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

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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
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
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…
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)
MSR Terminology
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
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
  - $^{235}\text{UF}_4$ dissolved in NaF-ZrF$_4$
  - $^{235}\text{U} - 93\%$
  - 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
Civilian MSR Program Emerges ~1958

1958 - Initial civilian MSR designs heavily leveraged ANP concept

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

1959 - Design began to resemble what we now recognize as MSRs
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 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\textsubscript{2} and moisture <10 ppm
  - UF\textsubscript{4} to UF\textsubscript{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.
MSRE—First Reactor to Operate Solely on $^{233}$U (1968)

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

<table>
<thead>
<tr>
<th>MSR Technical Issue—WASH-1222</th>
<th>Comments – Post-MSRE Advances</th>
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<tbody>
<tr>
<td>Structural material embrittlement</td>
<td>Modified Alloy N developed</td>
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<tr>
<td></td>
<td>• ~ 2% niobium – dispersed carbides act as He sink – corrosion studies</td>
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<tr>
<td></td>
<td>• Redox control – oxidation potential</td>
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<tr>
<td>Limited graphite lifetime</td>
<td>Lower power density designs – alternate forms of graphite</td>
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<tr>
<td>Molten salt chemistry / actinide solubility</td>
<td>Substantially improved understanding</td>
</tr>
<tr>
<td>Noble metal FP plate-out</td>
<td>Understand mechanisms and design impacts</td>
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<tr>
<td>Tritium management</td>
<td>Acceptable solution demonstrated at engineering scale</td>
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<td>MSRE power fluctuations</td>
<td>Not a significant issue – minor bubble formation</td>
</tr>
<tr>
<td>Equipment design immaturity</td>
<td>Code-rated heat exchanger designed for MSBR</td>
</tr>
<tr>
<td>Maintenance in high radiation areas</td>
<td>Recognized issue</td>
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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**: $^7\text{LiF-BeF}_2$
- **Fuel**: UCO TRISO
- **Uranium enrichment**: 9%
- **Fuel form**: Plate assemblies
- **Refueling**: 2 batch 6 month

**Small AHTR (SmAHTR) Properties**

- **Power (MWt)**: 125
- **Primary coolant**: $^7\text{LiF-BeF}_2$
- **Primary pressure (atm)**: $\sim$1
- **Core inlet temperature (°C)**: 650
- **Core outlet temperature (°C)**: 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
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: 700°C
Heat transfer system: Two loop system

Source: ORNL/TM-2016/85
Profile of current MSR developers
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
- Responded to RIS indicating potential application by late 2019

IMSR Salt Load

400 MWt/module
Transatomic Power (TAP)

- 5% LEU fuel salt – LiF-(Act)F$_4$
- Zirconium hydride moderator in movable rods
- 1250 MWt
- Most detailed information available in Transatomic’s white paper (version 2.1)
- Employs liquid metal extraction process (not described) to separate lanthanides as well as mechanical filtration and gaseous separations
Thorcon Power

- NaBe with 12% actinide loading
  - 80% Th, 16% $^{238}\text{U}$, 4% $^{235}\text{U}$ (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)

557 MWt per module
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
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

Elysium Molten Salt Reactor Concept

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