

Fuel Cycle and Nuclear Technology Seminars for DOE/NE Molten Salt Reactors

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Fuel Cycle and Nuclear Technology Seminars for DOE/NE Molten Salt Reactors

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March 2017

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Fuel Cycle and Nuclear Technology Seminars for DOE/NE – Molten Salt Reactors

**Nuclear Technology
Research and Development**

***Prepared for
U.S. Department of Energy
Fuel Cycle Options – Systems Analysis
and Integration Campaign
R. Wigeland, INL***

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SUMMARY

This report provides the information presented at the Molten Salt Reactor (MSR) Seminar held at DOE Headquarters in Germantown, MD on February 16, 2017. DOE/NE-43 had requested an informational seminar to provide a detailed technical background on the technology of molten salt reactors, the history of molten salt reactor development, the current status of the technologies, and the identified issues requiring R&D. To meet this need, the seminar had the following objectives:

1. Provide information specifically for DOE/NE Federal managers on the concepts, technologies, fuel cycles, and challenges associated with MSRs.
 - Provide a review of various MSR technologies
 - Domestic and international, historic and current
 - Describe the reasons behind the recent interest in MSR technologies
 - Potential advantages, disadvantages, and challenges
2. Provide a summary of the current status of MSRs and the major challenges to development and deployment.

The MSR seminar consisted of a series of presentations mainly developed by Oak Ridge National Laboratory, reviewed and coordinated by the Fuel Cycle Options – Systems Analysis and Integration campaign to meet the seminar objectives.

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FUEL CYCLE AND NUCLEAR TECHNOLOGY SEMINARS FOR DOE/NE MOLTEN SALT REACTORS

1. INTRODUCTION

A Molten Salt Reactor (MSR) Seminar held in Germantown, MD on February 16, 2017. DOE/NE-43 had requested an informational seminar to provide a detailed technical background on the technology of molten salt reactors, the history of molten salt reactor development, the current status of the technologies, and the identified issues requiring R&D. To meet this need, the seminar had the following objectives:

1. Provide information specifically for DOE/NE Federal managers on the concepts, technologies, fuel cycles, and challenges associated with Molten Salt Reactors (MSRs)

- Provide a review of various MSR technologies
 - Domestic and international, historic and current
- Describe the reasons behind the recent interest in MSR technologies
 - Potential advantages, disadvantages, and challenges

2. Provide a summary of the current status of MSRs and the major challenges to development and deployment

This report contains all of the seminar slide presentation materials, along with a brief description of each presentation. The presentations identify possible areas for R&D that may be used to inform the decision-making process concerning MSRs and the supporting technologies, but this report does not make any recommendations concerning MSR development or any directions for R&D.

2. MSR SEMINAR PRESENTATIONS

The seminar was organized into a series of modules, with each module providing information on specific aspects of MSRs. Table 1 shows the MSR seminar agenda, with all of the presentations listed. The following sections provide the slides presented at the seminar and a brief discussion of some of the significant points discussed during each presentation.


Table 1. MSR Seminar Agenda

| Introduction | | |
|--|---|--|
| 9:00 – 9:25 AM | Opening Remarks Meeting Overview and Background | BP Singh (NE-42) R. Wigeland (INL) |
| History, Concepts, and Current Technologies | | |
| 9:25 – 9:55 AM | Module 1: Brief History of the ORNL MSR Program | G. Mays (ORNL) |
| 9:55 – 11:25 AM | Module 2 – Part 1: Introduction to MSR Technologies and Variants - Potential Advantages, Disadvantages, and Challenges | D. Holcomb (ORNL) |
| 11:25 – 12:30 PM | Lunch | |
| 12:30 – 1:00 PM | Module 2 – Part 2: Status of Technologies Under Development; Domestic and International | D. Holcomb (ORNL) |
| MSR Basic Principles | | |
| 1:00 – 2:00 PM | Module 3: Reactor Chemistry, Materials Compatibility, and Separations | Dave Williams (ORNL) |
| 2:00 – 3:15 PM | Module 4: Reactor Safety, Physics, and Associated Fuel Cycle Performance | Ben Betzler (ORNL) Florent Heidet (ANL) |
| 3:15 – 3:30 PM | Break | |
| R&D Challenges | | |
| 3:30 – 4:30 PM | Module 5: Safeguards Considerations and Challenges | G. Flanagan (ORNL) |
| 4:30 – 5:00 PM | Module 6: Research, Development, and Deployment Challenges | G. Mays (ORNL) |
| 5:00 – 5:15 PM | Concluding Remarks and Seminar Close | R. Wigeland (INL) BP Singh (NE-42) |

2.1 Meeting Overview and Background

This presentation introduced the seminar and provided an overall perspective on MSRs in the context of other nuclear reactors and nuclear fuel cycles. Among the significant points made during the presentation are the following:

- There are two distinct types of MSRs
 - The molten salt is used as a coolant for traditional solid nuclear fuel, e.g., solid fuel with cladding, solid fuel in graphite pebbles, etc. In this case, the molten salt is only a coolant medium that carries the heat produced by the fuel to a heat exchanger. This is referred to as a "salt-cooled" MSR.
 - The molten salt also contains the nuclear fuel dissolved in the salt, i.e., the nuclear fuel is also a salt, and the molten salt mixture is circulated through a region where nuclear fission occurs to produce heat, which is then carried by the molten salt mixture to a heat exchanger. This is referred to as a "liquid-fuel" MSR. Many MSR concepts are liquid-fuel MSRs.
- Terminology for describing liquid-fuel MSRs is not the same as for traditional solid-fuel reactors, so care must be exercised in discussing liquid-fuel MSRs.
- Liquid-fuel MSRs are not just reactors, but entire recycle fuel cycles due to the separation of volatile materials such as noble gas fission products during normal operation. While this doesn't separate all fission products, this partial separation allows MSRs to use fuel to a higher burnup, just as with a recycle fuel cycle.
 - This is the same process that occurs with recycle fuel cycles using traditional solid fuels, where fission products are separated from potentially useful fuel materials
 - It is also possible to use additional separations online with a liquid-fuel MSR to completely separate fission products from the liquid fuel salt mixture.
- Thermal, intermediate, and fast neutron spectrum versions of MSRs are possible in principle.
 - Fast neutron MSRs may provide fuel cycle performance benefits associated with the use of a fast neutron spectrum in recycle fuel cycles using traditional solid fuel.
- MSRs may have potential advantages, disadvantages, and challenges compared to other types of reactors and fuel cycles.
 - Liquid-fueled MSRs circulate salt containing fuel and fission products through the core, piping, and heat exchanger, resulting in a much larger area of high radiation requiring shielding than for traditional solid-fueled reactors.




**U.S. DEPARTMENT OF
ENERGY** | **Nuclear Energy**

Informational Seminar on Molten Salt Reactors – Introduction

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February 16, 2017

Introduction Slide 1. Title Slide.




**U.S. DEPARTMENT OF
ENERGY** | **Purpose of the Seminar**
Nuclear Energy


- **Provide information specifically for DOE/NE Federal managers on the concepts, technologies, fuel cycles, and challenges associated with Molten Salt Reactors (MSRs)**
 - Provide a review of various MSR technologies
 - Domestic and international, historic and current
 - Describe the reasons behind the recent interest in MSR technologies
 - Potential advantages, disadvantages, and challenges
- **Provide a summary of the current status of MSRs and the major challenges to development and deployment**

February 16, 2017 Informational Seminar on Molten Salt Reactors 2


Introduction Slide 2. Purpose of the Seminar.

| | | | |
|--|---|--|---|
|  U.S. DEPARTMENT OF ENERGY Nuclear Energy | | | Seminar Agenda |
| Introduction | | | |
| 9:00 – 9:25 AM | Opening Remarks Meeting Overview and Background | BP Singh (NE-42) R. Wigeland (INL) | |
| History, Concepts, and Current Technologies | | | |
| 9:25 – 9:55 AM | Module 1: Brief History of the ORNL MSR Program | G. Mays (ORNL) | |
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| 11:25 – 12:30 PM | Lunch | | |
| 12:30 – 1:00 PM | Module 2 – Part 2: Status of Technologies Under Development; Domestic and International | D. Holcomb (ORNL) | |
| MSR Basic Principles | | | |
| 1:00 – 2:00 PM | Module 3: Reactor Chemistry, Materials Compatibility, and Separations | Dave Williams (ORNL) | |
| 2:00 – 3:15 PM | Module 4: Reactor Safety, Physics, and Associated Fuel Cycle Performance | Ben Betzler (ORNL) Florent Heidet (ANL) | |
| 3:15 – 3:30 PM | Break | | |
| R&D Challenges | | | |
| 3:30 – 4:30 PM | Module 5: Safeguards Considerations and Challenges | G. Flanagan (ORNL) | |
| 4:30 – 5:00 PM | Module 6: Research, Development, and Deployment Challenges | G. Mays (ORNL) | |
| 5:00 – 5:15 PM | Concluding Remarks and Seminar Close | R. Wigeland (INL) BP Singh (NE-42) | |
| February 16, 2017 | | | Informational Seminar on Molten Salt Reactors 3 |

Introduction Slide 3. Seminar Agenda.

| | | | |
|---|--|--|--|
|  U.S. DEPARTMENT OF ENERGY Nuclear Energy | | | Introduction to “Molten Salt Reactors” (MSRs) |
| <ul style="list-style-type: none"> ■ Molten salt can be used as a coolant, like water or sodium, for use with solid nuclear fuels (oxide, metal, carbide, nitride, etc.) <ul style="list-style-type: none"> • Salt is liquid at operating temperature • This MSR is like a traditional reactor ■ Nuclear fuel can also be in a salt form (fluoride, chloride, etc.), and mixed with other salts, with the fuel / salt mixture called “fuel salt” <ul style="list-style-type: none"> • At normal operating temperatures, the fuel salt is a liquid, and is circulated through a “core” region where most nuclear fission occurs • When people discuss MSRs, they are most often referring to the liquid fuel version <ul style="list-style-type: none"> – The fuel salt containing the fuel is not really a coolant in this case since it does not cool the fuel, but is part of the fuel “matrix” – Coolant salt, if used, is another physically-separate salt ■ Terminology for discussing liquid fuel MSRs is different from that for more traditional solid-fueled reactors | | | |
| February 16, 2017 | | | Informational Seminar on Molten Salt Reactors 4 |

Introduction Slide 4. Introduction to "Molten Salt Reactors" (MSRs).




U.S. DEPARTMENT OF ENERGY
Nuclear Energy

MSRs and Nuclear Fuel Cycles

- **The Nuclear Fuel Cycle Evaluation and Screening (E&S) Study (October 2014, <https://fuelcycleevaluation.inl.gov>) identified fuel cycles with the potential for significant improvements in performance compared to the current U.S. once-through LWRs**
 - Technology-neutral descriptions of fuel cycles were used, e.g.,
 - Thermal, intermediate, and fast neutron spectrum reactors
 - For recycle fuel cycles, separations defined only by what is separated
- **Fuel cycle descriptions**
 - Once-through – fuel is used once and then disposed
 - Limited recycle – fuel is reprocessed and recycled at most a few times, followed by disposal
 - Continuous recycle – all spent fuel is reprocessed and recycled
- **Fuel cycle waste generation characteristics**
 - Once-through fuel cycles only dispose of spent fuel
 - Limited recycle fuel cycles dispose of spent fuel and HLW
 - Continuous recycle fuel cycles only dispose of HLW

February 16, 2017 Informational Seminar on Molten Salt Reactors 5

Introduction Slide 5. MSRs and Nuclear Fuel Cycles.



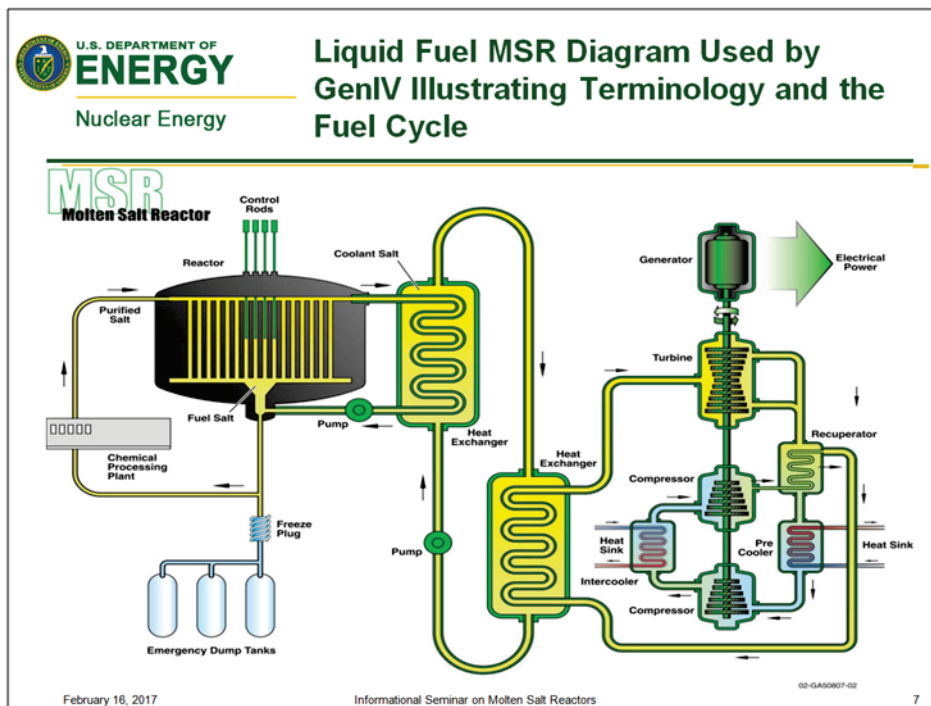
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Fuel Cycle Characterization of MSRs

- **Due to the use of a liquid fuel salt, volatile fission products automatically separate from the liquid fuel salt during operation**
 - Requires fission product capture, storage, and HLW production
 - Further online separations can be added to remove other fission products
 - In principle, all fission products could be removed from the fuel salt
- **What is the appropriate description of a liquid fuel MSR?**
 - Liquid fuel MSRs dispose of HLW in addition to any spent fuel (fuel salt) due to online separation of volatile fission products
 - If the salt is processed further to remove all fission products, only HLW would be disposed
- **As a result, the liquid fuel MSR itself is best described as a recycle fuel cycle, either limited or continuous, not just a reactor**
 - Thermal, intermediate, and fast spectrum versions are possible
 - The most promising fuel cycles from the E&S study all involved continuous recycle and fast spectrum reactors

February 16, 2017 Informational Seminar on Molten Salt Reactors 6

Introduction Slide 6. Fuel Cycle Characterization of MSRs.



Introduction Slide 7. Liquid Fuel MSR Diagram Used by GenIV Illustrating Terminology and the Fuel Cycle.

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

MSR Terminology and Fuel Cycles

- **It is very important to understand the terminology for MSRs, and to recognize that liquid fuel MSRs are more than just reactors, they are recycle fuel cycles based on their characteristics**
 - Replacing a once-through fuel cycle with a recycle fuel cycle can provide performance advantages as identified in the E&S study
 - However, any performance advantage for a specific system will depend on the system characteristics, and there are also potential disadvantages and challenges
 - There are many possibilities
- **The presentations in this seminar will discuss both kinds of MSRs, but the focus is on the liquid fuel MSR**
 - Many current concepts use this type of MSR
 - MSRs may have potential advantages, disadvantages, and challenges, as the following presentations will explain

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Introduction Slide 8. MSR Terminology and Fuel Cycles.

2.2 Module 1 – Brief History of the ORNL MSR Program

Gary Mays of ORNL assembled and gave this presentation that provided a review of the history of MSR development, mainly at ORNL, and the perspective for considering the current proposals and developments on MSRs. Among the significant points made during the presentation are the following:


- Development of MSRs in the U.S. began in the late 1940's at ORNL.
- ORNL designed, constructed, and operated two MSRs, the Aircraft Reactor Experiment (ARE, 1953-1954) and the Molten Salt Reactor Experiment (MSRE, 1960-1969).
- The original focus of MSR development was for aircraft nuclear propulsion, with civilian power reactor development starting in about 1958.
- ORNL successfully demonstrated a number of the key technologies for MSRs using the MSRE experiment.
- MSRE experience identified technical areas needing R&D for MSR development.
- Post-MSRE R&D made significant improvement on the identified MSR technical issues.
- Multiple international programs have been pursued, but at a smaller level of effort than the ORNL R&D efforts.

Module 1: Brief History of Development of MSRs

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Informational Seminar on Molten Salt Reactors
DOE Office of Nuclear Energy, Germantown, MD
February 16th, 2017

ORNL is managed by UT-Battelle
for the US Department of Energy

Module 1 – Slide 1. Title Slide.

Previewing MSR History Topics

- Development at ORNL (late 1940's - early 1980's)
 - 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
- Limited development work done internationally prior to recent program in China (to be covered in R&D challenges/needs presentation)
- Recent work done at ORNL since early 2000 on solid-fueled molten salt-cooled reactors

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Module 1 – Slide 2. Previewing MSR History Topics.

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)
 - **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)

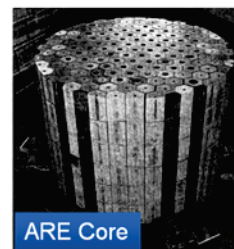
*** ORNL designed, constructed, and operated the only two MSRs - ARE and MSRE**



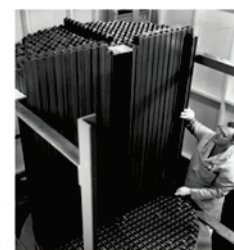
Convair NB-361
ORNL Museum Photo Archives

* ANP 1946-1961: \$1B

* ANP ended with advent of ICBM's in early 1960's



ARE Core



MSRE Core Assembly

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Module 1 – Slide 3. Molten Salt Reactor Technology has a Long-Term Development History.

1946 Nuclear Energy for Propulsion of Aircraft (NEPA) Project Started followed by 1951 Aircraft Nuclear Propulsion Program



- 1947 – Feasibility study for molten salt for ANP begun on “the initiative of V.P. Calkins, Kermit Anderson, and E.S. Bettis”
- 1949 – ORNL Selected as lead of AEC activities on ANP program with Alvin Weinberg as Director

- 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

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Module 1 – Slide 4. 1946 Nuclear Energy for Propulsion of Aircraft (NEPA) Project Started Followed by the 1951 Aircraft Nuclear Propulsion (ANP) Program.

1950-1952 MSRs Emerge As Primary Technology for ANP

- November 1949 - “No preferred reactor type, coolant mechanism, or shielding material for the nuclear airplane has yet been definitely chosen by any agency”
- August 1950 - “... studies have been initiated to ascertain whether uranium-bearing fused salt mixtures were of possible value in this connection.”
- December 1951 – “The search for a nonoxidative high-temperature fluid other than sodium which would be suitable as a reactor coolant has lead to the proposed use of fused fluoride salts containing uranium.”
- March 1952- “Studies of the performance and design of the circulating-fuel air- craft reactor are sufficiently encouraging that the first Aircraft Reactor Experiment (ARE) to be constructed by the Oak Ridge National Laboratory will be of this type.”

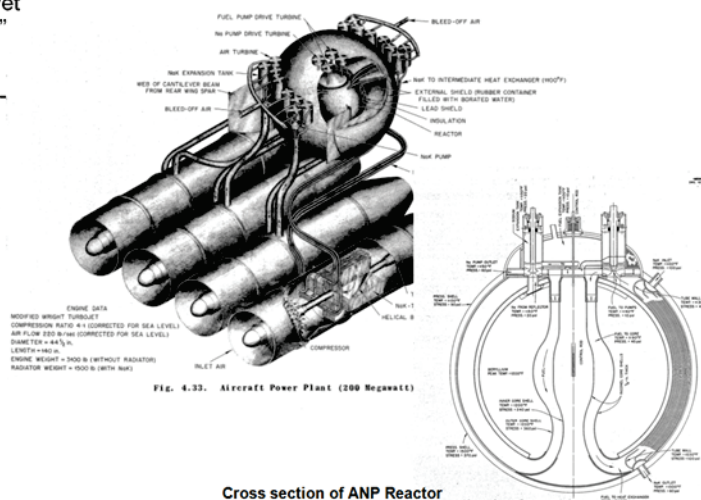


FIG. 4-33. Aircraft Power Plant (200 Megawatt)

Cross section of ANP Reactor

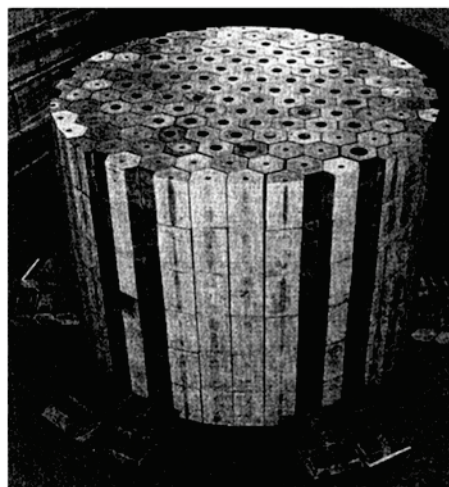
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Module 1 – Slide 5. 1950-1952 MSRs Emerge as Primary Technology for ANP.

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}U - 93%
 - Fuel system operated 241 hr before criticality
 - Nuclear operation over 221 hour period
 - Last 74 hours were in MW range
 - Produced 96 MW-hr of nuclear energy
 - Produced 2.5 MW of thermal power
 - Heat transferred from He loop to finned tube heat exchanger cooled by water

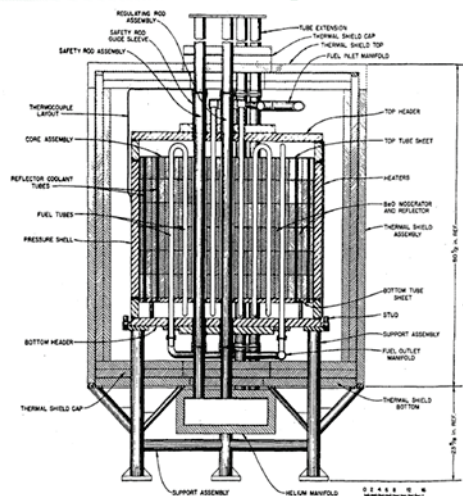
Aircraft Reactor Experiment



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Module 1 – Slide 6. 1954 Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept.

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



Core height: 90.93 cm
Core diameter: 84.60 cm
Fuel tube OD: 3.137 cm
66 fuel tubes
Pressure shell: Inconel
Pressure shell ID: 123.3 cm
Pressure shell thickness: 513 cm
Fuel tube wall thickness: 1.5 mm

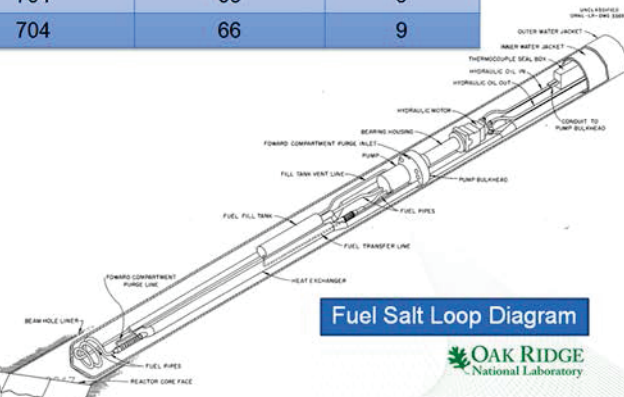
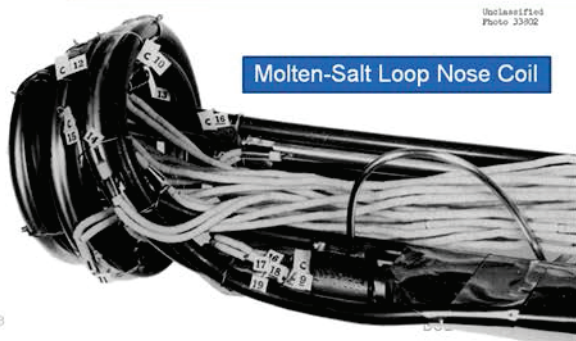
- Demonstrated ability to build and operate a hi-temp (860 °C) low power circulating fuel reactor
- Gaseous fission products were removed naturally through pumping action
- Very stable operation due to high negative reactivity coefficient
- Demonstrated load-following operation without control rods
- Low power experiments included
 - Reactor power calibration
 - Rod calibration
 - Prelim measurement of the temperature coefficient => negative at both subcritical and at low power
- High power experiments
 - Power levels: 10 kw, 100 kw, 500 kw, and 1MW
 - Temperature coefficient of reactivity
 - Reactor power calibration from process instrumentation
 - 25 hr Xe buildup experiment – no build up in salt
 - Rx temperature cycling - 21 times hi->low power
- Time lags - temp measurement responses - long transit time of fuel

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Module 1 – Slide 7. 1954 Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept.

ORNL Ran Five Pumped Fuel Salt Loops at INL's Materials Test Reactor Prior to the Aircraft Reactor Experiment

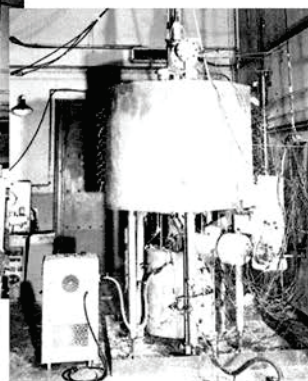
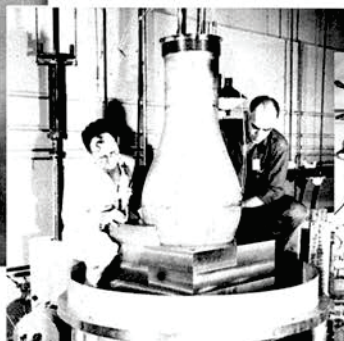
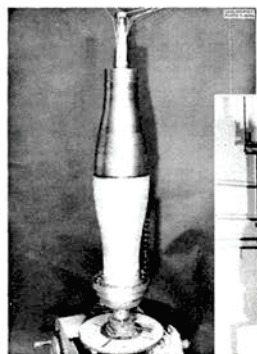
| Container Material | Salt (mole%) | Maximum Temperature (°C) | Average Power Density (W/cm ³) | Total Fission Power (kW) |
|--------------------|---|--------------------------|--|--------------------------|
| Inconel | 53.5 NaF – 40 ZrF ₄ – 6.5 UF ₄ | 816 | 200 | 27 |
| Inconel | 53.5 NaF – 40 ZrF ₄ – 6.5 UF ₄ | 816 | 232 | 31 |
| Inconel | 53.5 NaF – 40 ZrF ₄ – 6.5 UF ₄ | 871 | 250 | 34 |
| Alloy N | 62 ⁷ LiF – 37 BeF ₂ – 1 UF ₄ | 704 | 66 | 9 |
| Alloy N | 62 ⁷ LiF – 37 BeF ₂ – 1 UF ₄ | 704 | 66 | 9 |



Module 1 – Slide 8. ORNL Ran Five Pumped Fuel Salt Loops at INL's Materials Test Reactor Prior to the Aircraft Reactor Experiment.

1956 Low Power, Electrically Heated, High Temperature Critical Experiment operates at 1200 °F

The mockup differed from the ART principally in that the fuel was not circulated and there was no sodium in the reflector-moderator regions.



- Initial expt's at room temperature
- Established critical concentrations
- Measured temperature coefficients

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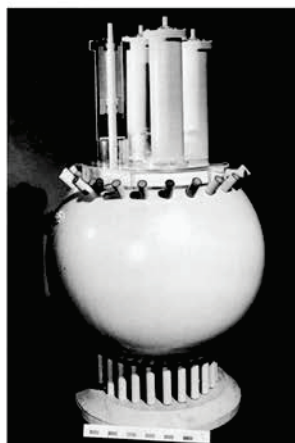
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Module 1 – Slide 9. 1956 Low Power, Electrically Heated, High Temperature Critical Experiment Operates at 1200°F.

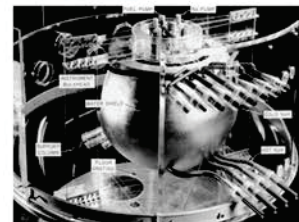
1961 ART Facility Construction and Engineering Test Unit Fabrication Were Near Completion When ANP Program Was Cancelled

ART Program Included Comprehensive Technology Development Effort

- 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



Full-Scale ART Model



Full-Scale ART Model



ART Building

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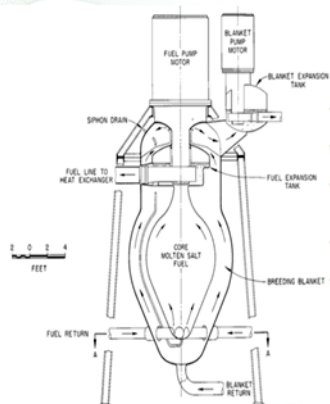
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Module 1 – Slide 10. 1961 ART Facility Construction and Engineering Test Unit Fabrication were near Completion when ANP Program was cancelled.

Civilian MSR Program Emerges ~1958

1958 Initial Civilian MSR Designs Heavily Leveraged ANP concept



- U^{235}/U^{233}
- U/Th Fuel Cycle
- Two Region/batch processing
- 640 MWt/260 MWe
- 1210 °F Exit Temperature

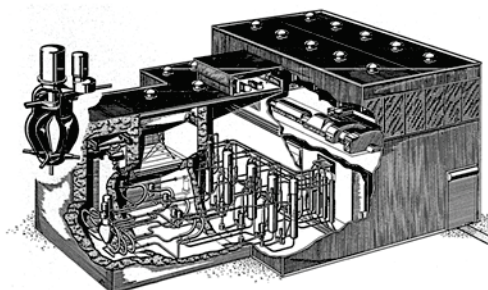
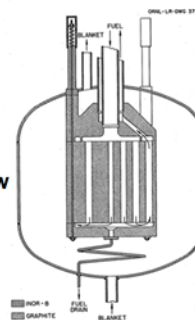


Fig. 1.1. Isometric View

1959 Design began to resemble what we now recognize as MSRs



MOX-B
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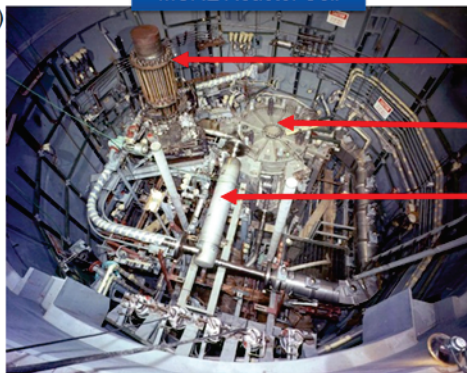
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Module 1 – Slide 11. Civilian MSR Program Emerges ~1958.

ORNL successfully demonstrated key MSR technology at the MSRE

Salt chemistry was well behaved (almost no corrosion)
Nuclear performance closely paralleled predictions
Molten-salts stable under reactor conditions

- 1965 (June) First Criticality
- 1966 (Dec) First Full Power Operation
- 1968 (Oct) First Operation on U-233
- 1969 (Dec) Shutdown
- Design features:
 - 8 MWt
 - Single region core - 33% U-235
- Graphite moderated
- Alloy 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



Fuel Salt Pump

Pressure Vessel

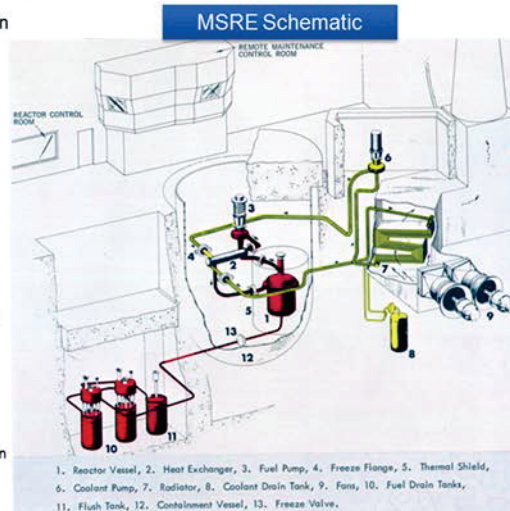
Heat Exchanger

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

Module 1 – Slide 12. ORNL Successfully Demonstrated Key MSR Technology at the MSRE.

MSRE successfully demonstrated key MSR technologies

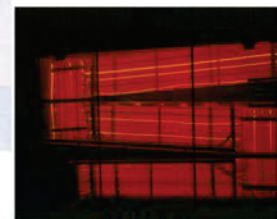
- Salt chemistry was well behaved (almost no corrosion)
=> Cr increased only 38-85 ppm - 3 yrs => 0.2 mil layer of Hastelloy N)
- Nuclear performance closely paralleled predictions
- Molten-salts stable under reactor conditions
 - He cover gas, O₂ & moisture <10 ppm
 - UF₄ to UF₃ maintained
- Fission products
 - Noble gases, Xe, and Kr efficiently stripped out in off gas system
 - Most other FP's remained in fuel salt
 - Analysis of specimens=>half of noble metals FP's plated out on graphite & metal surfaces exposed to salt
- Hastelloy-N performed as expected
 - Little change: ultimate strength, yield strength, creep rate
 - Rupture ductility & creep rupture life in specimens reduced
 - Improved specimens w/small amounts of titanium irradiated in MSRE showed improved ductility creep life
- Few grams of oil in off-gas line plugged fuel off gas system => installed larger/more efficient filter resolving problem



Heat rejected via air-blast radiators



MSRE core - graphite
- 69 ft³
- 513 core blocks



Module 1 – Slide 13. MSRE Successfully Demonstrated Key MSR Technologies.

MSRE—First Reactor to operate solely on U-233 (1968)



Glenn Seaborg starts MSRE U-233 operations



Capsule by which U-233 was added

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

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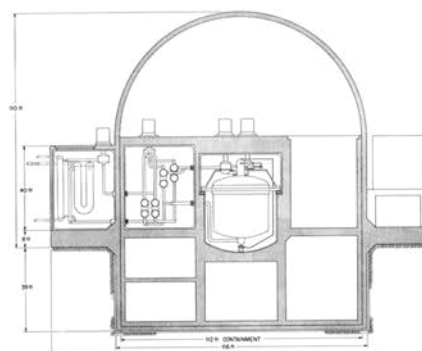
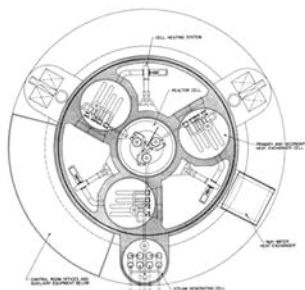
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Module 1 – Slide 14. MSRE – First Reactor to Operate Solely on U-233 (1968).

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

- 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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ORNL 2001-1660C EFG

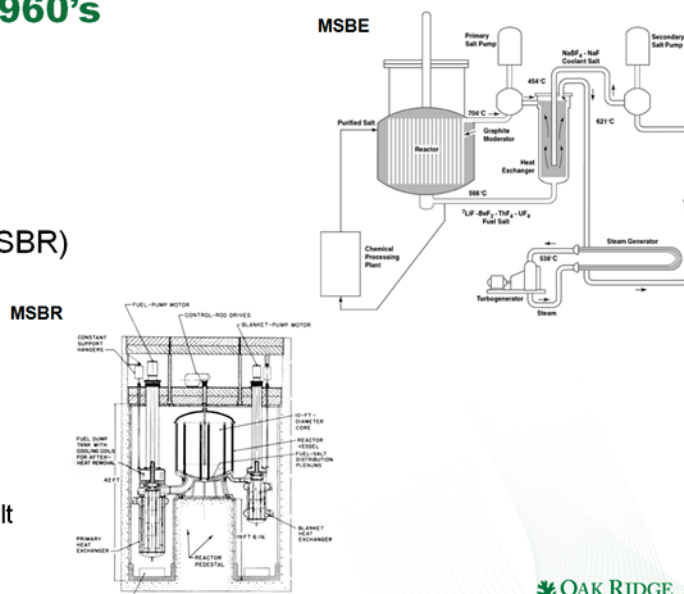
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Module 1 – Slide 15. Molten Salt Demonstration Reactor (MSDR) was Designed for 300 MW(e) Prototype Power Station.

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

- Molten Salt Breeder Experiment
 - 65 MW(e) (150 MW(t))
 - Single region – one fluid system
 - Fuel: $\text{LiF-BeF}_2\text{-ThF}_4\text{-UF}_4$
- Molten Salt Breeder Reactor (MSBR)
 - 1000 Mw(e) (2250 MWt)
 - 2-region-one-fluid system
 - Fuel: $\text{LiF}_4\text{-BeF}_4\text{-UF}_4$
 - Blanket: $\text{LiF}_4\text{-ThF}_4$
 - Breeding ratio: 1.06
 - Four fuel-salt circulation loops
 - Fuel salt separated from blanket salt by graphite tubes



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ORNL 2001-1661C EFG

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Module 1 – Slide 16. Significant Effort was expended on the Molten Salt Breeder Reactor Designs in the 1960's.

Technical Issues Identified from MSRE Operations and MSBR Studies

- Reactor materials – Testing of Hastelloy N, Hastelloy N modified w/Niobium and Titanium, Inconel 601, 316 SS in corrosion loops
 - Radiation embrittlement (common for Ni based alloys)
 - Te diffusion into grain boundaries => shallow cracking
- Reactor materials – graphite
 - Long-term radiation resistance – dimensional changes – some shrink/swell but maintained chemical compatibility with salt
 - Permeability to noble-gas and other volatile fission products (limited)
- Tritium management
 - Li-neutron reactions produce large amounts
 - Elemental ^3H transported to steam system
- MSRE small power fluctuations following a refueling (discussed earlier)
- Noble-metal fission products partially plated out on surfaces exposed to salt

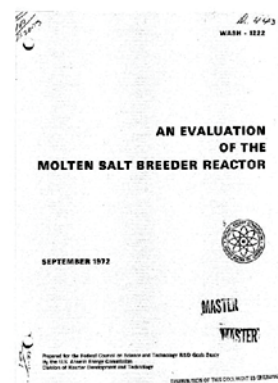
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Module 1 – Slide 17. Technical Issues Identified from MSRE Operations and MSBR Studies.

Post-MSRE R&D Made Significant Progress Towards Addressing WASH-1222 Identified Issues

| MSR Technical Issue | Comments - Post MSRE Advances |
|---|---|
| Structural material embrittlement | Modified Alloy N developed <ul style="list-style-type: none"> ~ 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 plateout | Understand mechanisms and design impacts |
| Tritium management | Acceptable solution demonstrated at engineering scale |
| MSRE power fluctuations | Not significant issue – minor bubble formation |
| Equipment design immaturity | Code rated heat exchanger designed for MSBR |
| Maintenance in high radiation areas | Recognized issue |



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

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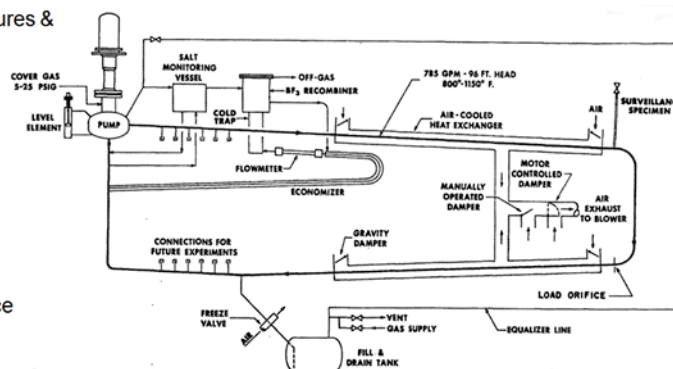
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Module 1 – Slide 18. Post-MSRE R&D made Significant Progress towards Addressing WASH-1222 Identified Issues.

ORNL's Coolant Salt Technology Facility Provided Engineering-Scale Experience with Molten Salts (Mid-1970's)

- Objective of CSTF – circulate coolant salt at temperatures & pressures typical of MSBR operating conditions
 - Sodium fluoborate (NaBF_4 - NaF)
 - Used coolant salt pump from MSRE
- Initial commissioning and testing from 1972 – early 1973
 - Salt circulated for 1060 hours
 - Testing focused on
 - Observing/measuring cavitation at load orifice
 - BF3 content of BF3-He off-gas stream
 - Chemical composition of salt
- Tritium experiments from 1974-1976 (MSBR to produce 2420 Ci/d)
 - Focus of exp'ts => determine if secondary salt would sequester tritium
 - Salt circulated for 8240 hours
 - Conducted 5 tritium tests
 - 90% tritium trapped in chemically combined form
 - Chemically reactive components (hydroxyl groups) are sink for tritium



- Hastelloy N pump – max flow 850 gal/m; 1790 rpm
- Piping - 10.7 m (35 ft) 5-in sched-40 Hastelloy N
- Operating temp range 850-1100 F
- Had containment and ventilation system

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Module 1 – Slide 19. ORNL's Coolant Salt Technology Facility Provided Engineering-Scale Experience with Molten Salts (Mid-1970's).

Denatured MSR (DMSR) Developed in early 1980's to Address Proliferation Concerns of the 1970s

- Online processing is not performed (other than Kr, Xe gas removal and noble metal plate out)
- Enriched uranium (19.75%) for startup and as feed material (to make up for limited processing)
- Operated as “once-through” system
- Lower reactor power density (no graphite replacement)
- Fueling
 - Thorium added only at initial loading
 - Enriched uranium added as required to maintain criticality
 - U-238 added as needed to maintain denatured state

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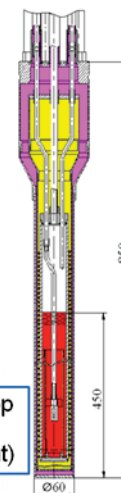
Module 1 – Slide 20. Denatured MSR (DMSR) Developed in Early 1980's to Address Proliferation Concerns of the 1970's.

Multiple Smaller International MSR Programs Have Been Pursued

- In 1970 – 1972, China built a zero-power cold state dissolved fuel salt reactor and reached criticality
- Russia has maintained a small-scale, broad-scope MSR program since 1976 that has included in-reactor test loops
- UK AEA and Swiss Federal Institute of Reactor Research both had fast spectrum chloride MSR design efforts in the 1960-70s with limited experimental programs
- US and India were collaborating prior their nuclear first weapons test
 - Thorium MSBR part of Indian *third phase* plan for nuclear power
 - Has a current FHR program for hydrogen production



Russian IR-8 test loop
 $66\text{LiF}-34\text{BeF}_2-\text{UF}_4$
(90% ^{235}U enrichment)

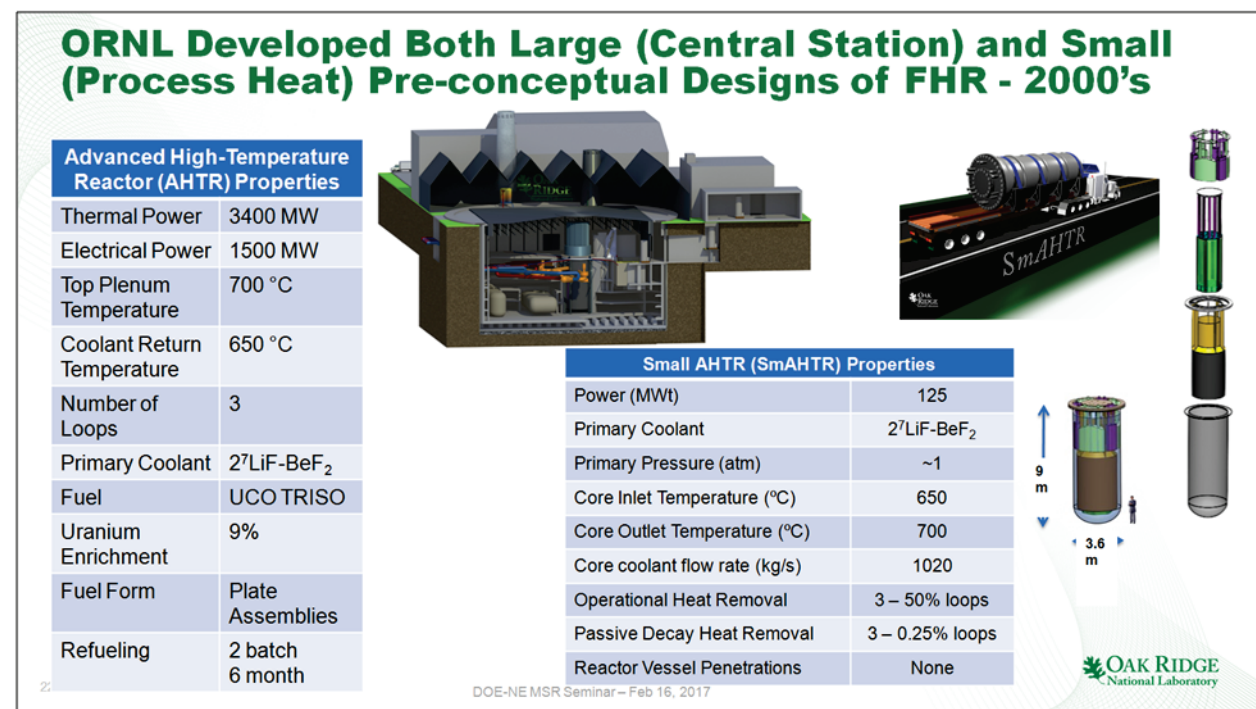


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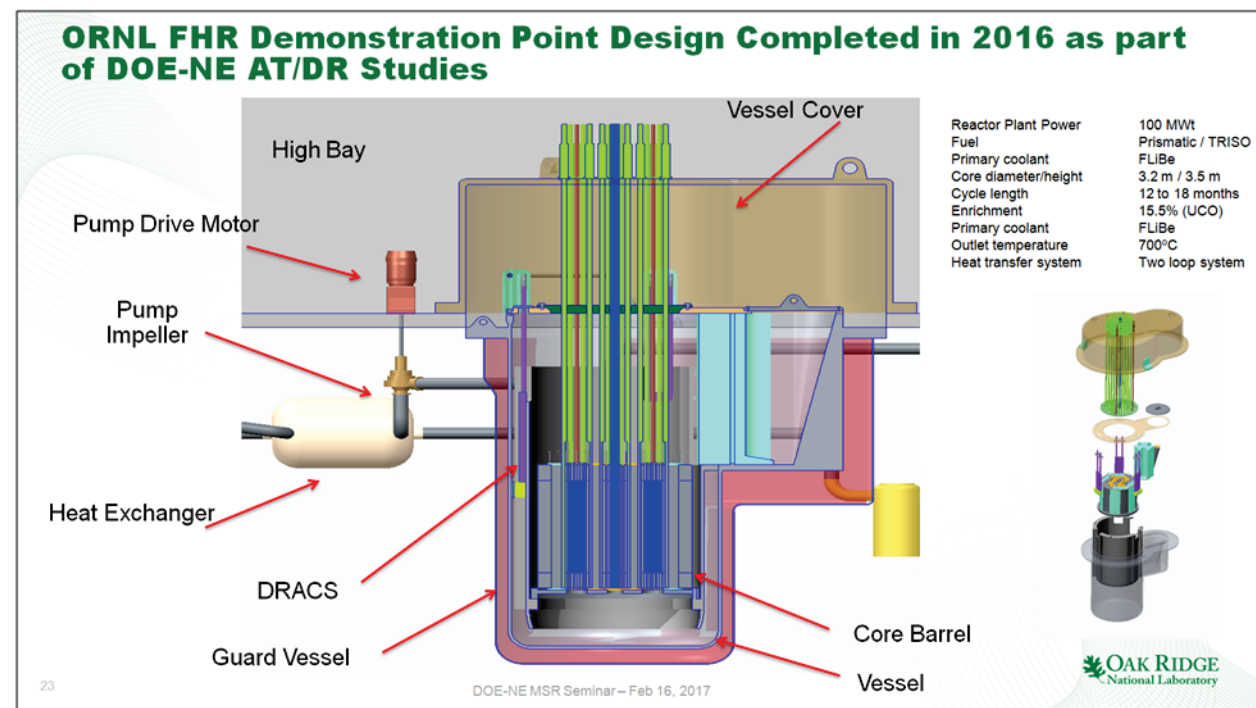
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Module 1 – Slide 21. Multiple Smaller International MSR Programs have been pursued.



Module 1 – Slide 22. ORNL Developed both Large (Central Station) and Small (Process Heat) Pre-conceptual Designs of FHR – 2000's.



Module 1 – Slide 23. ORNL HR Demonstration Point Design Completed in 2016 as Part of DOE-NE AT/DR Studies.

2.3 Module 2 – Introduction to MSR Technologies and Variants

David Holcomb of ORNL assembled and gave this presentation that provided technical descriptions of MSRs and the technologies, along with examples of MSRs that are currently under development. Among the significant points made during the presentation are the following:

Potential Advantages

- For the two basic types of MSRs, salt-cooled and liquid-fueled (also known as salt-fueled), there are variants for both a thermal and fast neutron spectrum.
 - Thermal spectrum resembles an LWR or a high temperature gas reactor (HTGR), while the fast spectrum resembles a sodium-cooled fast reactor as far as neutronic performance is concerned.
 - Fuel cycles based on U/Pu, U/TRU, and U/Th are all possible in MSRs.
 - Fissile breeder, burner, and converter designs are all possible in principle.
 - For salt-cooled, solid-fuel MSRs, once-through, limited recycle, and continuous recycle fuel cycles are all possible, while all liquid-fueled MSRs are recycle systems due to the inherent separation of volatile fission products from the molten fuel salt during operation.
- Molten salts are relatively stable under irradiation, have high boiling points, have excellent heat transfer characteristics (large heat capacity, low viscosity), and are chemically inert with respect to water and air.
 - High boiling points allow high temperature operation and low pressure, facilitating high thermal efficiency for electricity production.
 - The possibility of online refueling with liquid-fueled MSRs could potentially enable higher capacity factors, while online removal of volatile fission products allows slightly more effective use of fuel since fission products are typically neutron absorbers.
 - High boiling points and negative reactivity feedback for liquid-fueled MSRs facilitate incorporation of passive safety concepts in reactor design, while the high freezing temperature allows use of a freeze-plug concept to drain the liquid-fuel salt to a criticality-safe vessel in the event of reactor over-temperature conditions, shutting down the reactor.

Potential Disadvantages and Challenges

- Moisture content of the salt must be limited to control corrosion.
- For liquid-fueled MSRs:
 - Molten salts are initially transparent, but presence of fission products renders them opaque.
 - The radiation environment associated with circulating liquid fuel salt requires shielding, and maintenance activities are more challenging.
 - Nickel-based alloys used with some MSRs rapidly embrittle in high neutron flux environments at high temperature since neutron irradiation of nickel produces helium.
 - Large scale isotope separations for halide elements, e.g., to obtain ^7Li or ^{37}Cl , is immature and expensive.
 - Tritium production may be a significant issue especially when using lithium salts, and the proposed higher MSR operating temperatures make tritium containment more difficult (above 300°C tritium rapidly diffuses through structural alloys).

- The location of some fission products in the circulating liquid-fuel salt loop is uncertain.
- MSR modeling and simulation tools are immature and not well validated.
- High salt freezing temperatures mean that system temperatures must be managed to avoid unintended salt freezing.

Module 2: Introduction to MSR Technologies and Variants

David Holcomb

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Informational Seminar on Molten Salt Reactors,
DOE Office of Nuclear Energy, Germantown, MD
February 16th, 2017

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Module 2 – Slide 1. Title Slide.

Part 1: Potential Advantages, Disadvantages, and Challenges

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Module 2 – Slide 2. Part 1: Potential Advantages, Disadvantages, and Challenges.

What is an MSR?

- MSRs have two primary subclasses – salt-fueled and salt-cooled
 - Both subclasses have fast and thermal spectrum variants (temporally and spatially varying energy spectrums are also possible)
 - Salt-fueled systems (e.g. molten salt in fuel rods) can be cooled by non-fuel salt
 - Salt-fueled systems can employ non-salt coolants
- Fuel cycle of salt-fueled reactors is intimately connected with the reactor
 - U/Pu, Th/U, and TRU based fuel systems are all possible
 - Breeding, burning, converter fuel cycles are all possible
 - Once-through (including denatured), limited, and continuous recycle are all possible
 - Single and dual fluid systems are possible
- Fuel cycle of salt-cooled reactors resembles that of other solid-fuel reactors
 - Fast spectrum fuel cycle resembles SFR
 - Thermal spectrum fuel cycle similar to LWR or HTGR
- Tritium production is significantly larger in lithium salt systems than for LWRs

MSR design options are possibly even broader than those for water reactors, which include aqueous homogeneous, CANDUs, RBMKs, and LWRs

Any reactor that employs a molten salt to perform a significant function is a molten salt reactor.

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Module 2 – Slide 3. What is an MSR?

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

- Large 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, of course, there are challenges...

 Physical Properties of Coolants^a

| Coolant | T _{boil} (°C) | T _{sat} (°C) | ρ (kg/m ³) | C _p (kJ/kg °C) | ρC _p (kJ/m ³ °C) | k (W/m °C) | v · 10 ⁶ (m ² /s) |
|--|---------------------------|--------------------------|---------------------------|------------------------------|---|---------------|--|
| Li ₂ BeF 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-92NaBF 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 |

^aSalt 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-NaBF₄ 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, v is viscosity.

Molten Salt Performance Stems From Materials Characteristics

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Module 2 – Slide 4. What is so Special about Salts?

Selection of Fuel Form Substantially Alters the Reactor

Liquid Fuel

- More diverse fuel cycles possible
 - Improved fissile resource utilization
 - Decreased actinide wastes possible
- Fuel qualification will be size and radiation damage independent
- Higher radiation dose to first wall materials
- Fission products are mobile
 - Fewer available to release from core accidents
 - More complex containment (including ex-core fission products) and decay cooling

Solid Fuel (aka FHR)

- Closer analog to other reactor classes
 - Licensing path closer to known process
 - Safeguards resemble other solid fuel reactors
- Lower neutron flux on reactor vessel
 - Vessel embrittlement not an issue
- Lower cover gas handling requirements
- No fission products or actinides in salt
- Fuel forms not yet fully qualified
- TRISO fabrication is expensive

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Module 2 – Slide 5. Selection of Fuel Form Substantially Alters the Reactor.

Solid Fuel MSRs Have Fuel Format Options

TRISO

- Closer to qualification – AGR TRISO program
- Proven salt compatibility
- Can employ pebble format for on-line refueling
- Lower fissile loading
 - Requires > 5% ^{235}U enrichment

Accident Tolerant LWR Fuel

- SiC-SiC composite or molybdenum cladding possible
 - Fluoride salt compatible
- Enables higher fuel loading
 - < 5% ^{235}U enrichment
- Enables piggybacking on larger LWR industry

- FHR technology development roadmap was generated in 2013 under DOE-NE ART sponsorship
 - <http://www.osti.gov/scitech/biblio/1107839> (ORNL/TM-2013/401)
 - Depth and fidelity is limited by technology immaturity

6

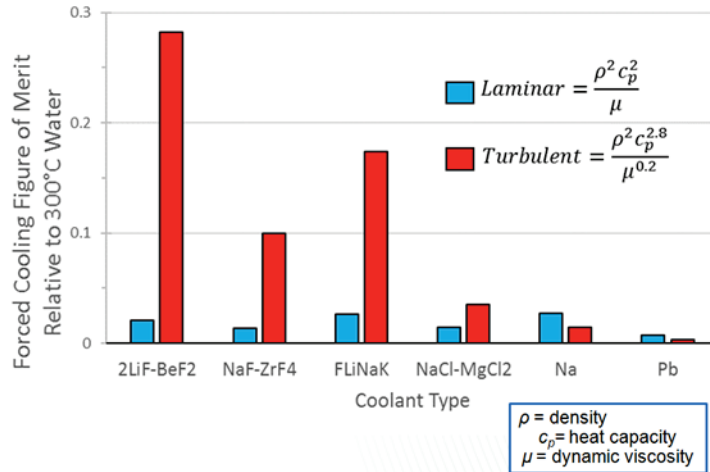
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Module 2 – Slide 6. Solid Fuel MSRs have Fuel Format Options.

Molten Salts Have Attractive Heat Transfer Properties But Significant Remaining Uncertainty

- Large heat capacity and low viscosity are key properties
- Heat transfer uncertainties affect operating margins and accident simulations
 - Fuel salts have larger uncertainties
- More targeted, controlled experimental data is required to improve the confidence in thermophysical property correlations



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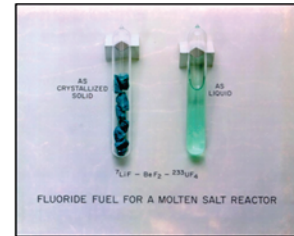
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Module 2 – Slide 7. Molten Salts have Attractive Heat Transfer Properties but Significant Remaining Uncertainty.

Potential Liquid-Fuel MSR Advantageous Features

- Enables high temperature at low pressure
 - High temperature increases thermal efficiency
 - Enables process heat products not economically feasible with LWRs
 - High exergy increases MSR heat delivery compatibility
 - Lower cooling water requirements increases siting flexibility
 - Low pressure removes primary driving force for radionuclide dispersal
 - Decreases component cost and weight
- Potential for readily apparent passive safety (reactivity, decay heat removal, and radionuclide containment)
 - Decreases licensing cost and uncertainties
 - Modular passive decay heat removal avoids core thermal size limit
 - Lack of cliff-like phenomena (e.g. DNB) relaxes safety system performance requirements
 - No off-site power requirements
 - Strong negative reactivity feedback
 - Avoids coolant voiding issues



8

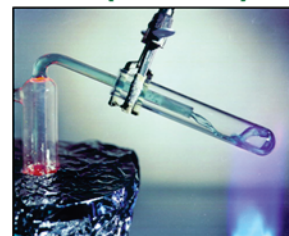
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Module 2 – Slide 8. Potential Liquid-Fuel MSR Advantageous Features.

Potential Liquid-Fuel MSR Advantageous Features (contd.)

- On-line refueling to maximize availability
- Potential to substantially reduce actinide waste production
 - Can employ used LWR actinides and/or excess plutonium as fuel
- No fuel fabrication (in the classic sense)
 - No cladding damage fuel burnup limits
- Vendor proliferation resistance claims are key to commercial development efforts
 - Breeder designs that include no separation of actinide materials (including no centrifuges) except for first core
 - Denatured designs that avoid on-site fissile material separations
 - Homogenized fuel results in an undesirable isotopic ratio a few months following initial startup (no short cycling)
 - Extreme radiation environment near fuel makes changes to plant configuration necessary for fuel diversion very difficult
 - High salt melting temperature makes ad hoc salt removal technically difficult
 - Low excess reactivity prevents covert fuel diversion



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Module 2 – Slide 9. Potential Liquid-Fuel MSR Advantageous Features (contd.)

Liquid Fuel MSR Challenges

- Maintenance activities in high radiation environments are much more challenging
- Some fuel cycles include on-site fissile materials separation (i.e. historic MSBR)
- Nickel based alloys rapidly embrittle in high neutron flux environments at high temperatures – some new designs employ internal shielding
- Clad alloys are largely unaddressed in high-temperature design code
- Chloride fuel salt properties have never been demonstrated in-core
- Large-scale isotope separations are immature and expensive
 - ^{37}Cl for some fast reactors and ^7Li for some thermal reactors
 - Tritium is a significant unresolved issue for high-temperature reactors that employ lithium salts
- Large scale components for fuel salt and cover gas are immature
- Distribution of fission products has significant remaining unknowns
- MSR modeling tools are immature and not well validated
- No licensing basis for commercial fluid-fueled systems
- High salt freezing temperatures

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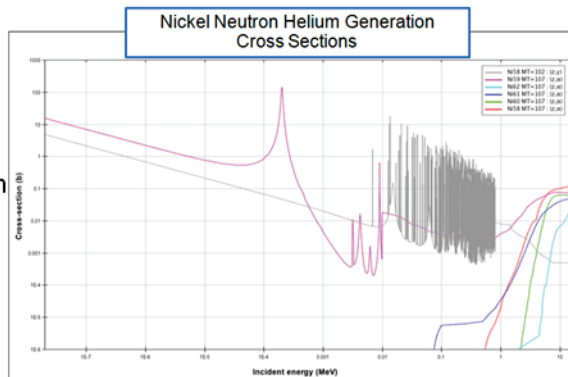
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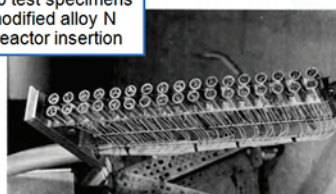
Module 2 – Slide 10. Liquid Fuel MSR Challenges.

Neutron Fluence Will Be a Significant Stressor For Container Materials

- Nickel based alloys embrittle when subjected to significant neutron fluxes at high temperatures
 - Neutron interactions with nickel generate helium
 - At high temperatures helium migrates to grain boundaries
- MSRE was ~1 year from shutdown due to decrease in vessel fracture toughness
- Modified Alloy N showed marked improvement up to ~700 °C
 - Formed finely dispersed carbide helium sinks
- Other radiation induced degradation mechanisms remain important



102 Creep test specimens of Nb modified alloy N prior to reactor insertion



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Module 2 – Slide 11. Neutron Fluence will be a Significant Stressor for Container Materials.

Isotope Separation Is a Significant Technical and Cost Issue for Both Fluoride and Chloride MSRs

- Some MSR design options call for tens of tons of separated lithium or chlorine
- Lithium enables optimal reactor physics
 - Lithium-6 is a large cross section thermal neutron absorber that yields tritium
 - Lithium isotope separation is also necessary for fusion and PWR chemistry control
 - Mercury amalgam based lithium isotope separation was performed at industrial scale in the 1950s for defense purposes
- Chlorine
 - Absorption reactions in ^{35}Cl both produces ^{36}Cl (long lived radionuclide) and results in a reactivity penalty
 - Lack of chlorine isotope separation technology was a key element in U.S. decision in 1956 to pursue thermal breeder MSR
- Modern organic chemistry techniques have the potential to enable large scale separation of both lithium and chlorine at reasonable cost

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Module 2 – Slide 12. Isotope Separation is a Significant Technical and Cost Issue for Both Fluoride and Chloride MSRs.

Tritium is Significant Issue For Lithium Bearing Salts

- Tritium is produced by neutron reactions with lithium, beryllium, and fluorine as well as being a ternary fission product
 - Tritium production levels are similar to HWRs
- Tritium chemical state in salt is determined by redox conditions
 - TF (oxidizing) or T⁺ (reducing)
- Above 300 °C tritium readily diffuses through structural alloys
 - Heat exchangers represent largest surface area for diffusion
- Escape through power cycle is potential route for radionuclide release into environment

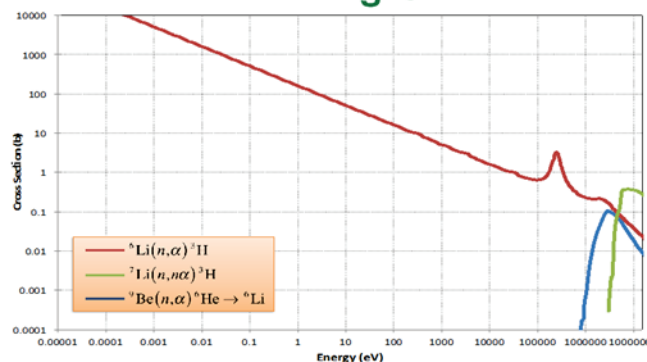


Table 1. Sources and rates of production of tritium in a 1000-MW(e) MSBR^a

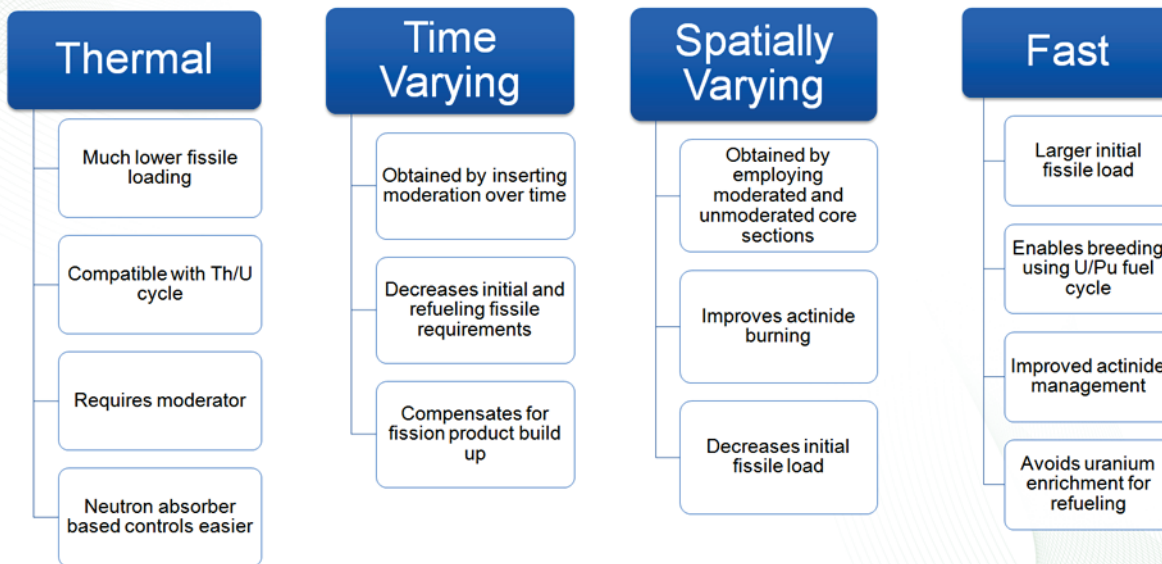
| | Production rate (Ci/day) |
|---|-----------------------------|
| Ternary fission | 31 |
| ⁶ Li(n, α) ³ H | 1210 |
| ⁷ Li(n, α) ³ H | 1170 |
| ⁹ Be(n, α) ⁶ He → ⁶ Li | 9 |
| Total | 2420 |

^aFrom Ref. 1.

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Module 2 – Slide 13. Tritium is a Significant Issue for Lithium Bearing Salts.

Reactor Neutron Spectrum is a Basic Design Decision



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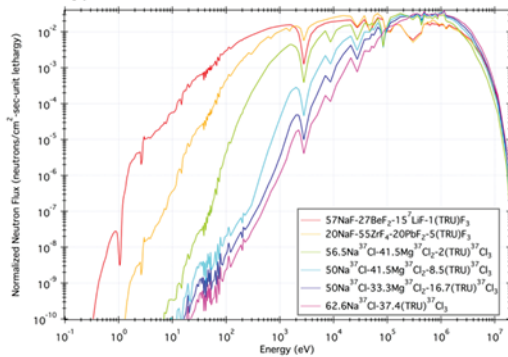
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Module 2 – Slide 14. Reactor Neutron Spectrum is a Basic Design Decision.

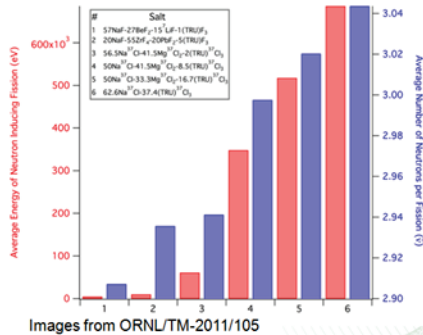
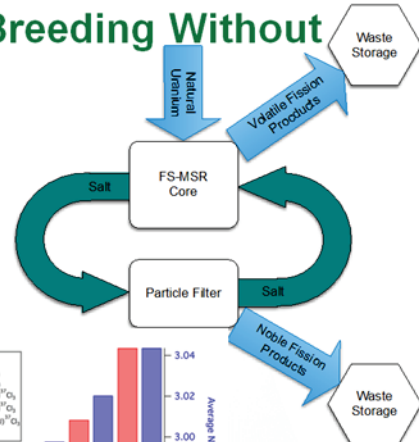
Fast Spectrum MSR May Achieve Net Breeding Without Actinide Separation From Fuel Salt

- Neutron absorption of fission products is dominated by thermal neutrons
- FS-MSRs have very few thermal neutrons
 - Thorium can be used without protactinium separation
- Neutron yield per fission increases substantially with incident neutron energy



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Module 2 – Slide 15. Fast Spectrum MSRs may achieve Net Breeding Without Actinide Separation from Fuel Salt.

Fluorine and Chlorine are the Leading Candidate Halides for Nuclear Fuel Salts

Fluorides

- Much larger in-core experience base
 - Two reactors, seven in-pile loops, many test capsules
- Corrosion control methods are well proven
 - Maintaining mildly reducing conditions key to structural alloy compatibility
- More electronegative than oxygen preventing use of protective oxide layers
- Radiolytically stable when liquid
- FLiBe diluent enables maintaining negative temperature reactivity coefficient with graphite moderator
 - Requires isotopically selected lithium-7
 - Results in significant tritium generation

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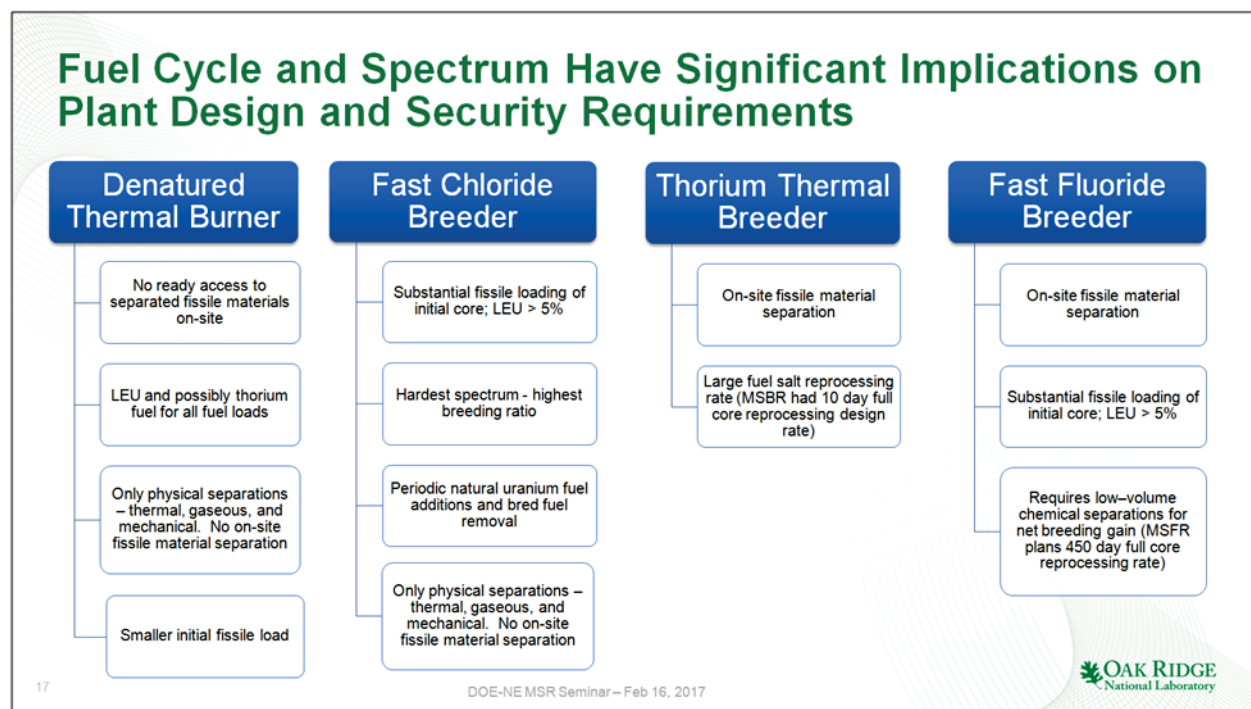
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Chlorides

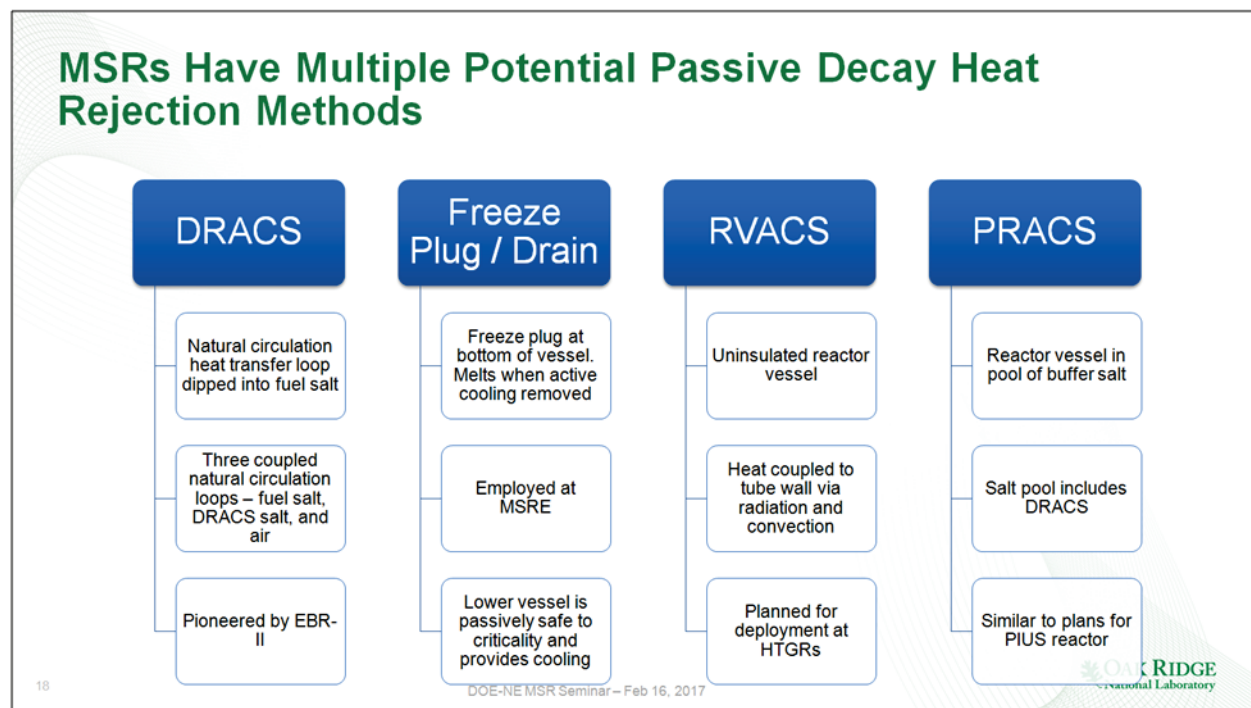
- Two isotopes ³⁵Cl & ³⁷Cl
 - ³⁵Cl has higher thermal neutron absorption and yields ³⁶Cl
- Lack of efficient means for isotope separation was rational for focusing on fluorides by the U.S. MSR program following 1956
- Almost no in-core experience
- Larger atomic mass promotes harder spectrum \Rightarrow increased neutron yield
- Dissolves larger quantities of fissile materials
 - Important for fast spectrum reactors
- Larger number of potential oxidation states results in more complex chemistry (-1, +1, +3, +4, +7)

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Module 2 – Slide 16. Fluorine and Chlorine are Leading Candidate Halides for Fuel Salts.

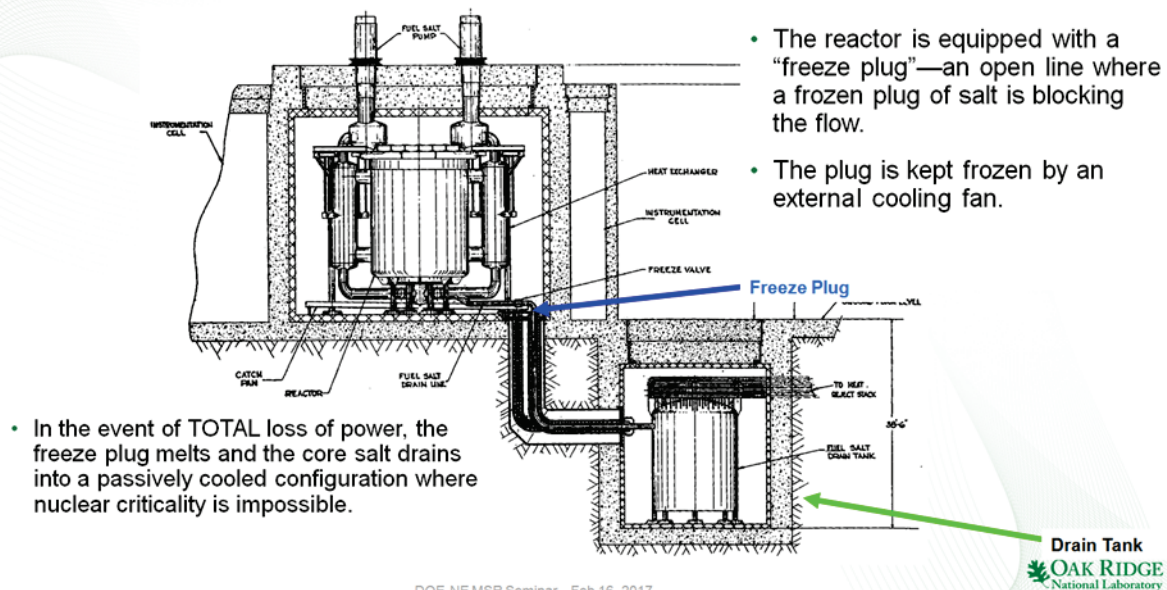


Module 2 – Slide 17. Fuel Cycle and Spectrum have Significant Implications on Plant Design and Security Requirements.



Module 2 – Slide 18. MSRs have Multiple Potential Passive Decay Heat Rejection Methods.

MSR Passive Safety: The Freeze Plug



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Module 2 – Slide 19. MSR Passive Safety: The Freeze Plug.

MSRs Can Also Be Designed With Containerized, Non-Circulating Fuel Salt

- Fuel pin configuration resembles vented “diving bell” SFR fuel pins
 - Small diameter pins with wire wraps
 - Initial *Aircraft Reactor Experiment* concept
- Avoids fuel pump – may avoid primary coolant pump
- Requires qualifying fuel tube (cladding)
 - Very high neutron fluence (dpa damage) to cladding
 - Helium embrittlement due to high neutron fluxes at high temperature
- Performance of chloride fuel salts remain unproven under in-core conditions
- Vented fuel has potential for blockage / pressurization
- Vented fuel does not provide containment
 - Escaping fission gasses and volatile fuel contaminate coolant salt increasing complexity of radionuclide distribution

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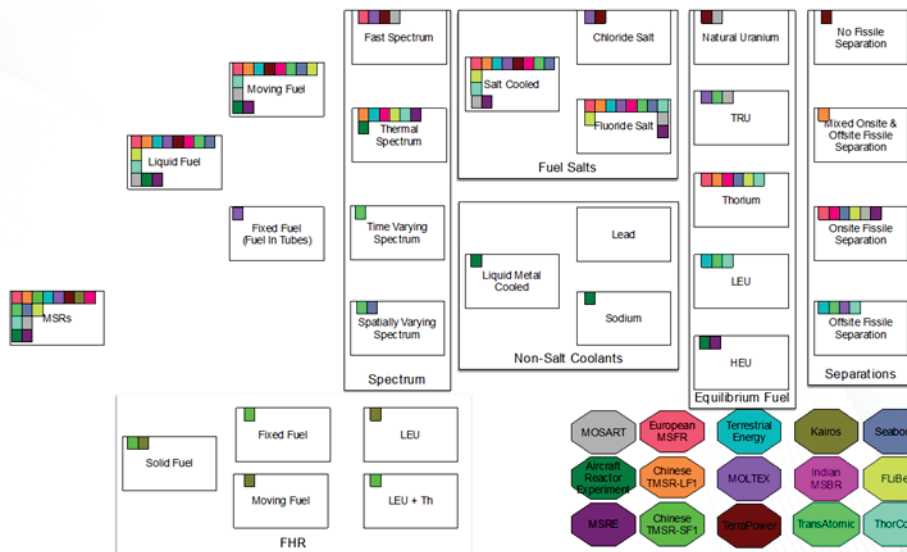
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Module 2 – Slide 20. MSRs can be designed with Containerized, Non-Circulating Fuel Salt.

Part 2: Status of Technologies Under Development: Domestic and International

Module 2 – Slide 21. Part 2: Status of Technologies Under Development: Domestic and International.

Multiple MSR Design Variants Have Been Considered



Module 2 – Slide 22. Multiple MSR Design Variants have been considered.

Terrestrial Energy USA

- U.S. 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



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400 MWth/module

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Module 2 – Slide 23. Terrestrial Energy USA.

Transatomic

- 5% LEU fuel salt – $\text{LiF}-(\text{Act})\text{F}_4$
- Zirconium hydride moderator in movable rods
- 1250 MWth
- Most detailed information available in Transatomic's white paper (version 2.1)
 - <http://www.transatomicpower.com/wp-content/uploads/2015/.../TAP-White-Paper-v2.1.pdf>
- Employs liquid metal extraction process (not described) to separate lanthanides as well as mechanical filtration and gaseous separations

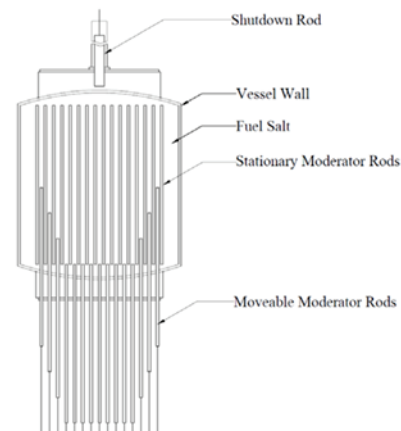


Image from TAP white paper

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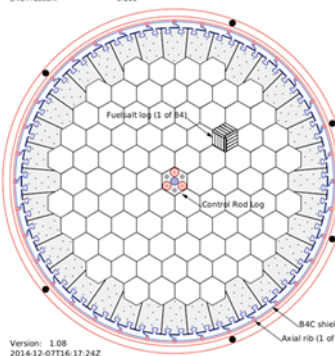
Module 2 – Slide 24. Transatomic.

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)

Number of fuel salt legs: 84
Salt Volume in loop(m³): 4.495
Moderator kg: 46289
Side reflector kg: 42197
Shield kg: 10462
B4C Fraction: 0.109

Hot Pot vessel ID(mm): 4860.96
Cold salt annulus width(mm): 5.00
Hot salt annulus width(mm): 25.24
Salt volume in annulus(m³): 1.15
Shield thickness(mm): 100.00



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557 MWth/module

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Module 2 – Slide 25. Thorcon Power.

TerraPower

- U.S. 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 support
- Additional information intended for release later in 2017

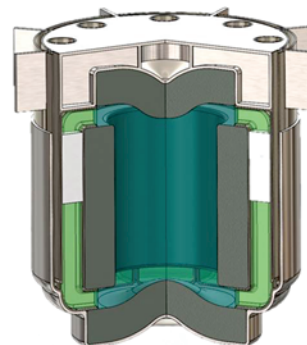


Image courtesy of TerraPower

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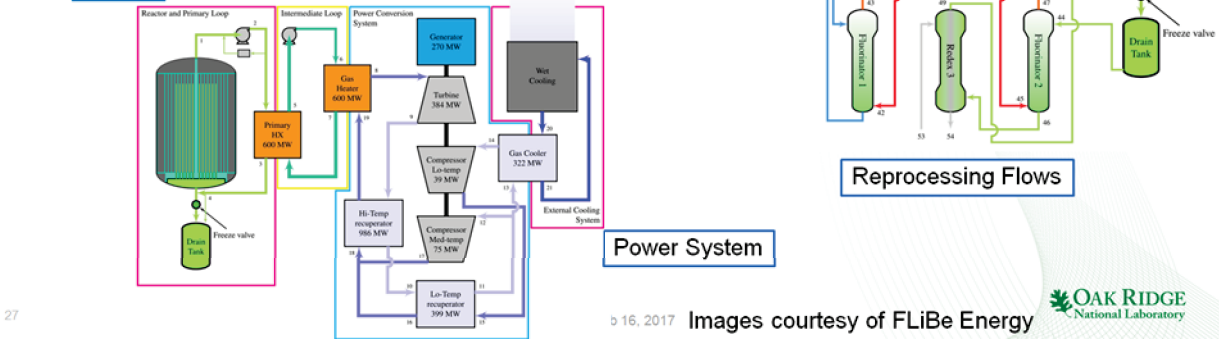
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Module 2 – Slide 26. TerraPower.

FLiBe Energy

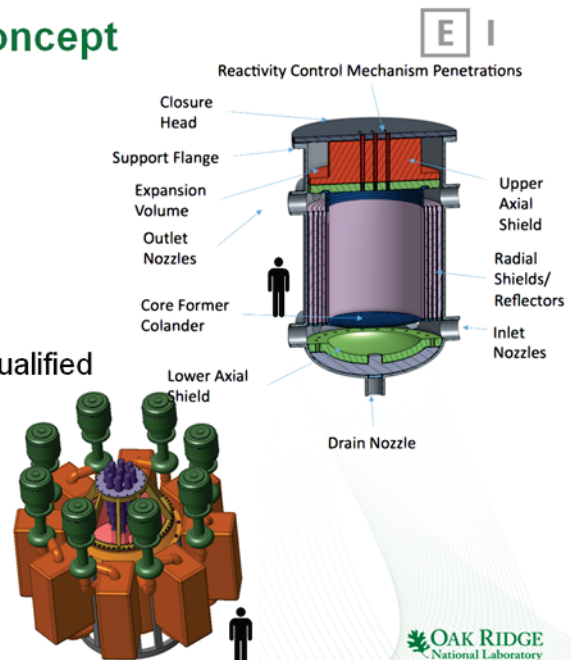
- U.S. Company
- Liquid Fluoride Thorium Reactor (LFTR) - Thorium breeder fuel cycle
- Graphite moderated, thermal spectrum, LiF-BeF₂-UF₄ fuel
- Freeze valve and drain tank based decay heat rejection
- Most detailed technical information available from EPRI technical report – 3002005460, October 2015
 - <http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=00000003002005460>



Module 2 – Slide 27. FLiBe Energy.

Elysium Molten Salt Reactor Concept

- Rated electric output 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

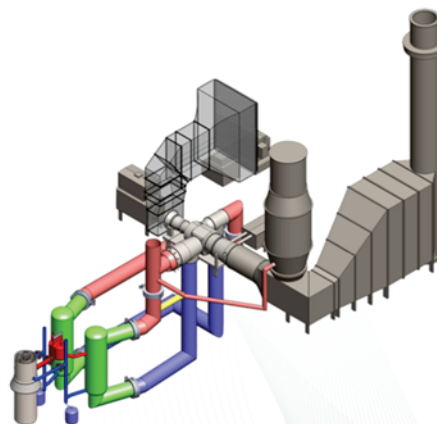


Module 2 – Slide 28. Elysium Molten Salt Reactor Concept.

Kairos Power



- Only solid-fuel commercial MSR concept in U.S.
 - 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



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Module 2 – Slide 29. Kairos Power.

Moltex Energy

- UK company - Stable Salt Reactor (SSR)
- $\text{NaCl}(\text{Act})\text{Cl}_3$ fuel salt (LEU < 15%)
 - Redox stabilized with Zr/ZrCl couple
- NaF-ZrF_4 coolant salt
 - Redox buffer $\text{ZrF}_2/\text{ZrF}_4$
- 750 MWth
- Vented fuel pins – natural circulation
- Steel cladding – used in Dounreay SFR
- RVACS decay heat removal
- IAEA ARIS database

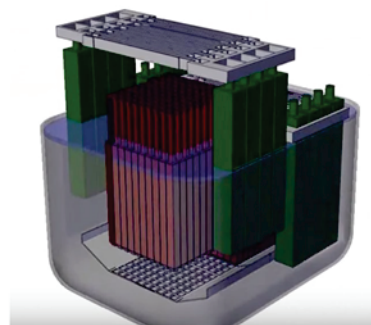


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Module 2 – Slide 30. Moltex Energy.

Another U.S. Design Has Recently Been Proposed Without Significant Publicly Available Information

- ATRC

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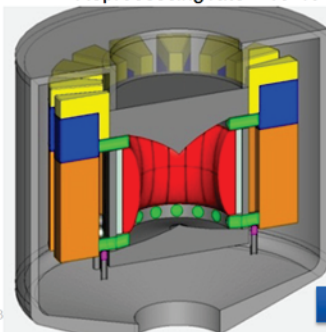
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Module 2 – Slide 31. ATRC.

European Union and Russian Federation are Examining Fast Spectrum Fluoride Salt MSRs

EU MSFR includes both fertile and fissile salts in single fluid

- $\text{LiF-ThF}_4\text{-UF}_4\text{-(TRU)F}_3$ with 77.7-6.7-12.3-3.3 mol%
- U enriched at 13%
- Melting point = 594 °C
- Reprocessing rate = 10-40 liters/day



MSFR Core Cross-Section

Russian MOSART can be configured as a burner or breeder

| System | burner | / breeder |
|--|---|--|
| Fluid streams | 1 | 2 |
| Power capacity, MWt | 2400 | 2400 |
| Fuel salt inlet/outlet temperature, °C | 600 / 720 | 600 / 720 |
| Fuel salt composition, mole % | 72LiF 27BeF ₂ 1TRUF ₃ | 75LiF 16.5BeF ₂ 6ThF ₄ 2.5TRUF ₃ |
| Blanket salt composition, mole % | no | 75LiF 5BeF ₂ 20ThF ₄ |

Both designs employ on-site fissile material separations

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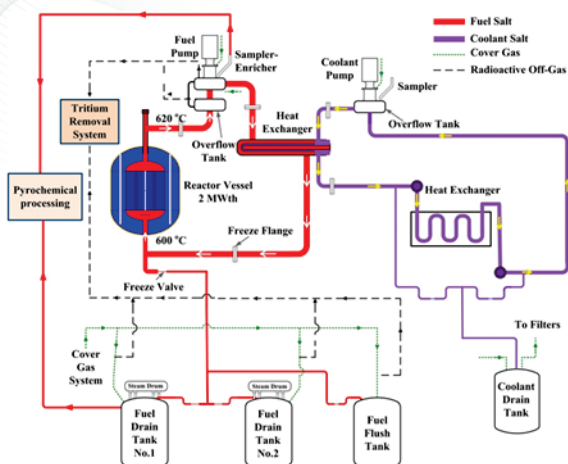
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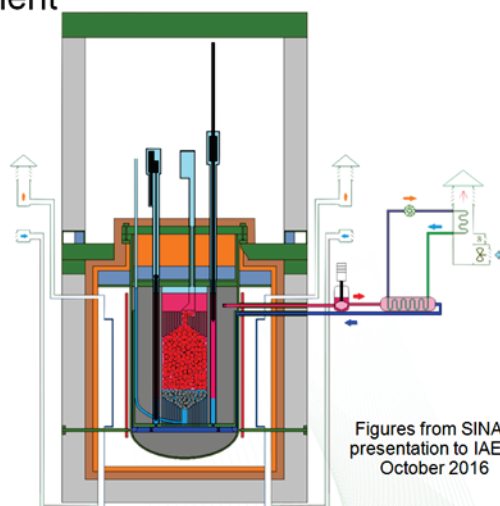
Module 2 – Slide 32. European Union and Russian Federation are Examining Fast Spectrum Fluoride Salt MSRs.

China is Pursuing Both Solid and Liquid Fueled MSR

- Thorium utilization is a key program element



Thorium Molten Salt Reactor – Liquid Fuel 1 Schematic



Thorium Molten Salt Reactor – Solid Fuel 1 Schematic

Figures from SINAP presentation to IAEA-October 2016

Module 2 – Slide 33. China is Pursuing both Solid and Liquid Fueled MSRs.

Most U.S. MSR Technology Developers Have Recognized MSR Issues

- Avoid creating separated streams of fissile materials on-site
 - Denatured or very hard spectrum
 - FLiBe Energy sole publically acknowledged exception
- Minimize radiation embrittlement of reactor vessel
 - Interior shielding
 - Periodic replacement
 - Use of cladding to separate chemical compatibility from structural requirements
- Minimizing maintenance within shielding
 - Design for automated replacement years after shutdown or following flushing
- Aqueous or organic chemistry routes to large scale, lower cost isotope separation
- Tritium management technology (albeit immature) is integrated into lithium bearing salt designs
 - Stripping, absorbing, and blocking are all being considered

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Module 2 – Slide 34. Most U.S. MSR Technology Developers have recognized MSR Issues.

2.4 Module 3 – Reactor Chemistry, Materials Compatibility, and Separations

David Williams of ORNL assembled and gave this presentation that provided information on the chemistry of molten salts, compatibility issues with structural materials, and the possible separations when using liquid-fueled MSR. Among the significant points made during the presentation are the following:

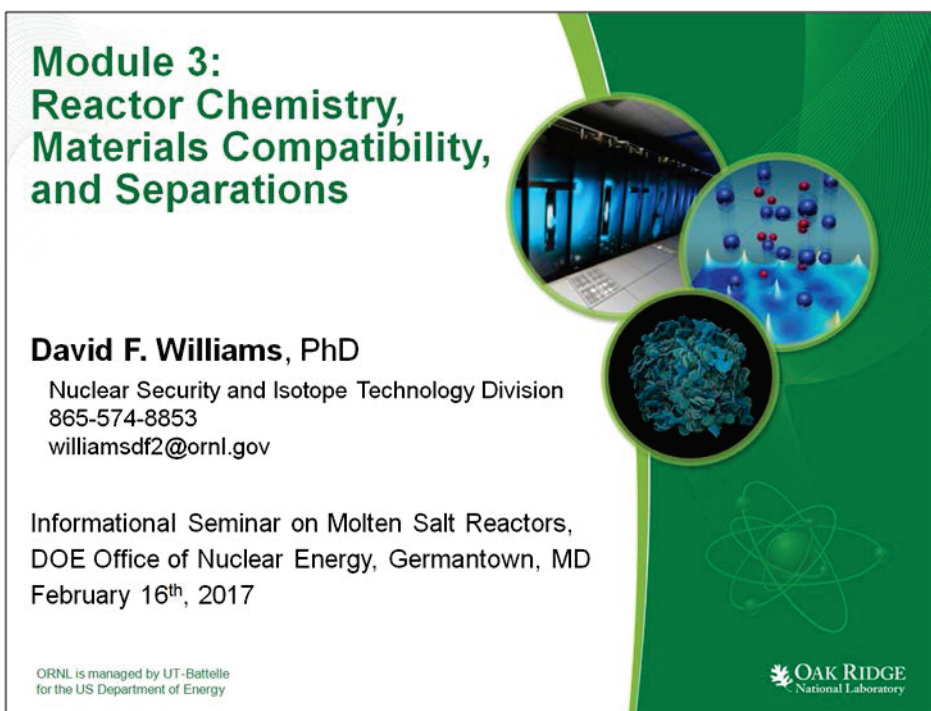
- Many fluoride- and chloride-based salts have been studied for use in liquid-fueled MSRs.
- Choice of salt and the composition can affect properties, including actinide solubility for liquid-fueled MSRs, vapor pressure, and freezing and melting points.
- For liquid-fueled MSRs, fission leads to chemically oxidizing conditions in the salt, with free halide available since while some fission products can form compounds with halide, others do not. Control of the oxidizing condition is needed to avoid corrosion of structural materials, although impurities (such as some fission products like tellurium with liquid-fueled MSRs) in the salt can also cause corrosion.
- Tritium production is primarily from ^6Li (which is why use of ^7Li is desirable for lithium-bearing salts as mentioned for Module 2, although this requires isotopic separation of lithium).
- There are significant materials corrosion issues with molten salts, particularly in liquid-fueled MSRs due to the development of oxidizing conditions in the salt resulting from fission. Structural materials also need to withstand exposure to air on outer surfaces for high temperatures.
- Online separations of fission products with liquid-fueled MSRs is described as being a "heavy-lift", i.e., difficult, and the suggestion is made to consider designs with offline batch reprocessing as is done with more traditional solid-fueled reactors, although volatile fission products will always separate from the salt during operation and will need to be managed.

Waste Production and Management

- Remediation activities related to the MSRE have resulted in several findings:
 - Solid halide salts are damaged by radiation and darken, corresponding to the development of metal regions and the release of halide gas.
 - Maintain fuel salts above 150°C to prevent radiolysis.
 - Some fission products were deposited in graphite porosity for the MSRE graphite.
 - Waste forms for the salts need to be developed.

Primary Research Issues

- Understanding and managing salt radiolysis.
- Understanding and managing "noble" fission products, i.e., those fission products that are not soluble in salt, since they have the potential to precipitate from the salt at any location in the circulating liquid-fuel salt loop.

The slide has a green background with a white sidebar on the left. The title 'Module 3: Reactor Chemistry, Materials Compatibility, and Separations' is in green. Below it is the speaker's name 'David F. Williams, PhD' and contact information. The main area features three circular images: a reactor core, a molecular model, and a material structure. The Oak Ridge National Laboratory logo is in the bottom right.

Module 3: Reactor Chemistry, Materials Compatibility, and Separations

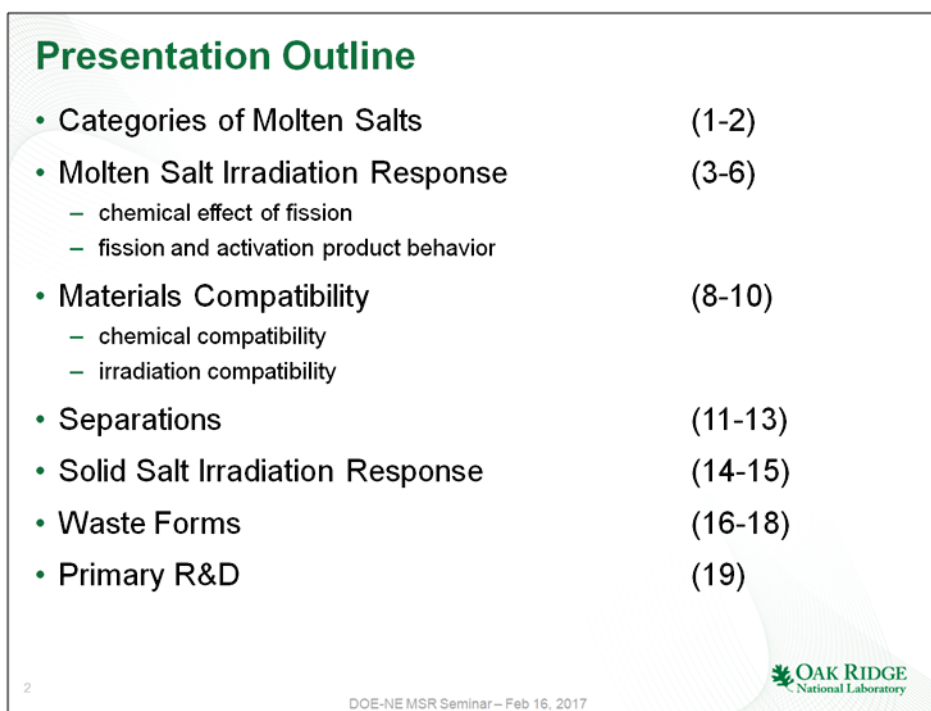
David F. Williams, PhD
Nuclear Security and Isotope Technology Division
865-574-8853
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Informational Seminar on Molten Salt Reactors,
DOE Office of Nuclear Energy, Germantown, MD
February 16th, 2017

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Module 3 – Slide 1. Title Slide

The slide has a white background with a green sidebar on the left. The title 'Presentation Outline' is in green. Below it is a bulleted list of topics and slide ranges. The Oak Ridge National Laboratory logo is in the bottom right.

Presentation Outline

- Categories of Molten Salts (1-2)
- Molten Salt Irradiation Response (3-6)
 - chemical effect of fission
 - fission and activation product behavior
- Materials Compatibility (8-10)
 - chemical compatibility
 - irradiation compatibility
- Separations (11-13)
- Solid Salt Irradiation Response (14-15)
- Waste Forms (16-18)
- Primary R&D (19)

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Module 3 – Slide 2. Presentation Outline.

Salt Categories for Reactor Application

Fluorides

BeF₂-based salts

e.g., ⁷LiF-BeF₂, NaF-BeF₂
(MSRE / MSBR)

ZrF₄-based salts

e.g., NaF-ZrF₄

Alkaline salts

⁷LiF-NaF-KF (FLINAK)

Actinide-rich eutectics

⁷LiF-ThF₄

NaF-UF₄

Chlorides

Actinide-rich eutectics

e.g., KCl-UCl₃

MgCl₂-based salts

e.g., NaCl-MgCl₂

Coolant or Processing only

Fluoroborates

e.g., NaF-NaBF₄

Alkaline chlorides

e.g., LiCl-KCl

Nitrates

Halide salts are thermally stable and immune to radiation damage when molten.

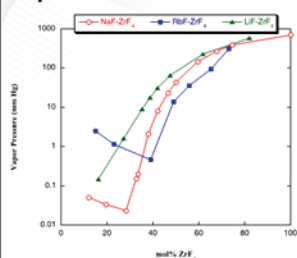


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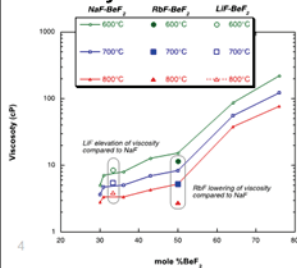
Module 3 – Slide 3. Salt Categories for Reactor Application.

Salt composition influences speciation and properties

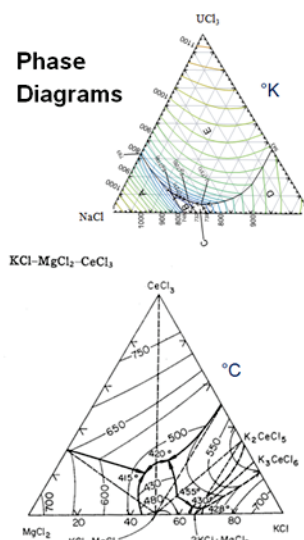
Vapor Pressure



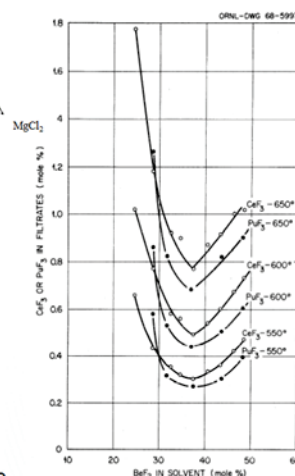
Viscosity



Phase Diagrams



Trivalent Solubility



There are gaps in the knowledge base needed to support new salt compositions.

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Module 3 – Slide 4. Salt Composition Influences Speciation Properties.

The Chemical Effect of Fission in Molten Salts is Typically Oxidizing

No net radiation damage has been observed in molten halides.

However after fission, halide anions from the parent actinide are not completely accepted by the fission products.

This imbalance leads to free fluoride that seeks the most susceptible specie to oxidize. In the MSRE this oxidation was accepted by the small amount of UF_3 that accompanied UF_4 in the fuel salt.

Periodically small amounts of reductant (Be-metal) were added to the MSRE fuel salt to counterbalance this oxidizing effect, maintain a UF_3/UF_4 redox ratio "window", and reduce container corrosion.

More about corrosion later. Redox is also important to understand how fission products distribute into three groups:

- Gases
- Salt seekers (halides)
- Insoluble fission products ("noble" metals group)

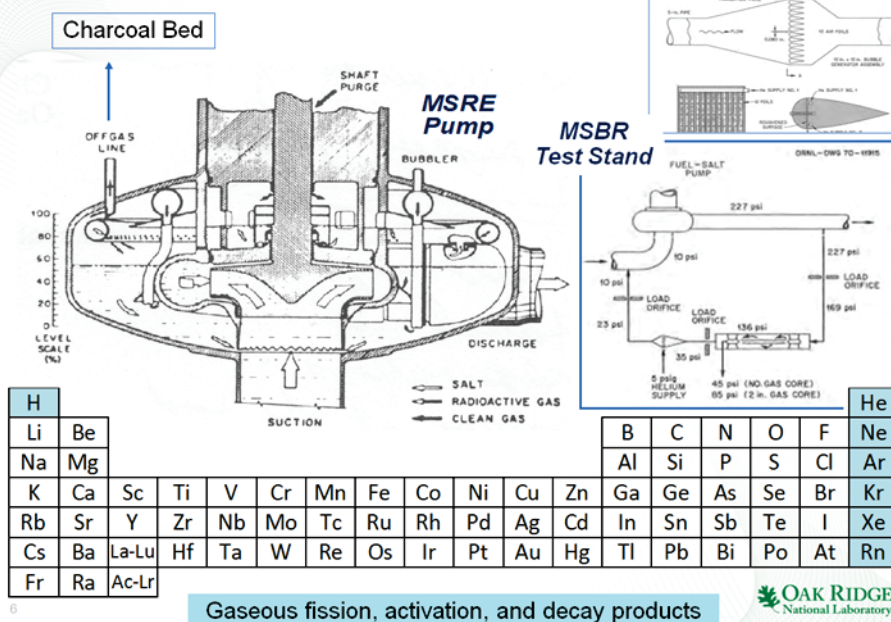
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Module 3 – Slide 5. The Chemical Effect of Fission in Molten Salts is Typically Oxidizing.

Fission Gas Poison Removal



Gaseous fission, activation, and decay products

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Module 3 – Slide 6. Fission Gas Poison Removal.

Tritium Production is primarily from ^6Li

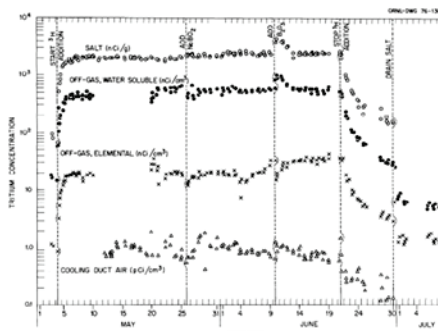
Large source term only for salts with lithium
 Little penetrating radiation, ~15y half-life
 Potential to create steam-generator-water LLW

At high-temperatures tritium penetrates most metals:

- same as in High Temperature Gas Reactors;
- no possibility of barrier film on surfaces wet by salt.

- Solution demonstrated for the fluoroborate coolant: the oxygen moiety in the salt captured tritium.

- This approach might be used with other molten salts, or
 - tritium transport barriers/traps could be external to the primary salt-wetted surface.



G. T. Mays et al., ORNL/TM-5759 (1977)

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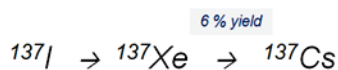
Module 3 – Slide 7. Tritium Production is Primarily from ^6Li .

Soluble Fission Products – “salt seeking fluorides” (MSRE experience)

A few elements are very sensitive to redox changes:

Nb behavior changed during MSRE operation after addition of Be^0

Transitional (*soluble* → *gas* → *soluble*) decay example:



fuel salt loop residence times
 = loop volume / flow rate
 typically < 1 minute

| | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|----|----------------------|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|---------------------|----|----|---|---|----|----|--|--|--|--|--|--|--|--|--|----|
| H | 25 sec. half-life | | | | | | | | | | | | | | | | 4-min. half-life | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | | | | | | | B | C | N | O | F | Ne | | | | | | | | | | |
| Na | Mg | | | | | | | | | | | | | | | | | Al | Si | P | S | Cl | Ar | | | | | | | | | | |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr | | | | | | | | | | | | | | | | |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe | | | | | | | | | | | | | | | | |
| Cs | Ba | La-Lu | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn | | | | | | | | | | | | | | | | |
| Fr | Ra | Ac-Lr | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

soluble

insoluble

sometimes soluble

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Module 3 – Slide 8. Soluble Fission Products.

Insoluble Fission Products (“noble” metals) (MSRE experience)

Behavior can change with redox state of salt:

Te is less “metallic” under reducing conditions (discussed later in corrosion slide)


Transitional (*soluble* → *insoluble* → *soluble* → *gaseous*) decay chains:

Noble Metal Fission Product Summary (220,000 g Pu)

| Noble Metal | Cumulative Yield of Precursor % | Direct Yield of Noble Metal % | Half-life of Precursor | Half-life of Noble Metal |
|-------------------|---------------------------------|-------------------------------|------------------------|--------------------------|
| ⁹⁹ Tc | 5.00 | 0.0 | 2.1 min | 66.5 hrs |
| ¹⁰³ Zr | 5.00 | 0.0 | 1.2 min | 39.7 days |
| ¹⁰⁶ Zr | 0.39 | 0.0 | <1 min | 1.0 ⁺ yrs |
| ¹²⁹ Xe | 0.71 | 0.0 | 1.6 hrs | 37 days |
| ¹³⁴ Xe | 4.71 | 0.0 | 0.1 min | 77 hrs |
| ¹³⁵ Xb | 6.22 | 0.0 | 65 days | 35 days |

| | | | | | | | | | | | | | | | | | | | | | |
|----|----|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|---|---|----|----|
| H | | | | | | | | | | | | | | | | | He | | | | |
| Li | Be | | | | | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr | | | | |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe | | | | |
| Cs | Ba | La-Lu | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn | | | | |
| Fr | Ra | Ac-Lr | | | | | | | | | | | | | | | | | | | |

soluble
insoluble
sometimes soluble



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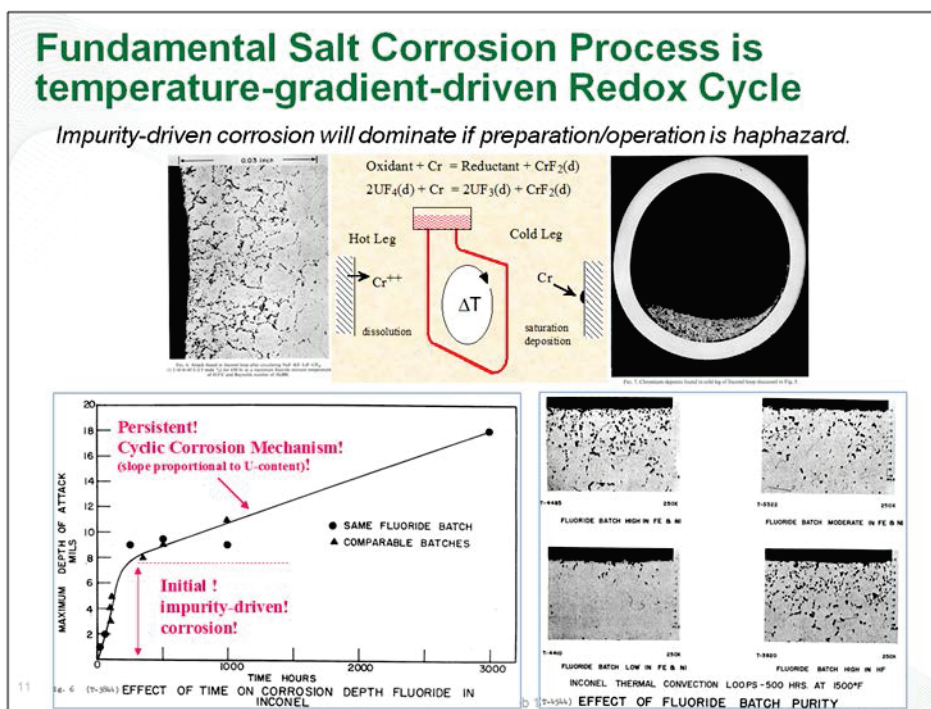
Module 3 – Slide 9. Insoluble Fission Products.

Material Compatibility: Balancing corrosion resistance and irradiation durability

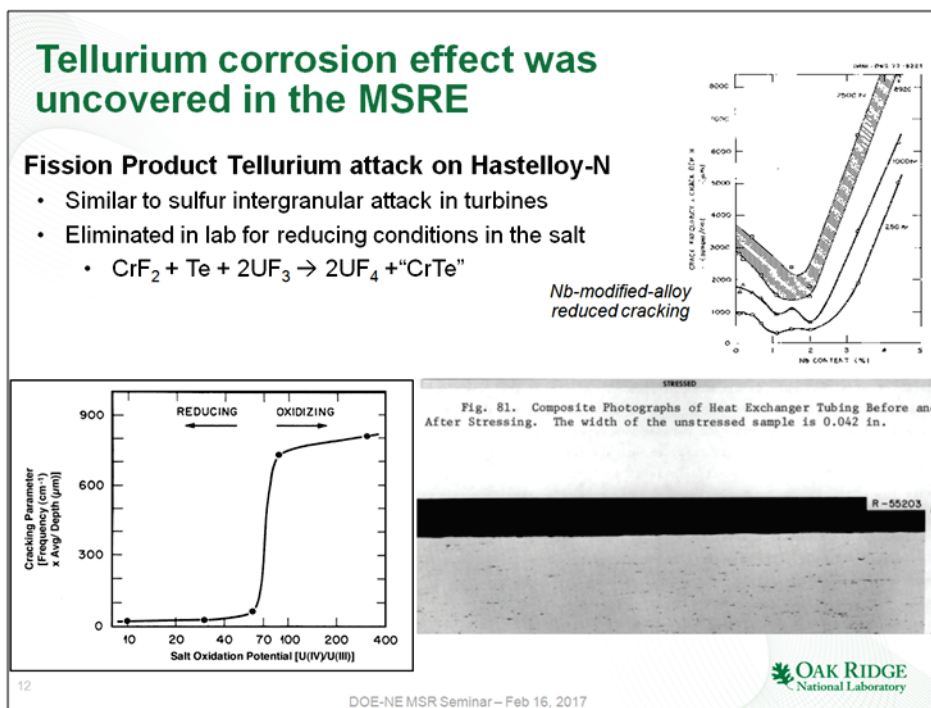
- Graphite is chemically compatible with molten halides, but has limited irradiation endurance.
- Fast spectrum places additional constraints on candidate materials:
 - It is unlikely that MSRE Hastelloy-N alloy (or other nickel alloys) will meet fast spectrum needs.
 - Hypothesis: Iron alloys might be used in a very reducing salt. The absence of alloying and other interactions needs to be proven.
- Some improvement of Ni-alloy radiation-durability is needed for 30-year life in thermal spectrum.
- Container alloys should also withstand high-temperature air exposure on outer surfaces.

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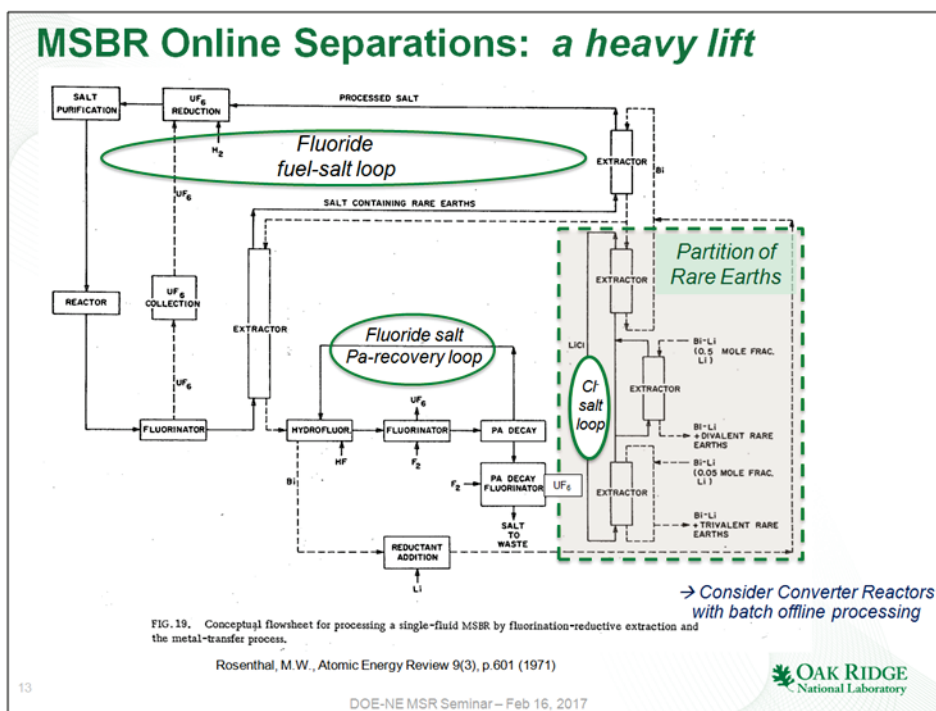
Module 3 – Slide 10. Material Compatibility.



Module 3 – Slide 11. Fundamental Salt Corrosion Process is Temperature-Gradient-Driven Redox Cycle.



Module 3 – Slide 12. Tellurium Corrosion Effect was Uncovered in the MSRE.



Module 3 – Slide 13. MSBR Online Separations: A Heavy Lift.

Time Scale for Fissile/Fertile Recycle driven by Economics

- Fluoride volatility is favored for uranium recovery from fluoride salts.
- Reductive processing applicable to halide flowsheets for fissile recovery:
 - Electro-metallurgical
 - Other metallurgical extractions (e.g., EBR-II process)
 - Electrodeposition oxide-precipitation (RIAR process)
- Evaluate interim storage of “spent” barren salts for decay and integrated disposition.
- Intragroup alkaline and alkaline earth element separations are the most difficult (unlikely).

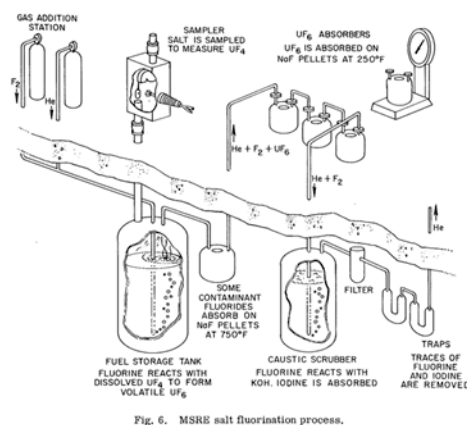


Fig. 6. MSRE salt fluorination process

Many New Pyrochemical and Hybrid Separations are possible – but will need to be screened

- New salts will require some separations development:
 - as compared to existing pyroprocessing technology.
- Chlorides afford option of aqueous processing:
 - fluorides are much harder to dissolve in water,
 - much higher resolution separations can be achieved in aqueous systems, but at the cost of complexity.
- New processes can be compared to option of interim decay-storage of “spent” salt, and then processing to a form for disposition.

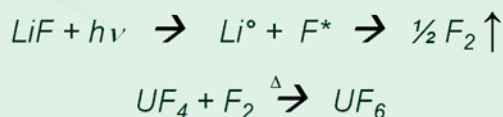
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Module 3 – Slide 15. Many New Pyrochemical and Hybrid Separations are Possible.

Lessons Learned from MSRE Remediation (1995-2000)



Solid halide salts are damaged by radiation and darken corresponding to the production of metal centers and halogen radicals \rightarrow halogen gas.

Storage of solid radioactive salt is an important issue:

- Don't store solid fuel-salt
 - remove UF_4 before allowing salt to freeze
- Provide reductant to counterbalance the generation of F_2 by β - γ radiolysis of the solid salt
- Maintain salts above 150°C to prevent radiolysis.

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Williams, D.F. et al, *Trans. of the American Nuclear Society*, **8**: 89-90; 1999.
L. M. Toth, L. K. Felker, "Radiation Effects and Defects in Solids", 112(4): 201-210 (1990).

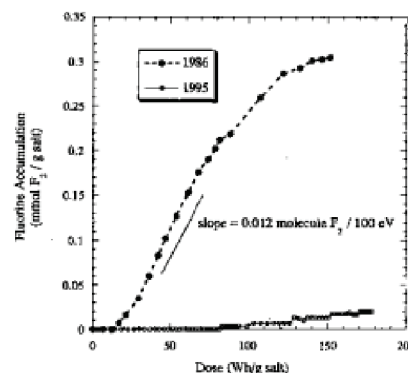
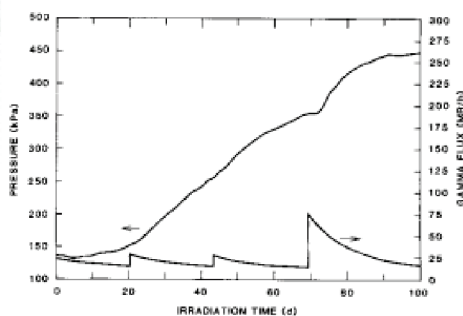
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Module 3 – Slide 16. Lessons Learned from MSRE Remediation (1995-2000).

Solid Salt Irradiation Response – cont'd

IRRADIATION OF FLUORIDE SALT



| | Measured Irradiation response |
|------------------|--|
| MSRE Salt | $G < 0.045$ molecule F_2 / 100 eV |
| ThF ₄ | $G < 0.015$ molecule F_2 / 100 eV |
| NaCl | Cl ₂ detected, but not quantified |

Most solid salt mixtures are heterogeneous polycrystalline materials. Each phase exhibits its own radiation response that reflects – in part – its crystal structure.

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Module 3 – Slide 17. Solid Salt Irradiation Response – cont'd.

Waste Form: Reactor Internals

- MSRE graphite contained only tiny amount of salt after defueling:
 - Fluoride flush salt worked well to reduce fission product levels in salt adhering to internals
 - For chloride systems graphite is unlikely, but aqueous leaches may provide a way to reduce contamination of other reactor internals.
- Some fission products (both noble metals and those with gaseous precursors) were deposited in the graphite porosity.

Table 12.3. Indicated distribution of fission products in molten-salt reactors

| Fission product group | Example isotopes | Distribution (%) | | | | |
|--|------------------------------|----------------------------|------------|-----------------------|----------------------------|-------------------------|
| | | In salt | To metal | To graphite | To off-gas | Other |
| Stable salt seekers | Zr-95, Ce-144, Nd-147 | ~99 | Negligible | < 1 (fission recoils) | Negligible | Processing ^a |
| Stable salt seekers (noble gas precursors) | Sr-89, Cs-137, Ba-140, Y-91 | Variable/ $T_{1/2}$ of gas | Negligible | Low | Variable/ $T_{1/2}$ of gas | |
| Noble gases | Kr-89, Kr-91, Xe-135, Xe-137 | Low/ $T_{1/2}$ of gas | Negligible | Low | High/ $T_{1/2}$ of gas | |
| Noble metals | Nb-95, Mo-99, Ru-106, Ag-111 | 1–20 | 5–30 | 5–30 | Negligible | Processing ^b |
| Tellurium, antimony | Te-129, Te-127, Sb-125 | 1–20 | 20–90 | 5–30 | Negligible | Processing ^b |
| Iodine | I-131, I-135 | 50–75 | < 1 | < 1 | Negligible | Processing ^c |

^aFor example, zirconium tends to accumulate with protactinium holdup in reductive extraction processing.

^bParticulate observations suggest appreciable percentages will appear in processing streams.

^cSubstantial iodine could be removed if side-stream stripping is used to remove I-135.

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Module 3 – Slide 18. Waste Form: Reactor Internals.

Waste Form: Fission Gases (but not Iodine)

- Reactor off-gas sorbent could also serve as the ultimate disposal medium –
 - The reactor off-gas sorbent must reject noble gas decay heat.
- Charcoal was used as sorbent during MSRE operation, and was deemed the best choice for MSBR development. This media could be ashed to a small volume for long-term disposal.

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Module 3 – Slide 19. Waste Form: Fission Gases.

Salt Waste Form

- If radiolysis can be managed/mitigated, both fluorides and chlorides are potential interim storage forms, and for disposition:
 - It has been proposed to make fluorides more refractory by conversion of fluorides to a fluorophosphate.
 - Chlorides are currently converted to a “salt-cake” waste form as part of the ongoing EBR-II processing campaign.
 - New chloride salt compositions may require additional developments

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Module 3 – Slide 20. Salt Waste Form.

Primary Research Issues

- Understanding and managing salt radiolysis.
- Understanding and managing “noble” metal fission products in reactor.
- Understanding in depth any new salts proposed as well as LiF-BeF₂ system was understood.

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Module 3 – Slide 21. Primary Research Issues.

2.5 Module 4 – Reactor Safety, Physics, and Associated Fuel Cycle Performance

Ben Betzler of ORNL and Florent Heidet of ANL assembled and gave this presentation that described the reactor physics characteristics of MSR, focusing on liquid-fueled MSRs, and discussed the associated safety issues and fuel cycle performance. Among the significant points made during the presentation are the following:

- Low-pressure (atmospheric) system reduces stored energy, reducing the risk of energetic burst or explosion
- Pure salts do not react with moisture or air, reducing fire or explosion hazards.
- Typical operating temperatures provide a very large margin to boiling
- Salts have a high heat capacity, potentially slowing the progression of some accidents since the volume of salt also affects the rate of temperature rise in the reactor.
- Safety of solid-fueled, salt-cooled MSRs is likely to be similar to that of other solid-fuel reactors.

Liquid-Fueled MSRs

Potential Advantages

- A temperature increase causes a reduction in density of the fuel salt, causing a rapid negative reactivity insertion corresponding to the reduced fuel mass in the core as a result of the lower salt density.
- Liquid-fueled MSRs have potential for low excess reactivity with continuous or batch feed of fissile and fertile material during operation and continuous removal of fission products to reduce neutron absorption in the salt, providing better neutron economy leading to greater fuel utilization.
 - Less active reactivity control is needed and accidents associated with excess reactivity are mitigated or avoided.
- There is a potential reduction of the radioactive source term in the case that the circulating liquid-fuel loop is breached due to the online removal of volatile components from the fuel loop during operation, although the system for collecting and managing the volatile materials must also be evaluated for safety concerns.

Potential Challenges

- Undesired freezing of the salt must be prevented.
- Managing waste forms from fission product and other material removals, since there are multiple radioactive source terms in multiple locations.
- Remote maintenance required due to high radioactivity of fuel salt flowing through the fuel loop.
- A loss of coolant accident or coolant leak would result in fuel material leaking out of the fuel loop, possibly into the containment building, depending on the design.
 - A non-negligible fraction of delayed neutrons is emitted in the circulating liquid-fueled salt loop instead of within the core. Depending on the fuel loop and core design, up to 50% of the delayed neutrons may be emitted within the fuel loop outside of the core (from 90–300 pcm). Testing with the MSRE determined that despite losing half of the delayed neutron margin, the reactor remained stable and controllable (delayed neutrons provide a time-bottleneck that limits the rate of the change in flux).

- The fuel can be in contact with the reactor vessel, so that fissions occur near structural components such as piping and the heat exchangers, areas that do not experience neutron irradiation in designs with solid fuel.
- Analysis of the reactor physics is different than for solid-fueled reactors.
 - There is movement of the delayed neutron precursors in flowing fuel, such that some emit neutrons outside of the core region, changing the neutron source distribution within the core from what it would be with solid fuel, as is typically modeled with standard reactor physics computer codes.
 - As a result, the fission source calculated by standard lattice physics codes is biased, where the prompt neutrons and some delayed neutrons are emitted in the liquid fuel while it is in the core (as with solid fuel), while some delayed neutrons are emitted after the liquid fuel leaves the core (coolant loop, chemical processing, etc.), which does not happen with solid fuel.
 - If online refueling is also used, then the changing composition from the fuel additions must also be accounted for in the calculations.
 - New reactor physics modeling capability is needed to accurately calculate MSR performance.
- Fast neutron spectrum MSRs may need to use chloride-based salts instead of the historical fluoride-based salts used in thermal neutron spectrum MSRs to reduce the neutron moderating effect. Much less is known about chloride-bases salts in MSR applications.

Module 4: Reactor Safety, Physics, and Associated Fuel Cycle Performance

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Florent Heidet

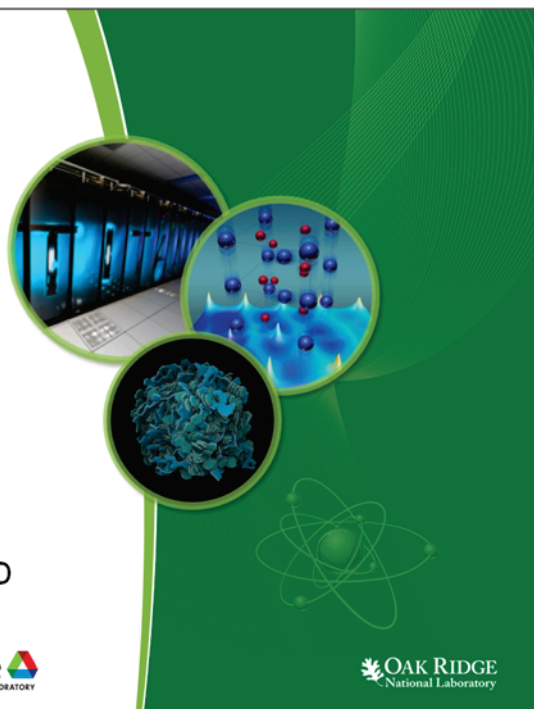
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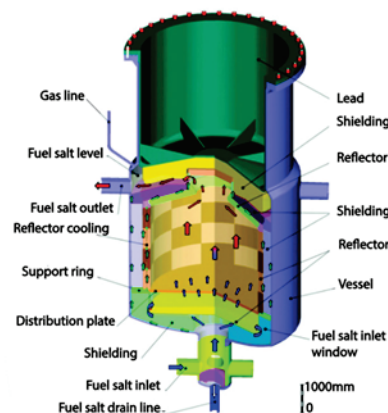
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Session Objectives

Safety, core physics, and fuel cycle performance

- Identify safety features and challenges
 - Features unique to liquid-fueled molten salt reactors
 - Challenges with moving fuel
- Highlight major reactor physics characteristics and challenges in modeling and simulation
 - Continuous material feed and removals
 - Delayed neutron precursor drift
 - Thermal and fast spectrum systems
- Discuss fuel cycle performance
 - TRU burning capabilities
 - Benefits from MSR technology



From: "A Technical Roadmap Update for Generation IV Nuclear Energy Systems" (2014).

Module 4 – Slide 2. Session Objectives.

Solid Fuel Molten Salt Reactors

Key points, discussion focuses on liquid fuel systems

- Similar to traditional reactors, except salt is used as a coolant
 - High temperature, low-pressure system
- Share some safety features and challenges with liquid fuel systems
 - Identify some features of both at the beginning of talk
- Reactor physics is similar to traditional solid fuel systems
 - Different coolant properties, neutron spectrum, and cross section sensitivities
- Fuel cycle outcomes are more similar to other solid fuel systems
 - Some potential for low excess reactivity (pebble bed fuel forms)
 - No continuous fission product removals
- Unless otherwise noted, discussion refers to liquid fuel MSRs

Module 4 – Slide 3. Solid Fuel Molten Salt Reactors.

Reactor Safety Characteristics

MSR key features (solid and liquid fuel, fast and thermal)

- Low-pressure (atmospheric) system reduces stored energy
 - Reduces risk of energetic burst or explosion
- Pure salts do not react with moisture or air, reducing fire or explosion hazards
- Typical operating temperatures provide a very large margin to boiling
- Salts have a high heat capacity, slowing the progression of some accidents
 - Volume of salt also effects rate of temperature rise

| Design | Operating temp. (K) | Melting point (K) | Boiling point (K) | Volumetric heat capacity* (kJ/m ³ K) |
|--|---------------------|-------------------|-------------------|---|
| Solid fuel with 2LiF-BeF ₂ coolant (FHR) | 970 | 730 | 1700 | 4540 |
| Molten Salt Breeder Reactor | 980 | 770 | > 1500 | 4455 |
| Molten Chloride Fast Breeder Reactor | 1260 | 960 | 1770 | 2226 |
| UF ₄ -LiF salt (27.5% UF ₄ by moles) | 900 | 770 | 1470 | - |

*water - 4186, sodium - 1190



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Module 4 – Slide 4. Reactor Safety Characteristics – MSR Key Features (Solid and Liquid Fuel, Fast and Thermal).

Reactor Safety Characteristics

MSR key features (liquid fuel, fast and thermal)

- Temperature increases causes thermal expansion of the fuel salt, causing a rapid negative reactivity insertion as fuel mass is removed from the core
 - Provides an additional negative reactivity insertion due to increasing temperatures in a potential accident scenario
 - In addition to Doppler, results in a negative reactivity temperature coefficient
 - Magnitude of total core reactivity coefficient dependent on core design: moderator, Doppler, salt density reactivity coefficients, moderator-to-fuel ratio
 - For example, single-fluid and two-fluid molten salt breeder reactor designs have reactivity coefficients of -0.87 dk/k-dT-K and -4.34 dk/k-dT-K, respectively
- Potential designs for draining the fuel or coolant salt from the core or fuel loop into a safe storage area under high temperature accident conditions
 - Drained into a subcritical configuration (e.g., via freeze valve above 970 K)



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Module 4 – Slide 5. Reactor Safety Characteristics – MSR Key Features (Liquid Fuel).

Reactor Safety Characteristics

MSR key features (liquid fuel, fast and thermal)

- When fuel is dissolved in the coolant, a loss of coolant removes the reactor fuel limiting the potential for re-criticality
 - Removes fuel material from the fuel loop
 - May be caught in an emergency tank
- Low excess reactivity due to online fuel feed and fission product removal
 - Fuel salt contains only sufficient fissile material to maintain criticality
 - Supercritical excursion not induced by excess fissile material
 - Reduction of source term by removal of gaseous and volatile components from the fuel loop, which are the most likely to disperse when containment is breached
- Coolant chemical reactions such as the sodium-water reaction in sodium fast reactors (SFRs) are eliminated



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Module 4 – Slide 6. Reactor Safety Characteristics – MSR Key Features (Liquid Fuel).

Reactor Safety Challenges

Key safety challenges to deploy MSR technology

- Undesired freezing of the salt must be prevented
 - Frozen salt may cause unwanted blockages or masses in fuel loop
- Possible fluctuations of reactivity caused by density or concentration changes in the fuel salt
 - Fuel salt density changes due to fission gases
 - Fission gases are continuously generated from fission (gas sparging for control)
 - Potential for coalescence of dissolved gas into large bubbles and their collapse could cause a reactivity insertion (e.g., bubbles collapsed with shockwave)
 - Postulated scenario has not been observed experimentally
- Managing waste forms from fission product and other material removals
 - Multiple source terms in multiple locations
 - Holdup tanks for material cleanup or processing



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Module 4 – Slide 7. Reactor Safety Challenges – Key Safety Challenges to Deploy MSR Technology.

Reactor Safety Challenges

Key safety challenges to deploy MSR technology

- Remote maintenance required due to high radioactivity of fuel salt flowing through the fuel loop
- A loss of coolant accident or coolant leak would result in fuel material leaking out of the fuel loop
 - Negative impact on reactivity, positive effect on source term outside of core
- A non-negligible fraction of delayed neutrons is emitted in the coolant loop instead of within the core
 - Depending on the fuel loop and core design, up to 50% of the delayed neutrons may be emitted within the fuel loop outside of the core (from 90–300 pcm)
 - Testing with the MSRE determined that despite losing half of the delayed neutron margin, the reactor remained stable and controllable (delayed neutrons provide a time-bottleneck that limits the rate of the change in flux)



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Module 4 – Slide 8. Reactor Safety Challenges – Key Safety Challenges to Deploy MSR Technology.

Reactor Safety Challenges

Key safety challenges to deploy MSR technology

- Cold fuel slug injection resulting in power excursion
 - Reactivity burst from insertion of cold fuel salt mitigated via pump design
- Fuel is in contact with the reactor vessel
 - Fissions occur near structural components
- Early analysis shows accident categories are similar to liquid metal reactors
 - Transients
 - Loss of flow
 - Loss of heat sink
 - Loss of coolant (fuel)
 - Overcooling



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Module 4 – Slide 9. Reactor Safety Challenges.

Reactor Physics Characteristics

Material feeds and removals

- Solid fueled-reactors typically exhibit a reactivity swing during operation
 - Starting with excess positive reactivity compensates for the loss of fissile material over the course of a cycle of operation (when conversion ratio (CR) is less than 1.0)
 - Excess reactivity is mitigated via specific fuel loading, soluble boron in the coolant (PWR), burnable absorbers (LWR), and/or control rods, which are gradually removed and/or depleted (neutrons are effectively lost in absorbers and control rods)
 - This swing is smaller when $CR = 1$ or positive when $CR > 1$
- Liquid-fueled MSR's have potential for low excess reactivity
 - Continuous or batch feed of fissile and fertile material during operation
 - Continuous removal of fission products reduces neutron absorption
 - Better neutron economy leads to greater fuel utilization
 - Potential for lower initial fissile loadings and no out of core time enable a faster transition



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Module 4 – Slide 10. Reactor Physics Characteristics – Material Feeds and Removals.

Reactor Physics Analysis

Challenges in neutronic modeling and simulation

- Delayed neutron precursor drift in flowing fuel
 - Delayed neutron precursors are radioactive fission products that release delayed neutrons upon decaying
 - In solid fuel systems, the movement of these delayed neutron precursors is negligible
 - In liquid fuel systems, the precursors move away from their birth location and may decay outside of the core, *changing the neutron source distribution within the core*
- Fission source calculated by standard lattice physics codes is biased
 - Prompt neutrons and some delayed neutrons are emitted in the liquid fuel while it is in the core
 - Some delayed neutrons are emitted after the liquid fuel leaves the core (coolant loop, chemical processing, etc.)



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Module 4 – Slide 11. Reactor Physics Analysis – Neutronic Modeling and Simulation.

Reactor Physics Analysis *Challenges in depletion modeling and simulation*

- Depletion with continuous and batch feeds and removals
 - Continuous processes in liquid fuel systems remove fission gases and potentially other elements during operation
 - In addition to continuous processes, material may be added to and removed from the liquid in batches at specific times
- Set of depletion equations describing the rate of change of the nuclides

$$\frac{dN_i}{dt} = \sum_{j=1}^m l_{ij} \lambda_j N_j + \bar{\Phi} \sum_{k=1}^m f_{ik} \sigma_k N_k - (\lambda_i + \bar{\Phi} \sigma_i + r_i^0) N_i$$

Decay rate
of nuclide j
into nuclide i

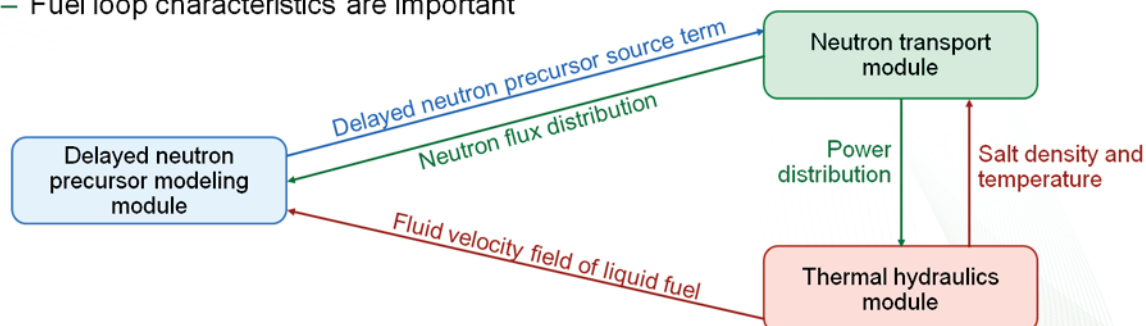
Production rate
of nuclide i
from irradiation

Loss rate of nuclide i due
to decay, irradiation, or
other means

Module 4 – Slide 12. Reactor Physics Analysis – Depletion Modeling and Simulation.

Reactor Physics Analysis *Challenges in coupled transient modeling and simulation*

- Delayed neutron precursor distribution must be tracked in time
 - Dependent on fluid velocity field from thermal hydraulics (TH)
 - Dependent on fission distribution from neutron transport
 - Fuel loop characteristics are important



Module 4 – Slide 13. Reactor Physics Analysis – Challenges in Coupled Transient Modeling and Simulation.

Reactor Physics Analysis

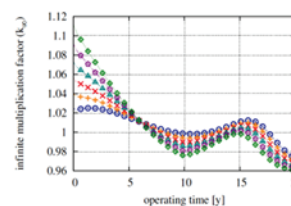
Modeling and simulation requirements

- Model the changing isotopic composition of an irradiated fuel salt
 - Fuel cycle analysis
- Delayed neutron precursor distribution during steady-state operation
- Model chemical addition and removal capabilities
 - Continuous and batch additions and removals
- Simulating MSR transients
 - Delayed neutron precursor movement
 - Molten salt properties and movement of fuel salt
 - Decay heat calculations

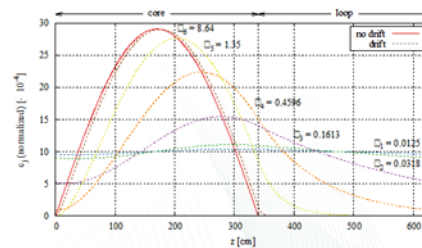


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Calculated k of an MSR unit cell with different reductions to the initial thorium loading.



Delayed neutron precursor concentrations in the primary loop of a liquid-fueled MSR.

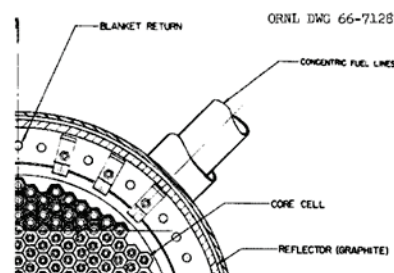


Module 4 – Slide 14. Reactor Physics Analysis – Modeling and Simulation Requirements.

Thermal Spectrum Reactors

General characteristics

- Thermal spectrum is achieved by incorporated moderator materials into the core, for example:
 - Graphite assemblies with holes for flowing fuel salt
 - Zirconium hydride rods
- The fuel-to-moderator ratio may be varied throughout the core to achieve desired spectrum
 - Converting fertile material
 - Reduce fluence to structural or moderator materials



From Design studies of 1000-MW(e) Molten-Salt Breeder Reactors (1966).



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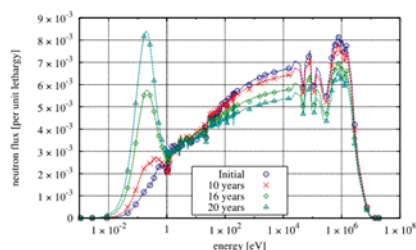
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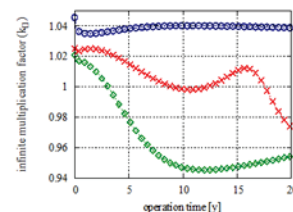
Module 4 – Slide 15. Thermal Spectrum Reactors – General Characteristics.

Thermal Spectrum Reactor Performance Effect of initial startup composition

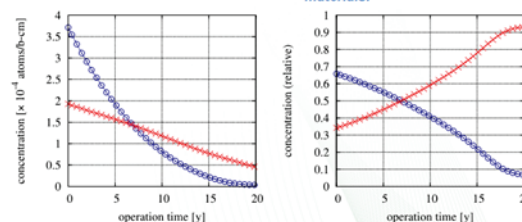
- Composition of the initial (startup) fuel salt has a significant effect on the viability of an MSR
 - Non-fissile heavy metals loaded at startup reside in the reactor for long periods of time
 - Neutron spectrum softens during operation



Spectral shift in a thorium MSR with plutonium as the initial fissile material.



MSR reactivity with different initial fissile materials.



Fissile and non-fissile plutonium concentrations during operation.

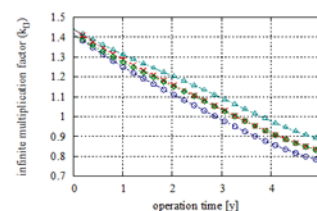
Module 4 – Slide 16. Thermal Spectrum Reactor Performance – Effect of Initial Startup Composition.

Thermal Spectrum Reactor Performance Effect of different material removal rates

- Some elements have strong effect on reactivity and reactor operation
 - Cycle times depend on the processing technology
 - Defined as the time it takes to completely remove a given element
 - Continuous removal of highly absorptive elements has largest impact

Effect of processing group removals on core lifetime for a thermal MSR.

| Removals | Core lifetime | |
|--|---------------|----------------|
| | time [y] | additional [%] |
| None | 2.73 | - |
| Volatile gases | 2.93 | 7.5 |
| Noble metals | 2.92 | 7.1 |
| Rare earth elements | 3.12 | 14.4 |
| Gases and noble metals | 3.14 | 15.1 |
| Gases, noble metals, and rare earth elements | 3.63 | 32.9 |



Calculated k of a unit cell with different removal groupings.

Removal rates of different processing groups.

| Processing Group | Elements | Cycle time |
|---------------------|--|------------|
| Volatile gases | Xe, Kr | 20 s |
| Noble metals | Se, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Sb, Te | 20 s |
| Seminoble metals | Zr, Cd, In, Sn | 200 d |
| Volatile fluorides | Br, I | 60 d |
| Rare earth elements | Y, La, Ce, Pr, Nd, Pm, Sm, Gd, Eu | 500 d |
| Discard | Rb, Sr, Cs, Ba | 3435 d |

Module 4 – Slide 17. Thermal Spectrum Reactor Performance – Effect of Different Material Removal Rates.

Fast Spectrum MSRs

Basic physics differences

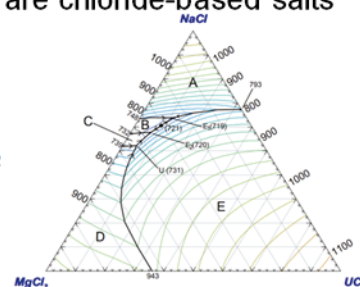
- Fast spectrum is achieved by having little/none moderating materials
 - No solid moderator materials (graphite, zirconium-hydride...)
 - Salt with no moderating element
- Typical “fast spectrum” physics applies to MSR:
 - Large neutron mean free path: large leakage probability and shielding needs
 - Lower neutron cross-sections
 - Reduced parasitic absorption (Fe-based materials; low reactivity penalty with fission products buildup)
 - Requires higher fissile concentration
 - Ability to create excess fissile material
 - Ability to consume minor actinides

Module 4 – Slide 18. Fast Spectrum MSRs – Basic Physics Differences.

Fast Spectrum MSRs

Chloride salt

- Most common salts considered for fast spectrum MSR are chloride-based salts
 - UCl_3 and TRUCl_3 fuel bearing salts (high solubility)
 - NaCl (and MgCl_2) as the carrier salts
 - Lower melting temperature with 32 mol% UCl_3 in UCl_3 - NaCl
 - Lower melting temperature with 51.5 mol% of NaCl in NaCl - MgCl_2
 - No tritium production
- Natural chlorine has two stable isotopes:
 - 75.8% ^{35}Cl and 24.2% ^{37}Cl
 - Capture cross-section of ^{35}Cl is larger than that of ^{37}Cl , even in a fast spectrum system
 - ^{36}Cl is also long-lived (301,000 years), especially compared to ^{38}Cl (37 minutes)
 - Isotopic enrichment of chlorine is preferable but not required



Module 4 – Slide 19. Fast Spectrum MSRs – Chloride Salt.

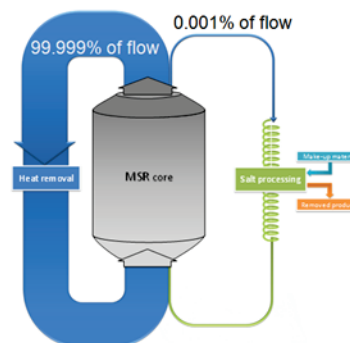
Fast Spectrum MSRs Capabilities overview

- Similarly to sodium-cooled fast reactors, MSR can be configured to achieve different goals
- MSR as burner:
 - Most easily achieved as neutron economy is not important
 - Large transuranics to heavy metal fraction favors burning
- MSR as breeder (or break-even)
 - Neutron economy is important
 - Need for low parasitic neutron absorption (may need chlorine enrichment)
 - Breed-and-burn mode may be feasible

Module 4 – Slide 20. Fast Spectrum MSRs – Capabilities Overview.

Fast Spectrum MSRs General Assumptions

- Salt composition affects the burning rate of transuranics in a MSR operating in a continuous recycle fuel cycle.
 - Study made possible by development of advanced modeling and simulation tools for MSR
 - Solubility limits and elements removed through salt processing may limit which salt forms can be used
- Assumptions:
 - 0.001% of salt routed through the processing loop
 - Same core dimensions for all cases
 - 30 W/gram of salt
 - Only partial fission products removal
 - No losses

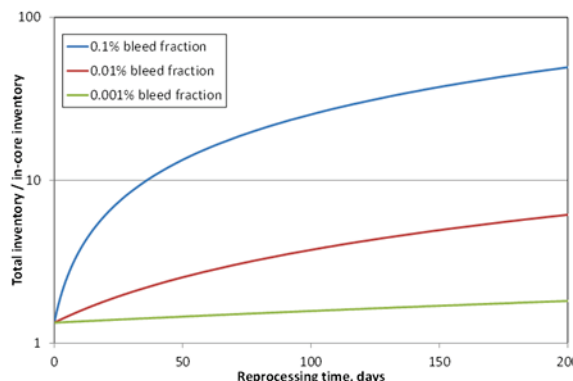


| Salt Composition (mol%) | Density @700°C, g/cm ³ |
|--|-----------------------------------|
| 40U/TRUCl ₂ -35.1NaCl-24.9MgCl ₂ | 3.87 |
| 30U/TRUCl ₂ -41.0NaCl-29.1MgCl ₂ | 3.42 |
| 20U/TRUCl ₂ -46.8NaCl-33.2MgCl ₂ | 2.96 |
| 15U/TRUCl ₂ -49.7NaCl-35.3MgCl ₂ | 2.65 |
| 10U/TRUCl ₂ -52.7NaCl-37.4MgCl ₂ | 2.37 |

Module 4 – Slide 21. Fast Spectrum MSRs – General Assumptions.

Fast Spectrum MSRs Material Inventory

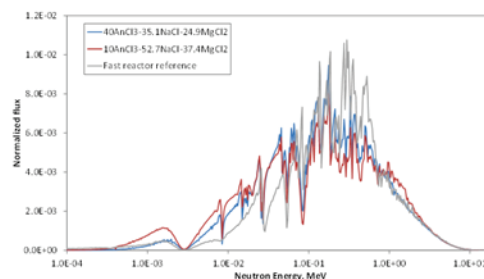
- Overall salt inventory depends on multiple factors:
 - In-core residence time (seconds to minutes)
 - Out of core time (seconds to minutes)
 - Required treatment/processing time and salt fraction bled to treatment/processing
- Representative **in-core** inventories for a 1 GW_{th} core:
 - 30-50 tons of salt
 - 15-25 tons of heavy metals
- Total** inventory (in-core, fuel loop, and processing)
 - Typically between 1.3x and 2.0x the in-core inventory
 - A smaller inventory is preferable for economics, safety, and safeguards considerations



Module 4 – Slide 22. Fast Spectrum MSRs – Material Inventory.

Fast Spectrum MSRs TRU burner designs

- Net TRU consumption is observed in all cases.
- As actinides represent a lower fraction of the salt:
 - Feed material needs to contain a larger fraction of TRU
 - Fuel at equilibrium contains a larger fraction of TRU
 - Fuel at equilibrium contains a larger mass of TRU
- Equilibrium TRU composition in the salt varies significantly between the different cases
 - From 55% fissile content to 25%, as the actinide mol% is decreased
 - Impacts waste characteristics of the fuel salt (decay heat, radiotoxicity)



| U/TRUCl ₃ mol% | 40 | 30 | 20 | 15 | 10 |
|--|-------|-------|-------|-------|-------|
| Salt through core, t/s-GW _{th} | 2.90 | 2.90 | 2.90 | 2.90 | 2.90 |
| HM + FP through core, t/s-GW _{th} | 1.52 | 1.33 | 1.08 | 0.90 | 0.68 |
| Salt through processing, g/s-GW _{th} | 29.0 | 29.0 | 29.0 | 29.0 | 29.0 |
| HM + FP through processing, g/s-GW _{th} * | 15.2 | 13.3 | 10.8 | 9.0 | 6.8 |
| TRU fraction in fuel | 20.0 | 26.9 | 40.7 | 55.4 | 85.7 |
| TRU consumption, kg/yr-GW _{th} | 44.5 | 107.5 | 194.4 | 264.4 | 353.4 |
| Required make-up fuel, kg/yr-GW _{th} | 370.9 | 370.9 | 370.9 | 370.9 | 370.9 |
| Conversion ratio | 0.88 | 0.71 | 0.46 | 0.29 | 0.05 |

* For comparison, SFR fuel reprocessing equates to 0.1 g/s-GW_{th}

Module 4 – Slide 23. Fast Spectrum MSRs – TRU Burner Designs.

Fast Spectrum MSRs *Breeding capabilities*

- MSR can easily be configured as a break-even:
 - Starting from the MSR burner using $40\text{U/TRUCl}_3\text{-}35.1\text{NaCl-}24.9\text{MgCl}_2$
 - Chlorine needs to be enriched to about 55% ^{37}Cl .
- With 100% ^{37}Cl , using the same core model:
 - About 70 kg of plutonium could be produced from 1 $\text{GW}_{\text{th-yr}}$ (SFR with blanket: 95 $\text{kg/GW}_{\text{th-yr}}$)
 - $\text{CR}=1.19$ for the MSR example ($\text{CR}=1.25$ for the SFR example)
 - Conversion ratio of the MSR could be slightly increased by optimizing the core design
 - Neutron economy of the system is not optimized
 - Use of blanket in MSR is not as straightforward as with solid fuel systems



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Module 4 – Slide 24. Fast Spectrum MSRs – Breeding Capabilities.

MSR in Recent DOE-NE Studies *Evaluation and screening groups*

- “Nuclear Fuel Cycle Evaluation and Screening,” 2014 (FCRD-FCO)
 - MSR used as the Analysis Example for two of the Evaluation Groups
 - Limited recycle of $^{233}\text{U/Th}$ in MSR (thermal) – EG10
 - Continuous recycle of $^{233}\text{U/Th}$ in MSR (thermal) – EG26
 - MSRs could be used as the thermal or fast reactors for other limited or continuous recycle fuel cycles
 - Liquid-fueled MSRs are inherently recycle systems due to the removal of fission products
- Due to the continuous removal of volatile fission products, and the possible addition of fuel during operation to achieve and maintain near zero excess reactivity, MSRs have a favorable neutron economy
 - Online processing is also possible to further clean the fuel/salt mixture of fission products, but a significant amount of salt might have to be processed
 - Material loss could be larger than for other reactor systems, but details are currently uncertain



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Module 4 – Slide 25. MSR in Recent DOE-NE Studies.

Session Summary

Safety, core physics, and fuel cycle performance

- Due to their nature, MSR's have a favorable **safety behavior**...but still need to address a few key safety challenges.
- By some aspects the **reactor physics** of MSR is simpler (no assemblies, no spatial self-shielding...), but it also brings new phenomena (precursor drift, gas bubbles) which are not yet well modeled.
- Determining accurate fuel and salt composition with burnup is essential to performing analyses for MSR's:
 - Need to improve state of modeling and simulation tools to appropriately represent unique features of MSR's



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Module 4 – Slide 26. Session Summary – Safety, Core Physics, and Fuel Cycle Performance.

Session Summary

Safety, core physics, and fuel cycle performance

- The wide variety of MSR's (thermal/epithermal/fast, power density, uranium/thorium, online/batch/no processing...) enables them to be considered for almost any application where more mature reactor types are currently being used.
 - Similar passive safety features as SFR's, with similar burning/breeding capabilities when fast spectrum is used;
 - High salt temperature, somewhat similar to HTGR's, enabling process heat applications;
 - Improved resource utilization compared to PWR's, even with thermal spectrum MSR's (e.g., LWR at ~0.6% compared to MSR concepts at ~1.0%).



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Module 4 – Slide 27. Session Summary – Safety, Core Physics, and Fuel Cycle Performance.

2.6 Module 5 – Safeguards Considerations and Challenges

George Flanagan of ORNL assembled and gave this presentation that provided an overview of the question of safeguards and proliferation risk, and discussed the issues of implementing safeguards for MSRs, focusing on liquid-fueled MSRs. Among the significant points made during the presentation are the following:

- Proliferation risk is the risk that a state would obtain nuclear weapons. As stated by the IAEA, "The objective of IAEA Safeguards is to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology."
- Proliferation risk has become a dominant concern for all fuel cycles. The potential contribution to proliferation risk for MSRs has not yet been evaluated, and MSR designs until the mid-1970s did not consider proliferation issues. The ability to implement international safeguards is key to addressing proliferation risk
- The use of a liquid fuel may complicate application of traditional safeguards approaches and technologies since it changes or removes some of the barriers to materials diversion. The lack of discrete fuel elements combined with continuous transmutation and online processing prevents traditional "item" accounting, although solid LEU fresh fuel salt in transport and storage accountancy resembles LWR fuel. The ease of access to nuclear materials will depend on design details for the plant, including any processing that is done on the liquid fuel/salt mixture.
- The path forward on how to approach the safeguards issues for MSRs is being developed at this time. Current reactor safeguards implementation strategies do not address the implications of fluid fuel forms, and MSRs will need the development and application of non-traditional safeguards approaches.

The slide features a green background with a stylized atomic symbol on the right. Three circular inset images are arranged vertically: the top one shows a reactor interior with blue lighting, the middle one shows a molecular model with blue and red spheres, and the bottom one shows a cluster of blue particles. The text is in white and green.

**Module 5:
Safeguards Considerations
and Challenges**

George Flanagan
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Informational Seminar on Molten Salt Reactors
DOE Office of Nuclear Energy, Germantown, MD
February 16th, 2017

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE
National Laboratory

What are Safeguards and How are they Related to Proliferation Resistance?

- **“The objective of IAEA Safeguards is to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology” - IAEA**
 - Safeguards are the technical means for the IAEA to verify that States are meeting their legally binding undertaking not to use nuclear material or other items for illicit purposes
 - Safeguards system was established by the Nuclear Non-Proliferation Treaty (NPT)
- **Proliferation resistance is a more recent concept intended to provide an indication of the intrinsic (physical/technical) and extrinsic (institutional) aspects of nuclear energy systems that can affect proliferation risk**
 - Proliferation resistance - the characteristics of a nuclear energy system that impede the diversion of undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices (IAEA 2002)
 - Evaluation methodologies for proliferation resistance are being developed, e.g., in GenIV

There is a necessity to safeguard facilities that involve nuclear material.
Does not consider the concept of proliferation resistance.

2

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Module 5 – Slide 2. Safeguards and How are They Related to Proliferation Resistance?

Proliferation Risk Has Become A Dominant Concern For All Fuel Cycles

- The potential contribution to proliferation risk for MSRs has not been evaluated
 - MSR designs until the mid-1970s did not consider proliferation issues
 - Results may be design and technology dependent
 - Ability to implement international safeguards is key to addressing proliferation risk
- The use of a liquid fuel may complicate application of traditional safeguards approaches and technologies
 - Changes the barriers to materials diversion
 - Lack of discrete fuel elements combined with continuous transmutation and online processing prevents traditional “item” accounting
 - Solid LEU fresh fuel salt in transport and storage accountancy resembles LWR fuel
 - Ease of access to nuclear materials will depend on design details for the plant, including any processing that is done on the liquid fuel/salt mixture

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Module 5 – Slide 3. Proliferation Risk has become a Dominant Concern for All Fuel Cycles.

Proliferation Resistance & Physical Protection (PRPP) may Consider, but is NOT the Same as, Safeguards

- Often confusion between “material attractiveness”, “proliferation resistance”, and “safeguardability”, etc.
- IAEA, GIF (and others) have developed guidelines for evaluating PRPP
 - GIF has been developing a methodology for assessing PRPP
- These methods typically consider the “value” / “attractiveness” of the material and the “access” / “barriers” to that material
- For GIF, that includes:
 - Value: Fissile material type
 - Barriers: Technical difficulty, proliferation cost and time, **detection probability, and detection resource efficiency**
- The latter two in particular take into account the safeguards or “safeguardability” considerations
- The remainder of this talk will focus on safeguards, and not PRPP

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Module 5 – Slide 4. Proliferation Resistance & Physical Protection (PRPP).

Fundamental Safeguards Concepts

- ...the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection.
- ...use of material accountancy as a safeguards measure of fundamental importance, with containment and surveillance as important complementary measures.
- ...the Agency...may...verify the design information [of a facility]...”
Paragraphs 28, 29, and 48 model comprehensive safeguards agreement (INFCIRC/153)

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Module 5 – Slide 5. Fundamental Safeguards Concepts.

DOE's National Nuclear Security Administration Has Begun to Evaluate MSR Safeguards Issues

- Develop path forward on how to approach the safeguards issues surrounding MSRs
- Effort leverages expertise in safeguards, proliferation resistance, and MSR technologies
- Scoping level study recently completed by a national laboratory team
 - Draft white paper approved by NA-241 sponsor
 - Detailed work products will have restricted access as they may reveal limitations/vulnerabilities
- Assessing and developing approaches and technologies to support IAEA is primary focus
 - Material control and accountability
 - Safeguards technology
 - Inspection regimes

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Module 5 – Slide 6. DOE's National Nuclear Security Administration has begun to Evaluate MSR Safeguards Issues.

Significant Quantities, Form of Material and IAEA Detection Timeliness Goals

Used for
determining
frequency of
inspections

Type of
Nuclear
Material



Form of
Material



IAEA
Timeliness
Goals

Significant Quantity (SQ)

- Pu: 8 kg (<80wt% Pu238)
- U-233: 8 kg
- HEU: 25 kg (>20 wt% U235)
- LEU: 75 kg (<5 wt% U235)
- Th: 20 t

| Classification *Direct use **Indirect use | Pu, HEU, U-233 unless stated | Conversion time | Timeliness Goal |
|---|---|-----------------|--------------------|
| 1* | metal | 7-10 d | 1 m |
| 2* | oxides, nitrates (U-235+U-233 ≥ 20%) | 1-3 w | 1 m |
| 3* | irradiated fuels | 1-3 m | 3 m |
| 4** | <20% U-235+U-233; Th | 3-12 m | 12 m |

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Module 5 – Slide 7. IAEA Significant Quantities, IAEA Form of Material, and IAEA Detection Timeliness Goals.

Nuclear Material Accounting - Fundamental to International Safeguards

- Nuclear material must be accounted for at each stage of operations
- Design of Material Balance Areas
 - Allow a Mass Balance to be achieved
 - Determine Material Unaccounted For (MUF)
 - Allow Physical Inventory Verification
- Design of inventory and flow Key Measurement Points (KMPs) to measure nuclear material
- Design of containment and surveillance systems

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Module 5 – Slide 8. Nuclear Material Accounting – Fundamental to International Safeguards.

Current Reactor Safeguards Implementation Strategies Do Not Address the Implications of Fluid Fuel Forms

- MSR fuel will be a homogenous mixture of actinide salt, solvent salt, and fission products
- Continuous variation over time of isotopic concentrations in the fuel salt
- Challenging measuring environment
 - High operating temperature, high neutron and gamma flux, corrosive environment
- On-line fissile material separations possible, and hence associated diversion
- Fissile material present in piping, storage tanks, heat exchangers and salt cleanup systems outside reactor vessel
 - Fissile materials may accumulate in salt polishing systems or cover gas management systems
 - Needs to be monitored in each area, and at all times
- Unique refueling/breeding schemes
 - Accumulating additional fissile material outside of vessel (breeder)
 - Non-traditional solid fuel forms e.g., drums, capsules etc. (burner)

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Module 5 – Slide 9. Current Reactor Safeguards Implementation Strategies do not address the Implications of Fluid Fuel Forms.

Safeguards Technology & Instrumentation Challenges Exist

- Safeguards goals for MSR designs must be developed because they determine instrumentation requirements
- High material throughput, results in significant measurement uncertainty
 - Will have to be factored into the overall performance requirements.
- Nuclear material signatures dictate the type of instruments that can be applied
 - Not all instruments measure the same signatures or give the same results.
- High thermal & radiation environment, remote & unattended monitoring likely required and different technologies will have to be developed.
 - Reliability issues; consider lifetime of instruments in the reactor system.
 - Access for maintenance, periodic upgrades of instruments & supporting software
- Extensive assessment of current safeguards technology required
 - Applicability to MSR safeguards & what further development, modifications, upgrades should occur

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Module 5 – Slide 10. Safeguards Technology & Instrumentation Challenges Exist.

MSRs Blend Features From Bulk and Item Facilities

- MSRs share characteristics of both reactors (transmutation) and spent fuel reprocessing plants (change in chemical and physical material forms)
 - With the added complication of the intense heat and radiation arising from active nuclear fissioning
- Unlike reactors, the nuclear material may not be solid and fixed and would therefore be considered as bulk facilities
- Unlike reprocessing plants, MSRs are not throughput facilities, i.e., comparatively little material is being added or withdrawn - such that it can be considered a “closed loop”

Item Facilities: Reactors

- Materials are kept in item form and the integrity of the item remains unaltered

Bulk Facilities: Conversion, Enrichment, Fuel Fabrication, Reprocessing

- Nuclear material can get held up, processed, or used in bulk form

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Module 5 – Slide 11. MSRs Blend Features from Bulk and Item Facilities.

MSRs Will Require Non-Traditional Safeguards Approaches

| LWR (Traditional) | MSR (Non-Traditional)* |
|--|---|
| Safeguards routinely applied | Traditional safeguards techniques may not be applicable |
| Reactor and fuel cycle facilities are distinct | Reactor and fuel cycle essentially may be combined in a single facility |
| Fuel assemblies are discrete items – with offline refueling | Fuel can be a mixture of fuel salt, coolant salt, fission products, and actinides – some with online refueling; continuous feed and removal of salt |
| Monitor transfers in/out: monitor core and power level. Bar code reader I.D. and item counting of individual units (fuel assemblies) | Additional monitoring will be required that doesn't exist today. Item counting and visual accountability of fuel may not be possible |

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Module 5 – Slide 12. MSRs will require Non-Traditional Safeguards Approaches.

Several technical factors will show departure from conventional safeguards for liquid fueled MSRs

- Homogeneous mixture of fuel, coolant, fission products, and actinides
- Continuous variation of isotopic concentrations in the fuel salt, including removal (passive or active) of fission products, rare earth elements, and noble metals
- High temperature/high radiation levels
- Potential for online reprocessing whereby some fraction of the inventory can be removed while the reactor is operational
- Unique refueling schemes including the ability to continuously feed the core with fresh fissile or fertile material
- Presence of frozen fuel potentially requiring a different safeguards process to the liquid fuel
- Presence of fuel outside the vessel

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Module 5 – Slide 13. Several Technical Factors will show Departure from Conventional Safeguards for Liquid Fueled MSRs.

Molten Salt Reactor's Unique Features Imply Designers Should Consider Safeguards as Part of the Design: *Safeguards by Design (SBD)*

- SBD: process of incorporating features to support international safeguards into nuclear facility designs starting in its conceptual design phase.
 - Element of the design process for a new nuclear facility from initial planning through design, construction, operation, and decommissioning.
 - Similar to safety features for today's reactor designs
- SBD includes use of design measures that make the implementation of safeguards at such facilities more effective and efficient
 - Will be less costly to introduce measures to address safeguards needs at the beginning of the design process
- DOE/NNSA, NRC, and IAEA advocate SBD

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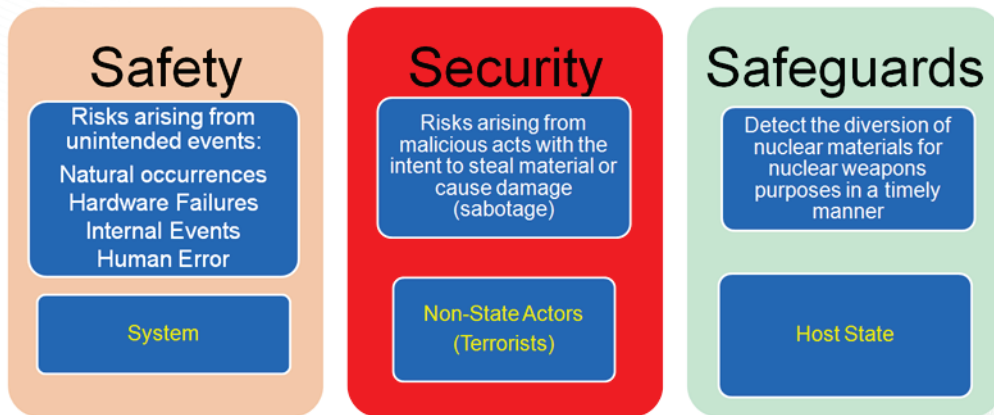
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Module 5 – Slide 14. Molten Salt's Unique Features imply Designers should consider Safeguards as Part of the Design.

Safeguards, Security, and Safety can Affect Each Other

- These should all be considered as part of the design process, e.g., using Safeguards-by-Design principles
 - To ensure compatibility and proper functioning to meet design goals



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Module 5 – Slide 15. Safeguards, Security, and Safety can affect each other.

It Is Important that MSRs Consider Safeguards & Security Early in the Design

- Difficulty/Expensive to retrofit the design
 - Retrofits may interfere with operations, maintenance, radiation protection, or safety aspects of the design
 - post design introduction may conflict with safety aspects already existing in design which has been reviewed by regulatory body
- Safeguards
 - Designers/researchers need to work with the regulators to develop methods that make it easier to implement safeguards in the design
 - monitoring - challenging in an advanced reactor (temperature, tritium, high radiation, inert atmospheres, toxic materials)
 - remote sampling capability (counting and visual accountability won't work for MSR)
 - reduce quantities of fuel outside the vessel
 - accessibility for inspections
- Design Security into the advanced reactors
 - Perform vulnerability studies early and as necessary as the design progresses
 - Use modern technology to reduce the need for guards, guns and gates

IAEA activities and resources are determined by member states. Member states need to indicate that MSR safeguards are of high importance for IAEA to take action.

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Module 5 – Slide 16. It is Important that MSRs consider Safeguards & Security Early.

Why Should Designers/ Vendors Take Note?

- IAEA Safeguards will be required if MSRs are deployed in non-nuclear weapons states
 - Safeguards are required by the NRC for U.S. deployment
- New technologies will stress the IAEA International Safeguards system and this may have consequences on MSR deployment
- Strong negative impacts if MSRs are perceived to have safeguards/proliferation issues
- Application of safeguards for MSRs may face technology challenges and new safeguards approaches
 - May require combination of bulk and item methods
 - Environment in MSR significantly more severe than in reprocessing plant
 - Fissile material location is distributed

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Module 5 – Slide 17. Why should Designers / Vendors take note?

Key Questions that Remain to be Addressed

- Is the IAEA and international safeguards system ready for MSR? If not, what steps should be taken to prepare?
- Are the safeguards inspection regimes of today valid for proposed MSR designs and the associated fuel cycles?
- Have the appropriate safeguards approaches been determined for MSRs?
- Are the safeguards approaches for one MSR design valid for another design?
- Are the safeguards inspectors of today aware of and prepared for the challenges presented by MSRs?
- Is the safeguards technology of today sufficiently mature to meet the verification challenges posed by MSRs and their associated fuel cycles?
- Are non-destructive assay technologies and other measurement instruments ready for deployment to meet these new verification challenges?

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Module 5 – Slide 18. Key Questions that Remain to be Addressed.

2.7 Module 6 – Research, Development, and Deployment Challenges

Gary Mays and George Flanagan of ORNL assembled and gave this presentation that presented the current status of R&D planning, and described paths forward for pursuing development of MSRs. Among the significant points made during the presentation are the following:

- MSR R&D needs have been identified by a task force representing developers in industry, as well as by DOE laboratory researchers.
- ORNL has prepared a draft MSR strategic plan and provided the plan to DOE/NE as input for MSR R&D moving forward.
- ORNL identified 7 strategic objectives to support MSR development goals.
- The presentation listed specific MSR R&D areas that are recommended for DOE/NE consideration, especially near term activities that have potential value to most or all MSR developers.



**Module 6:
Research, Development, and
Deployment Challenges**

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Informational Seminar on Molten Salt Reactors
DOE Office of Nuclear Energy, Germantown, MD
February 16th, 2017

ORNL is managed by UT-Battelle
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Module 6 – Slide 1. Title Slide.

Previewing MSR R&D Challenges and Needs

- MSR R&D underway includes private sector and government-private section collaborations => not the traditional R&D approach by government only
- R&D areas identified by MSR Technical Working Group via GAIN
- Draft ORNL MSR Strategic Plan – R&D areas to consider for all MSRs
- DOE-NE MSR actions/initiatives
- ARC 2015 Award – Molten Chloride Fast Reactor
- DOE/ORNL – CAS/SINAP CRADA
- Two example areas – issues on materials development and fuel qualification

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Module 6 – Slide 2. Previewing MSR R&D Challenges and Needs.

Challenges for Successful Development and Commercial Deployment of of MSRs

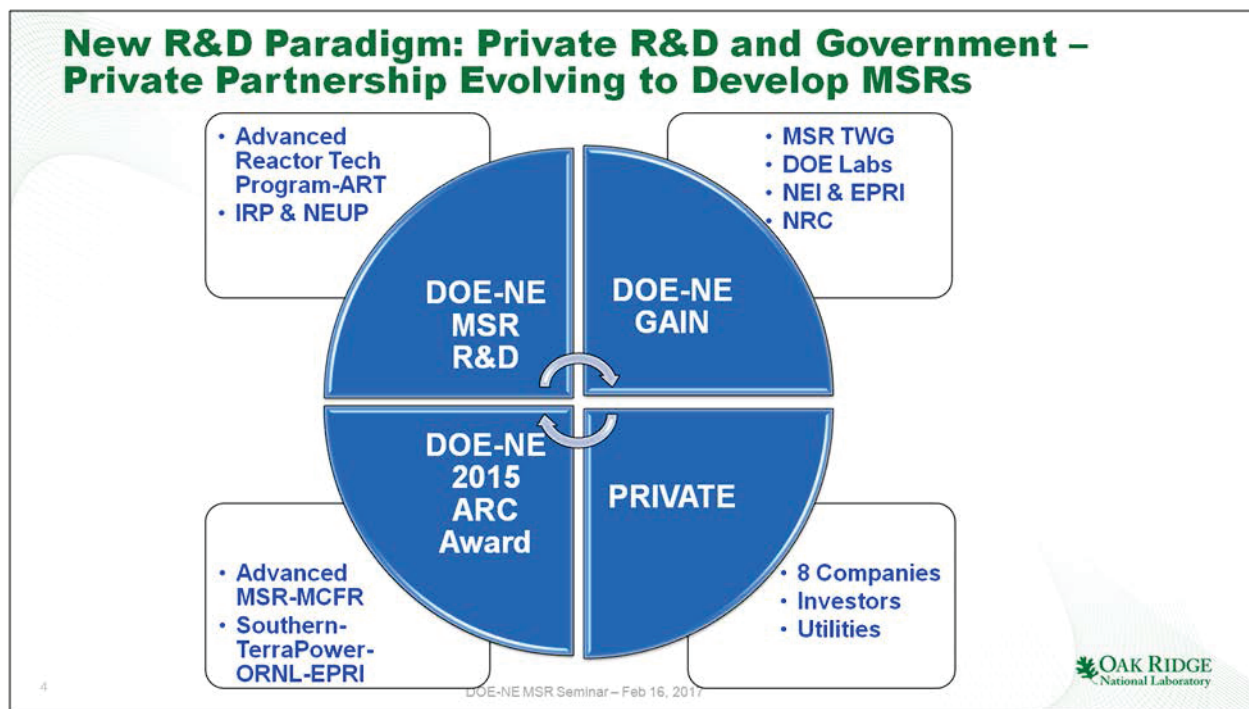
- 50 years since US operated an MSR
- Lower TRL vs other advanced reactors
- Sustained RD&D effort required
- "Different" reactor technology for NRC
- Need for test and experimental facilities
- Need for mod-sim capabilities
- Different safeguards approach
- Commercial supply chain
- Demonstrated economic performance

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Module 6 – Slide 3. Challenges for Successful Development and Deployment of MSRs.



Module 6 – Slide 4. New R&D Paradigm.

MSR Technical Working Group Identifies R&D Needs from 6 MSR Companies

Separate effects test program highlighted in December 2016 letter to GAIN Director – provided to DOE-NE

- Base Technology
 - Salt synthesis and purification
 - Physical properties and static corrosion studies
- Modeling and simulation
 - Gap analysis
 - Tool selection, development, and integration
 - Verification and validation
- Flow loops
 - Small-scale forced convection (250-500 kW) - multiple materials and salts
 - Medium-scale forced convection (2-3 MW) – fluoride and chloride loops

- Irradiation studies
 - Material coupon studies and PIE
 - Salt capsule testing (variety of salts and materials – corrosion studies)
 - In-core salt flow loops (one fluoride and one chloride)
- Vendor development
 - Pump development
 - Heat exchanger development
 - Valve development

MSR TWG Request Profile:

| FY18 | FY19 | FY20 | FY21 | TOTAL |
|--------|--------|--------|--------|-------|
| \$23 M | \$45 M | \$77 M | \$62 M | \$207 |

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Module 6 – Slide 5. MSR Technical Working Group Identifies R&D Needs.

“End Goal” for Development of MSRs Derived from DOE-NE’s For Nuclear Power and Advanced Reactors

DOE Mission for Nuclear Power

... to advance nuclear power as a resource capable of meeting the Nation's energy, environmental, and national security needs by resolving technical, cost, safety, proliferation resistance, and security barriers through research, development, and demonstration as appropriate.

DOE Vision for Advanced Reactors*

By 2050, advanced reactors will provide a significant and growing component of the nuclear energy mix both domestically and globally, due to their advantages in terms of improved safety, cost, performance, sustainability, and reduced proliferation risks.

DOE Goal for Deploying Advanced Reactors*

By the early 2030s, at least two non-light water advanced reactor concepts have reached technical maturity, demonstrated safety and economic benefits, and completed licensing reviews by the U.S. Nuclear Regulatory Commission (NRC). sufficient to allow construction to go forward.

Start with end in mind ...

The United States will establish and maintain the leading position worldwide in designing, fabricating, and demonstrating liquid-fueled molten salt reactors (MSRs) with a goal of meeting future electricity and process heat needs. By the early 2030's MSRs will have reached technical maturity, demonstrated safety and economic benefits, and completed licensing reviews by the U.S. Nuclear Regulatory Commission (NRC) sufficient to allow construction to go forward through strong engagement among the nuclear industry, DOE and its national laboratories, and universities.

* Draft DOE report – “Vision and Strategy for Development and Deployment of Advanced Reactors” - 2016

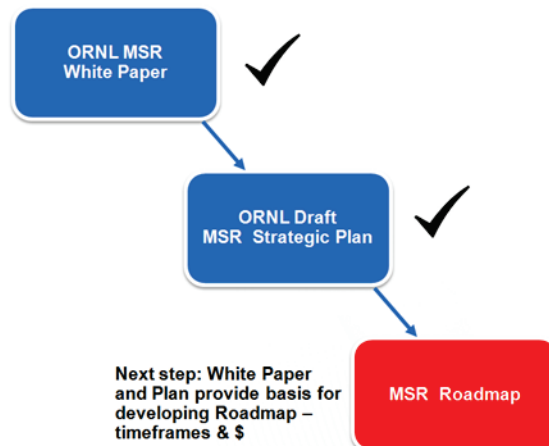
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Module 6 – Slide 6. "End Goal" for Development of MSRs.

ORNL Has Prepared an MSR Strategic Plan and Provided as Input for MSR R&D Moving Forward

- Initiated and funded internally – no formal request
- Follow-up to earlier MSR white paper
- Focused on liquid-fueled MSRs => elements applicable to solid-fueled MSRs as well
- Two parts
 - Part 1: 7 strategic goals => gov't – private partnership
 - Part 2: Implementation plans => identifies R&D actions
- Supporting objectives:
 - Engage US nuclear industry => collaborate to retire technical risk and increase TRL
 - Engage US Nuclear Regulatory Commission => establish defined pathway for licensing MSRs
 - Establish options non-nuclear separate and integrated effects test facilities, test reactors, and/or demonstration reactors



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Module 6 – Slide 7. ORNL has prepared an MSR Strategic Plan.

ORNL Identified 7 Strategic Objectives to Support MSR Goal

1. Establish the technical and safety basis for liquid-fueled MSRs by retiring the technical risks associated with MSR performance, safety, and licensing.
2. Identify and establish the physical R&D infrastructure (loops, test stands, etc.) needed to support the development of MSRs.
3. Demonstrate the technology viability, component and system reliability, and safety of MSRs by constructing and operating appropriate test and/or demonstration reactors to support the ultimate deployment and licensing of MSRs.
4. Establish the technologies to enable a commercial MSR fuel cycle.
5. Incorporate modern modeling and simulation capabilities into the development of tools and methods to support the design, operations, and licensing of MSRs.
6. Enable the NRC to achieve a well-defined and timely pathway for licensing by providing the information needed to formulate a licensing framework and basis for MSRs.
7. Support and enable private sector development and deployment of MSRs by key stakeholders via public-private partnerships.

From draft ORNL
MSR Strategic
Plan provided to
John Herczeg
Jan 2017



Module 6 – Slide 8. ORNL Identified 7 Strategic Objectives to Support MSR Goal.

RD&D Technical Challenges for MSRs Presented Earlier Addressed in MSR Strategic Plan

- Maintenance activities in high radiation environments are much more challenging
- Some fuel cycles include on-site fissile materials separation (i.e. historic MSBR)
- Nickel based alloys embrittle in high neutron flux environments at high temperatures – some new designs employ internal shielding
- Clad alloys are largely unaddressed in high-temperature design code
- Chloride fuel salt properties have never been demonstrated in-core
- Large-scale isotope separations are immature and expensive
 - ^{37}Cl for some fast reactors and ^7Li for some thermal reactors
 - Tritium is a significant unresolved issue for high-temperature reactors that employ lithium salts
- Large scale components for fuel salt and cover gas are immature
- Distribution of fission products has significant remaining unknowns
- MSR modeling tools are immature and not well validated
- No licensing basis for commercial fluid-fueled systems
- High salt freezing temperatures



Module 6 – Slide 9. RD&D Challenges for MSRs Presented Earlier Addressed in MSR Strategic Plan.

Example from MSR Strategic Plan Showing Structure & Content Detail

Strategic Objective 1: Establish technical and safety basis for liquid-fueled MSRs by retiring the technical risks associated with MSR performance, safety, and licensing.

Strategic Issues

- Identify & qualify a liquid molten fuel and materials system (analogous to a solid fuel and clad system) to understand and validate fission product behavior and fuel salt interactions with primary system materials;
- Qualify structural materials and fabrication methods, which is especially challenging for complex structures such as heat exchangers, for both fluoride- and chloride-based salts;
- Demonstrate passive decay heat removal systems and to validate models;
- Obtain more knowledge of the properties and associated processes for chloride-based salts, and the need to extend fluoride salt chemistry baseline information that will also aid in further understanding of chloride salts;
- Develop and demonstrate potential technology options for sequestering tritium produced in MSRs that use fluoride salts;
- Develop manufacturing capability for key commercial scale MSR components such as pumps and valves;
- Determine the availability of and potential options for separations processes for industrial-scale production of chlorine and lithium isotopes, and knowledge of the potential costs for such processes; and
- Develop remote tooling, instrumentation, and control systems to perform operational and maintenance activities within the highly radioactive containment



| Strategy/Actions for First Issue under SO 1 | |
|--|--|
| i. Identify and rank the phenomena, variables, and parameters associated with the fuel that dictate the safety and operations of a liquid-fueled MSR, including | <ul style="list-style-type: none"> • introduction of fission products into the fuel, changing composition of fissile/fertile material, • introduction of corrosion products due to interaction with fuel and structural materials or the chemical control system, and • changes in flow rate and temperature associated with operational adjustments. |
| ii. Devise capsule tests to be run at ORNL's HFIR and/or Advanced Test Reactor (ATR) to address the stability of chloride salt solutions under irradiation. | Stability of salts, particularly chloride salts, under irradiation must be confirmed. |
| iii. Develop the infrastructure to perform special effects tests to determine the changes in physical properties deemed important from (i) above, including the ability to vary composition by introducing surrogate materials covering the range of composition changes anticipated and to vary the salt temperature within the ranges anticipated. | |
| iv. Based on the data and observations from iii above, develop thermodynamic models could be used to provide phase diagrams based on salt composition and temperature for use by designers and safety analysts to ensure safe, efficient MSR operations. | |

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Module 6 – Slide 10. Example from MSR Strategic Plan Showing Structure and Content Detail.

Supporting MSR Goals to Aid Commercial Deployment Complement Strategic Objectives

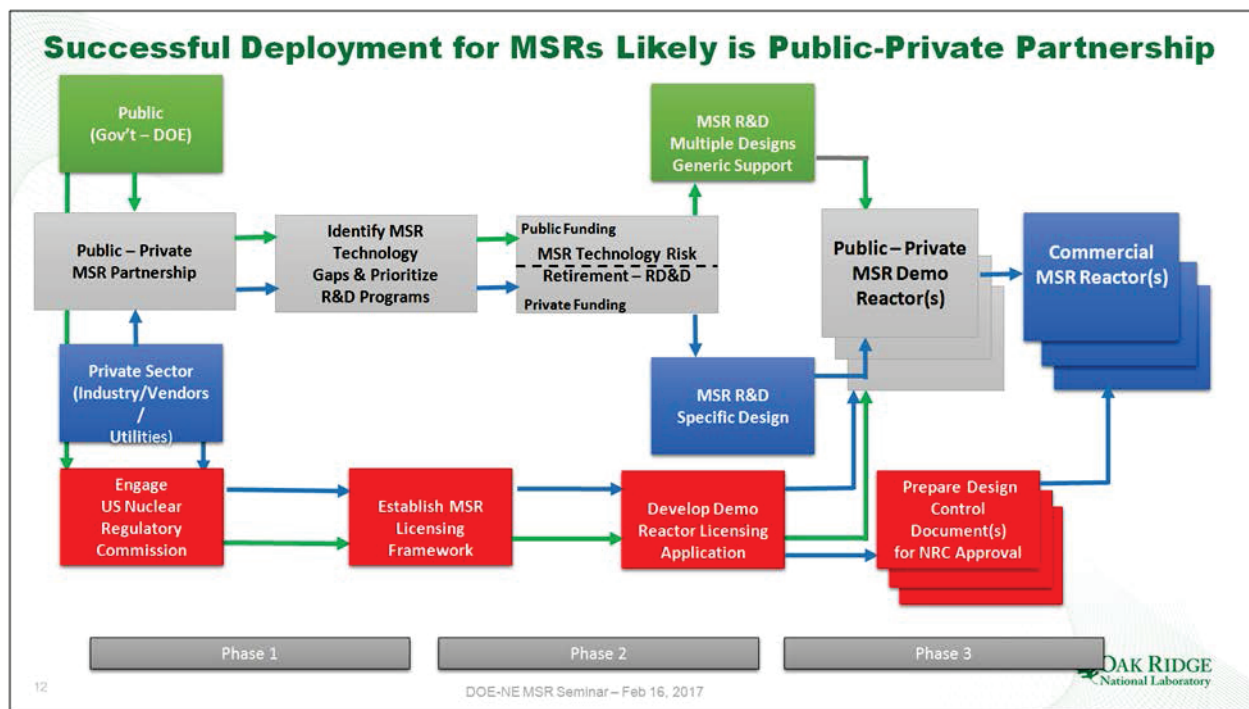
- Safeguards monitoring of liquid-fueled MSRs will be a departure from that required for traditional LWR technologies
- Expanded participation in Generation IV International Forum => leadership role in development of MSRs
- Siting requirements and evaluations
 - Co-location for process heat applications
 - Use of non-steam based power conversion systems offers additional siting options
- Regular MSR technical exchanges
 - Foster cooperation and communication on public-private partnership
 - Provides opportunity for NRC engagement

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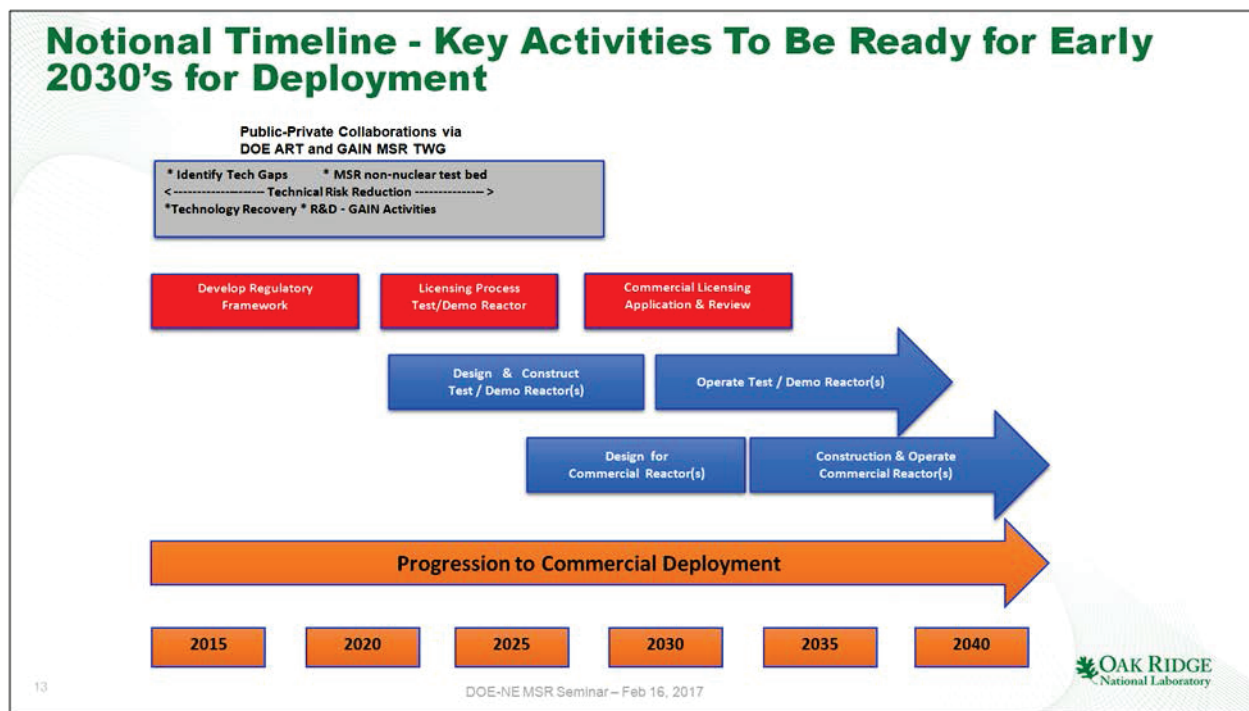
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Module 6 – Slide 11. Supporting MSR Goals to Aid Commercial Deployment Complement Strategic Objectives.



Module 6 – Slide 12. Successful Deployment for MSRs Likely is Public-Private Partnership.



Module 6 – Slide 13. Notional Timeline – Key Activities to be Ready for Early 2030's.

MSR R&D Areas Recommended for DOE-NE Consideration – - Near Term - Potential Value to all/most MSR Developers

- Determine what the equivalent of a fuel qualification program looks like for a liquid-fueled reactor
- Develop a code qualified base structural alloy and coating (chemical compatibility) for both fluoride and chloride systems
- Develop salt chemistry capability to perform thermal and physical property evaluations and measurements (plans underway)
- Perform chloride salt capsule testing and loop testing
- Address need for developing modern salt components (pumps and valves) needed for loops and scaling up to commercial scale
- Demonstrate passive decay heat removal systems and validate models => confirm for NRC
- Plan and conduct zero power critical experiments – develop international benchmark
- Identify and develop safeguards approach and I&C needed for safeguards measurements
- Identify how automation effectively impacts maintenance for MSRs – high temp and rad areas
- Develop point designs for both fluoride and chloride MSRs to focus development of safety analysis tools and experiments

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Module 6 – Slide 14. MSR R&D Areas Recommended for DOE-NE Consideration.

DOE-NE R&D Initiatives Shaping MSR R&D Plan

- Including a National Technical Director for MSRs in ART program
- Developing plans for April 10-12 Molten Salt Chemistry workshop at ORNL
 - Objective: Identify potential science-based, technology-drive research opportunities to facilitate and accelerate MSR technologies development
 - DOE-NE lead: Stephen Kung ORNL lead: David Williams
- Providing MSR developers access to MSR historical documents (~210 to date) via GAIN
- Planning MSR Roadmap => starting point
 - MSR Strategic Plan (2017)
 - FHR Roadmap (2013)



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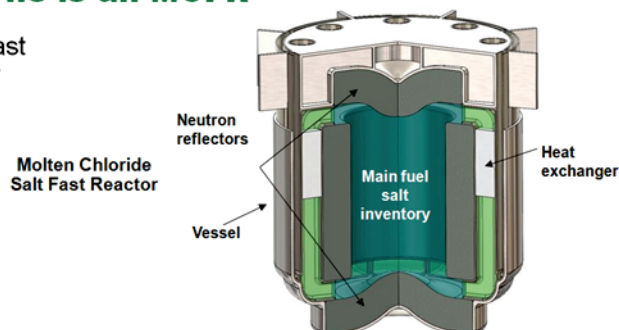
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Module 6 – Slide 15. DOE-NE R&D Initiatives Shaping MSR R&D Plan.

DOE ARC 2015 Awards - 2 New Investments in Advanced Reactors Announced in 2016 – One is an MCFR

- Southern Company leads team to develop fast spectrum molten chloride salt-cooled reactor
 - Team includes TerraPower, ORNL, EPRI, & Vanderbilt University
 - ORNL principal roles include
 - Reactor systems & technology development
 - Safety assessment and licensing strategy
 - Materials assessment
 - Salt purification and property measurements
- 5 year ARC R&D award to culminate in IET facility
- TerraPower is reactor design lead with 4 years R&D complete – new facilities enable
 - Salt synthesis
 - Flow loops
 - Separate effects



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TerraPower Test Facilities

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Module 6 – Slide 16. DOE ARC 2015 Awards – 2 New Investments in Advanced Reactors Announced in 2016 – One is an MCFR.

Phase 1 of SINAP-ORNL CRADA* Completed June 2016

- Successfully commissioned and operated ORNL's Liquid Salt Test Loop
- Procured and set up experimental facility for salt flow meter calibration
- Updated SCALE 6.2 with salt property data
- Reviewed salt pump history and completed initial hydraulic and vibration modeling of LSTL pump
- Held FHR safety and licensing workshop in Shanghai for 270 CAS, SINAP, NNSA (regulator) staff members in Dec 2015
- Phase II awaiting approval by DOE-NE and DOE-NNSA
 - LSTL operation and component testing
 - Materials roadmap support
 - PIRT exercise – FHR safety and performance issues
 - Reactor system modeling tool development

* Does not include fuel development or fissile material separation technology

| | |
|-------------------------|-------------------------------------|
| Salt | FLiNaK (initial) |
| Operating temperature | ≤ 710 °C |
| Operating pressure | ≤ 2 bar (≤ 30 psig) |
| Operating run time life | 2+ years |
| Flow rate | ≤ 5.8 kg/s ~4.5 m/s (1 in. pipe) |
| Cross pipe ID | 2.67 cm (1.05 in.) |
| Salt volume | 120 L (240 kg) |
| Trace heating | ~27 kW |
| Temperature measurement | ~52 thermocouples 2 RTDs |
| Pressure gauges | 2 in gas spaces |
| Salt mass measurement | 2 × 3 load cells |



ORNL Liquid Salt Test Loop – configuration and thermal image



FHR Safety & Licensing Workshop



ORNL Flow Meter Calibration Facility
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Module 6 – Slide 17. Phase 1 of SINAP-ORNL CRADA Completed June 2016.

R&D Example 1: Materials Development Issues and Approaches

- Harsh environments (radiation, chemical corrosion, and temperature) limit the selection of materials for use in MSR
- Currently high nickel based alloys appear to have the best high temperature and salt compatibility
 - Hastelloy-N (used in MSRE) – resistant to salt corrosion -not ASME nuclear code qualified , temperature limitations of $T < 704^{\circ}\text{C}$, and has poor neutron irradiation tolerance (He production)
- All current high nickel alloys have poor irradiation resistance => results in design penalties such as replacing components, systems and structures exposed to high irradiation frequently (in the range of 6-8 years)

=> However, some reactor designers appear to be willing to take this replacement approach in order to get to market sooner while others are expecting materials development to enhance their business case
- Need for development of new irradiation tolerant structural alloys to allow 30 or more years of operation without replacement (needed for both fluoride and chloride fueled systems)
- Alternative is to clad irradiation tolerant and temperature tolerant materials such as SS with corrosion tolerant materials such as Mo or ceramics.

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Module 6 – Slide 18. R&D Example 1: Materials Development Issues and Approaches.

R&D Example 2: Fuel Qualification Issues for MSRs

- For heterogeneous reactors the fuel/cladding system is the principal barrier to release of fission products
- Extensive effort has been placed by the industry and regulator (NRC) on assuring that the behavior of the fuel is well understood under all perceived operational conditions \Leftrightarrow fuel qualification
- Introduction of a new solid fuel type can be expected to take hundreds of millions of dollars and up to 25 years for qualification
 - Includes extensive irradiation and hot cell examinations

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Module 6 – Slide 19. R&D Example 2: Fuel Qualification Issues for MSRs.

R&D Example 2: Fuel Qualification Issues for MSRs (cont'd)

- MSRs have no equivalent to the traditional fuel qualification process
- MSRE indicates that the salt compounds are insensitive to irradiation damage
- Major concern will be changing chemical behavior during dwell time in the reactor and in storage
 - No irradiation
 - No hot cell examination
 - Small samples/ no geometric requirements
 - Should be less expensive and less time consuming
- Issue: there is no regulatory precedence for what are the controlling parameters.

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Module 6 – Slide 20. R&D Example 2: Fuel Qualification Issues for MSRs (cont'd).

2.8 Concluding Remarks

This presentation provided the concluding remarks about the information provided in the seminar. Among the significant points made during the presentation are the following:

- Many MSR concepts are being developed today by industry, universities, and governments.
- Most of the MSRs under development are liquid-fueled MSRs, which are not just reactors, but represent either limited recycle or continuous recycle fuel cycles.
 - The amount of R&D needed to bring a concept to maturity varies depending on the design.
 - Some R&D appears to be common to many of the MSR concepts, while other R&D may be specific to only one or just a few concepts.
- The capability to analyze MSR performance needs to be improved to allow accurate assessment of MSR potential.
- Possible R&D plans need to be developed to inform the DOE/NE decision-making process concerning nuclear energy R&D.



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**Informational Seminar on
Molten Salt Reactors –
Concluding Remarks**

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Conclusion – Slide 1. Title Slide.




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Seminar Summary

- **The presentations have provided a review of MSR technology, including possible variations**
 - History of MSR development
 - MSR characteristics
 - Potential MSR benefits, disadvantages, and challenges
 - Recommended R&D
- **There are many MSR concepts being promoted today**
 - For liquid fuel MSRs, both limited and continuous recycle
 - Some concepts are being promoted as possible for demonstration and deployment in the near term
 - Other concepts appear to have more R&D needs, especially with respect to structural materials, that will likely require more time

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Conclusion – Slide 2. Seminar Summary.



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Next Steps

- **Some R&D needs may be common to all MSRs, while others may apply only to specific concepts**
 - R&D recommendations have been obtained by DOE/NE from both the ORNL draft R&D plan and from the industry-led MSR Technology Working Group
- **A next step would be to develop R&D plan proposals, along with time and funding estimates, facility needs, etc., supported by the needs for the specific MSR concepts**
 - Common R&D
 - Concept-specific R&D
- **At the same time, improving analysis capability to provide accurate assessment of MSR potential should proceed**
 - Evaluation of the performance potential of MSR concepts
- **Both the R&D plans and the potential MSR performance benefits would be input to the DOE/NE R&D decision-making process**
 - The same approach supported by the E&S study

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Conclusion – Slide 3. Next Steps.

3. Summary

This report has documented the presentations given at the MSR seminar, DOE Headquarters, Germantown, MD, on February 16, 2017. The presentations represent the history and state of knowledge about MSRs at that time, and were provided to the DOE Federal managers as background information. The identified R&D may be used to inform the decision-making process concerning MSRs and the supporting technologies, but this report does not make any recommendations concerning MSR development or any directions for R&D.