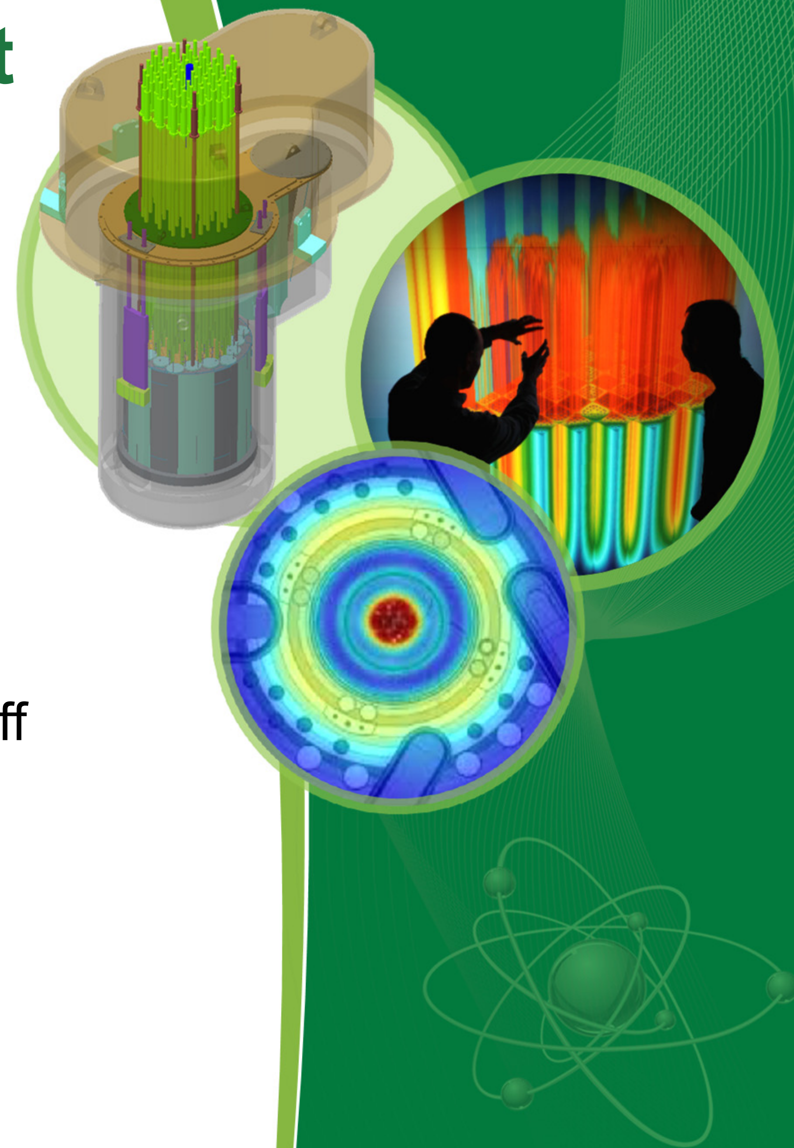
Module 1: History, Background, and Current MSR Developments

Presentation on Molten Salt Reactor Technology by:
David Holcomb, Ph.D.
Advanced Reactor Systems and Safety
Reactor and Nuclear Systems Division

Presentation for:
US Nuclear Regulatory Commission Staff
Washington, DC

Date:
November 7–8, 2017



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Summary of Modules

- Module 1 – History, Background, and Current MSR Developments
  - Introduction to MSRs, early development, current developers
- Module 2 – Overview of MSR Technology and Concepts
  - System overviews, technical maturity
- Module 3 – Overview of Fuel and Coolant Salt Chemistry and Thermal Hydraulics
  - Salt properties and characteristics
- Module 4 – MSR Neutronics
  - Comparison with LWRs, reactivity feedback, challenges

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Summary of Modules (cont.)

- Module 5 – Materials
  – Requirements, options, challenges
- Module 6 – Systems and Components
  – Nuclear heat supply, heat transport, support systems, balance of plant
- Module 7 – Overview of MSR Instrumentation
  – Key process parameters, support for automation, tritium monitoring, fissile material tracking
- Module 8 – Fuel Cycle and Safeguards
  – Reactor technology, neutron spectrum, fundamental concepts

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Summary of Modules (cont.)

- Module 9 – Operating Experience
  - Corrosion studies, OpE issues, remote handling, long-term storage
- Module 10 – Safety Analysis and Design Requirements
  - MSR events, accident sequences, hazards analysis, distributed source terms
- Module 11 – Regulatory Issues and Challenges
  - Salt chemistry effects, mobile fuel, distributed source terms
- Module 12 – MSR Development and R&D Issues
  - Technology today, key development issues, challenges

Module 1 – History, Background, and Current MSR Developments

- Brief introduction to MSRs
- Development at ORNL (late 1940s – early 1980s)
  - Most experimental and development work done at ORNL prior to recent renewed interest in MSRs
  - Only two MSR reactors to operate were at ORNL - reactor experiments
- Recent work done at ORNL since early 2000 on solid-fueled, molten salt-cooled reactors
- Profile of current MSR developers
- DOE Office of Nuclear Energy activities

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

- High solubility for uranium, plutonium, and thorium
- Stable thermodynamically
  - No radiolytic decomposition in liquid phase
- Chemically inert (no chemical reactions with air or water)
- Excellent heat transfer
  - Forced and natural circulation
  - Large heat capacity
- Very high boiling points
  - Low vapor pressure at operating temperatures
- Compatible with nickel-based structural alloys and graphite
- Compatible with chemical processing
- Transparent without fission products

But, there are challenges…

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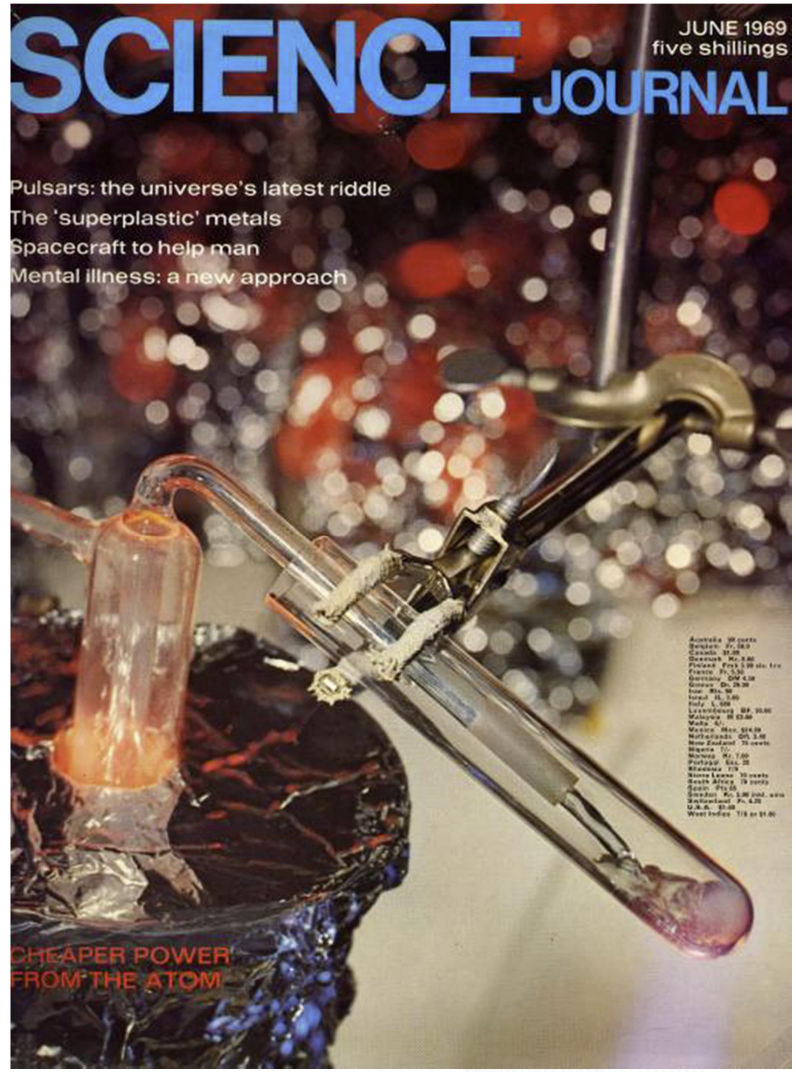
Molten Salt Reactor Technology Developed at ORNL

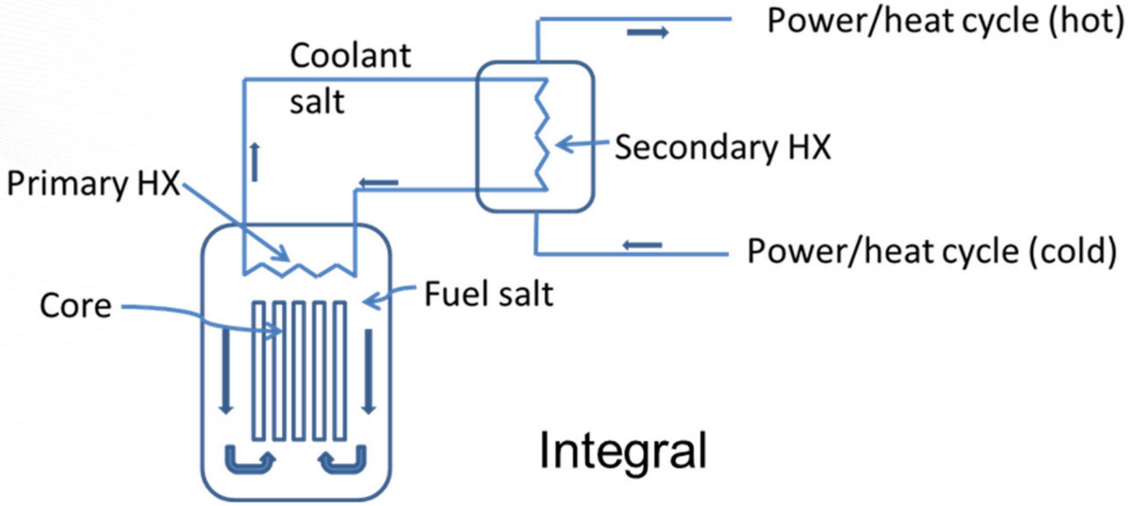
- Molten-salt-fueled reactors
  - Reactors with fuel dissolved in fluoride or chloride salt (fluid-fuel reactors)
  - Extensive development program from 1940s to 1970s including MSRE
  - Developed as breeder option to sodium-cooled fast reactor breeder
  - Thorium considered in development, but can support several different fuels
- Molten-salt-cooled reactors (liquid salt-cooled reactors)
  - Development over the past 15 years
  - Design alternative to gas-cooled systems that take advantage of the better coolant properties of liquid salt

    => Fluoride salt-cooled High-temperature Reactors (FHRs)

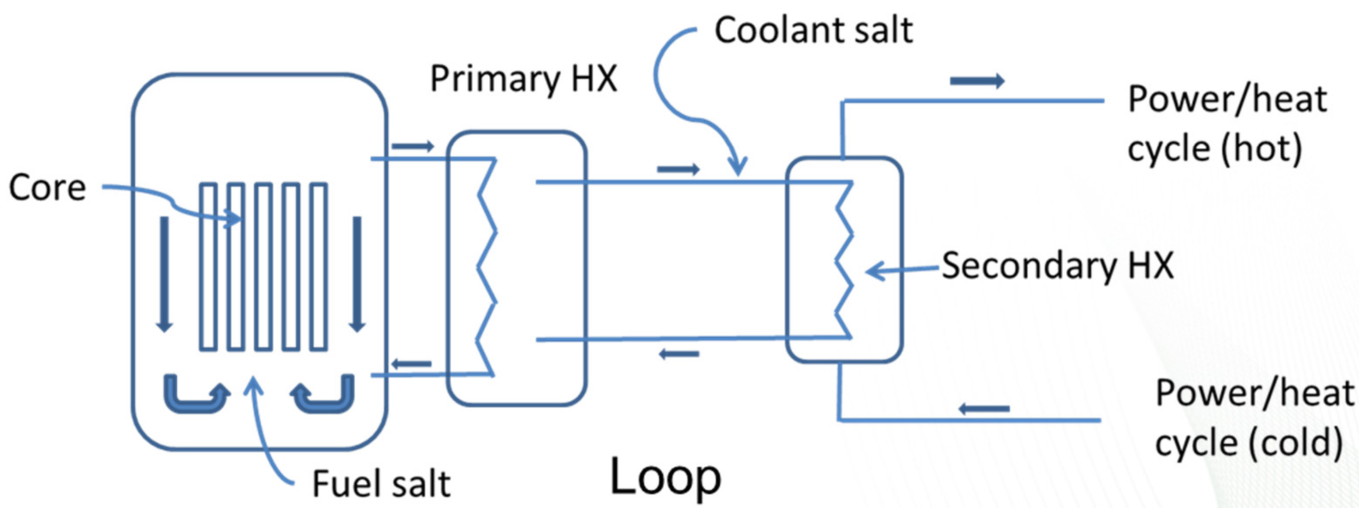


ORNL photograph of molten salt, featured on the cover of the British *Science Journal* in June 1969. (Used by permission)

MSR Terminology



Integral



Loop

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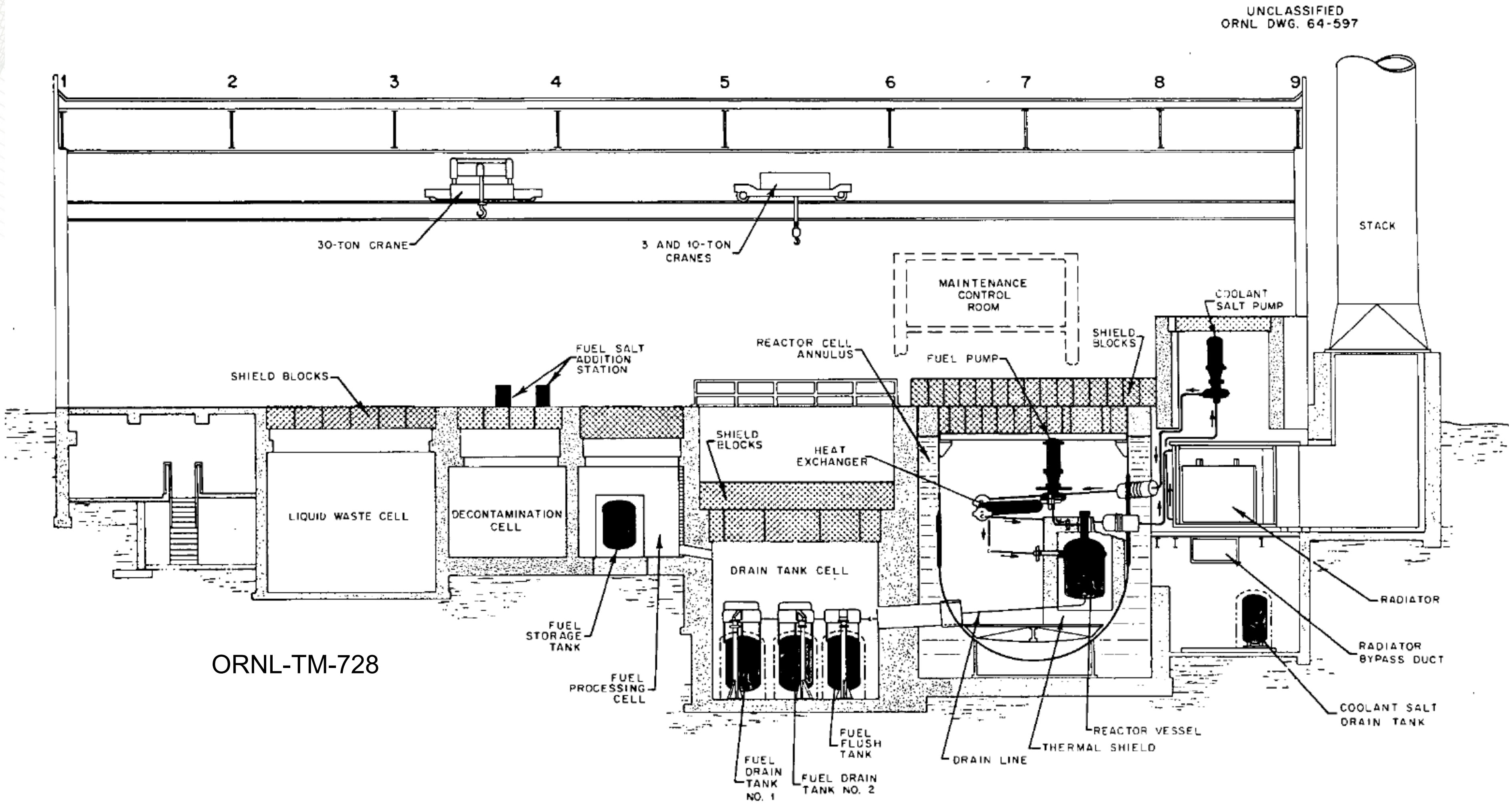
MSRE Elevation Schematic



ORNL-TM-728

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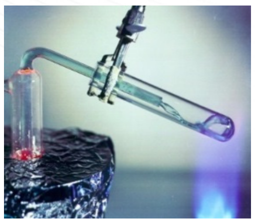
Early MSR Technology Success Underpins Renewed Commercial Interest Today

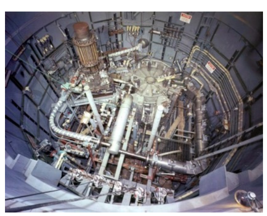


Early History

- Liquid-fueled Molten Salt Reactor (MSR) Experiment 1960-1969

Expertise Reinvigorated

- Removal of fueled salt from MSRE
- GEN-IV: Conceived solid-fueled, high-temperature molten salt systems with passive safety features (FHRs)



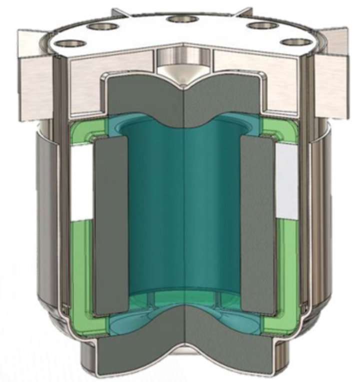
Interest Expands

- DOE funds molten salt R&D
- International interest in molten salt systems
- DOE invests heavily in university program
- CRADA with China's Shanghai Institute of Applied Physics (SINAP)

Present

- Robust university program
- MSR representative to GEN IV International Forum
- Diverse GAIN MSR activities
- DOE FOA team for molten chloride fast reactor
- Phase I of SINAP CRADA successful

The FUTURE?
- Resolve S&T questions
- R&D leadership that enables commercialization
- Framework for regulatory and safety issues is established



TerraPower MSR concept

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Molten Salt Reactor Technology Has a Long-Term Development History at ORNL

- Originally proposed by Ed Bettis and Ray Briant of ORNL in late 1940s
- Aircraft Nuclear Propulsion Program (1946–1961)
  - Large investment ($1B)
  - **Aircraft Reactor Experiment (1953–1954)***
  - Aircraft Reactor Test (1954–1957)
- Civilian Molten Salt Reactor Program (1958–1960)
- **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 (1978–1980)

*** ORNL designed, constructed, and operated the only two MSRs - ARE and MSRE**

*** ANP 1946–1961: $1B**

*** ANP ended with advent of ICBMs in early 1960s**

MSRE Core Assembly

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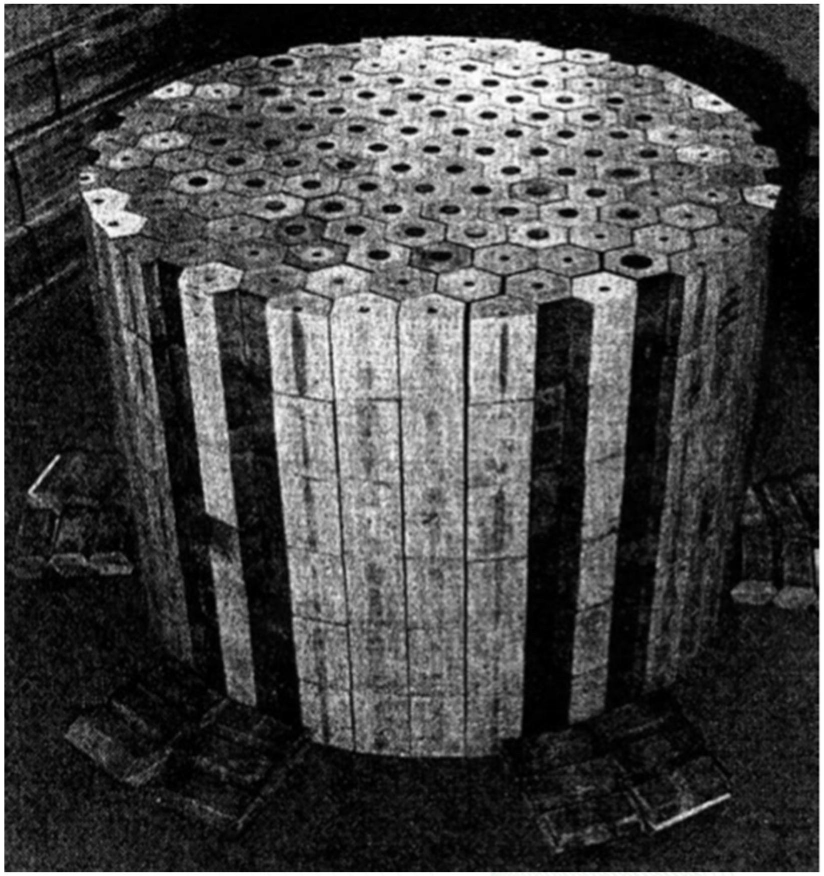
1954 Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept

- In order to test the liquid-fluoride reactor concept, a solid-core, sodium-cooled reactor was converted into a proof-of-concept liquid-fluoride reactor.
- Aircraft Reactor Experiment Operations
  - 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
  - ^{235}U - 93%
  - Fuel system operated 241 h before criticality
  - Nuclear operation over 221 h period
  - Last 74 hours were in MW range
  - Produced 96 MW-h of nuclear energy
  - Produced 2.5 MW of thermal power
  - Heat transferred from He loop to finned tube heat exchanger cooled by water

Aircraft Reactor Experiment



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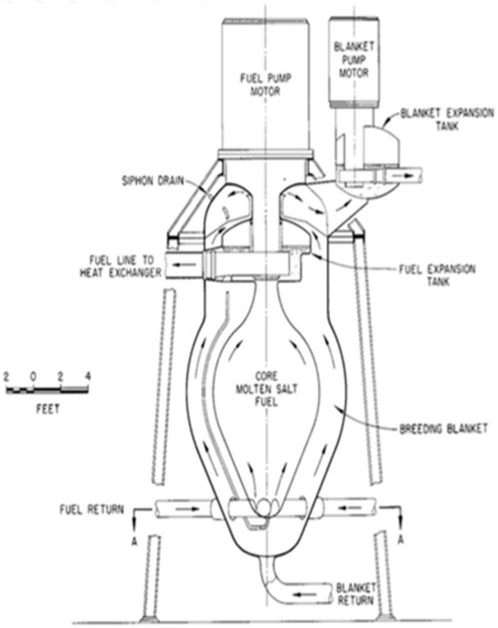
Civilian MSR Program Emerges ~1958

1958 - Initial civilian MSR designs heavily leveraged ANP concept



- $^{235}U/^{233}U$
- U/Th fuel cycle
- Two region/batch processing
- 640 MWt/260 MWe
- 1210°F exit temperature

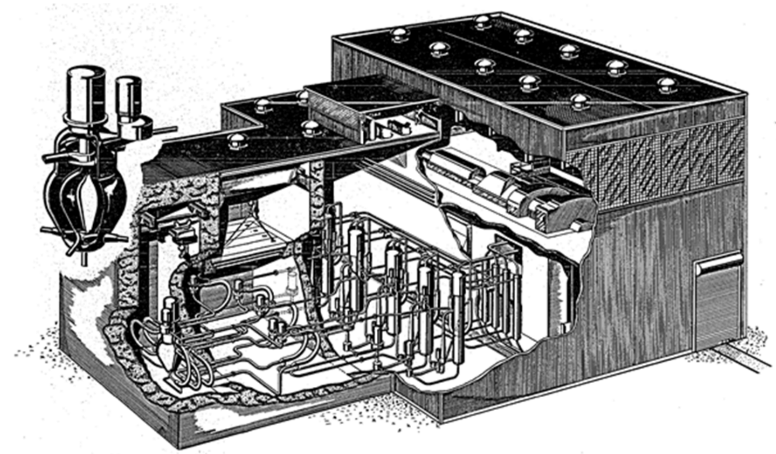
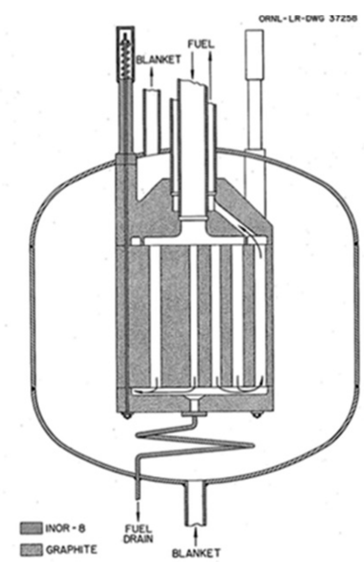


Fig. 1.1. Isometric View of Molten Salt Power Reactor Plant.

1959 - Design began to resemble what we now recognize as MSRs



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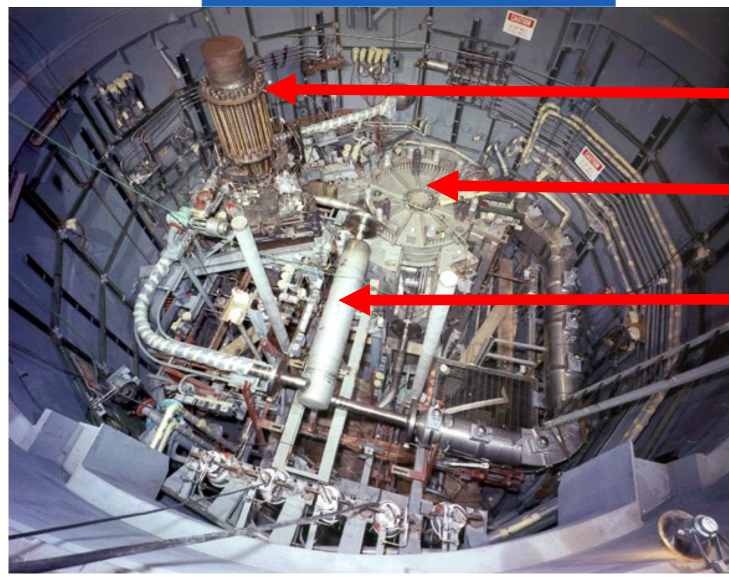
ORNL Successfully Demonstrated Key MSR Technology at the MSRE

- 1965 (June) First Criticality
- 1966 (Dec) First Full Power Operation
- 1968 (Oct) First Operation on ^{233}U
- 1969 (Dec) Shutdown
- Design features:
  - 8 MWt
  - Single region core - 33% ^{235}U
  - Outlet temperature ~700°C
- Graphite moderated
- Alloy N vessel and piping
- Achievements
  - First use of ^{233}U fuel
  - First use of mixed U/Pu salt fuel
  - Online refueling
  - > 13,000 full power hours

MSRE Reactor Cell



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MSRE Successfully Demonstrated Key MSR Technologies

- Salt chemistry was well behaved (almost no corrosion => Cr increased only 38-85 ppm in
  3 years =>0.2 mil layer of Hastelloy N)
- Nuclear performance closely paralleled predictions
- Molten salts stable under reactor conditions
  - He cover gas, O_2 and moisture <10 ppm
  - UF_4 to UF_3 maintained
- Fission products
  - Noble gases Xe and Kr efficiently stripped out in offgas system
  - Most other FPs remained in fuel salt
  - Analysis of specimens => half of noble metals FPs plated out on graphite and metal surfaces exposed to salt
- Hastelloy N performed as expected
  - Little change: ultimate strength, yield strength, creep rate
  - Rupture ductility and creep rupture life in specimens reduced
  - Improved specimens with small amounts of titanium irradiated in MSRE showed improved ductility creep life
- Few grams of oil in offgas line plugged fuel off- gas system => installed larger/more efficient filter resolving problem

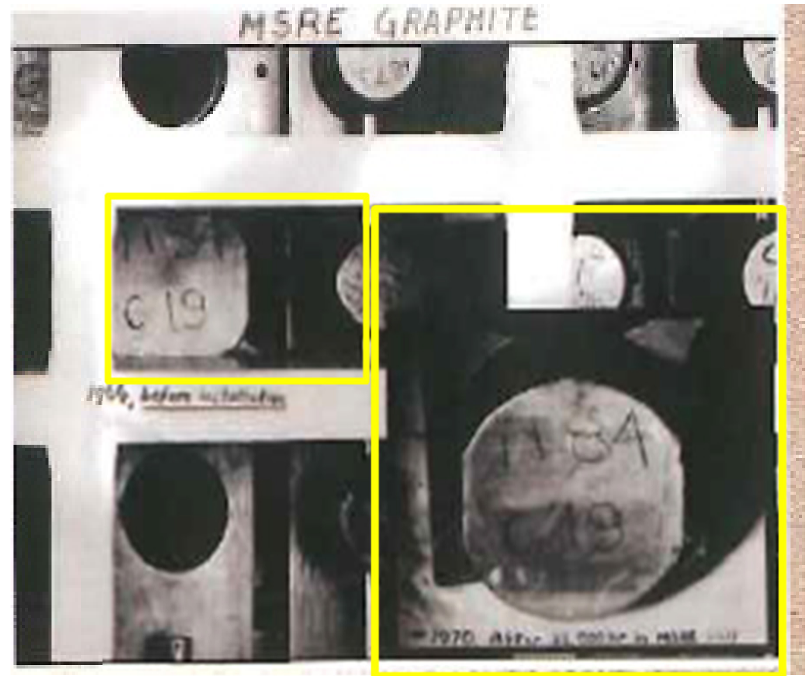

Image shows chemical compatibility of the salt with graphite. The condition of this graphite rod is virtually identical in the left image from 1964 before operation and in right image from 1970 after shutdown.

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MSRE—First Reactor to Operate Solely on ^{233}U (1968)

Glenn Seaborg starts MSRE ^{233}U operations

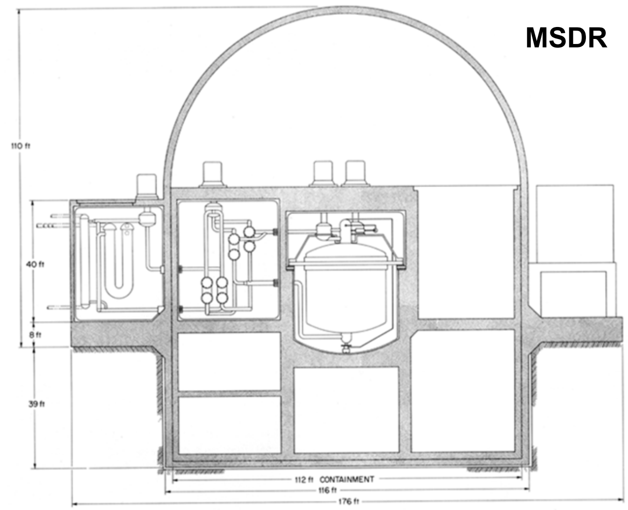
Capsule by which ^{233}U was added

- After last 6-month run on ^{235}U MSRE shut down and uranium in fuel salt stripped via fluorination
- ^{233}U added to carrier salt
- MSRE operated over 2500 equivalent full-power hours on ^{233}U
- New ^{233}U fuel salt added with off-spec chemical impurities (Fe, Cr)
  - Operation of offgas removal system degraded by impurities
  - Result was occasional bubbles in core and associated localized power fluctuations
  - Reducing fuel pump speed eliminated fluctuations

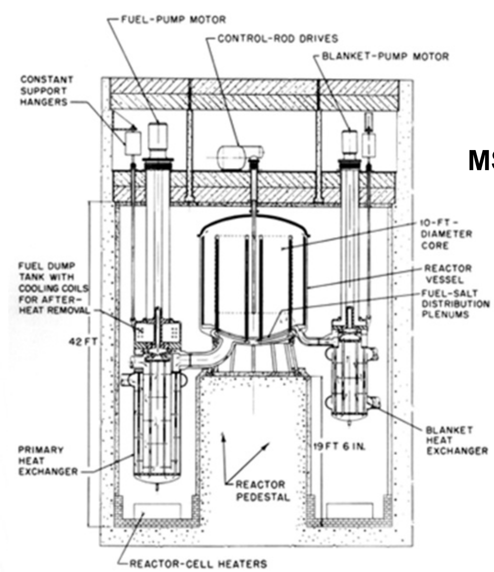
Further MSR Development was Planned

- Molten salt demonstration reactor for (750 MWt, 300 MWe) protoype
- Molten salt breeder reactor experiment (150 MWt, 65 MWe)
- Molten salt breeder reactor (2250 MWt, 1000 MWe)
- Denatured MSR addressed proliferation concern (no online processing)

MSDR



MSBR



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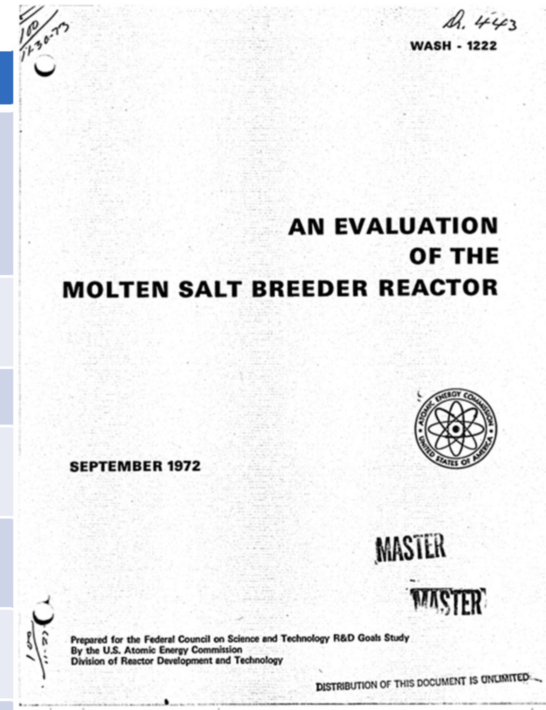
Post-MSRE R&D Made Progress on Technical Issues from MSRE Operation and MSBR Studies in WASH-1222

MSR Technical Issue—WASH-1222	Comments – Post-MSRE Advances
Structural material embrittlement	Modified Alloy N developed • ~ 2 % niobium – dispersed carbides act as He sink – corrosion studies • Redox control – oxidation potential
Limited graphite lifetime	Lower power density designs – alternate forms of graphite
Molten salt chemistry / actinide solubility	Substantially improved understanding
Noble metal FP plate-out	Understand mechanisms and design impacts
Tritium management	Acceptable solution demonstrated at engineering scale
MSRE power fluctuations	Not a significant issue – minor bubble formation
Equipment design immaturity	Code-rated heat exchanger designed for MSBR
Maintenance in high radiation areas	**Recognized issue**


WASH - 1222

AN EVALUATION
OF THE
MOLTEN SALT BREEDER REACTOR

SEPTEMBER 1972

MASTER

Prepared for the Federal Council on Science and Technology R&D Goals Study
By the U.S. Atomic Energy Commission
Division of Reactor Development and Technology

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AEC Technology Assessment of MSBR for Federal Council on S&T R&D Goals

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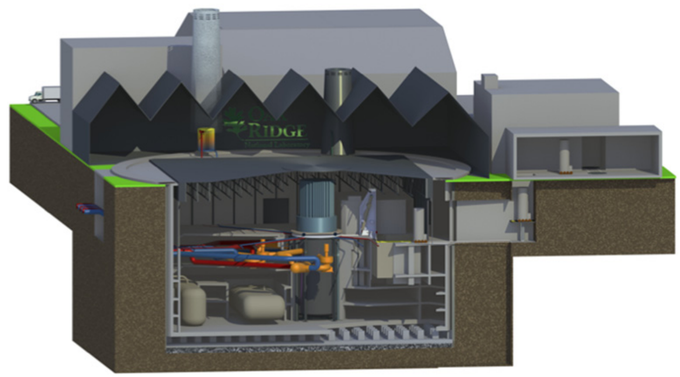
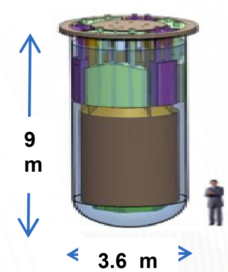
ORNL Developed Both Large (Central Station) and Small (Process Heat) Preconceptual Designs of FHR - 2000s

Advanced High-Temperature Reactor (AHTR) Properties	
Thermal power	3400 MW
Electrical power	1500 MW
Top plenum temperature	700°C
Coolant return temperature	650°C
Number of loops	3
Primary coolant	2 $^{7}LiF\text{-}BeF_2$
Fuel	UCO TRISO
Uranium enrichment	9%
Fuel form	Plate assemblies
Refueling	2 batch 6 month



Small AHTR (SmAHTR) Properties	
Power (MWt)	125
Primary coolant	2 $^{7}LiF\text{-}BeF_2$
Primary pressure (atm)	~1
Core inlet temperature (ºC)	650
Core outlet temperature (ºC)	700
Core coolant flow rate (kg/s)	1020
Operational heat removal	3 – 50% loops
Passive decay heat removal	3 – 0.25% loops
Reactor vessel penetrations	None



Source: ORNL/TM-2010/199

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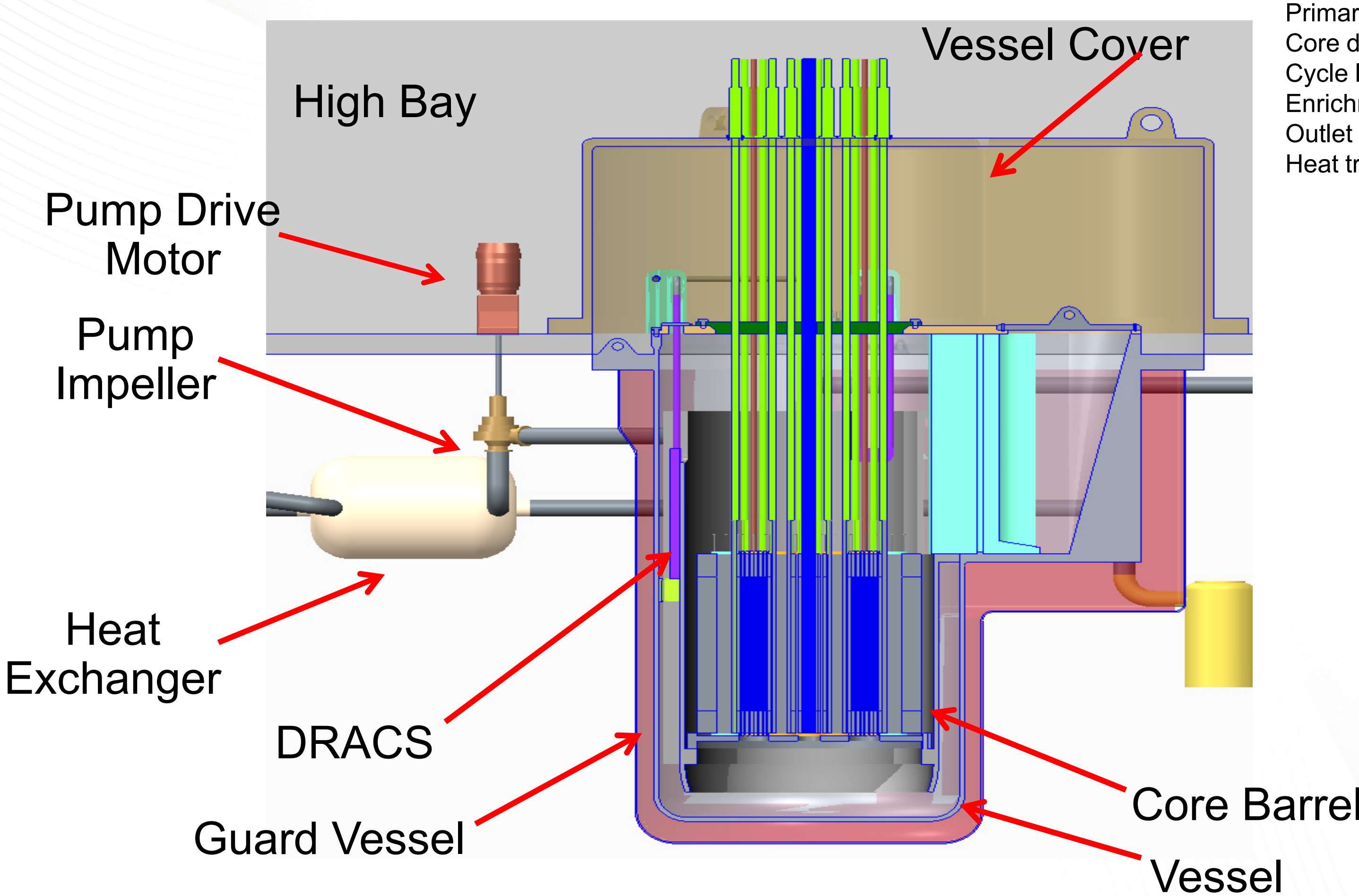
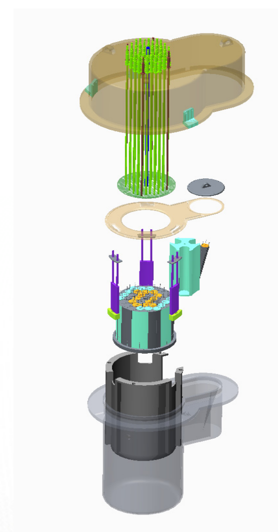
ORNL FHR Demonstration Point Design Completed in 2016 as Part of DOE-NE AT/DR Studies

Reactor Plant Power	100 MWt
Fuel	Prismatic / TRISO
Primary coolant	FLiBe
Core diameter/height	3.2 m / 3.5 m
Cycle length	12 to 18 months
Enrichment	15.5% (UCO)
Outlet temperature	700ºC
Heat transfer system	Two loop system





Source: ORNL/TM-2016/85

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Profile of current MSR developers

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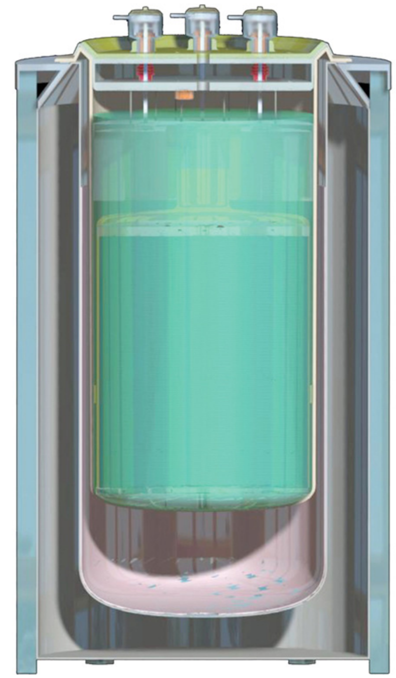
Terrestrial Energy USA (TE-USA)

- US company affiliated with Canadian company Terrestrial Energy Inc.
- Design referred to as IMSR (Integral Molten Salt Reactor)
  - Denatured U/Pu fuel cycle – LEU fuel
  - Graphite moderator
  - Sealed unit with integrated pumps, heat exchangers, and shutdown rods
- Seven-year reactor vessel, moderator, and fuel salt lifetime – replaced as a unit
- Twin reactor configuration
  - Reactor swapped every seven years
- Most detailed public information available from IAEA ARIS database
  - https://**aris.iaea**.org/Publications/**SMR**-Book_**2016**.pdf
- Responded to RIS indicating potential application by late 2019

IMSR Salt Load



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400 MWt/module

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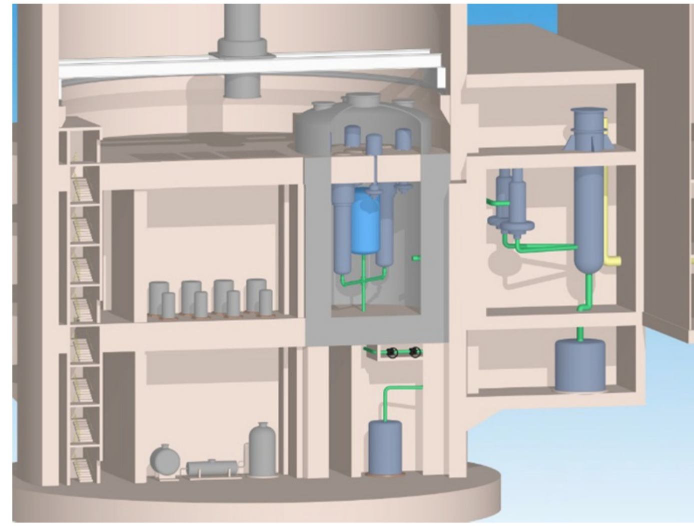
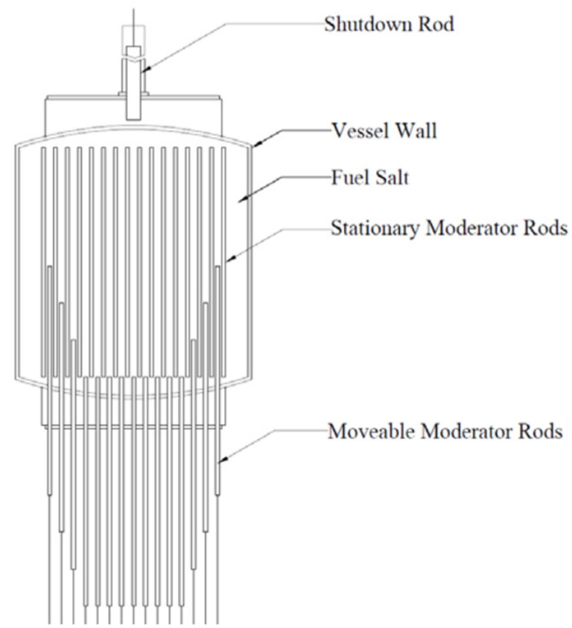
Transatomic Power (TAP)

- 5% LEU fuel salt – $LiF\text{-}(Act)F_4$
- Zirconium hydride moderator in movable rods
- 1250 MWt
- Most detailed information available in Transatomic's white paper (version 2.1)
  - http://www.transatomicpower.com/wp-content/uploads/2015/04/TAP-White-Paper-v2.1.pdf
- Employs liquid metal extraction process (not described) to separate lanthanides as well as mechanical filtration and gaseous separations





Images from TAP white paper

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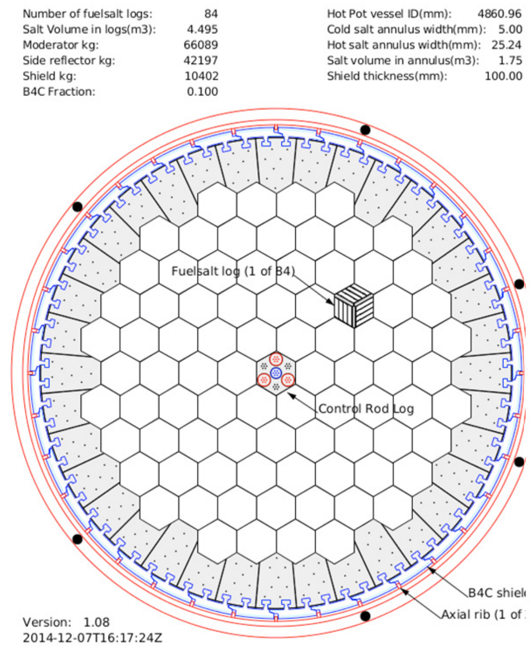
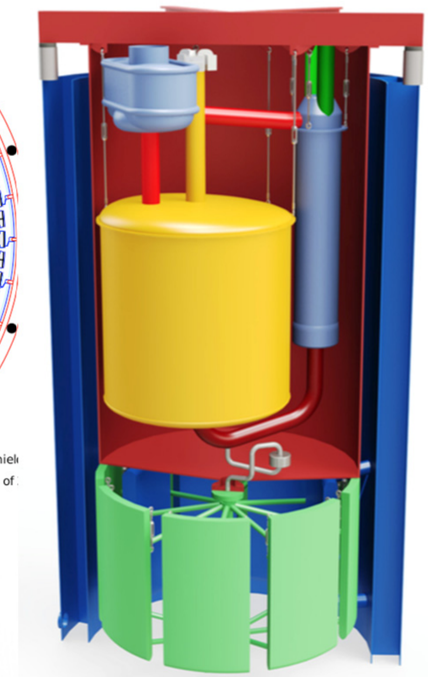
Thorcon Power

- NaBe with 12% actinide loading
  - 80% Th, 16% ^{238}U, 4% ^{235}U (19.7%)
- Fuel salt and moderator graphite replaced every four years
  - Twin reactor configuration
- Vessel life extended by interior neutron shielding
- Fuel salt drain tanks for criticality safety
- Wet cooling wall for decay heat rejection
- Thorconpower.com provides most detailed information on reactor design (also in ARIS)





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557 MWt per module

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TerraPower

- US company
- Fast spectrum molten chloride fuel salt - MCFR
- Employs reflector
  - Reduce dose to containment
  - Improve neutron economy
  - Reduces radiation level within shielding
- Integral heat exchangers
- Being developed in cooperation with Southern Company
  - ORNL, EPRI, and Vanderbilt are providing technical support under DOE ARC 2015
- Additional information intended for release later in 2017

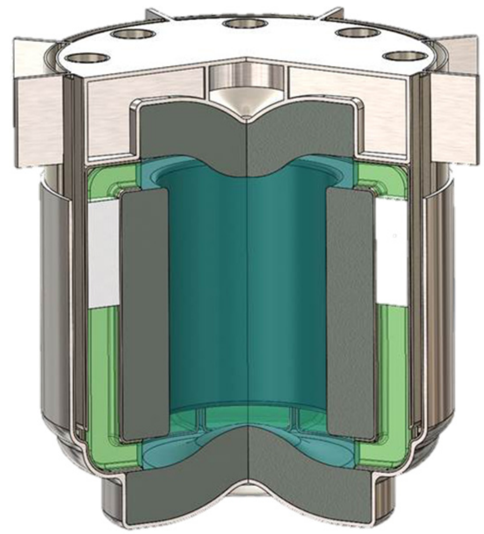
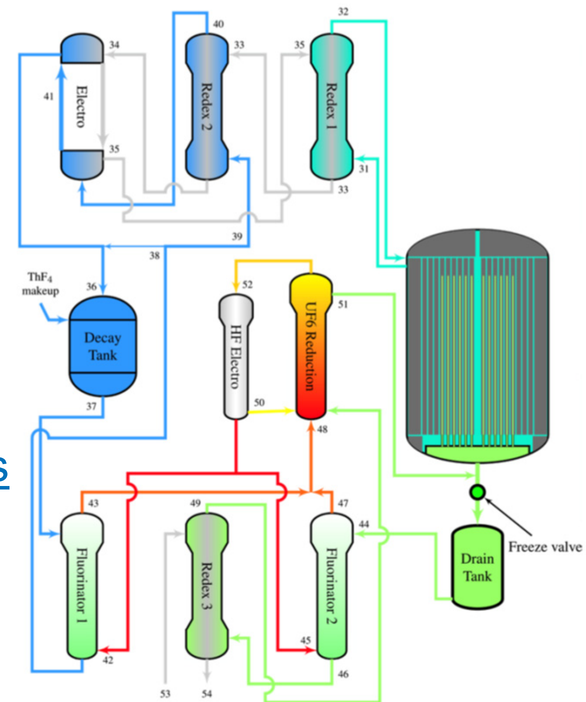


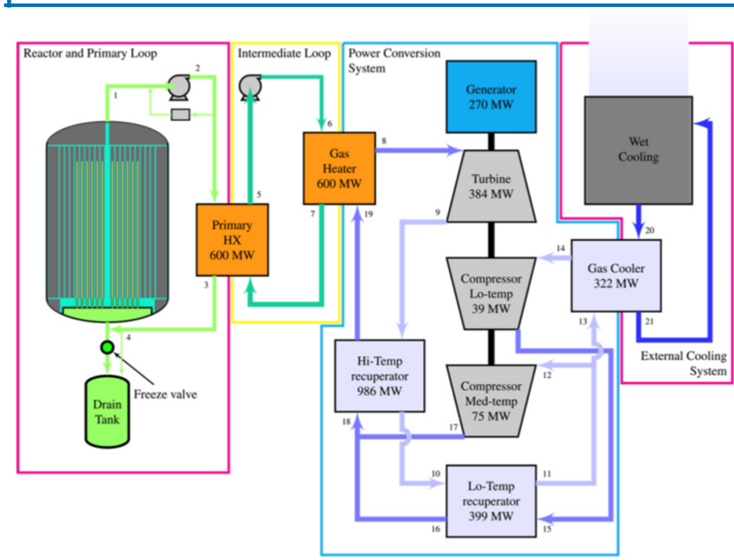
Image courtesy of TerraPower

Flibe Energy

- US Company
- Liquid Fluoride Thorium Reactor (LFTR) - thorium breeder fuel cycle
- Graphite moderated, thermal spectrum, LiF-BeF_2-UF_4 fuel
- Freeze valve and drain tank based decay heat rejection
- Most detailed technical information available from EPRI technical report – 3002005460, October 2015
  - http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002005460



Reprocessing Flows

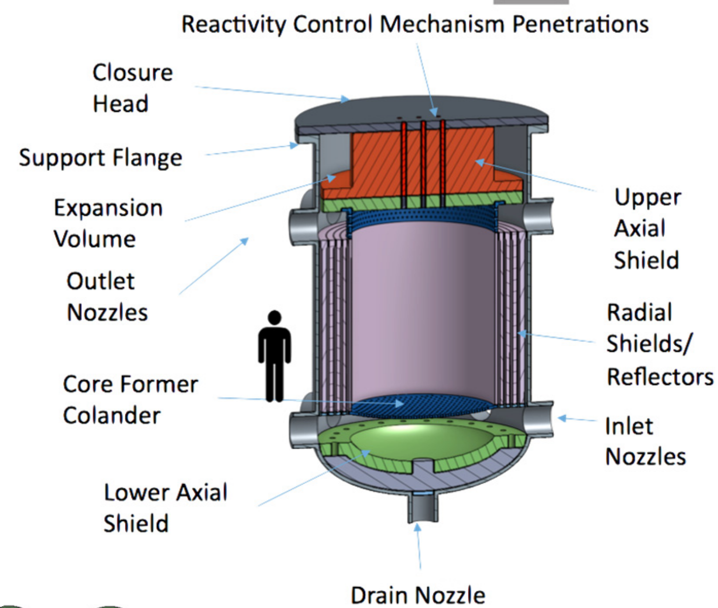


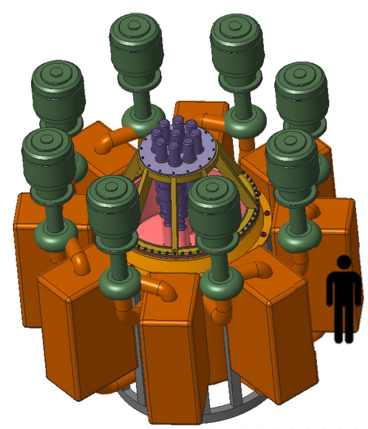
Power System

Images courtesy of Flibe Energy

Elysium Molten Salt Reactor Concept

- Rated electric output ~2500 MWt (1000 MWe)
- Chloride fuel salt
- Fast spectrum neutron flux
- Core outlet temperature of > 600ºC
- Core inlet temperature of ~ 500ºC
- Structural components made from code qualified materials
  - Shield assemblies periodically replaced
- Superheated steam Rankine power cycle
- May employ active corrosion control
- Employs drain valve





Elysium images used with permission

Kairos Power

- Only solid-fuel commercial MSR concept in US
  - Aimed at demonstration by 2030
- Relies on the advanced gas reactor TRISO qualification effort to provide salt-compatible qualified fuel
- Plans to leverage DOE programmatic efforts
- Extensive use of simulant fluids for thermal and hydraulic design validation
- Based upon University of California at Berkeley Pebble Bed FHR concept
- Coupled with a gas turbine for peaking
  - 100 MWe nuclear only
  - 242 MWe with natural gas

Kairos Power

Current Developments and Related Activities by DOE and Industry Put More Emphasis on MSRs

DOE Office of Nuclear Energy

- DOE ARC 2015 Award – Southern Company Services with TerraPower, EPRI, Vanderbilt University, and ORNL
- Awarded 2 GAIN vouchers* for MSR R&D, June 2016
- Held GAIN sponsored MSR Workshop*, July 2016
- Signed MOU with NRC on GAIN collaborations, November 2016
- With EPRI jointly held "Advanced Reactor Modeling and Simulation Workshop," January 2017*
- Named first National Technical Director for MSRs under its Advanced Reactor Technologies (ART) program (Lou Qualls, ORNL), Feb. 2017
- Draft DOE-NE MSR Roadmap in preparation
- Held Molten Salt Chemistry Workshop at ORNL April 10–12, 2017
- Awarded 7 GAIN vouchers* for MSR R&D, June 2017
- Planning multiple R&D MSR projects for FY18 and beyond

* Note: DOE GAIN focus and related activities are on all advanced reactor types (MSRs, GCRs, and LMRs) and advanced technologies for all reactor types

Current Developments and Related Activities by DOE and Industry Put More Emphasis on MSRs (cont.)

- ORNL hosted MSR-related workshops
  - 2015 – Molten Salt Reactor Technologies – 50th Anniversary of Startup of MSRE (130 attendees)
  - 2016 – Moving MSRs Forward – The Next Steps (200 attendees)
  - Upcoming: 2017 MSR Workshop at ORNL – October 3-4
- MSR Developers and Industry
  - Formed MSR Technology Working Group (TWG) from July 2016 DOE Workshop
  - Sent GAIN/DOE-NE letter identifying 4-year program for series of separate effects testing, December 2016