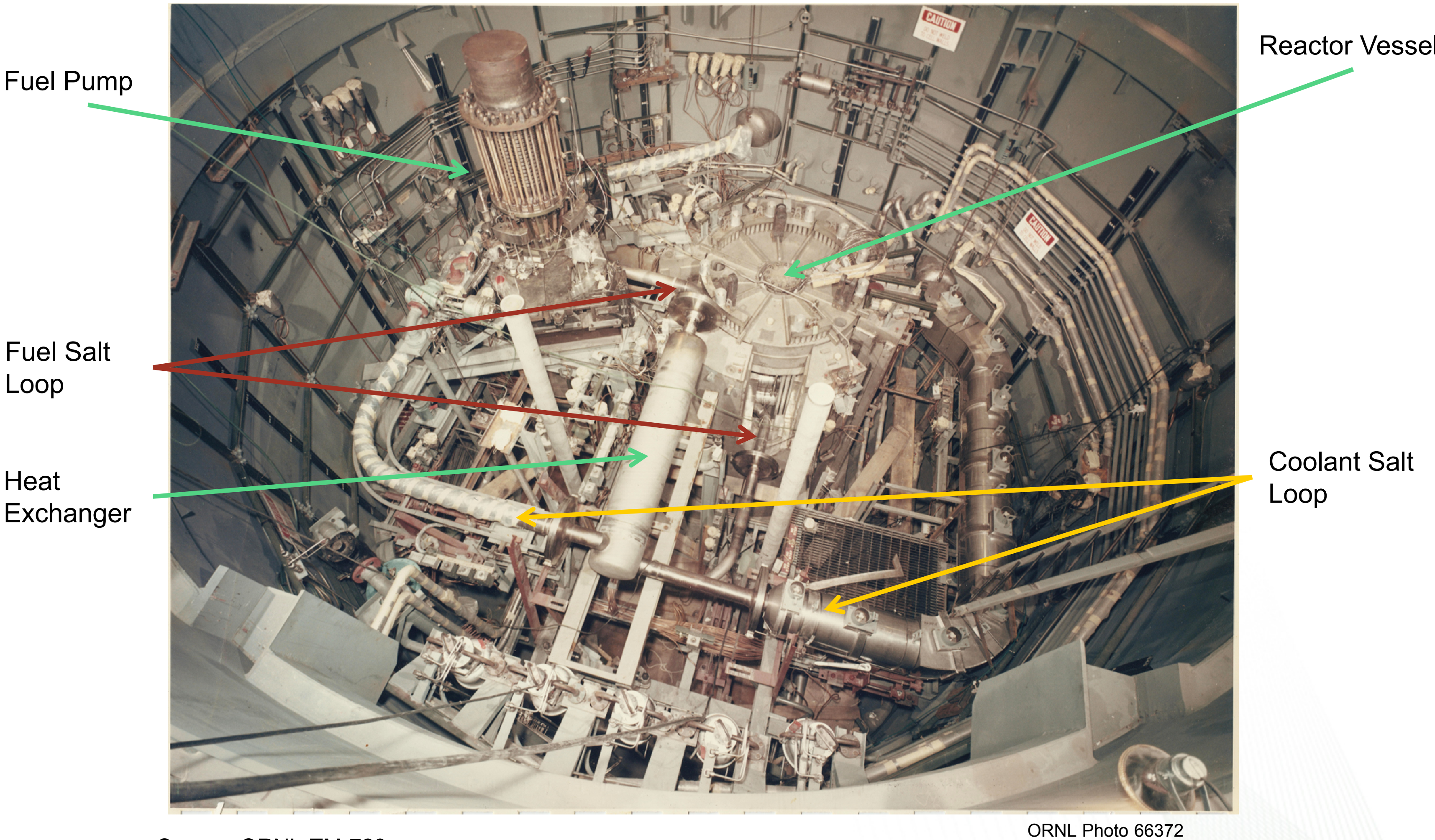



- Horizontal, shell and U-tube
- Fuel salt circulating in the shell
- Shell has ~16 in. OD and is about 8 ft 3 in. long
- Fuel salt connected by 5 in. pipe

# Modern MSR Will Likely Use Most Recent HX Technology

- MSR HX designs may incorporate
  - Twisted tubes and more complex structures to reduce or eliminate tube vibration
  - Compact and diffusion bonded heat exchangers to address challenges with fabrication
- Natural draft heat exchangers need to be designed/tested to use in DRACS loops for those MSR designs that propose this method of decay heat removal

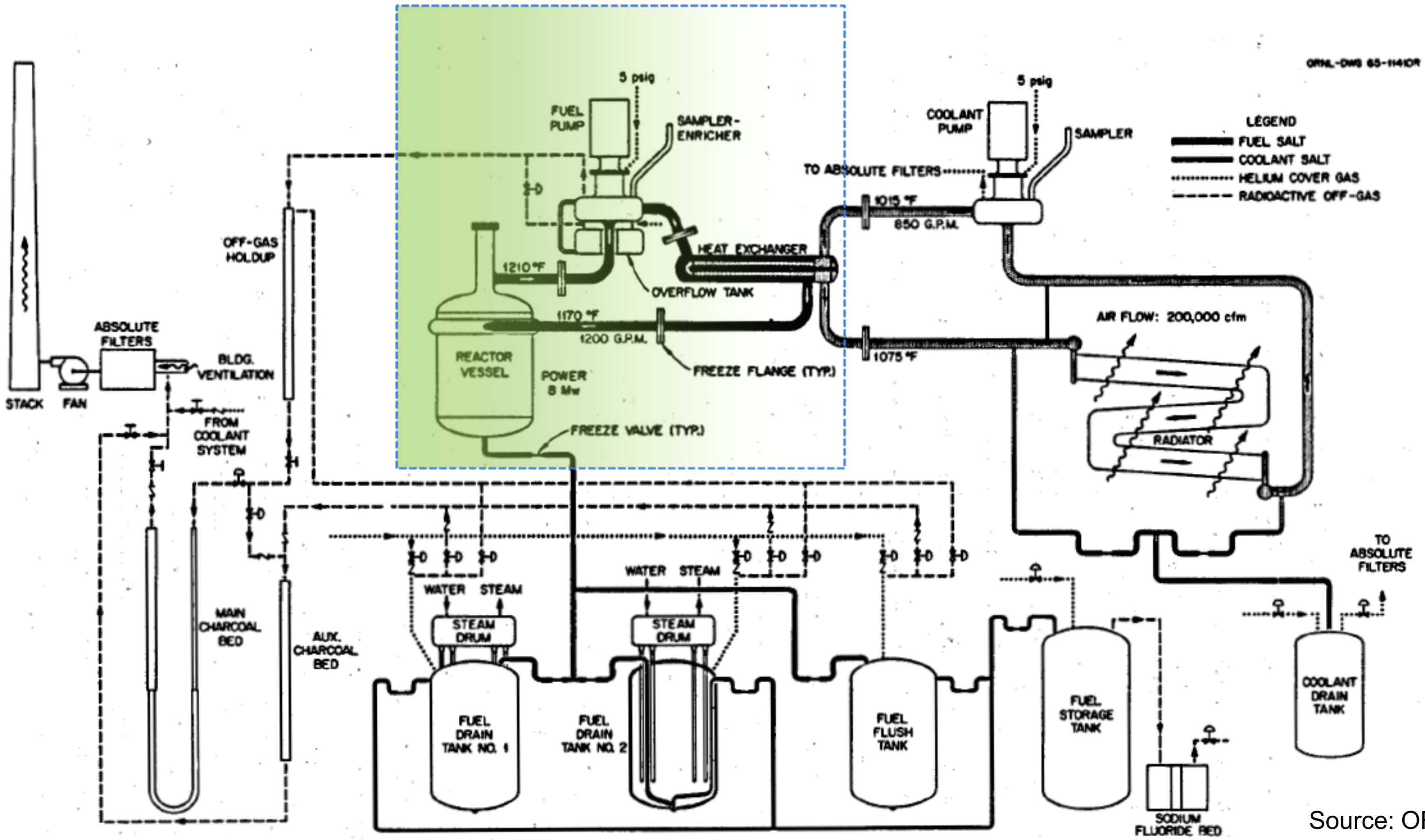
# MSRE Reactor Cavity from Above




Source: ORNL-TM-728

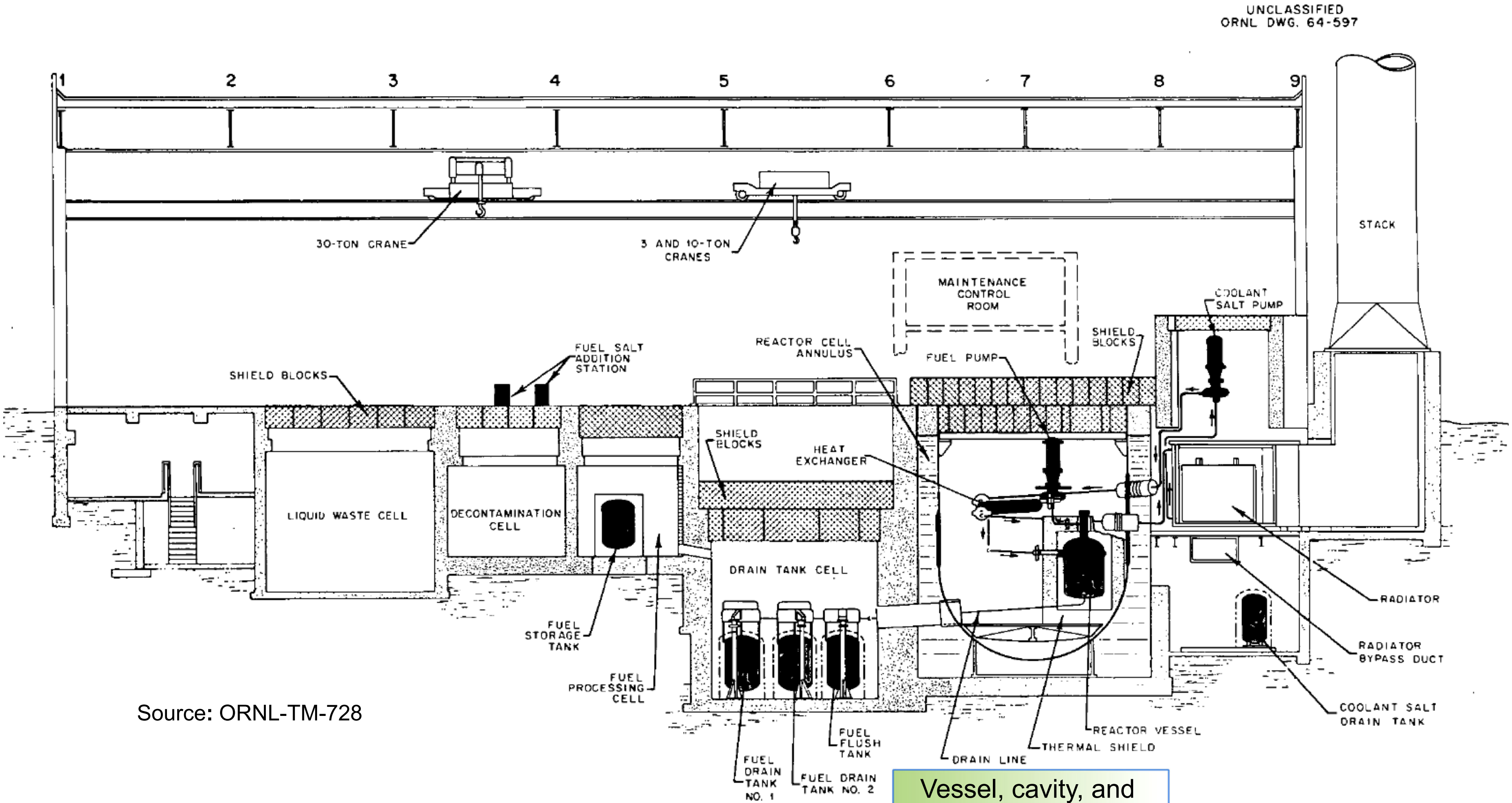
# MSRE Simple Piping Diagram with Fuel Salt Loop Components Highlighted

Fuel Salt System




Source: ORNL-TM-3039

# MSRE Elevation Diagram Showing the Vessel, Cavity, and Fuel Salt System

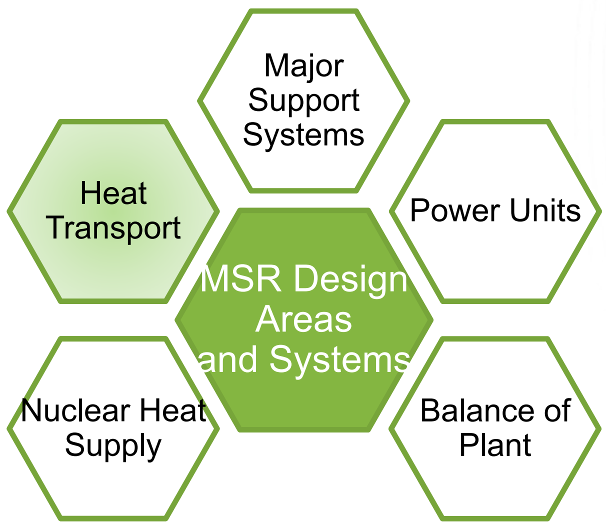



Source: ORNL-TM-728

Vessel, cavity, and fuel salt system

# Heat Transport

- Coolant Salt Loop

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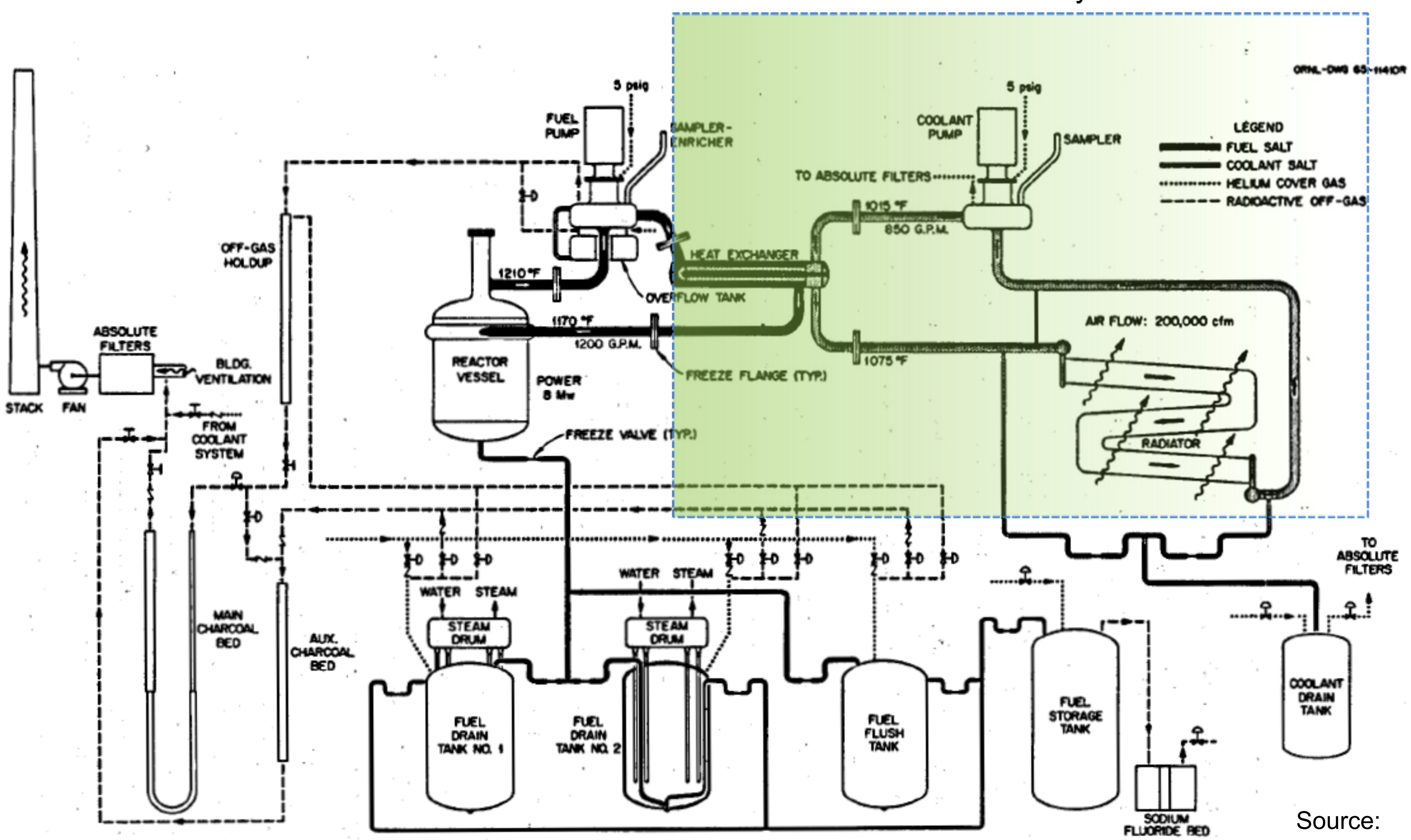
# MSRE Simple Piping Diagram with Coolant Salt Loop Components Highlighted



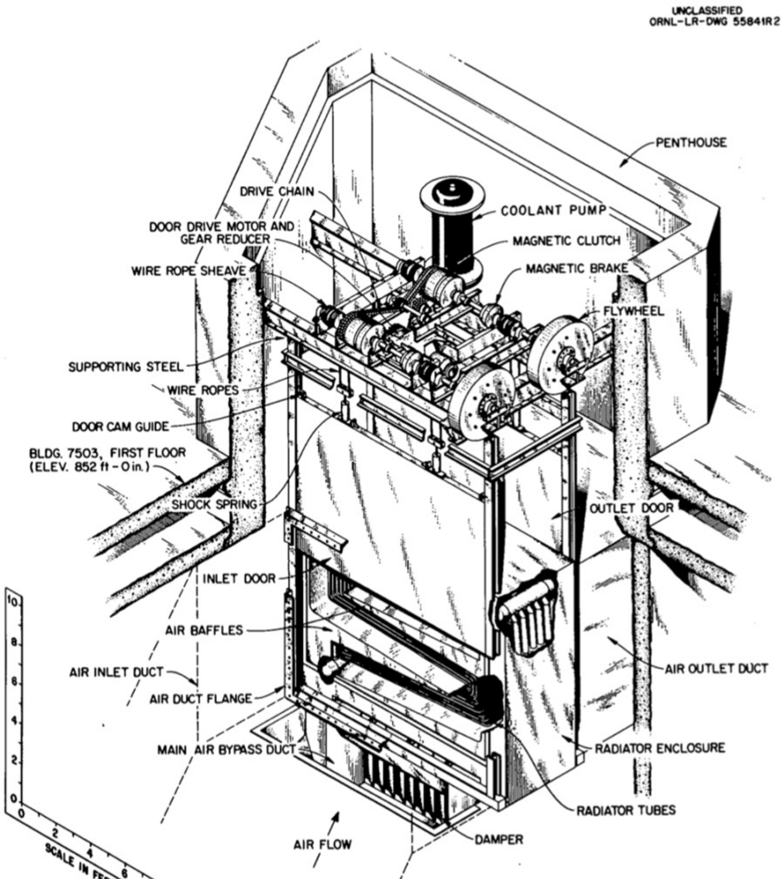

Source: ORNL-TM-3039

# MSRE Coolant Salt Loop Characteristics

- 5 in. piping
  - Compatible salt without fissile material
- 75 hp coolant-salt circulating pump (similar to the fuel pump)
- Fuel-salt heat exchanger (coolant salt in tube side)

Source:
**ORNL-TM-728**

# MSRE Heat Rejected to Atmosphere




MSRE Radiator

Source:
ORNL-TM-728

## Air-cooled Radiator

- 120 tubes
- 700 ft$^2$ cooling surface
- Air flow provided by 2 blowers
- Quick-closing doors guard against coolant salt freeze

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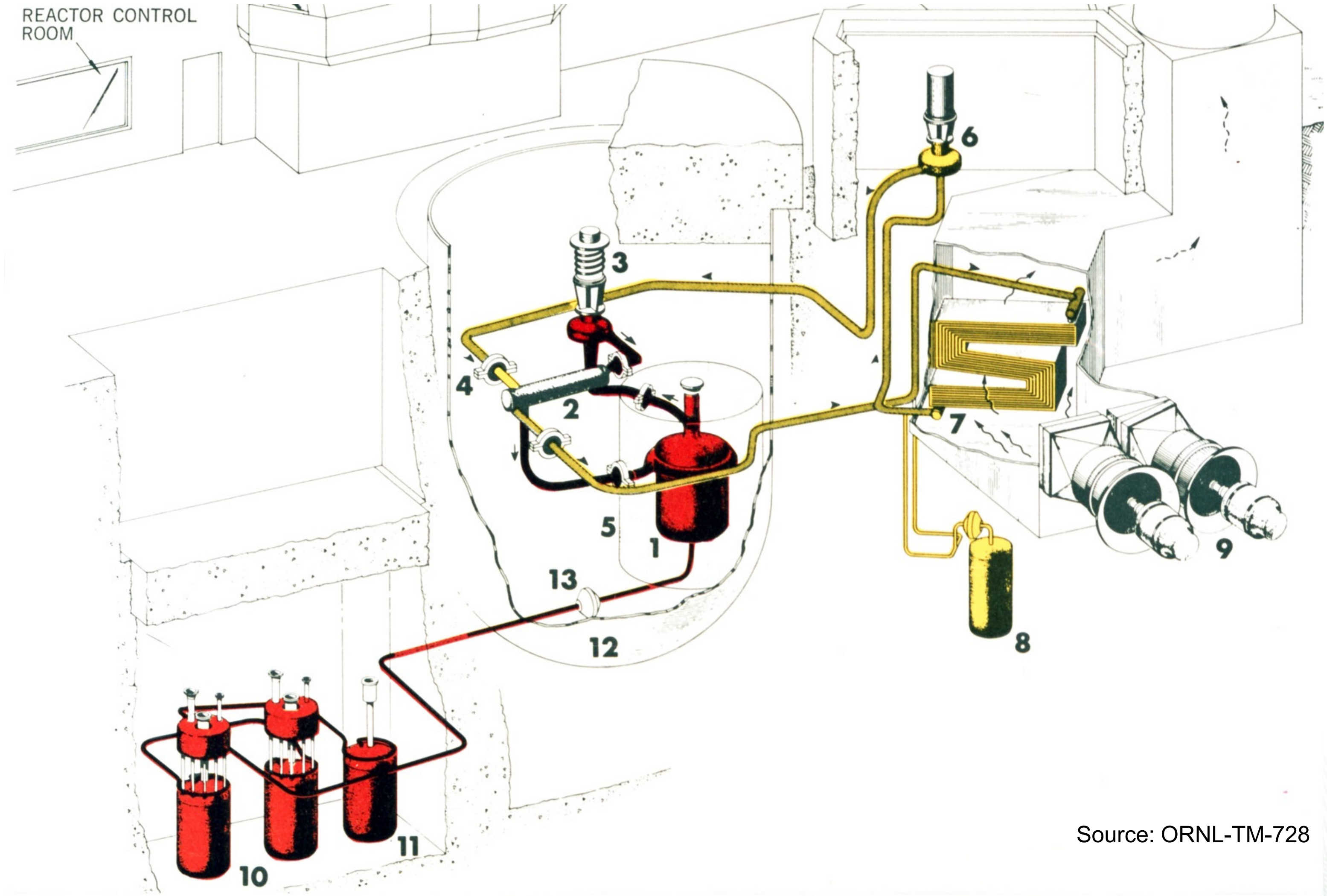
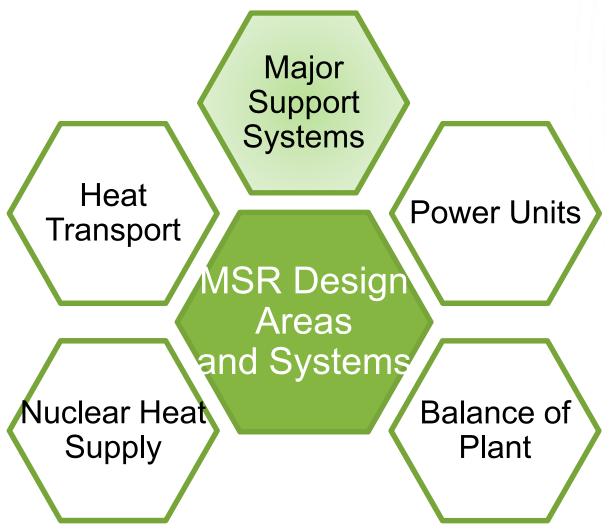
# MSRE Elevation Diagram Focusing on the Coolant Salt Loop and Radiator



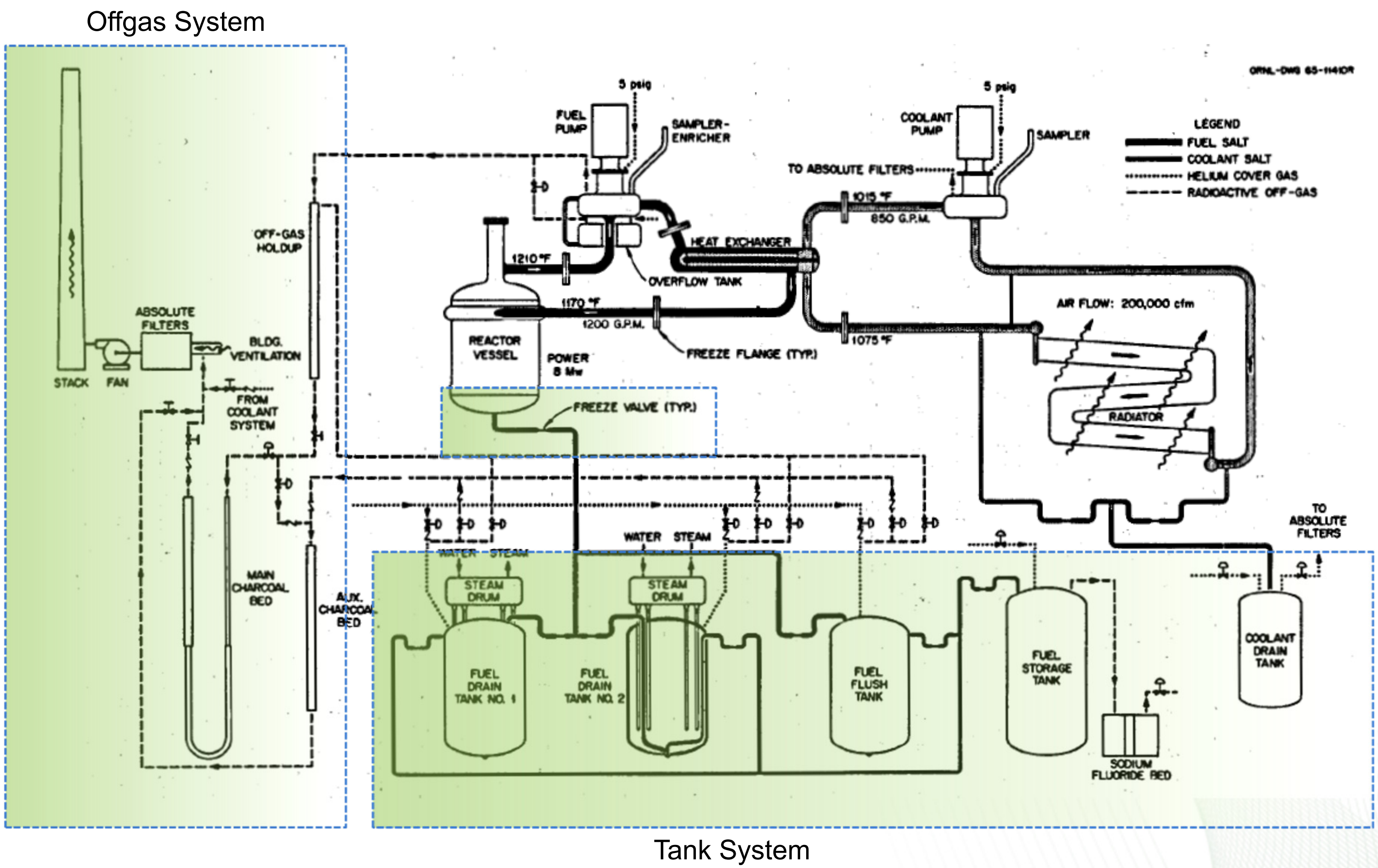

Source: ORNL-TM-728

# Major Support Systems

- Salt chemistry and inventory control
- Cover gas chemistry and inventory control
- Fuel processing
- Instrumentation and controls
- Other systems

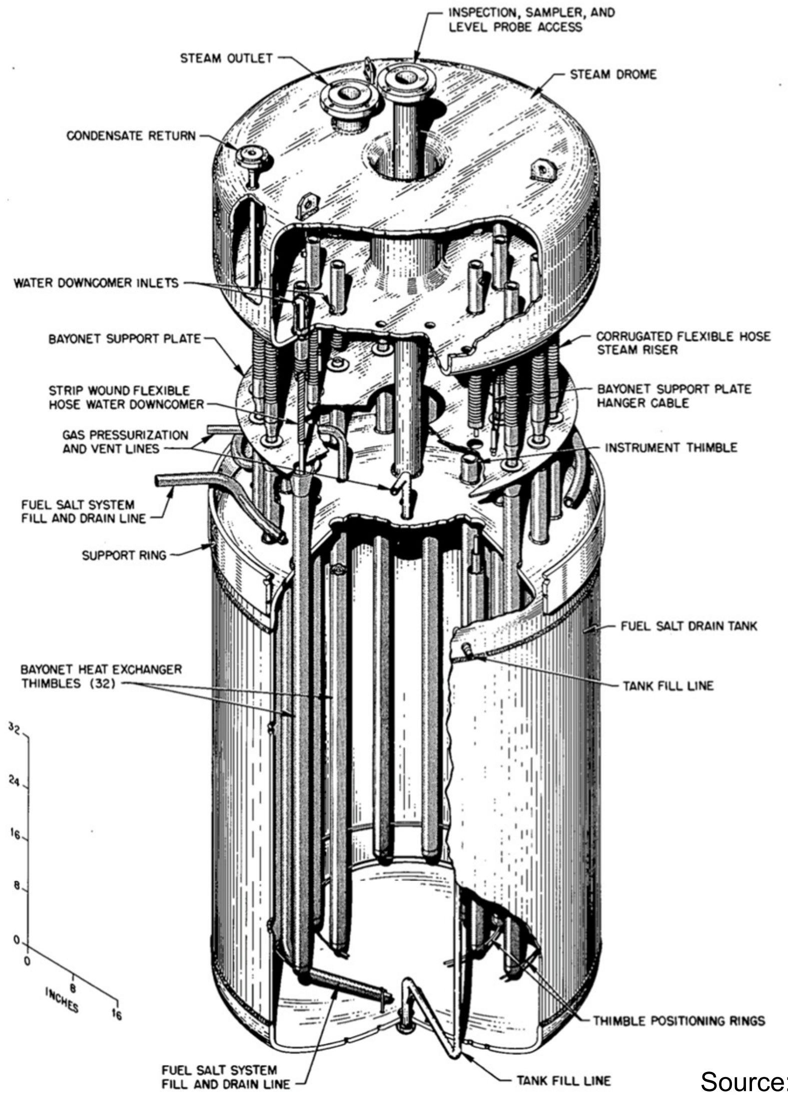


# MSRE Simple Piping Diagram with Fuel Salt Loop Support Components Highlighted




Source: ORNL-TM-3039

# MSRE Salt Drain Tank System (fuel-salt drain tank shown)




- Four tanks are provided for safe storage of the salt mixtures
  - There is also a fifth fuel storage and reprocessing tank
- Two fuel-salt drain tanks
  - One tank can hold all the fuel salt in the fuel circulating system in a noncritical configuration
  - Safety system
- One flush-salt tank
  - No fissile material
  - Used to wash fuel circulating system
- One coolant-salt tank
  - Holds coolant salt

Source: ORNL-TM-728

# MSRE Drain Tank Decay Heat Removal System

- Decay heat removed by boiling water in bayonet tubes in the fuel-salt drain tanks
- Water and steam separated in a steam drum
  - Steam condensed in an air-cooled condenser and gravity fed back to drain tanks
  - Feedwater tank holds additional cooling water

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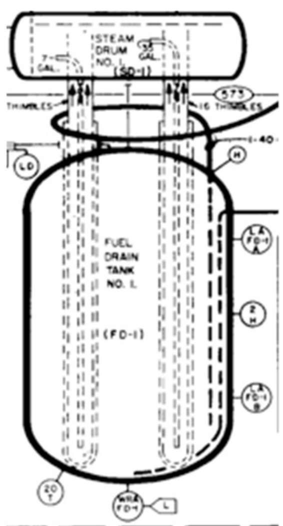
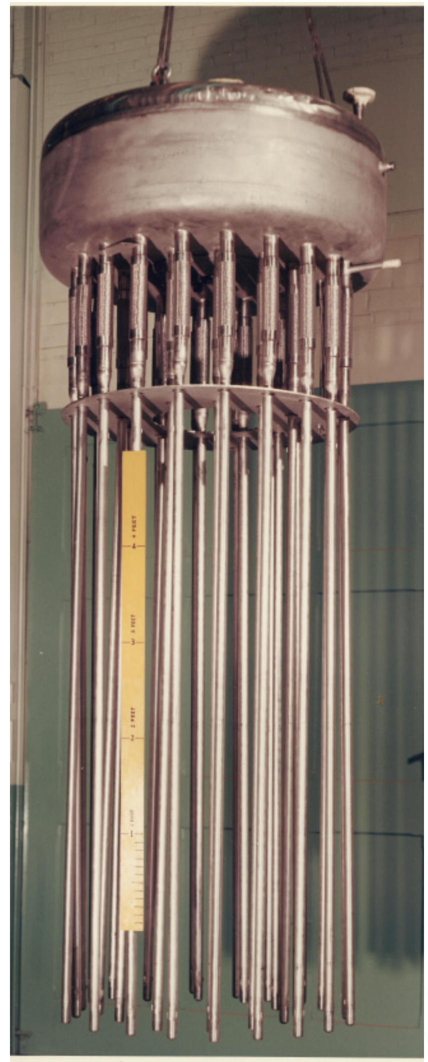
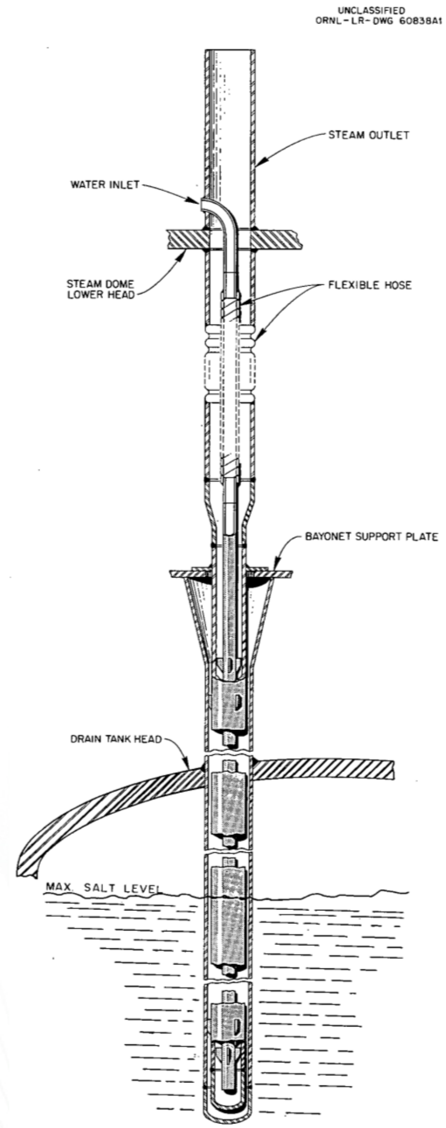


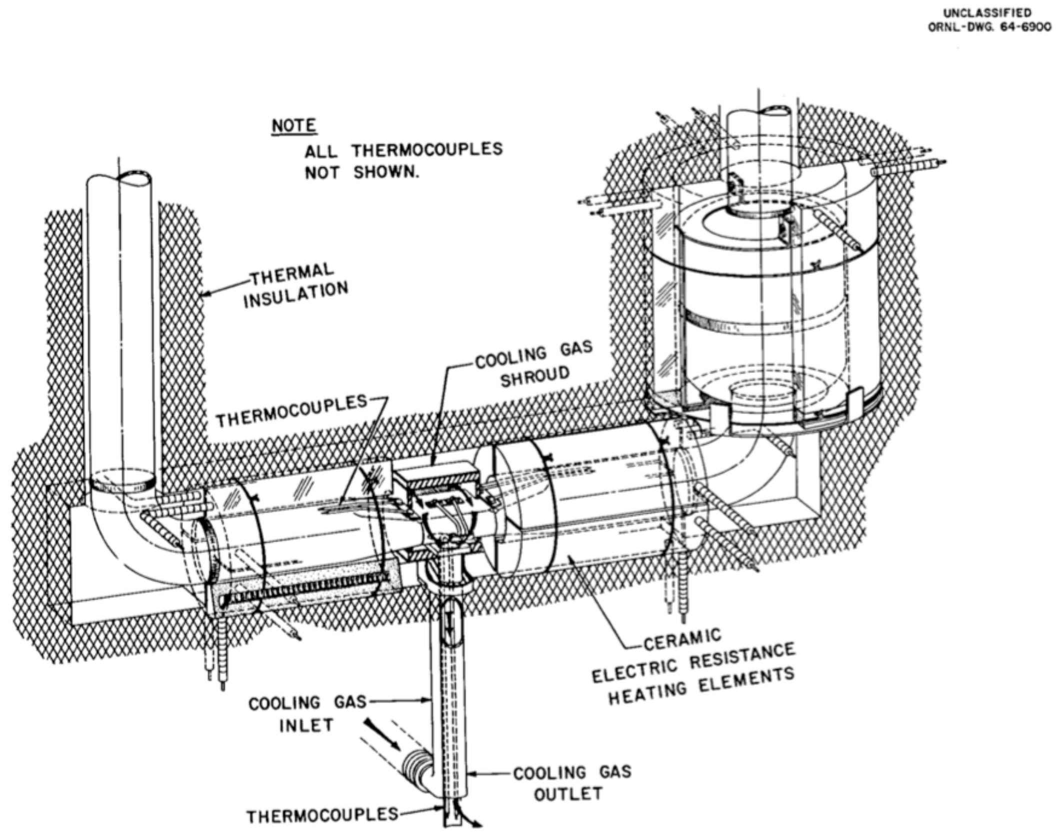






Source: ORNL-TM-728

# MSRE Freeze Valves Control Flow to the Various Drain Tanks

- Flow of salt in the drain, fill, and processing systems is controlled by freezing or thawing a short plug of salt
  - Reliable in molten salt service at time of MSRE design
- 1.5 in. drain line flattened for a length of ~ 2 in. in a horizontal plane
- Frozen by cooling gas system
  - 1500 W heater saddled over pipe section controls cooling rate

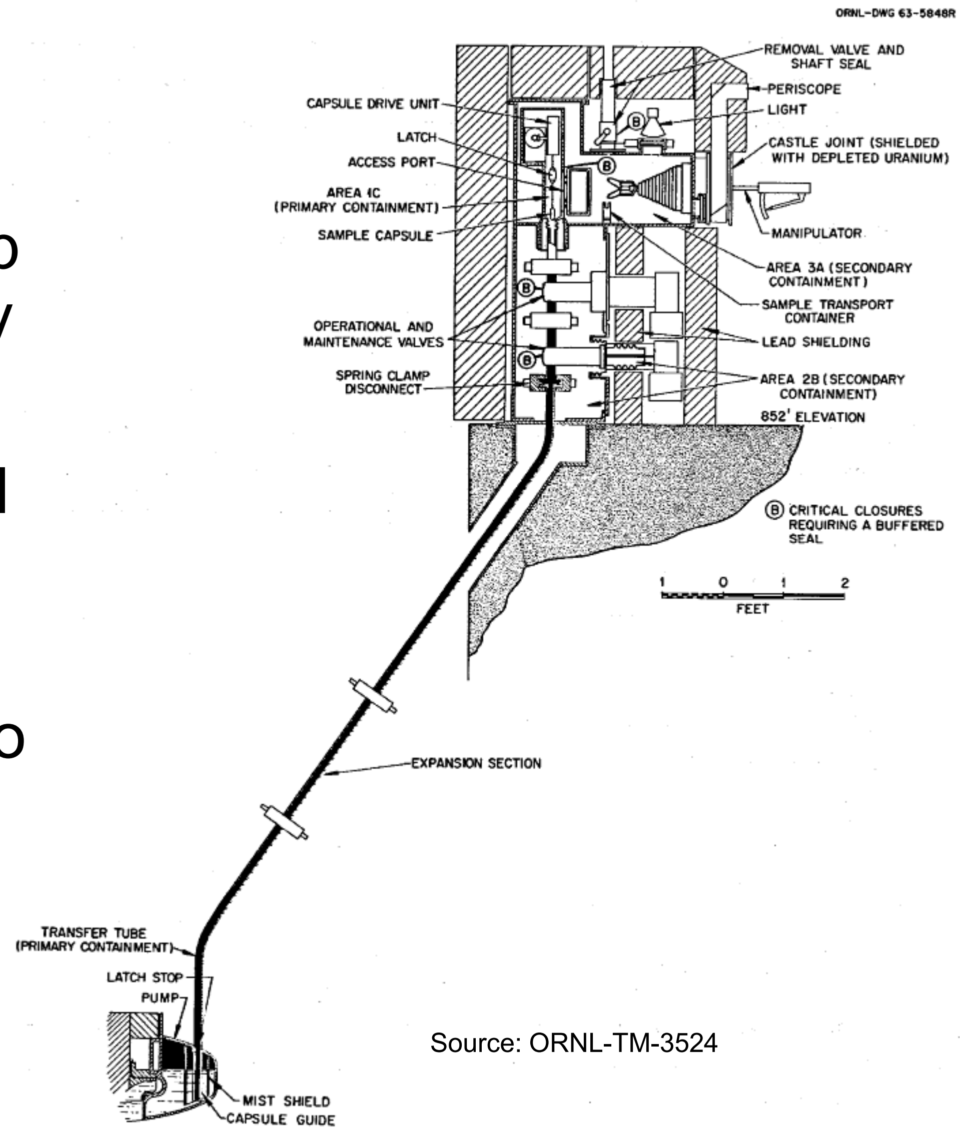



Source: ORNL-TM-728

# MSRE Sampler-Enricher System

## Sample salt or add fuel

- Samples drawn from pump bowl to 2-compartment dry box through transfer tube
- 10 gram sample evaluated in chemistry lab
- Salt enriched by adding $UF_4$-LiF from the dry box to fuel pump bowl




Source: ORNL-TM-3524

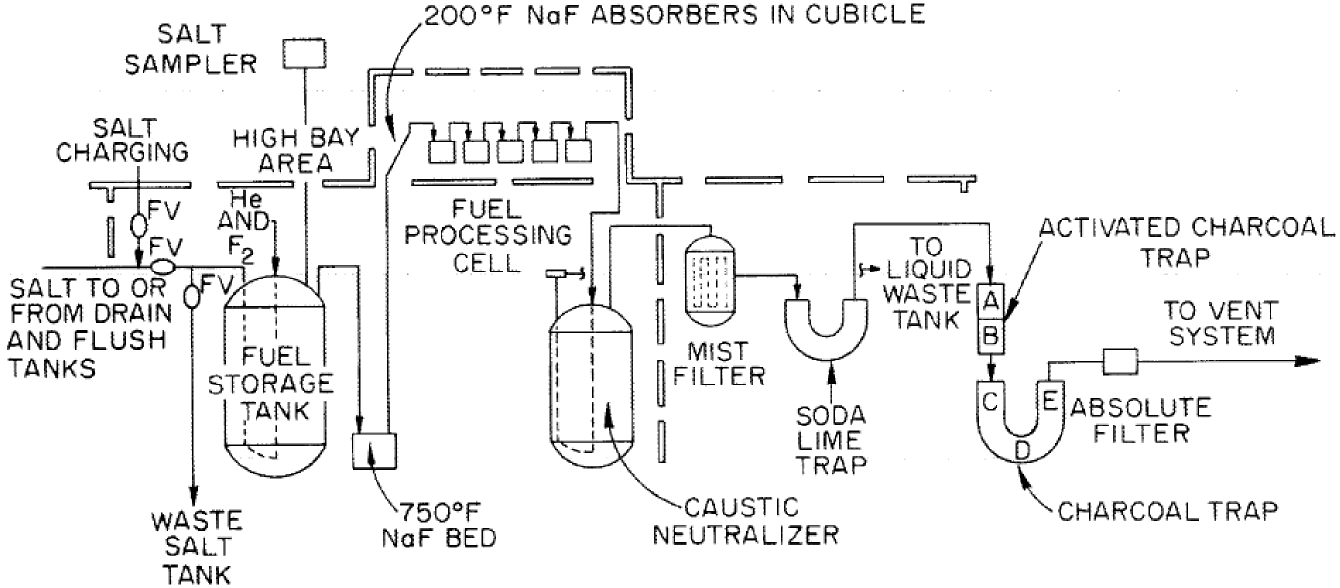
# MSRE Chemistry Control

- During operation, samples of reactor salts removed routinely and analyzed for:
  - Major constituents
  - Corrosion products
  - Oxide contamination
- No perceptible composition changes over first 20 months of MSRE operation
- Beryllium metal added through pump bowl to control $U^{4+}$ to $U^{3+}$ ratio to help control corrosion
- Helium introduced to pump bowl ~ 4 L/min to strip Kr and Xe from the fuel

Source: ORNL-TM-1853

# MSRE Fuel Processing System (off-line process)

ORNL-DWG 68-8994




Source: ORNL-TM-2578

- Molten salt from drain tank
- Salt sparged with pure fluorine or fluorine-helium mixture to convert $UF_4$ to $UF_6$
- $UF_6$ collected on NaF absorbers
- Remaining gas stream treated such that only helium and oxygen released to the vent system
- Additional treatment allowed the salt in the fuel storage tank to be returned to the reactor system



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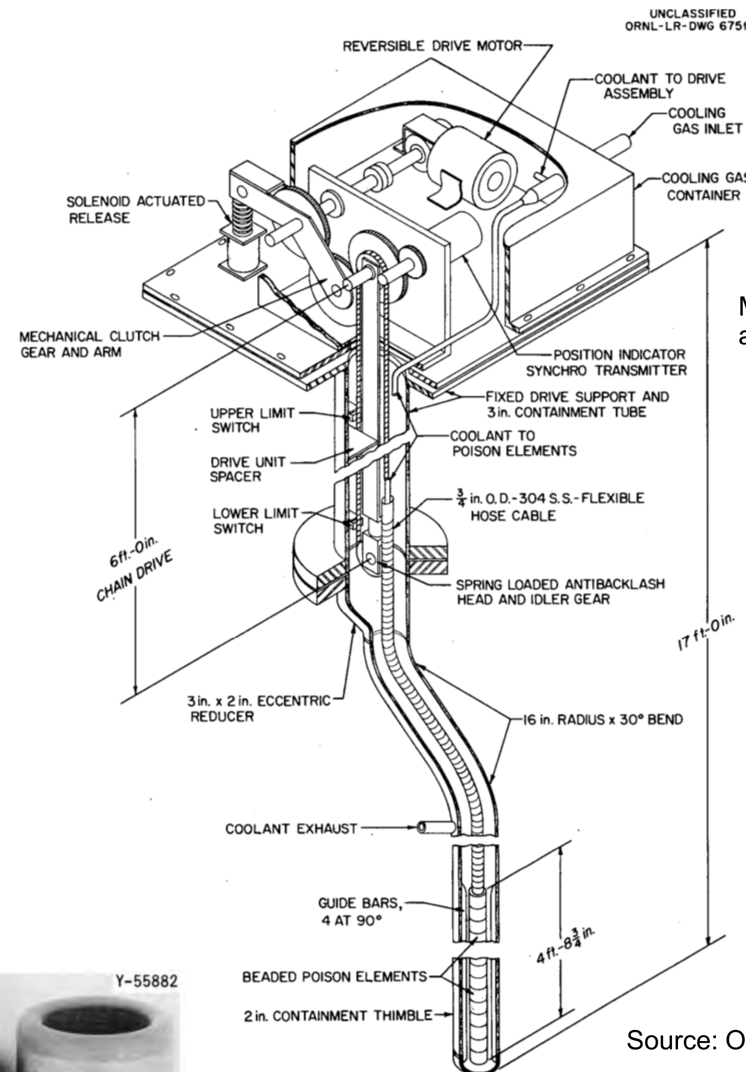
# MSRE Reactivity Control System

- 3 control rods provide adjustment for reactivity
  - Rod worth 5.6-7.6% Δk/k (3 rods)
  - Control flux at low power
  - Dampen temperature swings at power
  - Not required for fast-acting, nuclear safety purposes
- Complete reactor shutdown accomplished by draining fuel salt
- Power level determined by coolant loop ΔT (via radiator blower) and flow



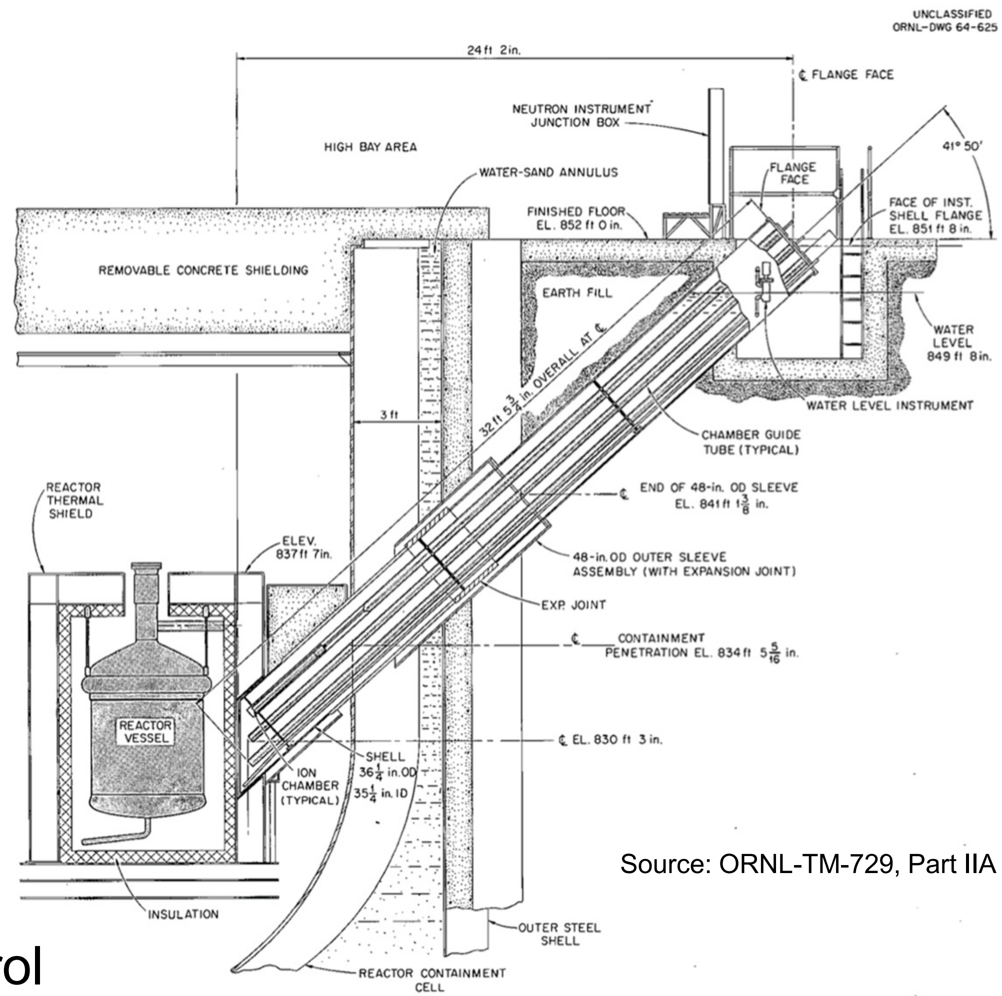

MSRE Control Rod and Drive Assembly

Source: ORNL-TM-728

MSRE Control Elements
Source: ORNL-4123

# MSRE Nuclear Instrumentation

- Employs principles of separation, protection, and independence for safety systems
- $BF_3$ source range monitor
- Wide range monitor
- Power range monitor
- Rod scram safety channels
  - High flux
  - Short reactor period
  - High outlet temperature
  - 3 channels, 2x3 logic
- Shim and regulating rod control system (non-safety)




Source: ORNL-TM-729, Part IIA

Fig. 2.1.2 MSRE Elevation View of Nuclear Instrument Penetration

# Other MSRE Support Systems

- Heaters
  - All salt-containing systems are heated to maintain MSRE salts above melting temperature at 840 to 850ºF (~450-455ºC)
    - Maintains convection heat transfer and promotes mixing thus avoiding hot spots
  - Total capacity 1930 kW – about double required capacity
    - Diesel generators can provide ~ 300 kW heating capacity
- Cover and offgas systems
  - Helium cover-gas system
    - Protects the oxygen-sensitive fuel from air or moisture
    - Passed through fuel pump bowl to sweep fission product gases
    - Hot helium used to keep drain tank system hot prior to salt dump
  - Offgas system
    - Pump bowl, salt transfer operations, purge flow from cells
    - Holdup volume to allow for decay
    - Charcoal adsorber beds
    - Stack

Source: ORNL/TM-2009/297



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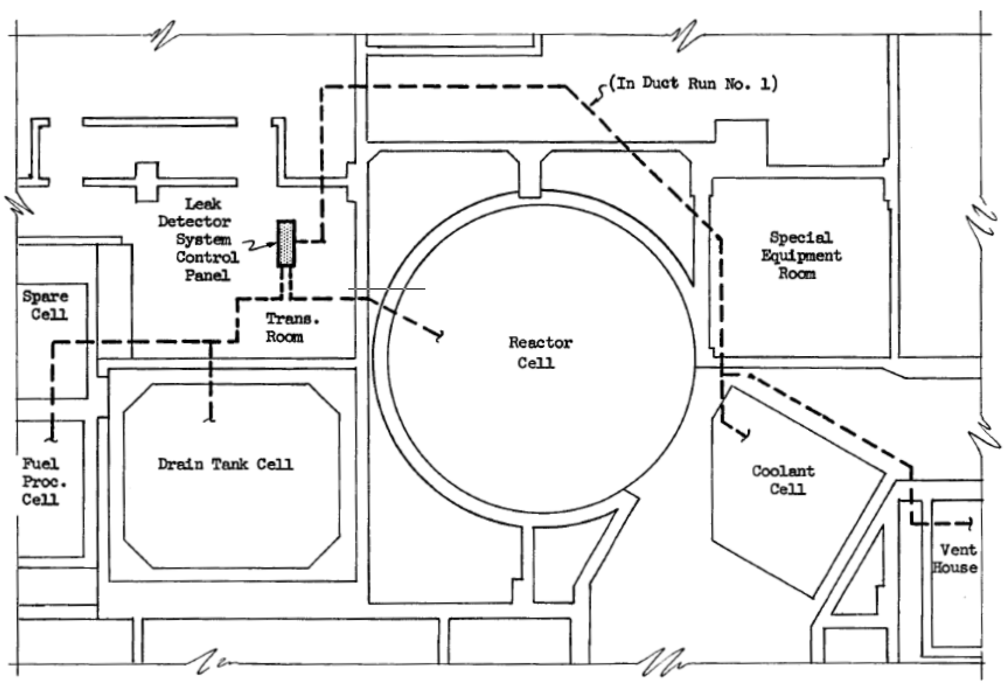
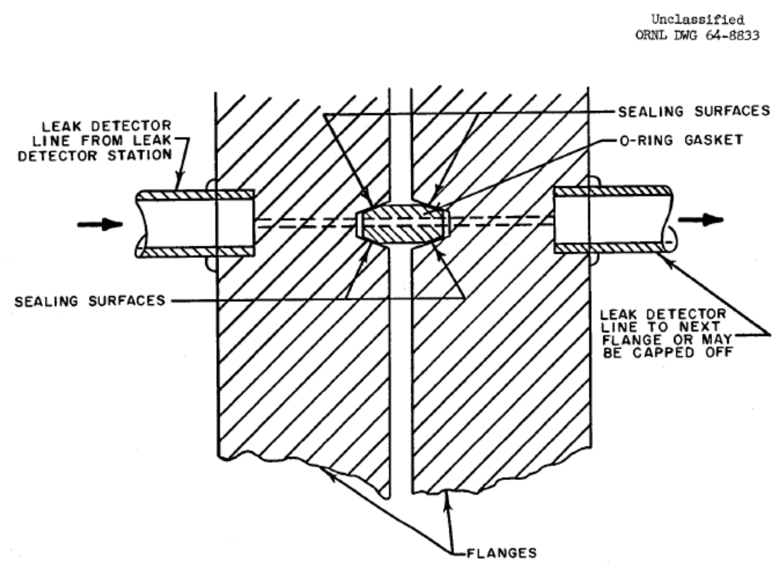
# Other MSRE Support Systems (cont.)

- Leak detection system
  - Approximately 100 flanges with leak detection
    - 100 psig overpressure of helium on joints
    - Helium will flow out a leak triggering a low pressure alarm

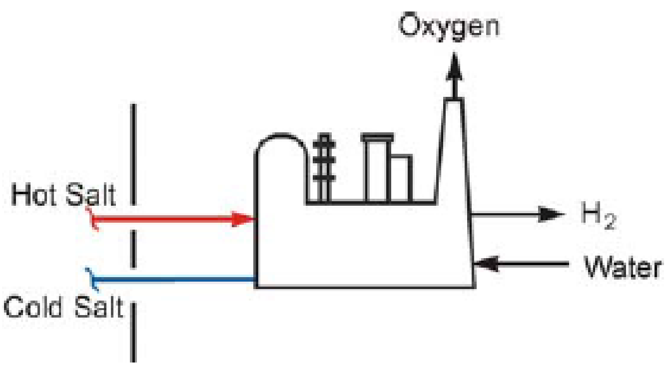


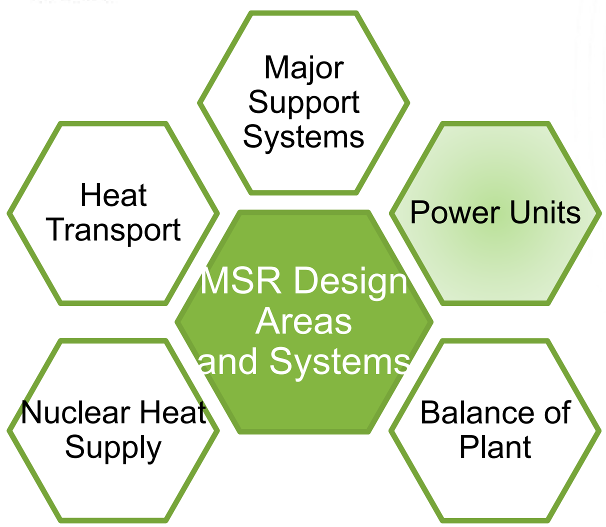




Source: ORNL-TM-728

# Power Units

- Power conversion
- Process heat

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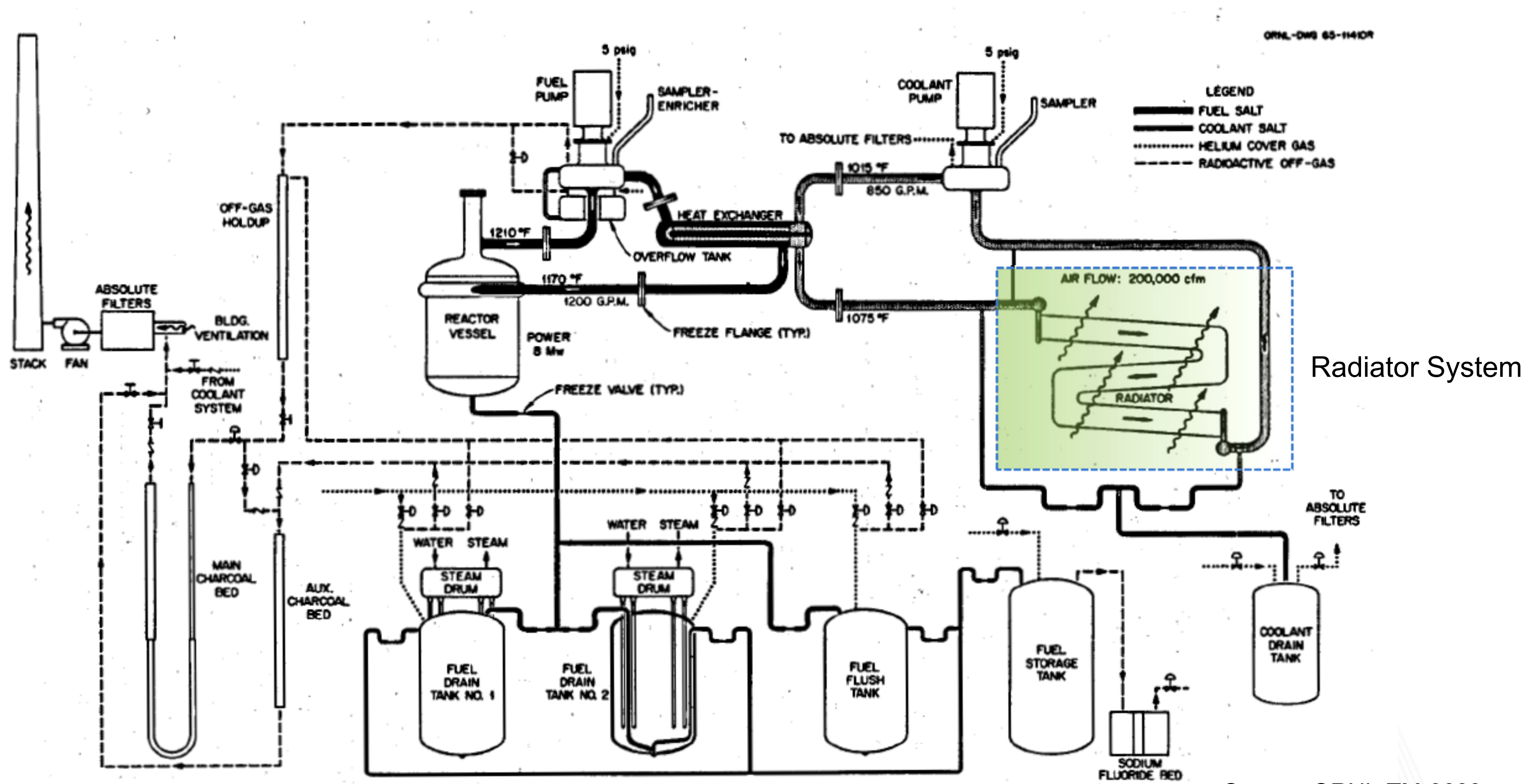
# The MSRE Did Not Demonstrate Power Conversion



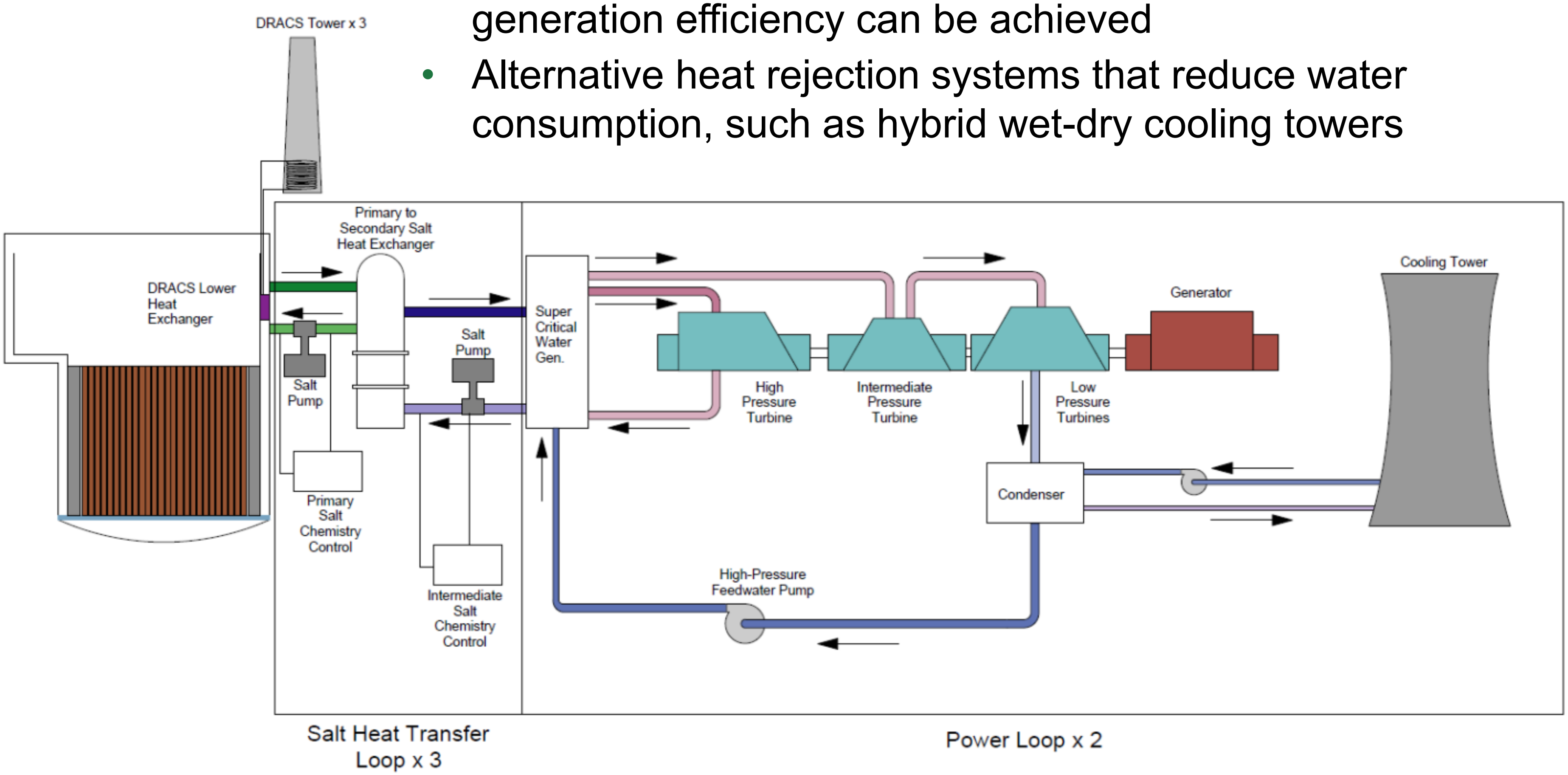

Source: ORNL-TM-3039

# Possible Secondary Systems

- Process heat
  - 600 to 700°C useful for desalination, hydrogen production, or other high temperature applications
- Rankine cycle
  - Water-based; base load efficiency of ~45%
- Closed gas cycle
- Brayton cycle
  - MSR coupled with a nuclear air–Brayton combined cycle (NACC) is projected to have a base load efficiency between 40% and 47%, which is significantly greater than the efficiencies of current nuclear power plants

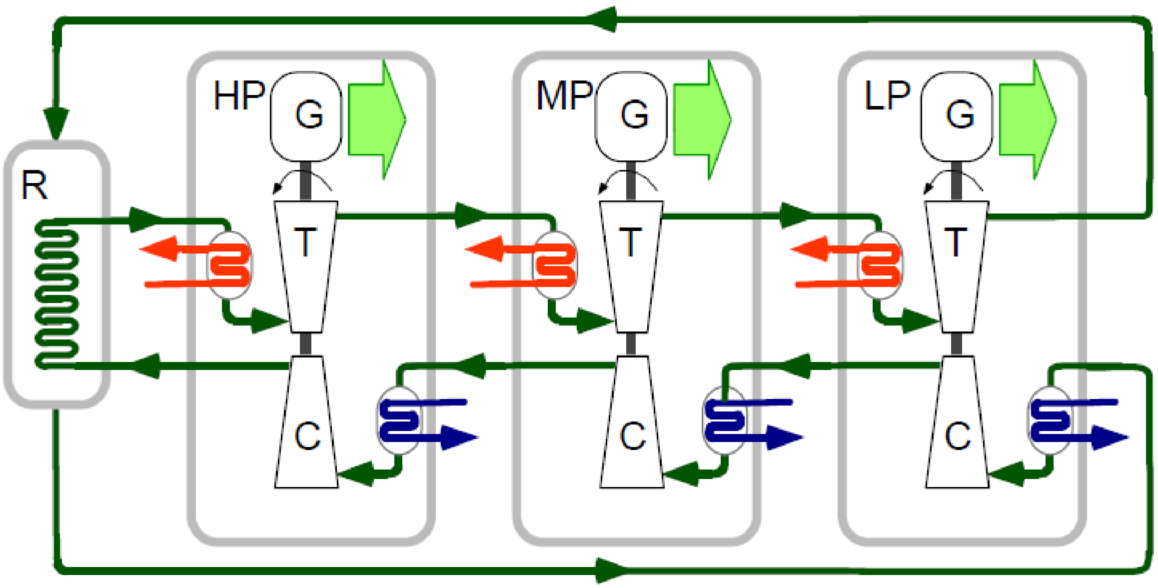
# Electric Power Generation Configuration

- Heat from the coolant salt cycle is used to produce supercritical and reheat steam in the power cycle
- With the high steam temperature, reasonable power generation efficiency can be achieved
- Alternative heat rejection systems that reduce water consumption, such as hybrid wet-dry cooling towers



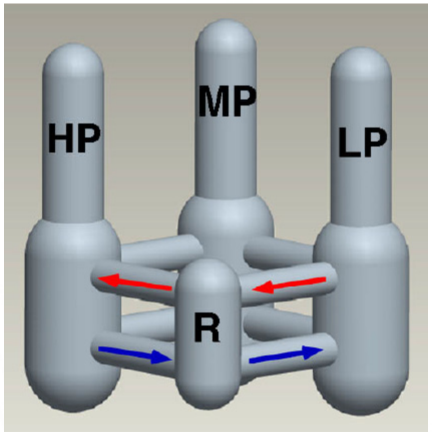

Source: ORNL/TM-2012/320

# Multistage Brayton Power System




**Red** – heat input from coolant loop molten salt
**Green** – gas in closed-cycle Brayton PCU
**Blue** – cooling water

- Compact design (smaller turbine building)
- High thermal efficiency
- Less cooling water required

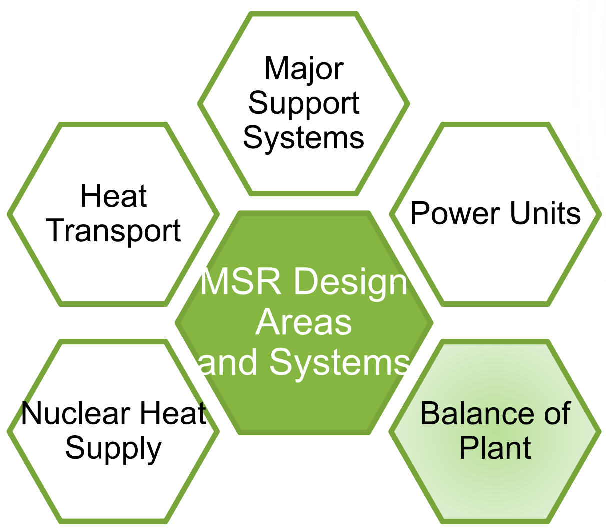



HP – high pressure power conversion unit (PCU)
MP – medium pressure PCU
LP – low pressure PCU
R – recuperator
G – generator
T – turbine
C – compressor

Source: ORNL/TM-2004/104

# Balance of Plant

- Control room
- AC/DC power and distribution
- Radioactive waste handling
- Fire protection
- External event mitigation
- Component cooling systems
- HVAC

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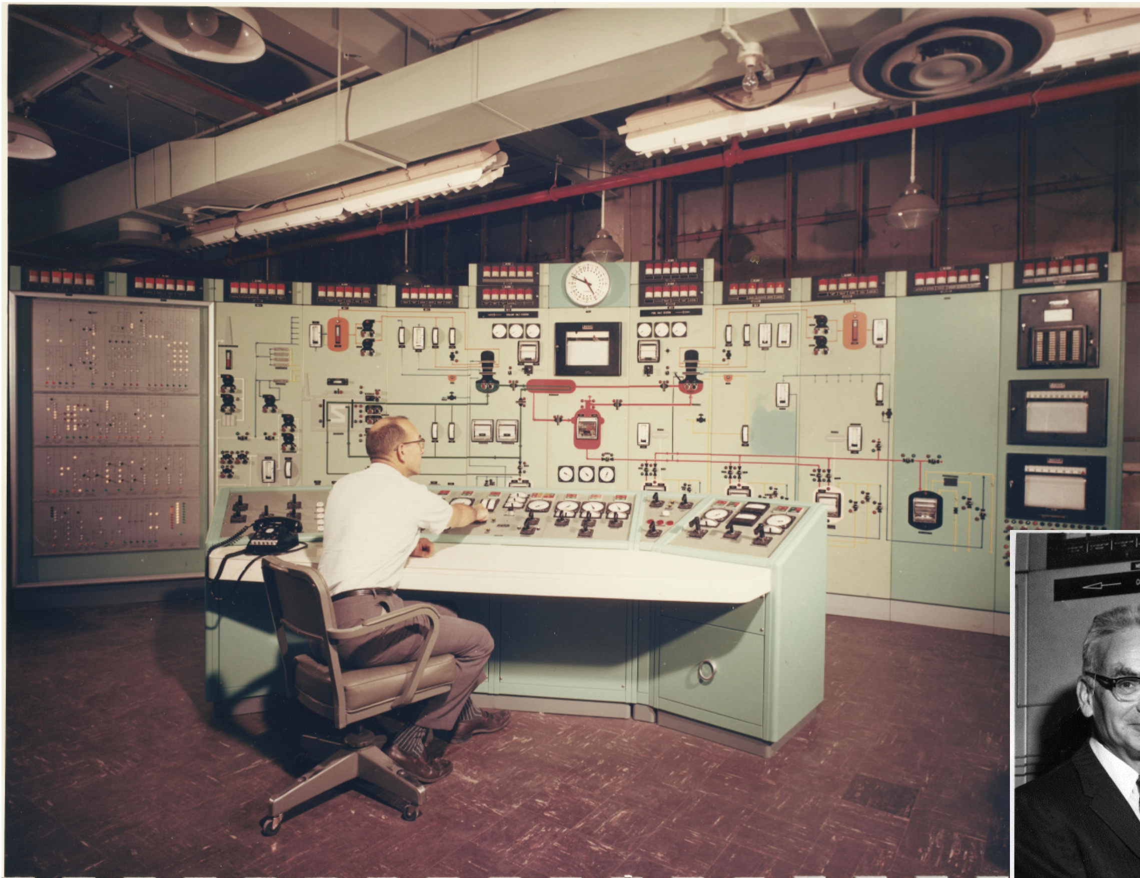
# MSRE Control Room



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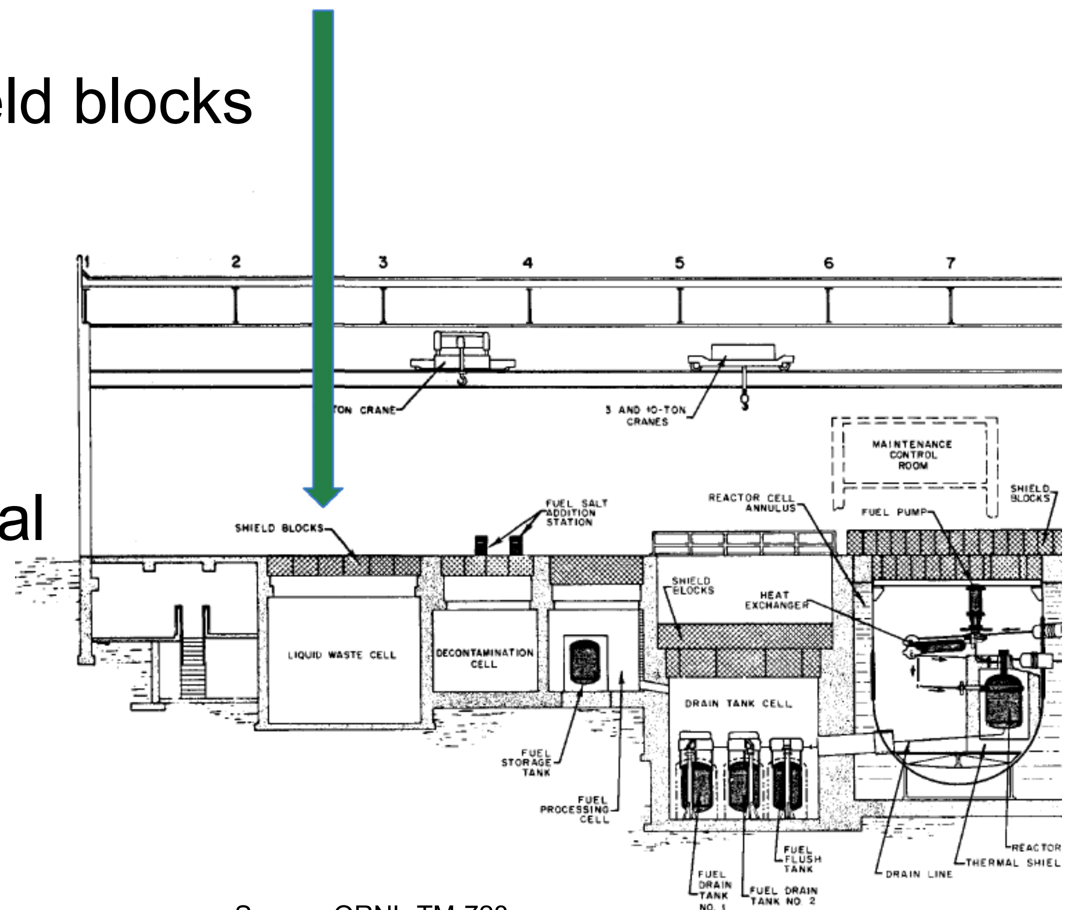
# MSRE Electrical Distribution System

- Two 13.8 kV transmission lines service the reactor from offsite
- Three transformers convert 13.8 kV to three 480 V switchgear buses
  - Each is backed by a 300 kW emergency diesel generator
  - Duplicate reactor process equipment is supplied from separate buses
- Two 48 V motor-generator set supplies DC voltage to reactor control and safety circuits
  - 24-cell battery system supplies emergency power
- Diesel motor startup and switching is manual
- Batteries "float" for instantaneous power following outage and to allow for manual power decrease if sustained power outage (>2 h)
  - Reduces scrams but not designed to operate the reactor when not connected to grid
  - If unable to start diesels or restore grid power, the fuel salt was drained

Sources: ORNL-TM-728
ORNL-TM-732

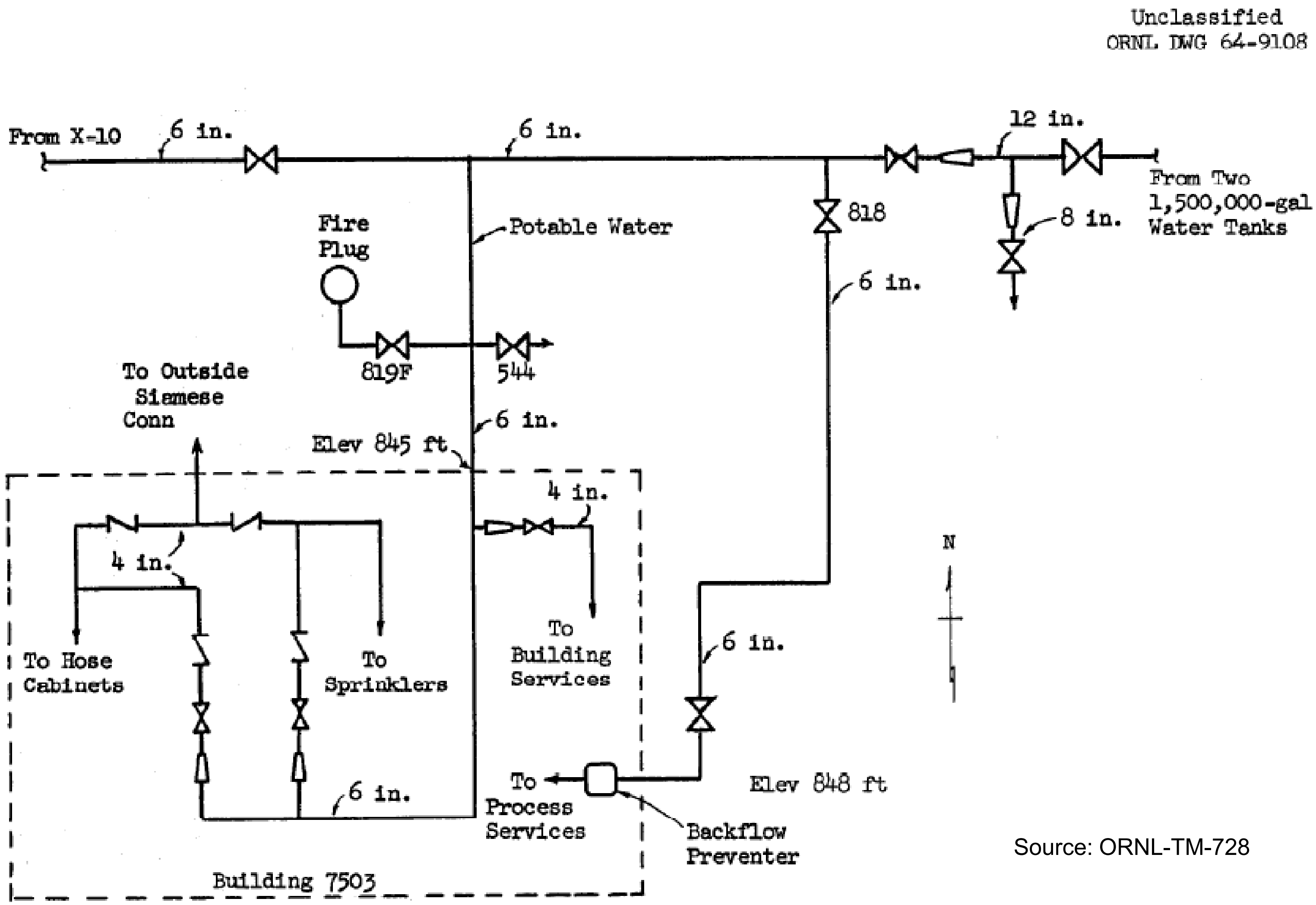
# MSRE Liquid Waste System

- Collect and store all waste water
  - 11,000 gal tank
  - Cell covered with shield blocks
- Treat as necessary
  - Sand and gravel filter
- Waste pump
  - Directs waste to central waste facility
- Various sump pumps




Source: ORNL-TM-728

# MSRE Fire Protection Provided by the Site Potable Water System




Source: ORNL-TM-728

# Other Issues

- Tritium control

# Tritium Is the Most Mobile Activation Product Formed in MSRs

- Note: Applies mostly to Li- and Be-bearing salts and therefore not to chloride fast reactors
- Tritium is generated by the interaction of neutrons with the lithium and beryllium in the fuel salt in and near the core
- Tritium production is an important safety issue because of the potential for significant release under normal operating conditions
- At high temperatures (>300°C) tritium can permeate through structural alloys
  - Large contact surface area and thin walls of heat exchanger tubes
  - Heat exchangers are a primary release pathway into the power cycle steam, maintenance heat exchanger coolant, and/or DRACS natural draft heat exchanger and eventually out into the environment

Source: ORNL/TM-2012/320

# Production of Tritium in an MSR is More than an Order of Magnitude Greater than Tritium Production in LWRs

- MSR total tritium production has been estimated to be roughly one Curie per MWt per day
  - Approximately 0.015 Ci/MWt per day in a LWR
  - Approximately 1.75 Ci/MWt per day in a PHWR
- Strategy for tritium control depends on the power conversion technology used
  - Steam-Rankine and open air-Brayton cycles have more challenging tritium control needs
  - Closed gas-Brayton cycles have less challenging tritium control needs
  - In all cases, some type of tritium recovery will likely be needed to control worker exposure and environmental releases

Source: ORNL/TM-2012/320

# Tritium Was Not Tracked in MSRE Until Late

- Fuel salt enriched to 99.993% $^7$Li to minimize tritium production
- Tritium migrated from fuel salt, through HX into coolant salt, and then through radiator into air
  - Also through fuel salt vessel and piping into cover gas system
- Measurements taken from gas exiting the stack, air leaving radiator, and fuel salt
  - Calculated Production: 60 Ci/day
  - Measured Stack: 4.6 Ci/day, Radiator: 0.6 Ci/day, Fuel Salt: 22.7 Ci/day
- Originally considered that “missing” tritium was held up in metal, pump lubricating oil, and graphite with uncertainty as to quantities in each given unknown chemistry
  - Post-operations measurements of a single graphite stringer indicated ~15% (~9 Ci/day) of tritium held up in graphite
  - Unable to completely resolve tritium transport issues due to measurement and property uncertainties
- Subsequently, MSBR was to use NaF-$NaBF_4$ coolant salt as it was experimentally shown to bind tritium

Sources: ORNL-4658, ORNL-4548, ORNL/TM-5759, ORNL CF-70-7-13

# Possible Tritium Control Mechanisms

- Heat exchangers utilizing a double-walled shell and tube configuration
  - Yttrium-based tritium trap included between the double walls
- DRACS natural draft HX utilizing flappers to isolate fuel salt shell side
  - Tritium evolving from the NDHX tubes contained within the shell and removed by trapping as a metal hydride
  - Increased temperature of accident conditions will cause the NDHX shell-side flappers to open

Source: ORNL/TM-2014/88

# Possible Tritium Control Mechanisms (cont.)

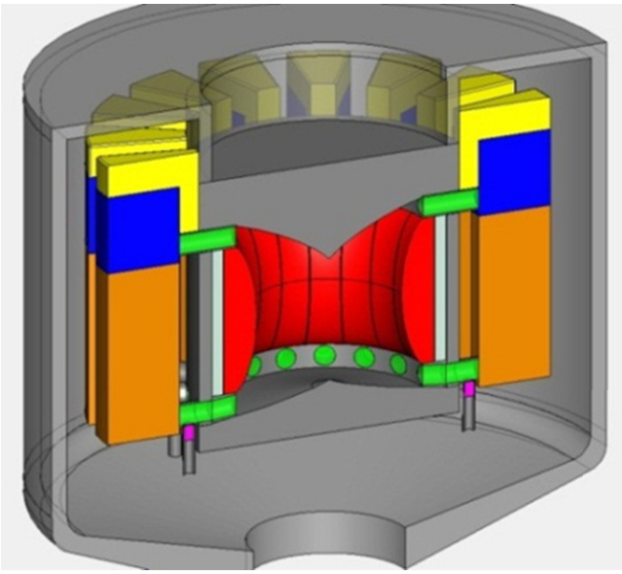
- Heated metal filters and a hot copper oxide bed
  - Oxidize the tritium into tritiated water
  - Capture water and dry
- Tritium that escapes into the steam cycle must be removed prior to the water being discharged
  - Possible membrane diffusion tritium stripping
- Developing and demonstrating the technologies necessary to understand and mitigate tritium is a high priority technology development item

Source: ORNL/TM-2012/320

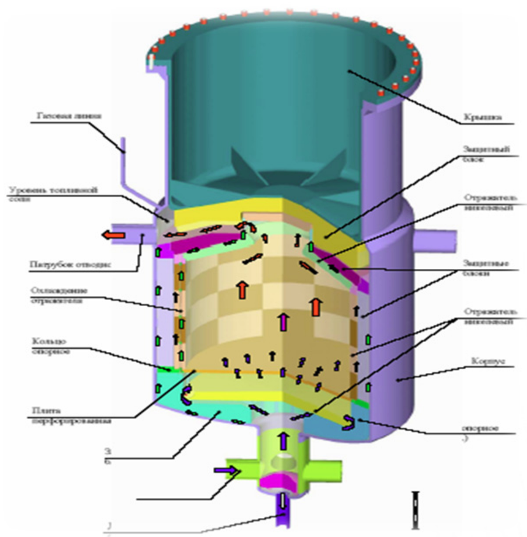
# Fast Spectrum MSRs Systems

- Structures and materials
- Control
- Chemistry

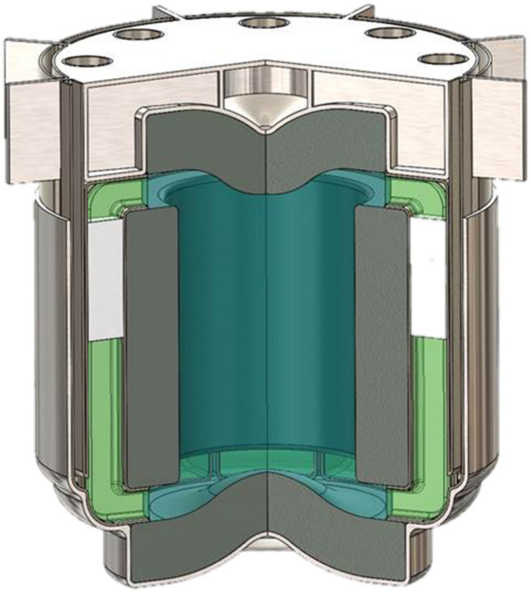
# Fast Spectrum MSRs Look Different



European MSFR [1]



Russian MOSART [2]



TerraPower MCFR [3]

# Fast Spectrum MSRs Have Different Structural Requirements

- FS MSRs have no core structure
  - No fixed moderator required
  - Only a region of critical geometry is required
- Structural materials for use in chloride salt systems require additional R&D
  - Ni alloy embrittlement at high fluence
  - Limited data on chloride salt material compatibility
- Fast spectrum fuel likely will require replacement of large components (e.g., reactor vessel) during the lifetime of plant unless accommodated for in the design
- Therefore, components may require different materials with different lifetimes compared to thermal and fluoride salt designs

Source: ORNL/TM-2011/105

# Fast Spectrum MSRs Have Multiple Possible Control Schemes

- Power can be controlled by fuel salt pump speed combined with corresponding secondary heat removal change
- Negative temperature and void coefficients
  - Compares to SFRs which can be challenged by this due to solid fuel fissile loading
- Bubble injection control schemes considered
- Subcritical, passively cooled dump tanks for accident mitigation
- Active and passive heat rejection (DRACS/RVACS) viable as in thermal MSRs

Source: ORNL/TM-2011/105

# Fast Spectrum MSRs Have Different Chemistry Requirements

- Without Li or Be, relatively little tritium is produced
- Chloride salt chemistry different than fluoride salt given increased number of valence states for chlorine (5 vs. 1)
- Fast spectrum allows for many possible fuel salts
  - U either natural, enriched, or depleted
  - Spent LWR fuel
  - TRU, Pu, or Th
- Online or batch processing different as actinides are not necessarily detrimental compared to thermal spectrum MSRs
- Due to possible high conversion ratio, online processing of actinides may not be necessary since minor actinides fission
- Chlorine isotope separation
  - 76% $^{35}Cl$, 24% $^{37}Cl$
  - $^{35}Cl$ activates appreciably into $^{36}Cl$, which has 301,000 year half-life and 700 keV $\beta^-$

Source: ORNL/TM-2011/105

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