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

R. Wigeland

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

March 31, 2017
NTRD-FCO-2017-000264

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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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.

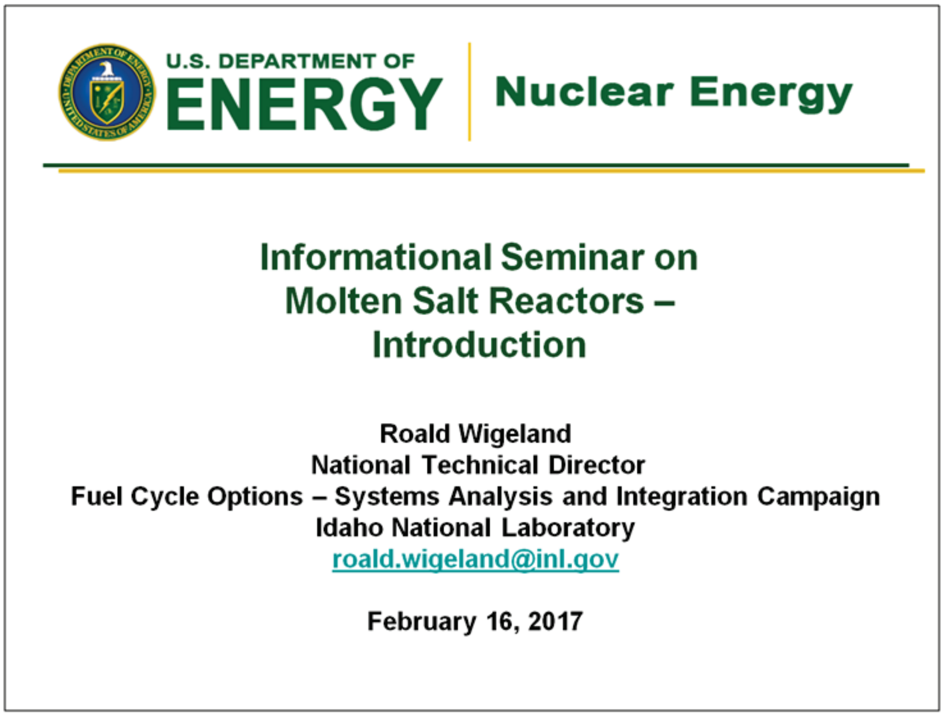
Table 1. MSR Seminar Agenda

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)

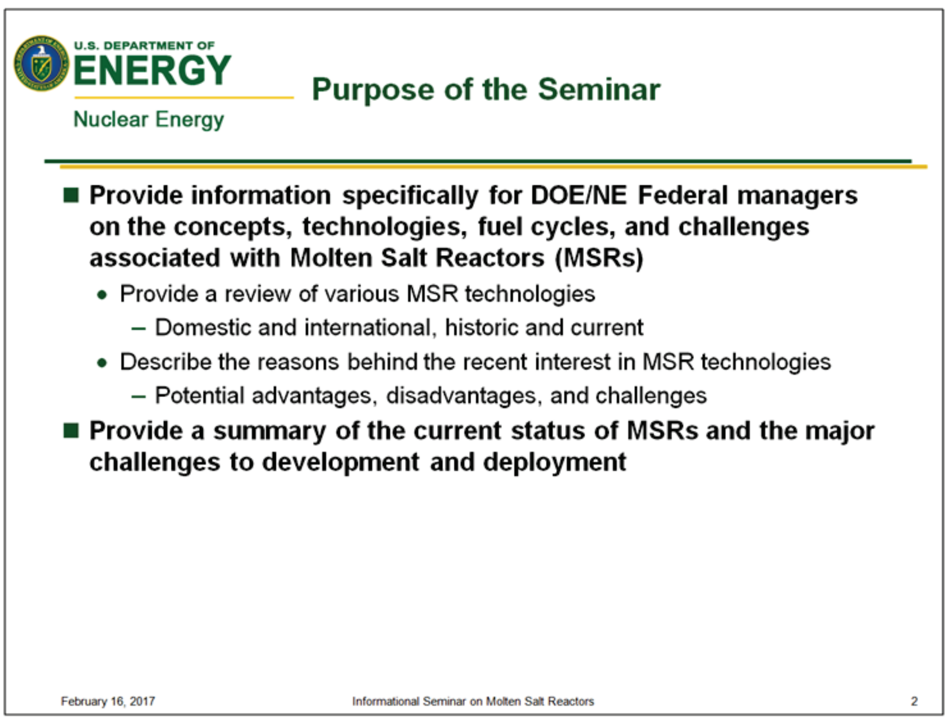
2.1 Meeting Overview and Background

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.



Introduction Slide 1. Title Slide.



Introduction Slide 2. Purpose of the Seminar.

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Seminar Agenda

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Introduction Slide 3. Seminar Agenda.

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Introduction to "Molten Salt Reactors" (MSRs)

- **Molten salt can be used as a coolant, like water or sodium, for use with solid nuclear fuels (oxide, metal, carbide, nitride, etc.)**
  - 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"**
  - 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
    - 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**

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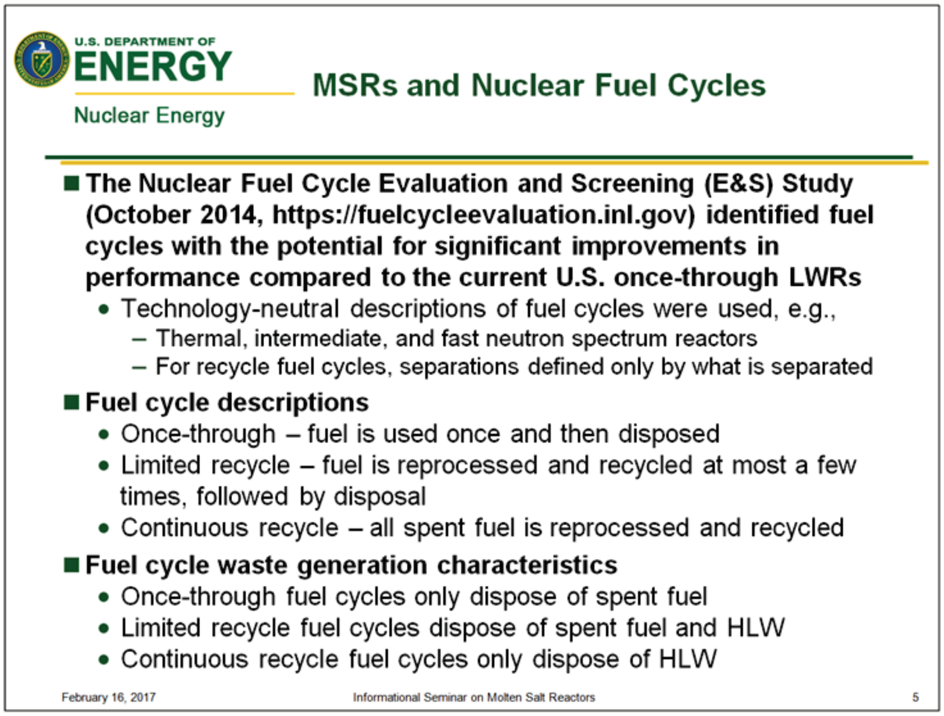
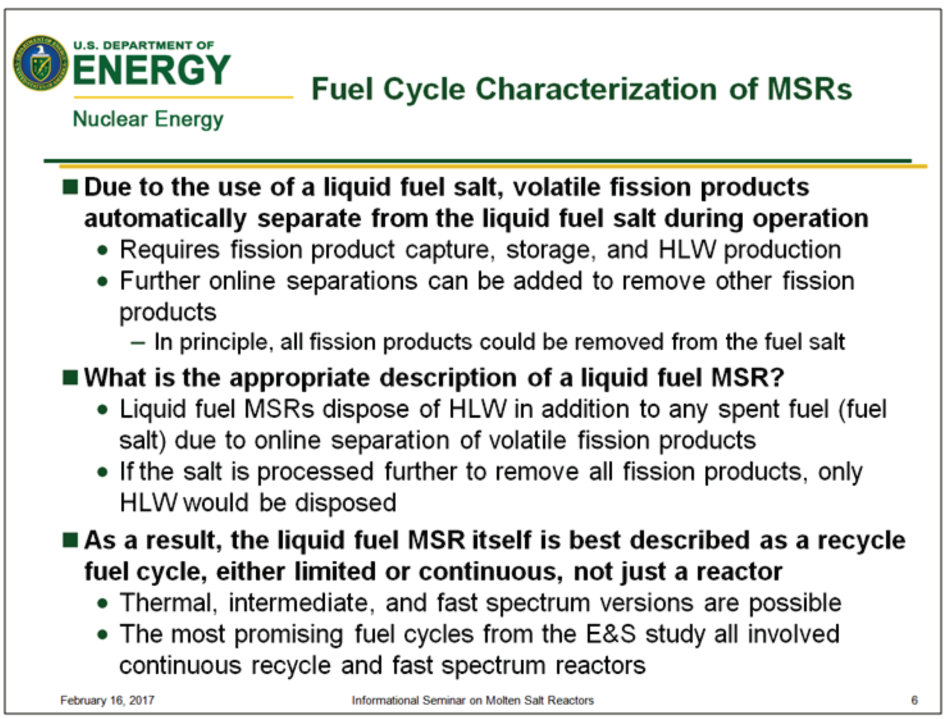
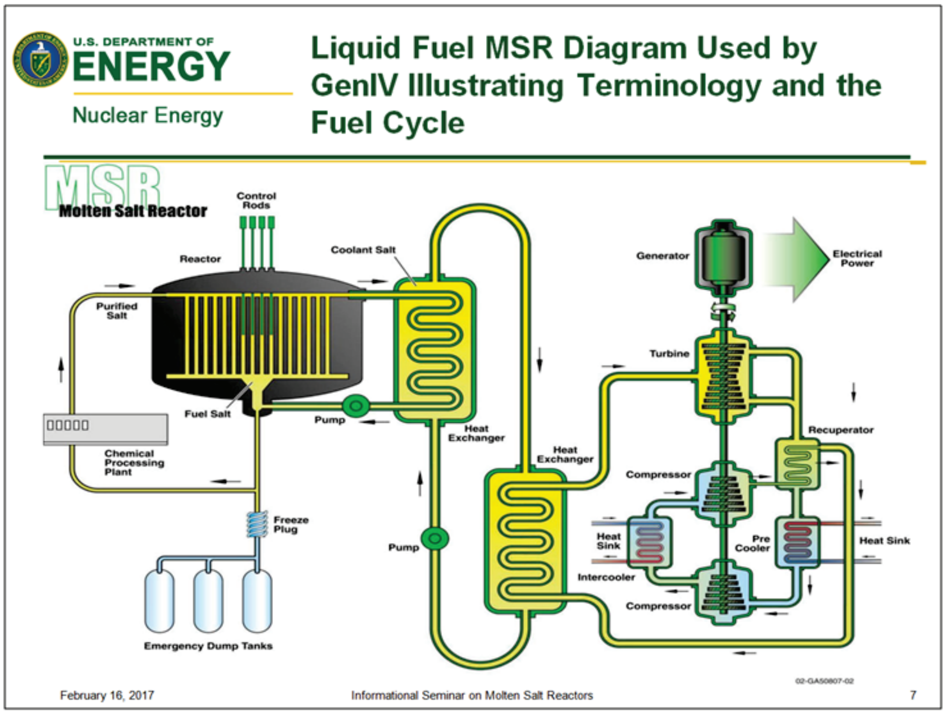
Introduction Slide 4. Introduction to "Molten Salt Reactors" (MSRs).



Introduction Slide 5. MSRs and Nuclear Fuel Cycles.



Introduction Slide 6. Fuel Cycle Characterization of MSRs.



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

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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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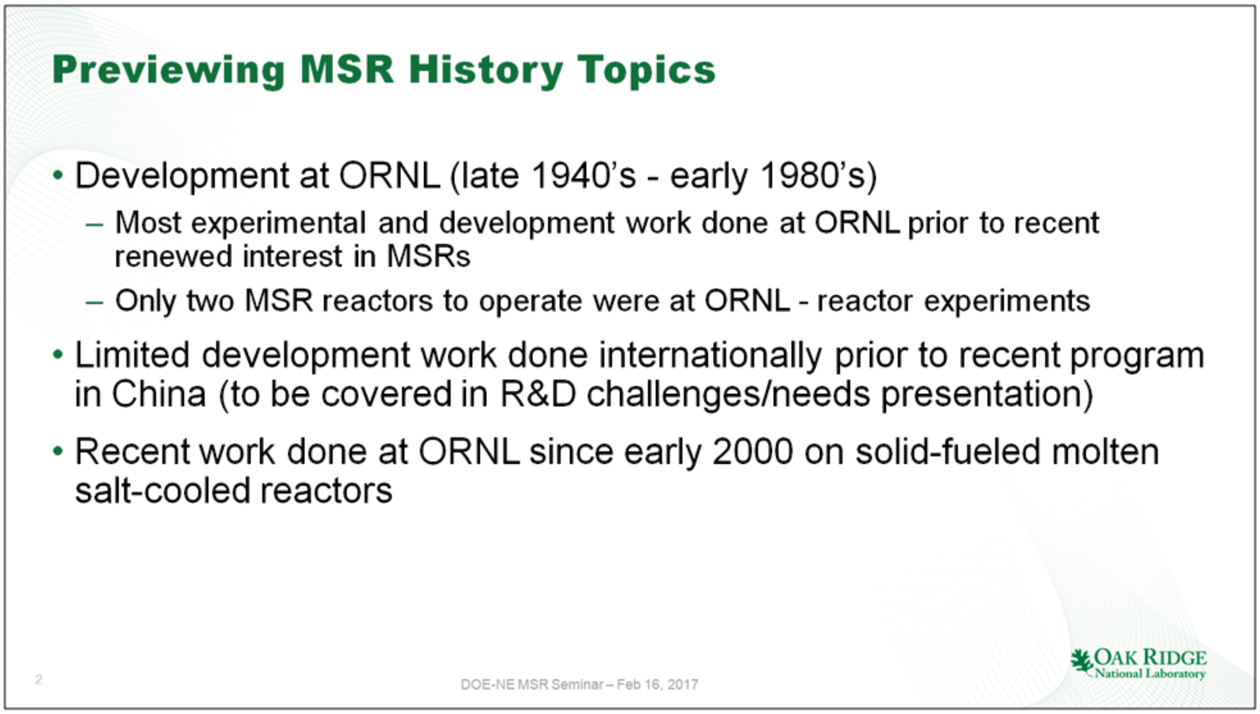
Introduction Slide 8. MSR Terminology and Fuel Cycles.

2.2 Module 1 – Brief History of the ORNL MSR Program

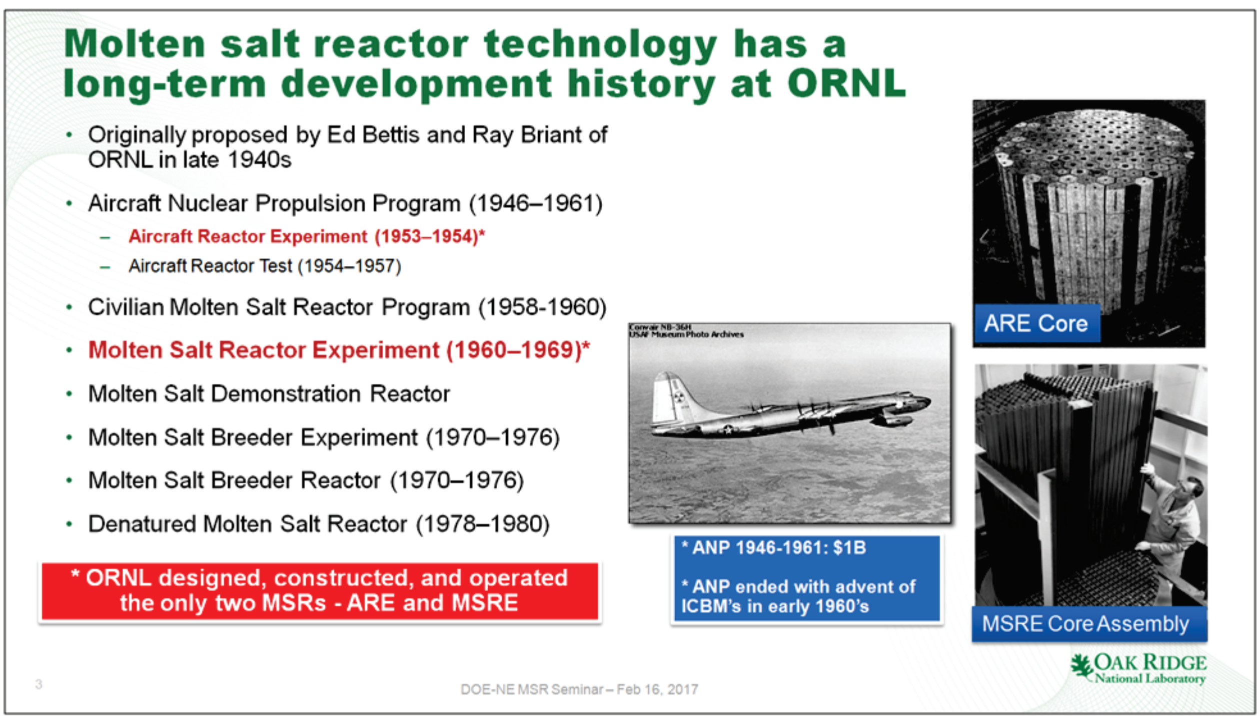
Gary Mays of ORNL assembled and gave this presentation that provided a review of the history of MSR development, mainly at ORNL, and the perspective for considering the current proposals and developments on MSRs. Among the significant points made during the presentation are the following:

- 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.

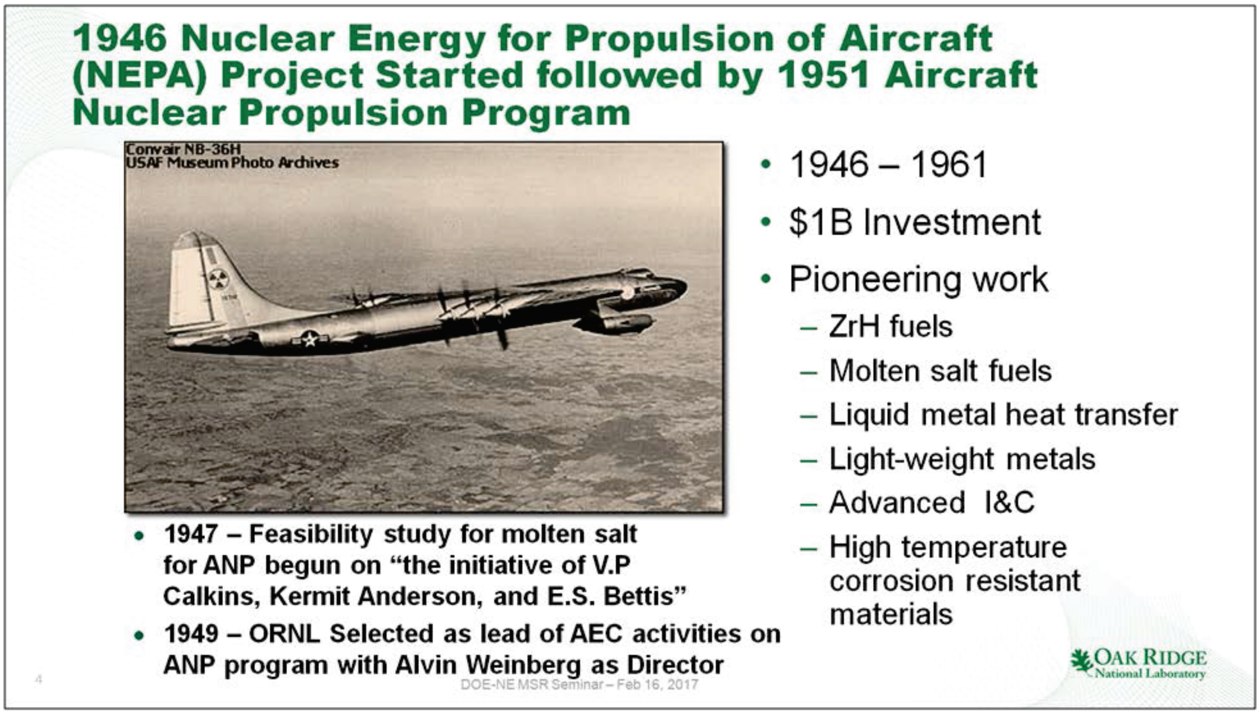
Module 1 – Slide 1. Title Slide.



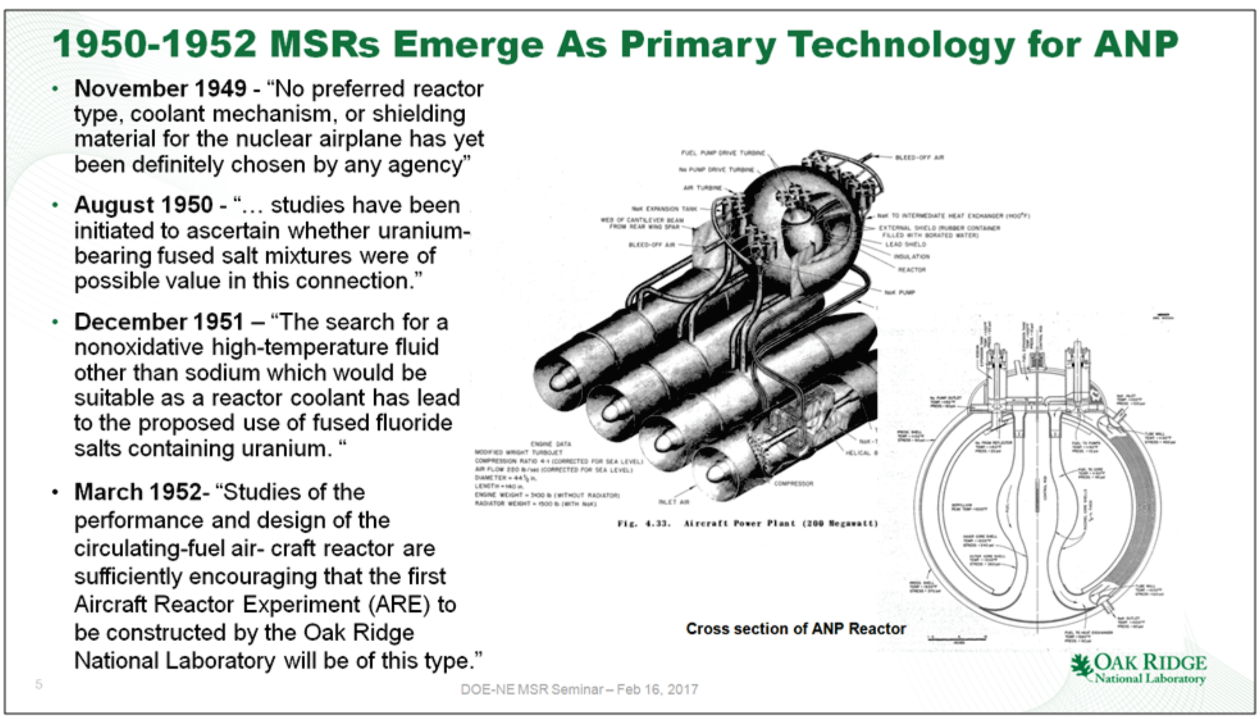
Module 1 – Slide 2. Previewing MSR History Topics.



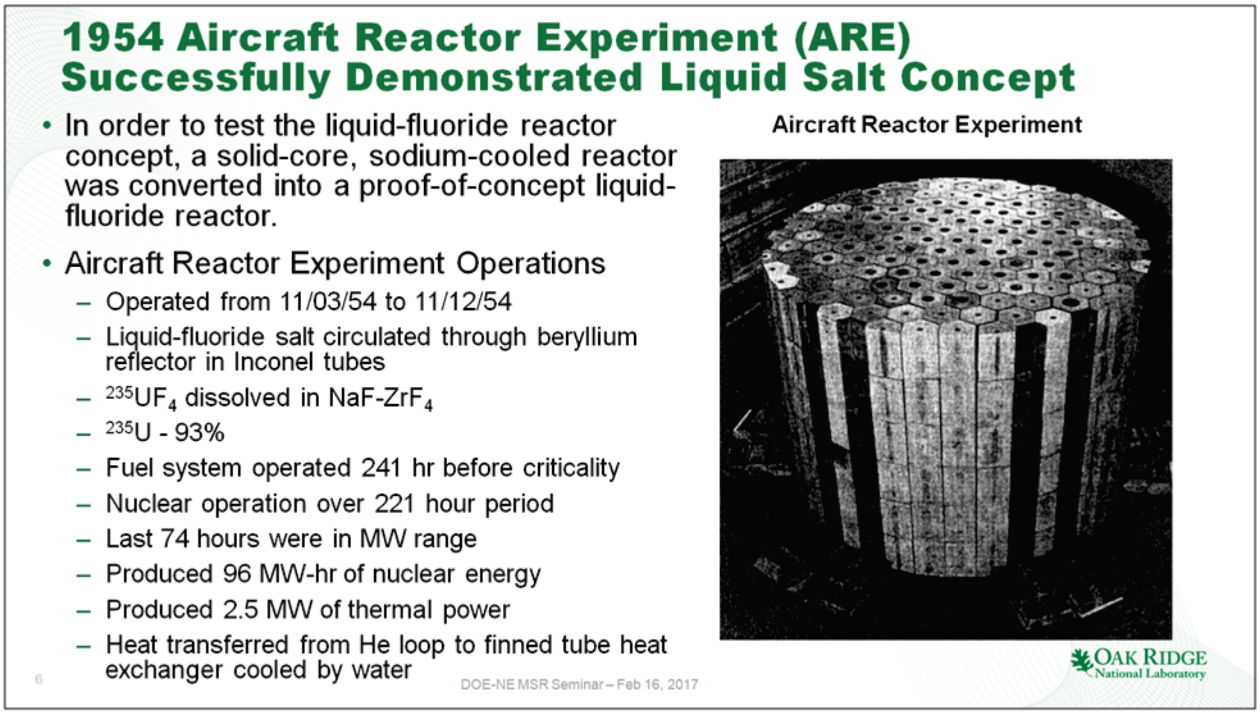
Module 1 – Slide 3. Molten Salt Reactor Technology has a Long-Term Development History.



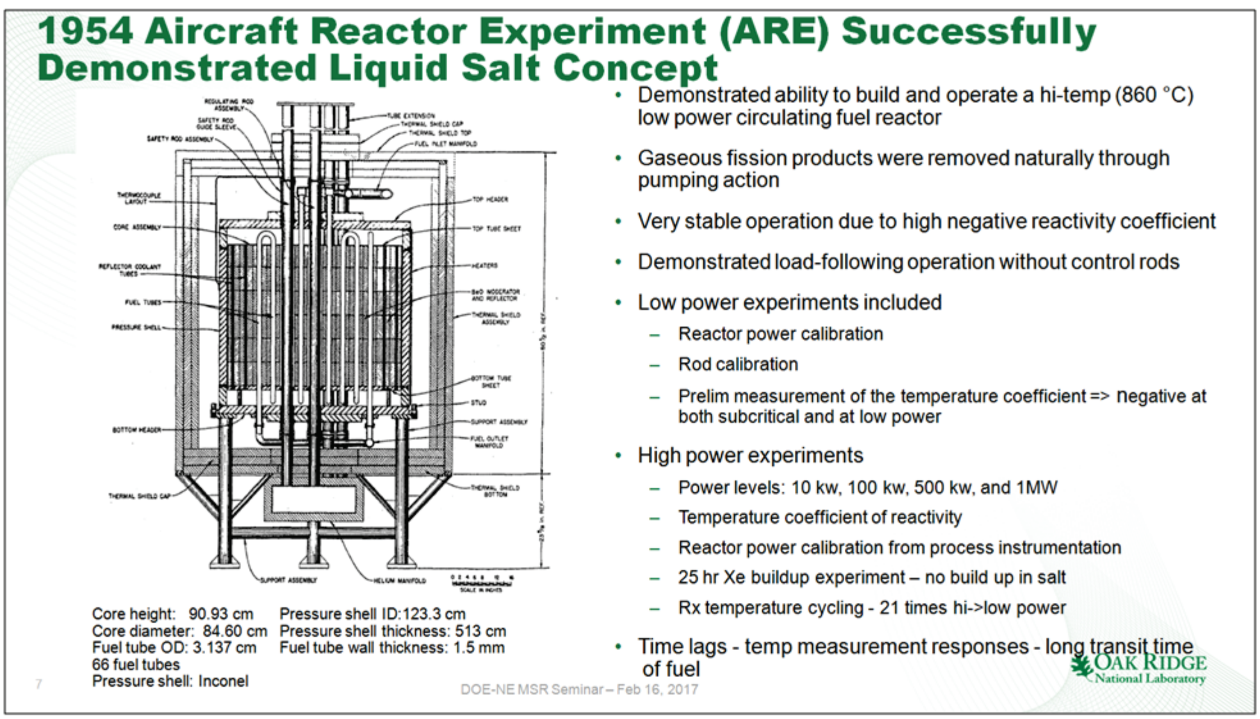
Module 1 – Slide 4. 1946 Nuclear Energy for Propulsion of Aircraft (NEPA) Project Started Followed by the 1951 Aircraft Nuclear Propulsion (ANP) Program.



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



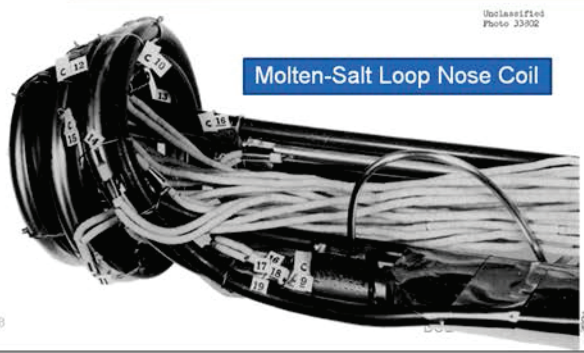
Module 1 – Slide 6. 1954 Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept.

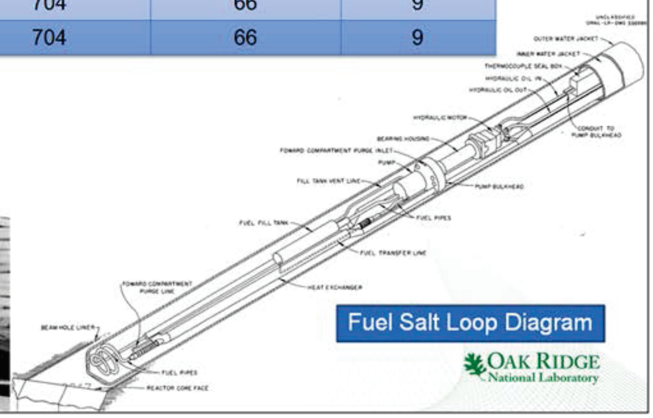


Module 1 – Slide 7. 1954 Aircraft Reactor Experiment (ARE) Successfully Demonstrated Liquid Salt Concept.

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/cm³)	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 ^7LiF – 37 BeF_2 – 1 UF_4	704	66	9
Alloy N	62 ^7LiF – 37 BeF_2 – 1 UF_4	704	66	9





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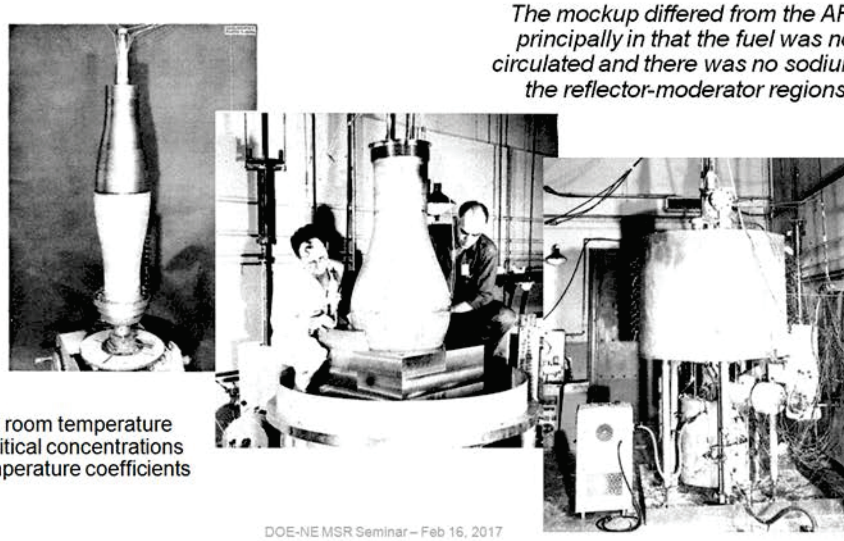
Module 1 – Slide 8. ORNL Ran Five Pumped Fuel Salt Loops at INL's Materials Test Reactor Prior to the Aircraft Reactor Experiment.

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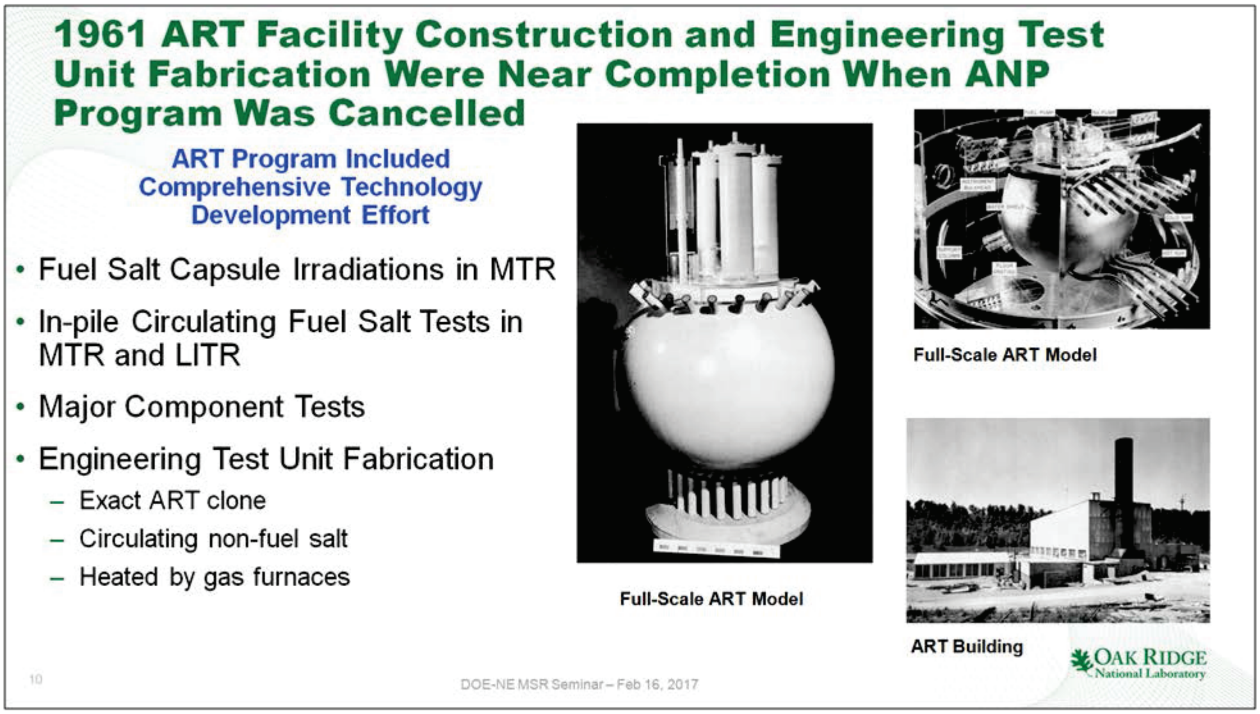
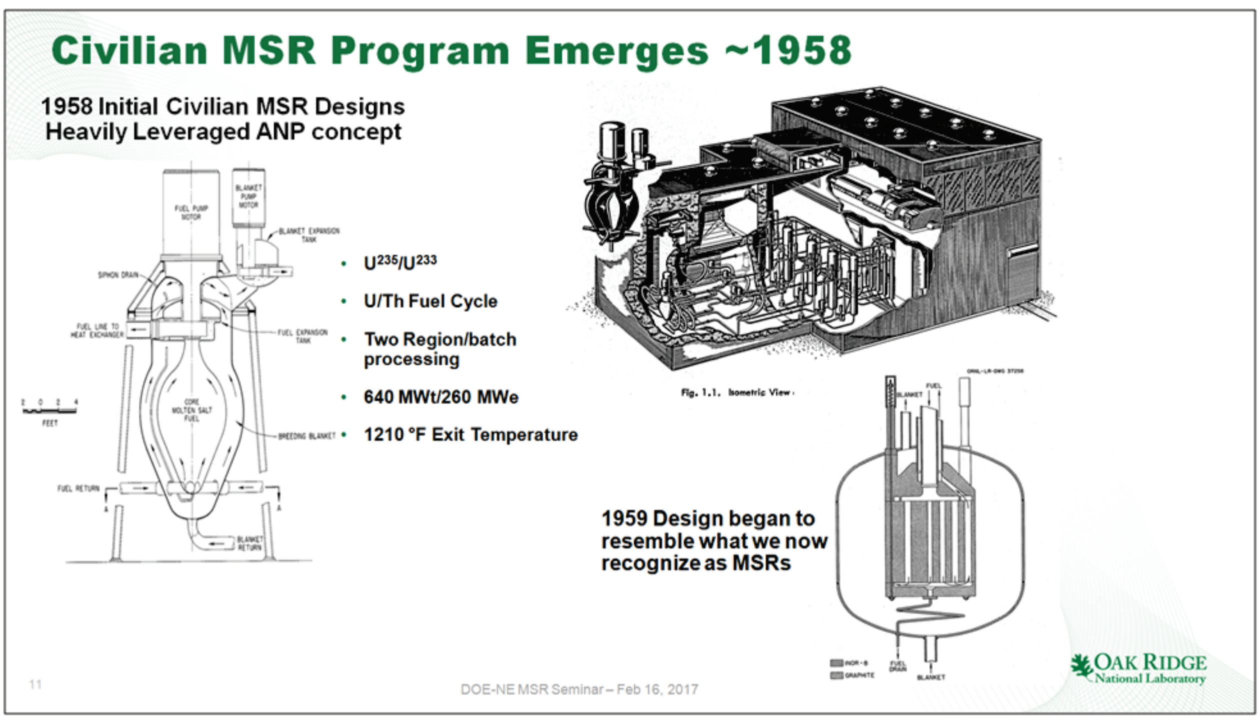
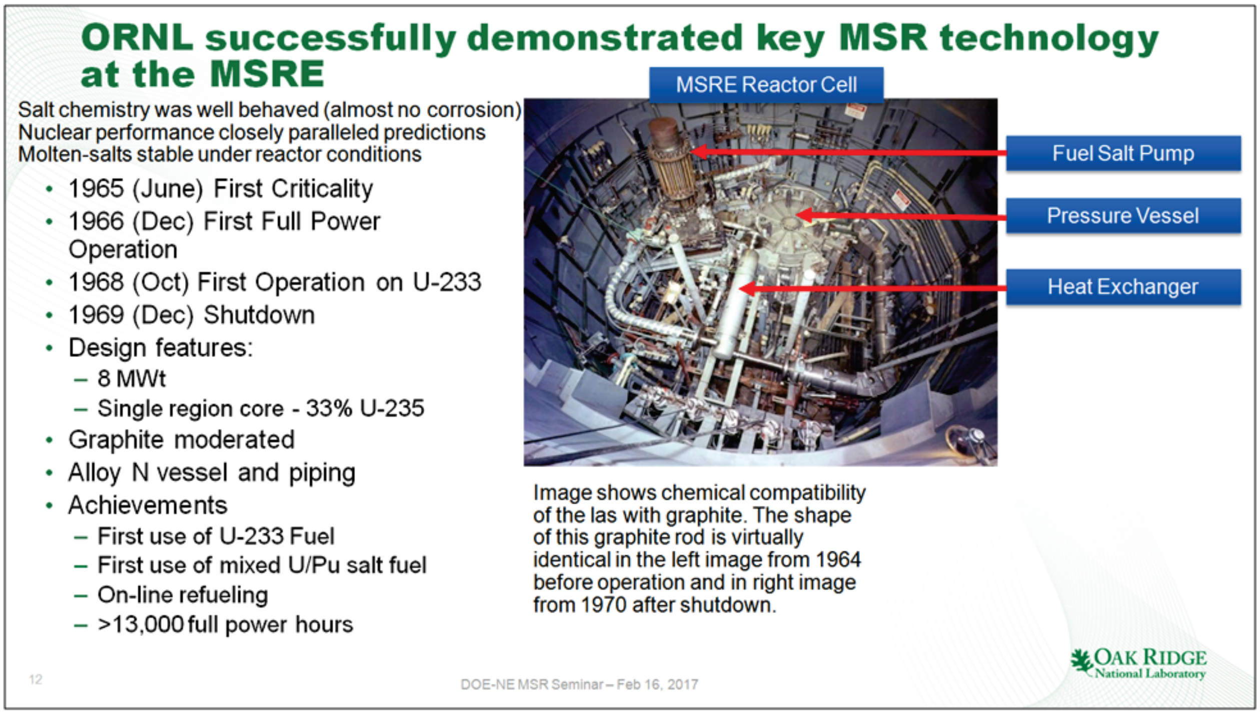
Module 1 – Slide 9. 1956 Low Power, Electrically Heated, High Temperature Critical Experiment Operates at 1200ºF.



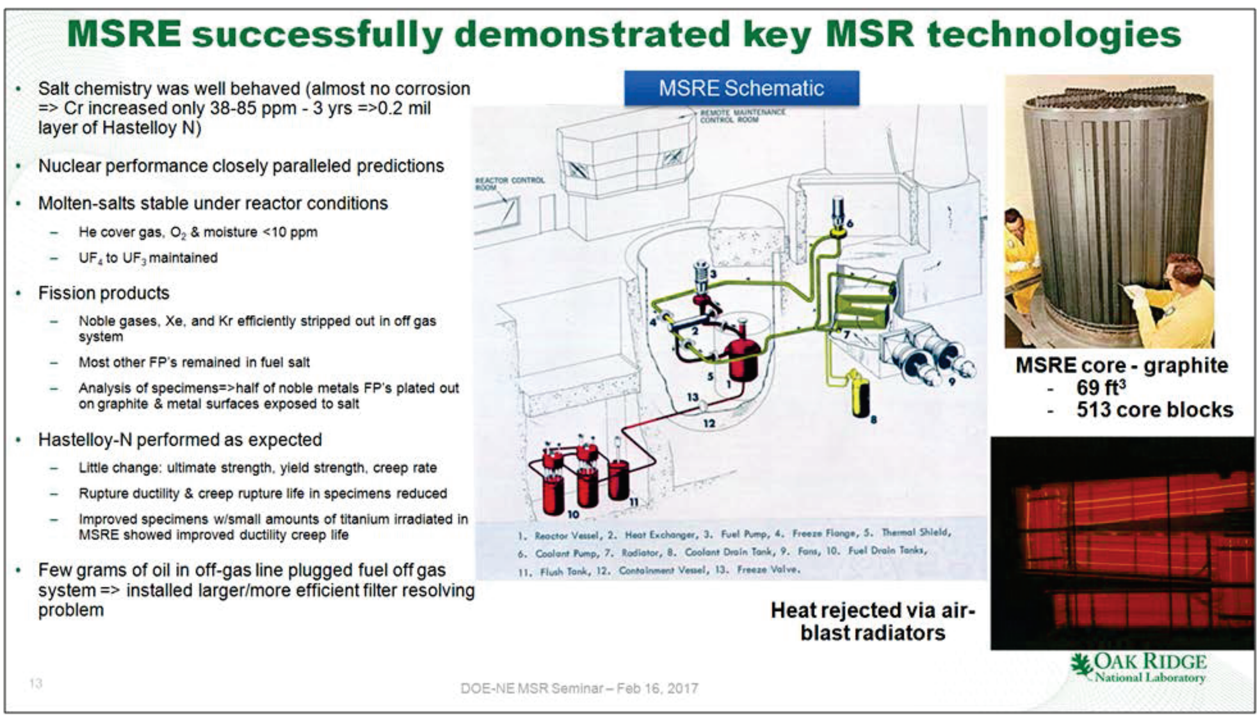
Module 1 – Slide 10. 1961 ART Facility Construction and Engineering Test Unit Fabrication were near Completion when ANP Program was cancelled.



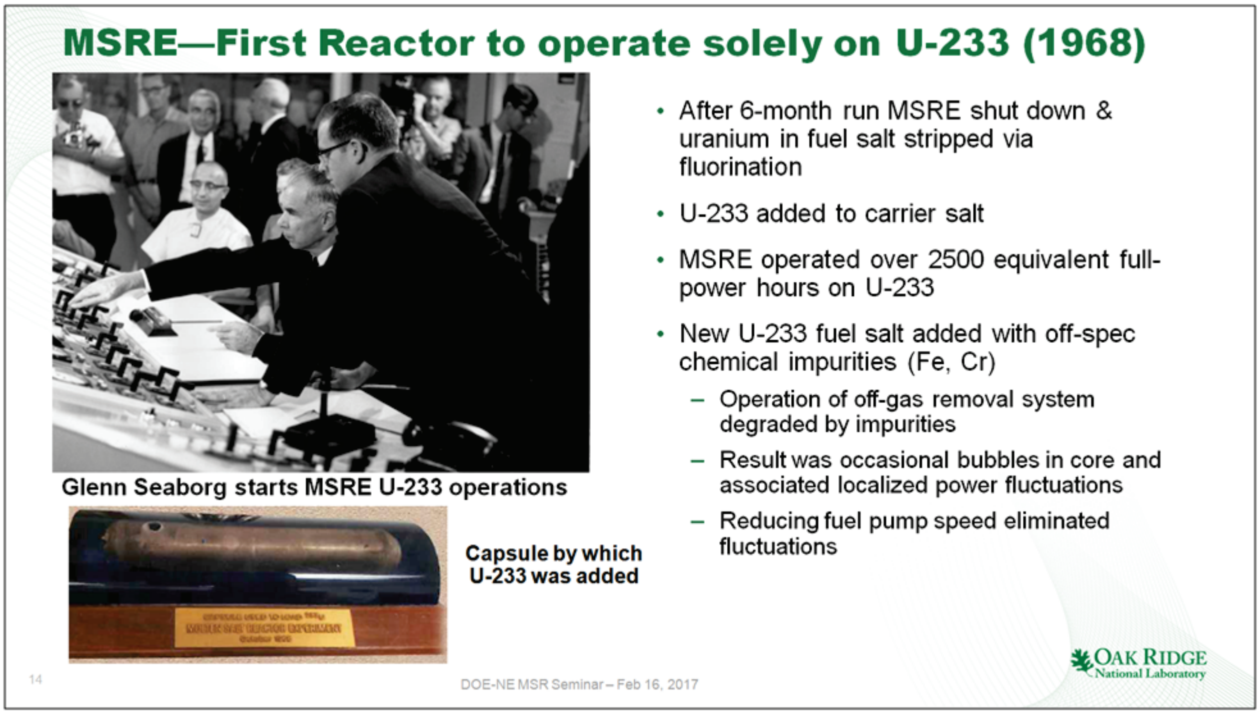
Module 1 – Slide 11. Civilian MSR Program Emerges ~1958.



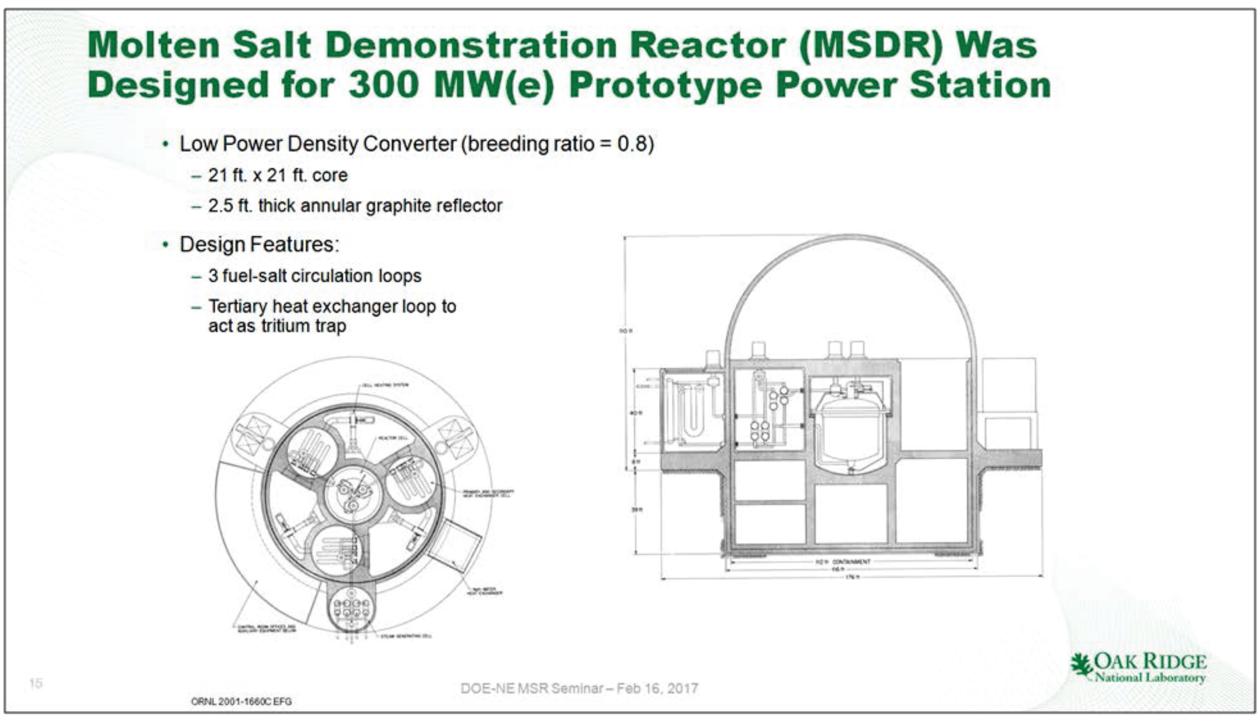
Module 1 – Slide 12. ORNL Successfully Demonstrated Key MSR Technology at the MSRE.



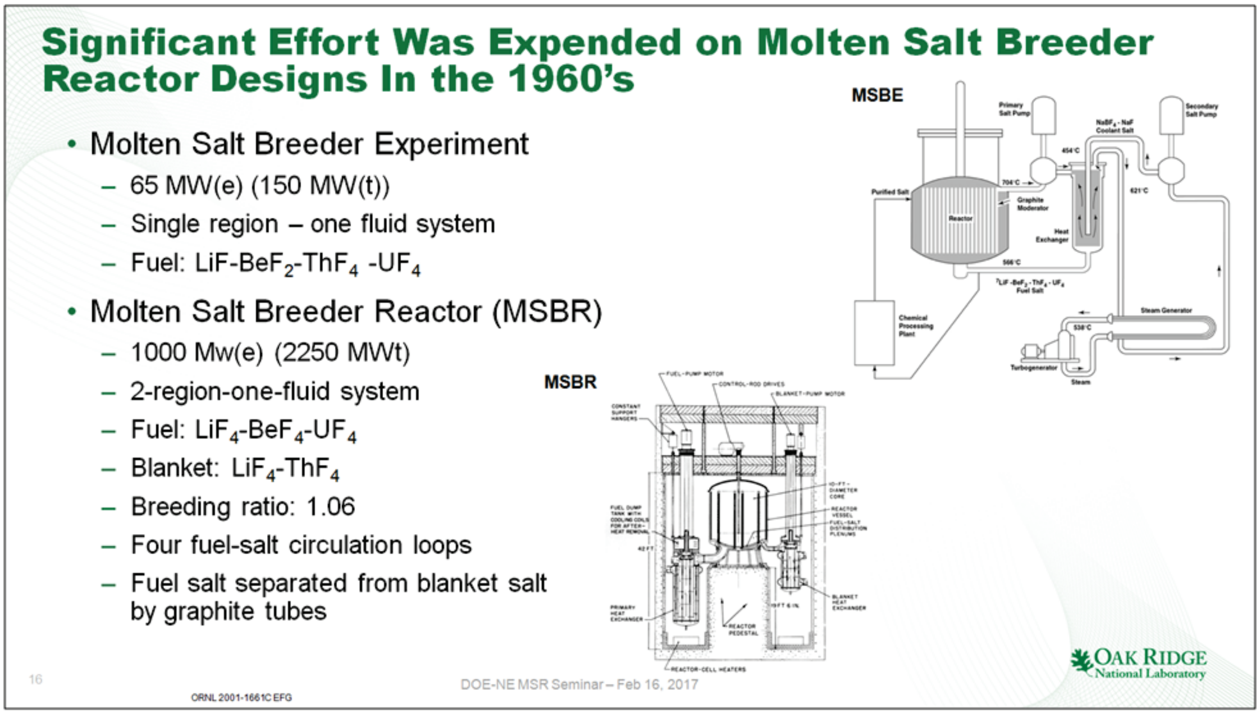
Module 1 – Slide 13. MSRE Successfully Demonstrated Key MSR Technologies.



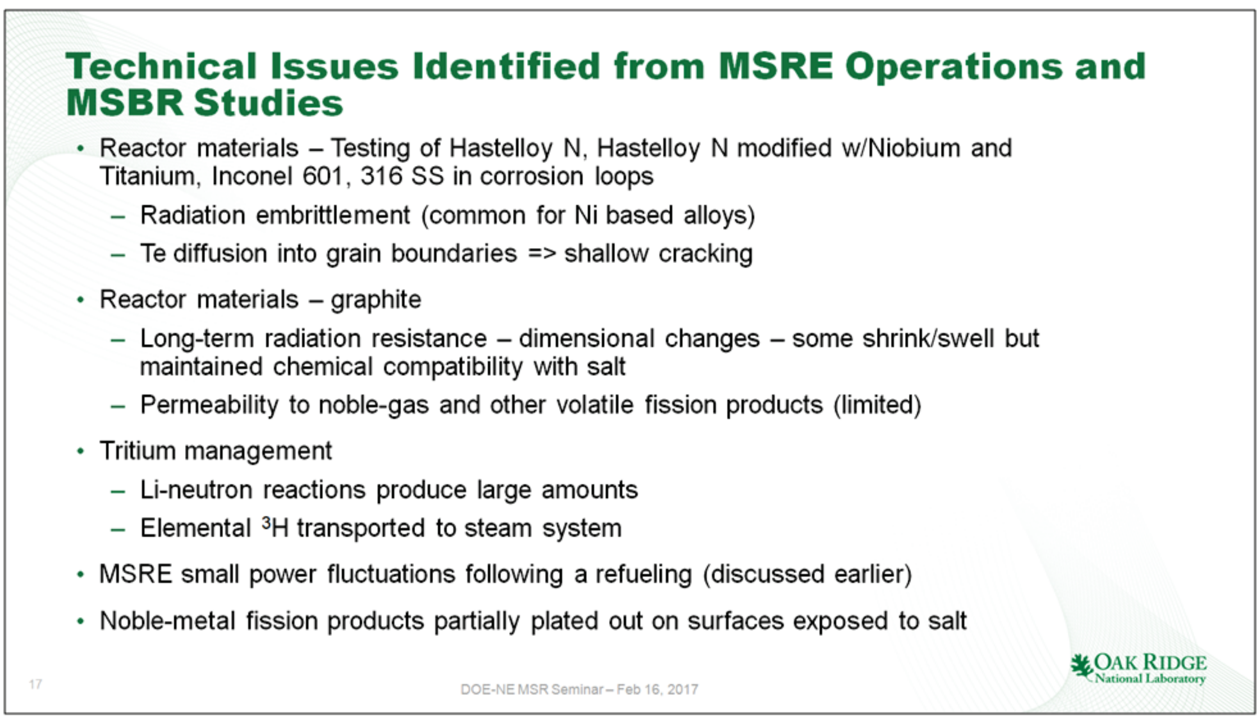
Module 1 – Slide 14. MSRE – First Reactor to Operate Solely on U-233 (1968).



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



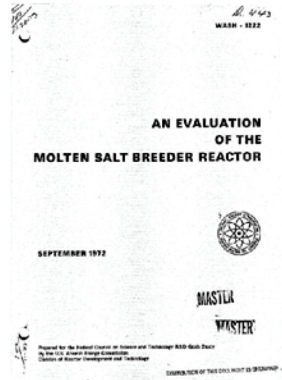
Module 1 – Slide 16. Significant Effort was expended on the Molten Salt Breeder Reactor Designs in the 1960's.



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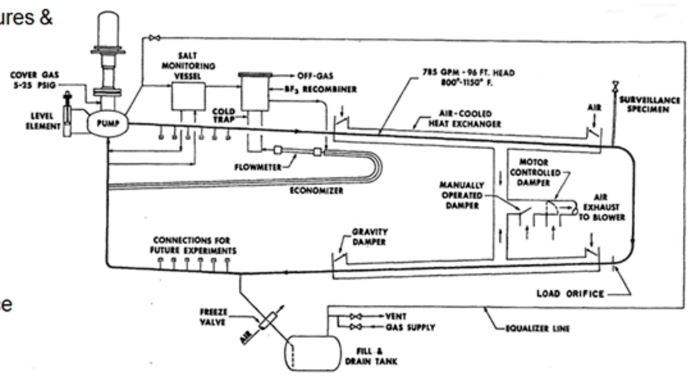
Module 1 – Slide 18. Post-MSRE R&D made Significant Progress towards Addressing WASH-1222 Identified Issues.

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 fluroborate ($NaBF_4$- 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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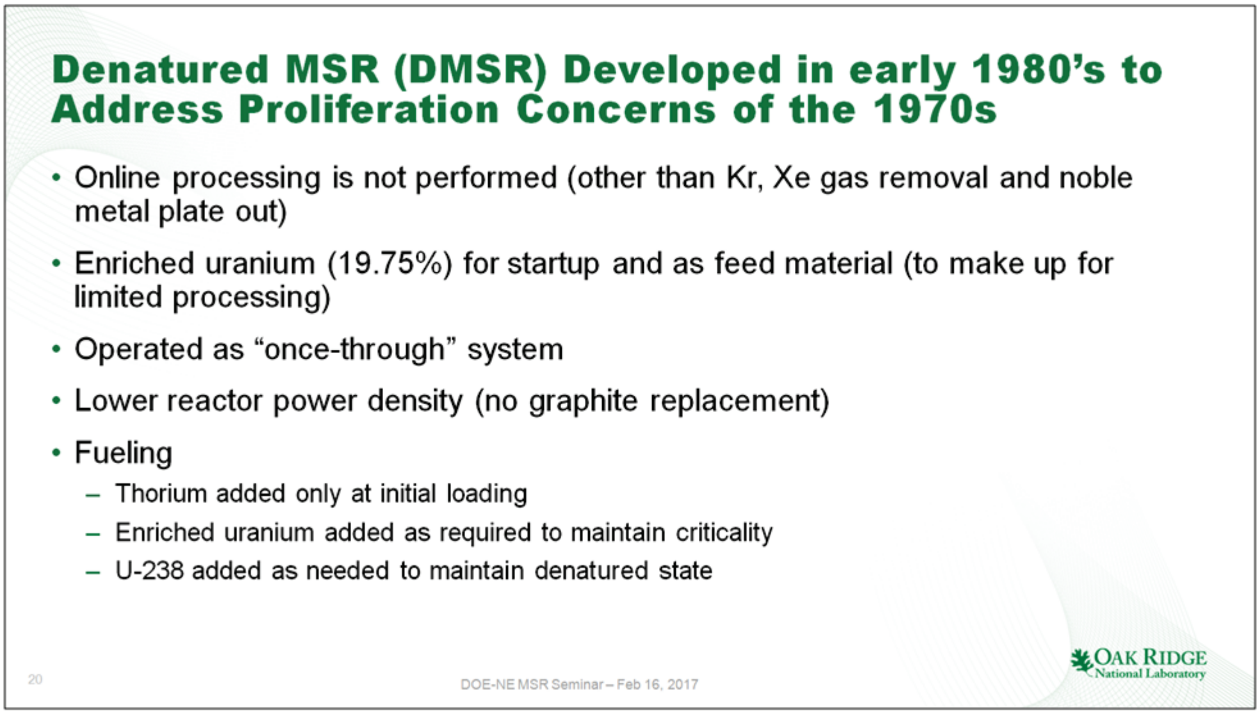
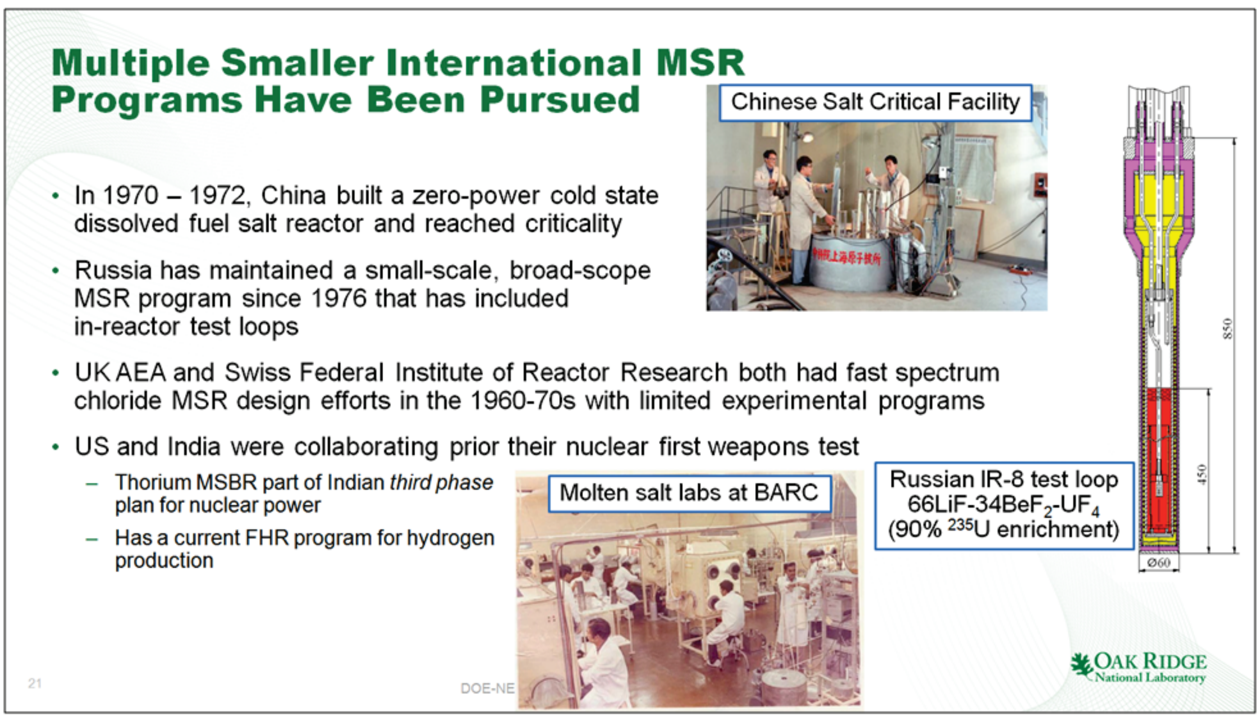
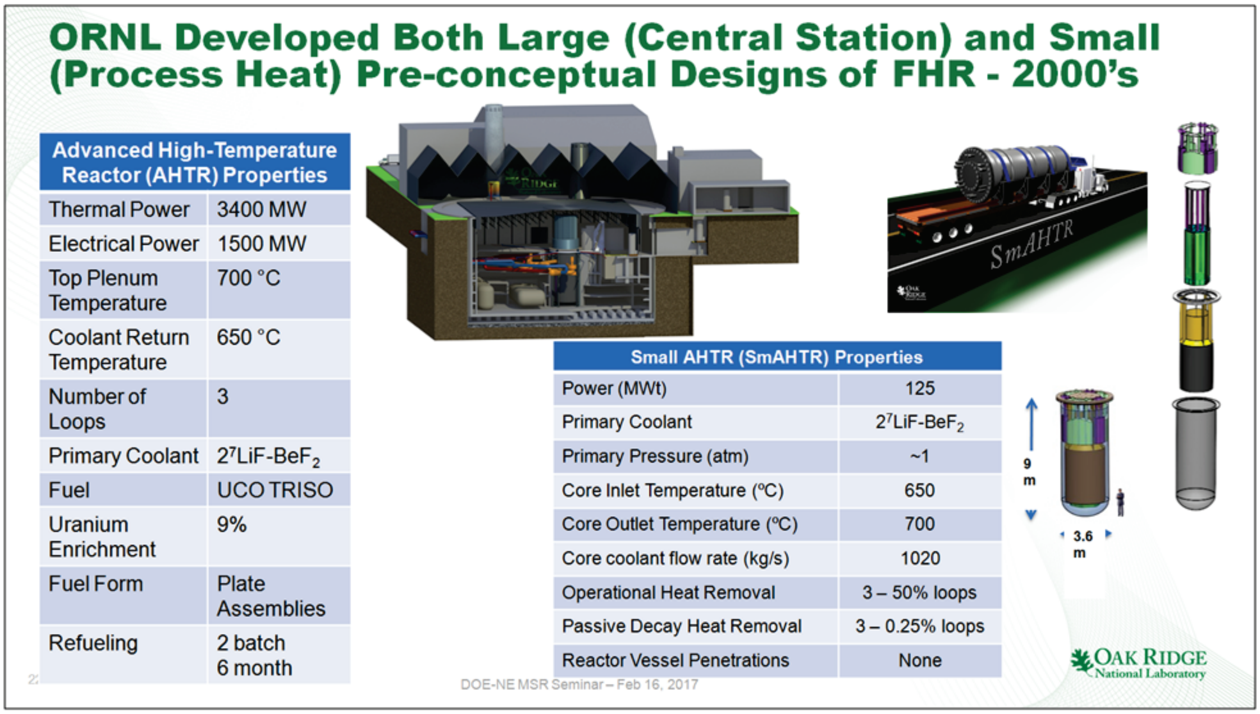
Module 1 – Slide 19. ORNL's Coolant Salt Technology Facility Provided Engineering-Scale Experience with Molten Salts (Mid-1970's).



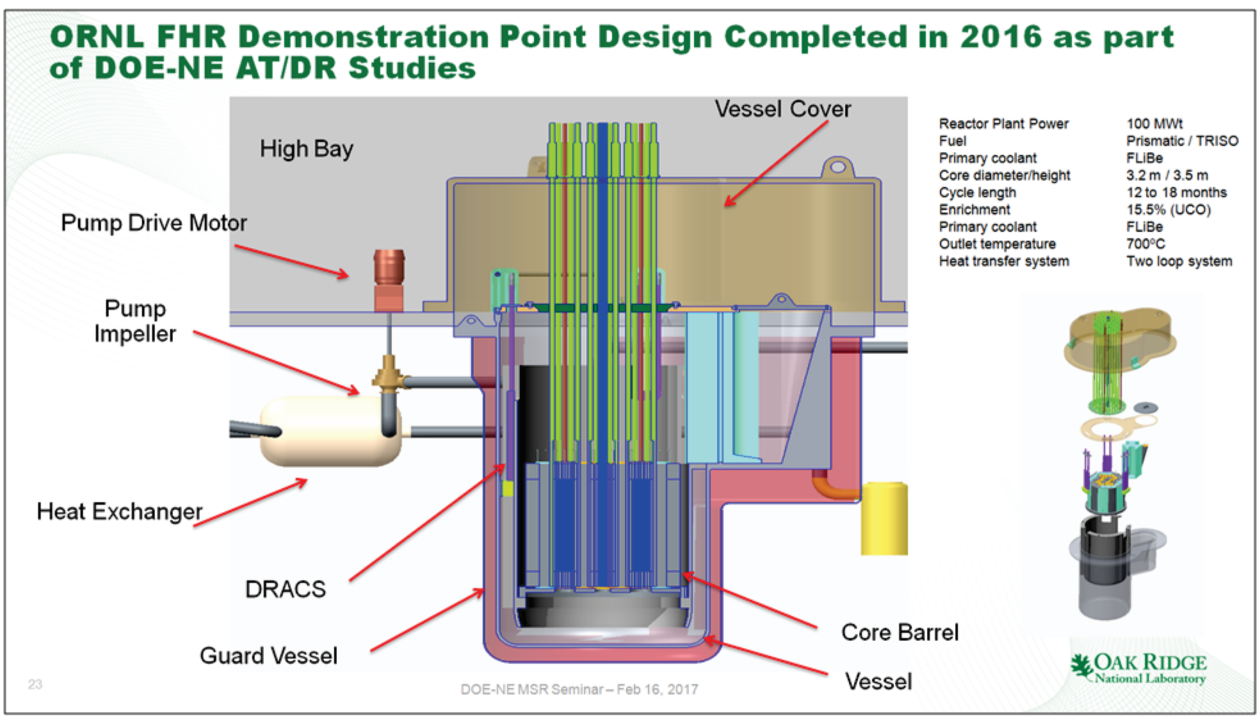
Module 1 – Slide 20. Denatured MSR (DMSR) Developed in Early 1980's to Address Proliferation Concerns of the 1970's.



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.

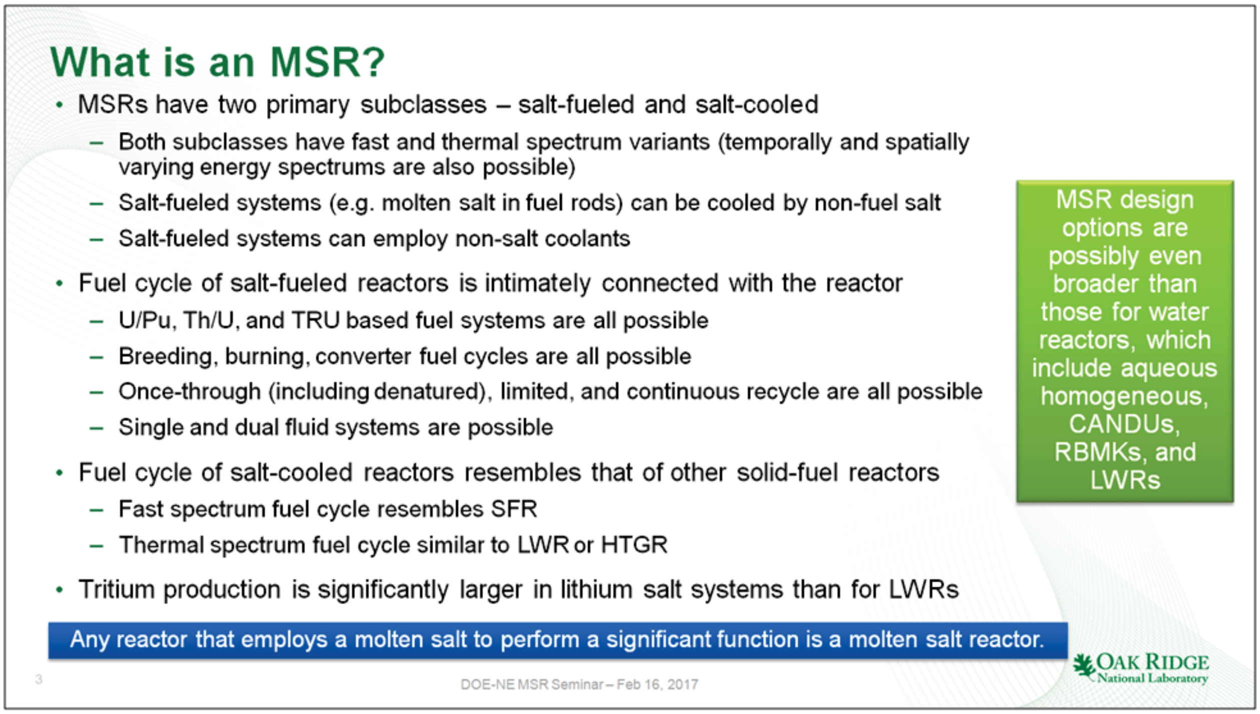
Potential Disadvantages and Challenges

- 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 ^{7}Li 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 300ºC tritium rapidly diffuses through structural alloys).

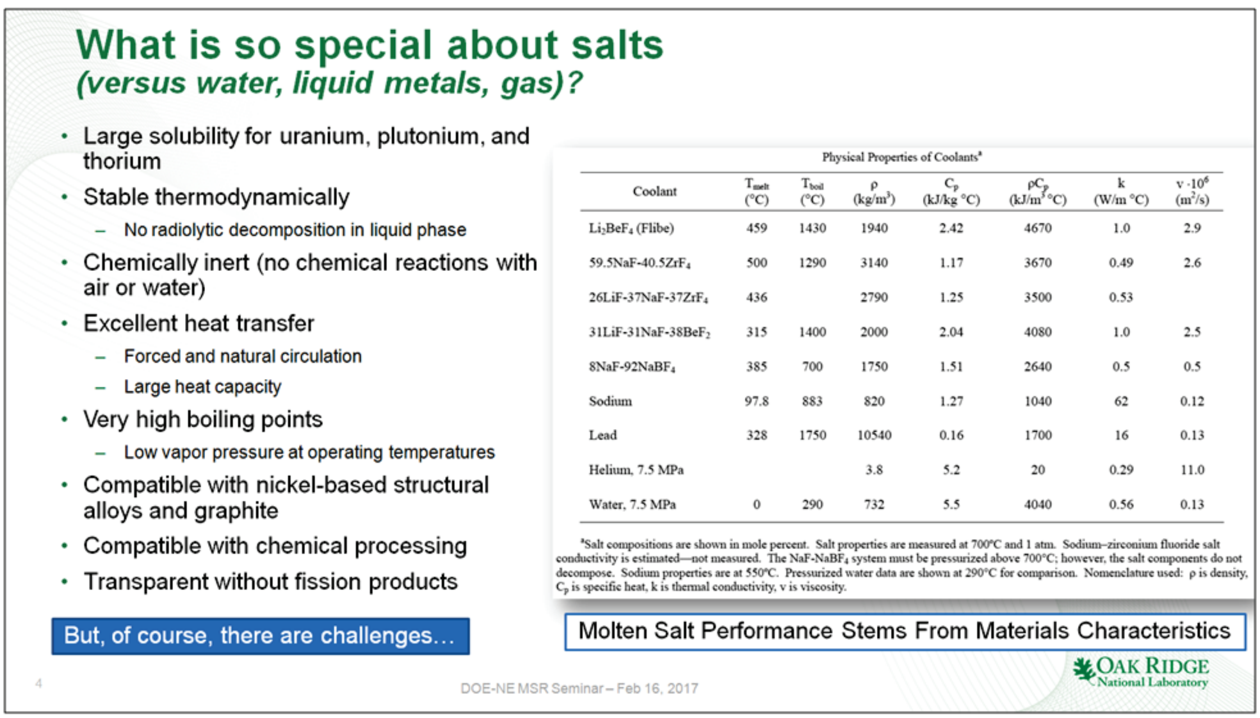
- The location of some fission products in the circulating liquid-fuel salt loop is uncertain.
- MSR modeling and simulation tools are immature and not well validated.
- High salt freezing temperatures mean that system temperatures must be managed to avoid unintended salt freezing.

Module 2 – Slide 1. Title Slide.

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



Module 2 – Slide 3. What is an MSR?

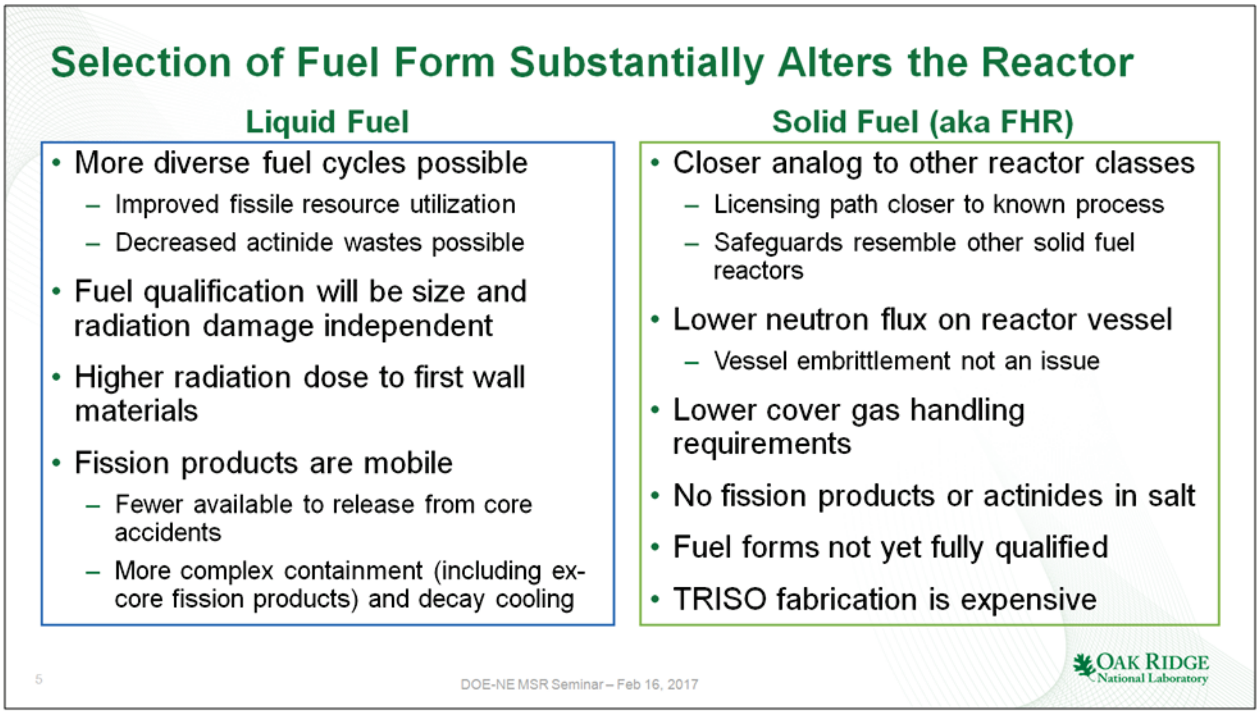


Physical Properties of Coolants[a]

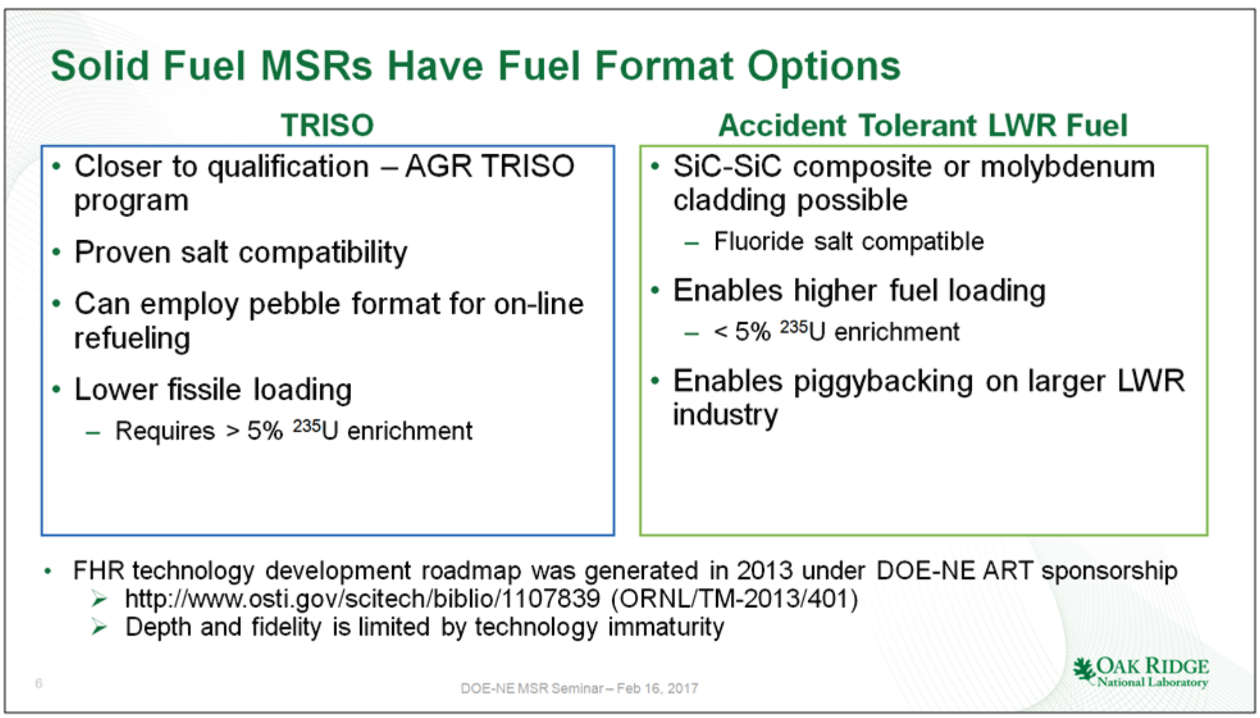
Coolant	T_{melt} (°C)	T_{boil} (°C)	ρ (kg/m³)	C_p (kJ/kg °C)	ρC_p (kJ/m³ °C)	k (W/m °C)	$\nu \cdot 10^6$ (m²/s)
Li_2BeF_4 (Flibe)	459	1430	1940	2.42	4670	1.0	2.9
59.5NaF-40.5ZrF_4	500	1290	3140	1.17	3670	0.49	2.6
26LiF-37NaF-37ZrF_4	436		2790	1.25	3500	0.53	
31LiF-31NaF-38BeF_2	315	1400	2000	2.04	4080	1.0	2.5
8NaF-92$NaBF_4$	385	700	1750	1.51	2640	0.5	0.5
Sodium	97.8	883	820	1.27	1040	62	0.12
Lead	328	1750	10540	0.16	1700	16	0.13
Helium, 7.5 MPa			3.8	5.2	20	0.29	11.0
Water, 7.5 MPa	0	290	732	5.5	4040	0.56	0.13

[a]Salt compositions are shown in mole percent. Salt properties are measured at 700°C and 1 atm. Sodium–zirconium fluoride salt conductivity is estimated—not measured. The NaF-$NaBF_4$ system must be pressurized above 700°C; however, the salt components do not decompose. Sodium properties are at 550°C. Pressurized water data are shown at 290°C for comparison. Nomenclature used: ρ is density, C_p is specific heat, k is thermal conductivity, ν is viscosity.

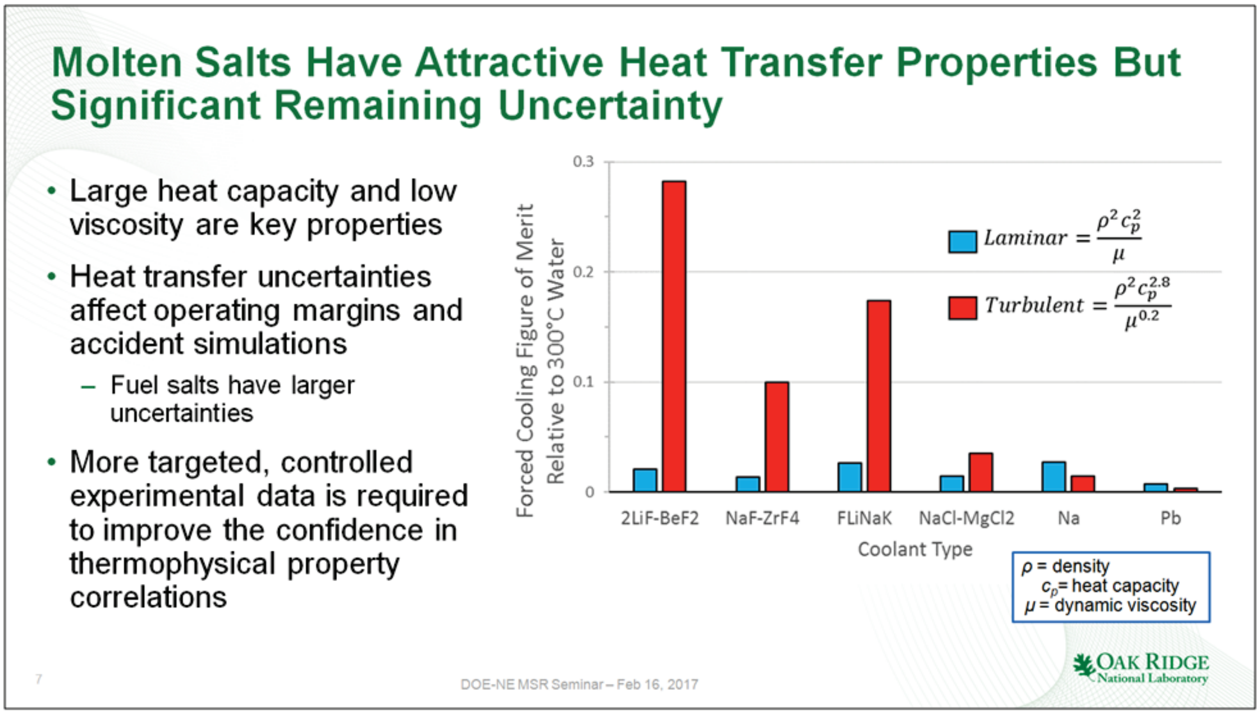
Module 2 – Slide 4. What is so Special about Salts?



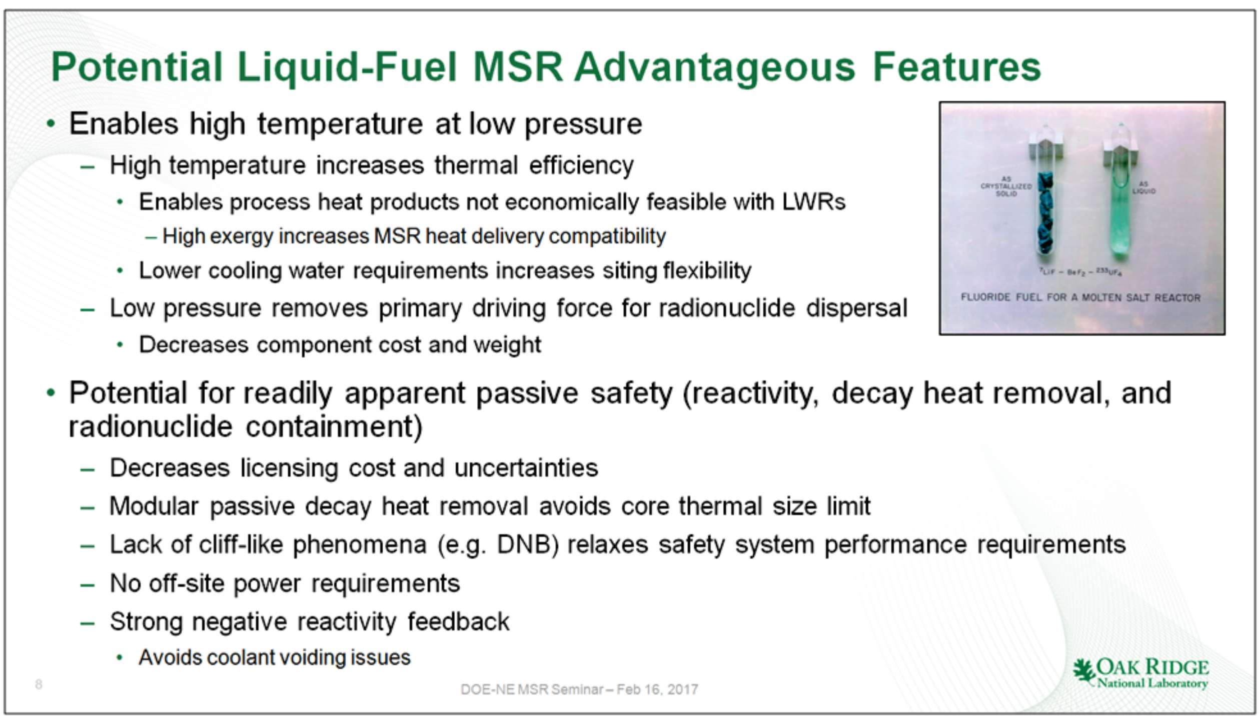
Module 2 – Slide 5. Selection of Fuel Form Substantially Alters the Reactor.



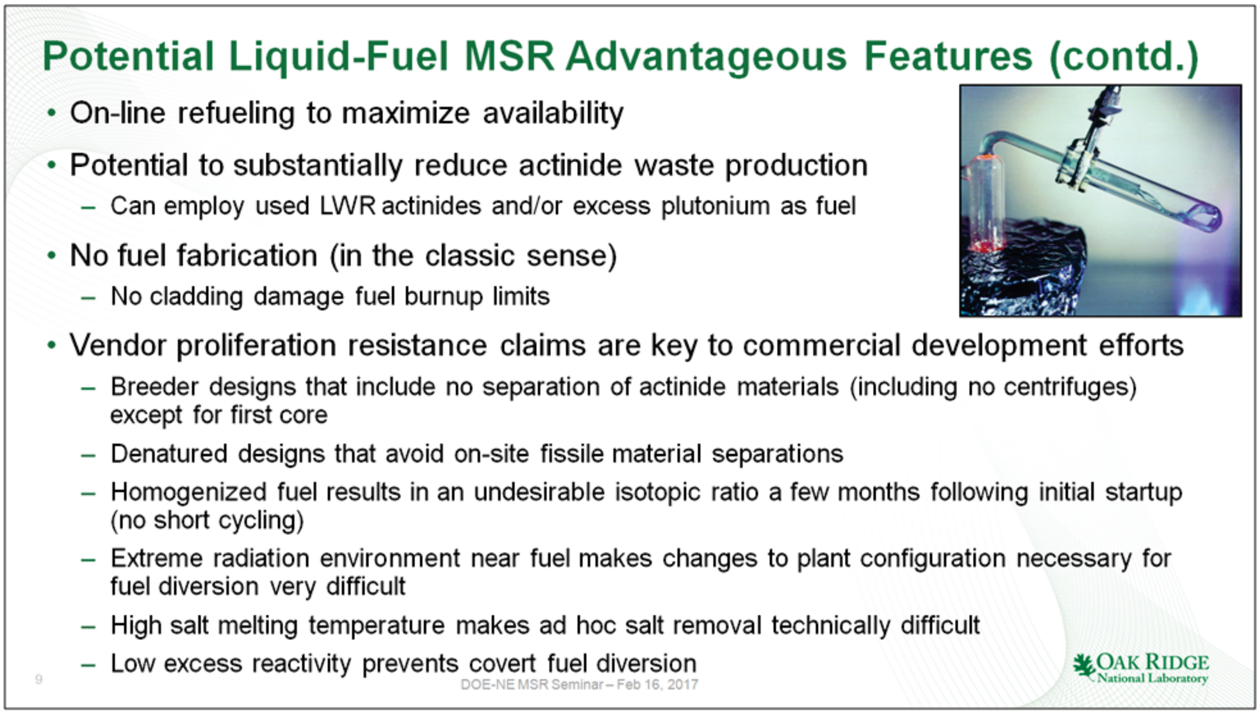
Module 2 – Slide 6. Solid Fuel MSRs have Fuel Format Options.



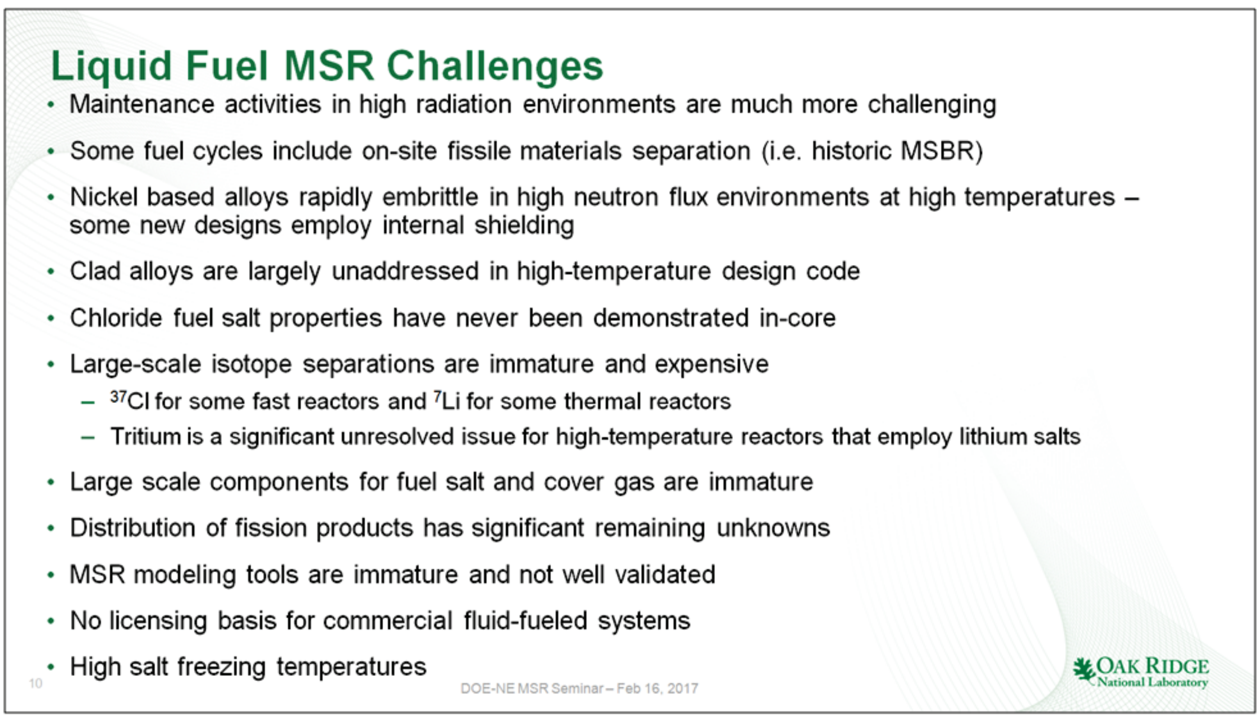
Module 2 – Slide 7. Molten Salts have Attractive Heat Transfer Properties but Significant Remaining Uncertainty.



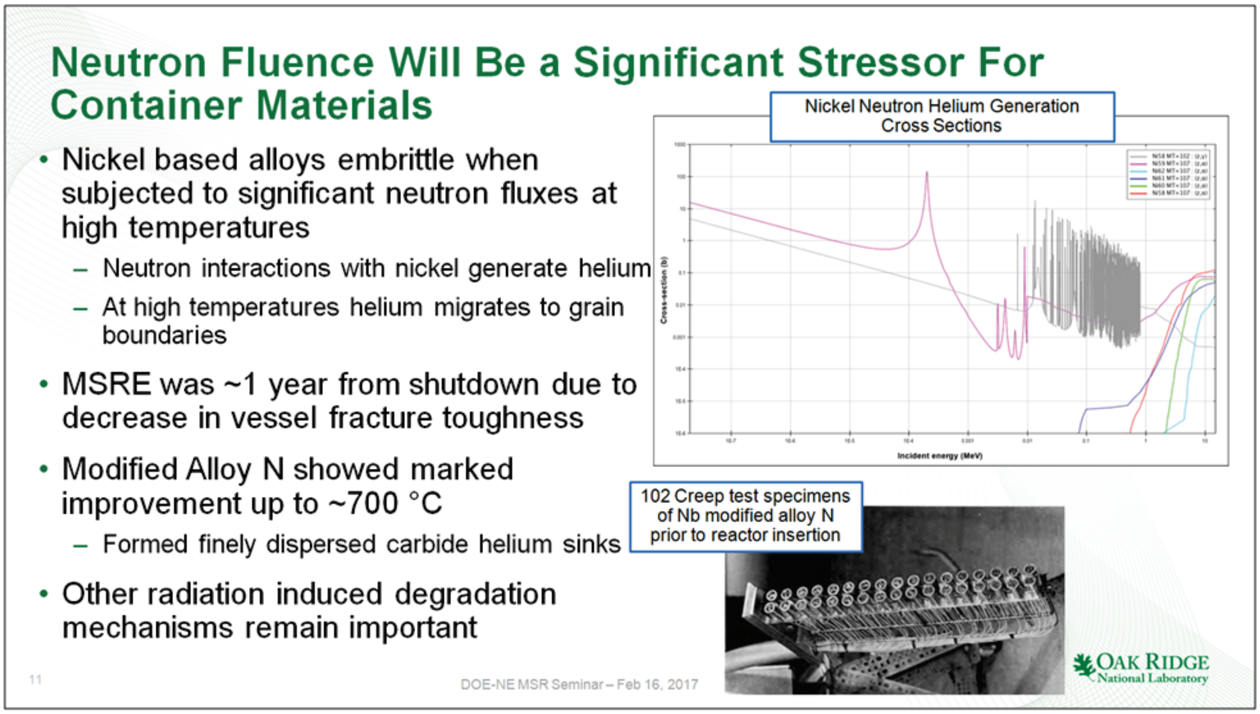
Module 2 – Slide 8. Potential Liquid-Fuel MSR Advantageous Features.



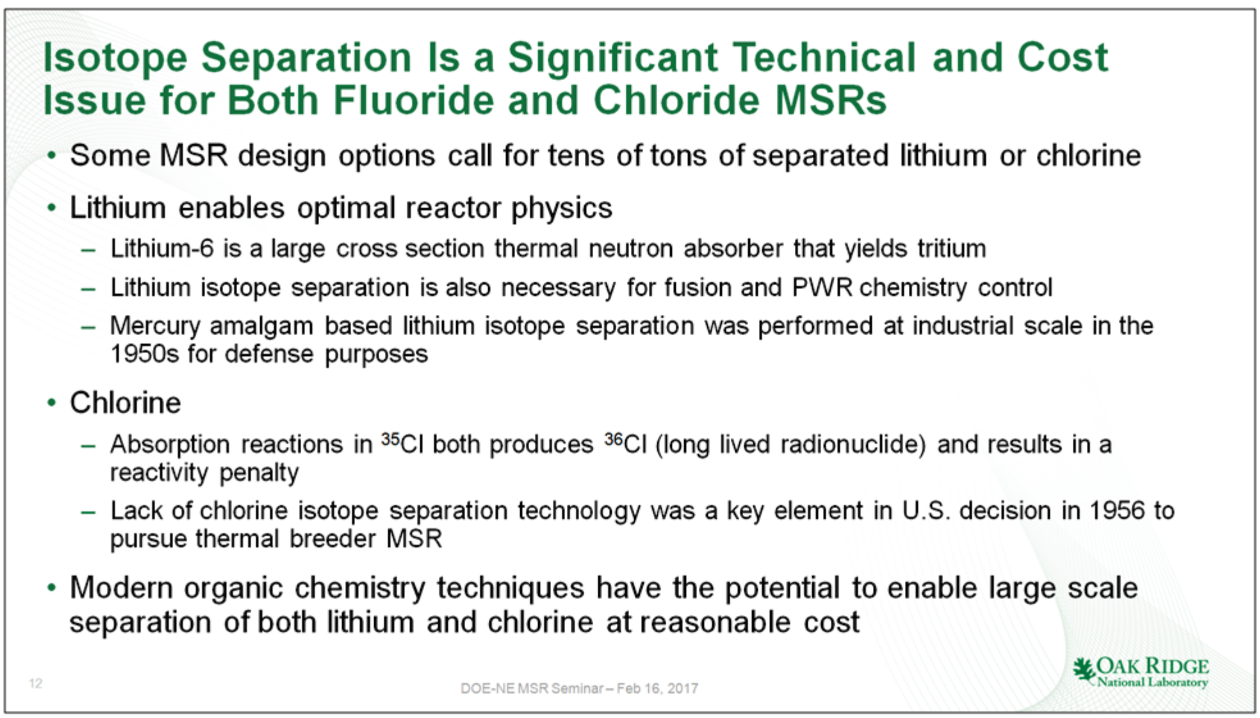
Module 2 – Slide 9. Potential Liquid-Fuel MSR Advantageous Features (contd.)



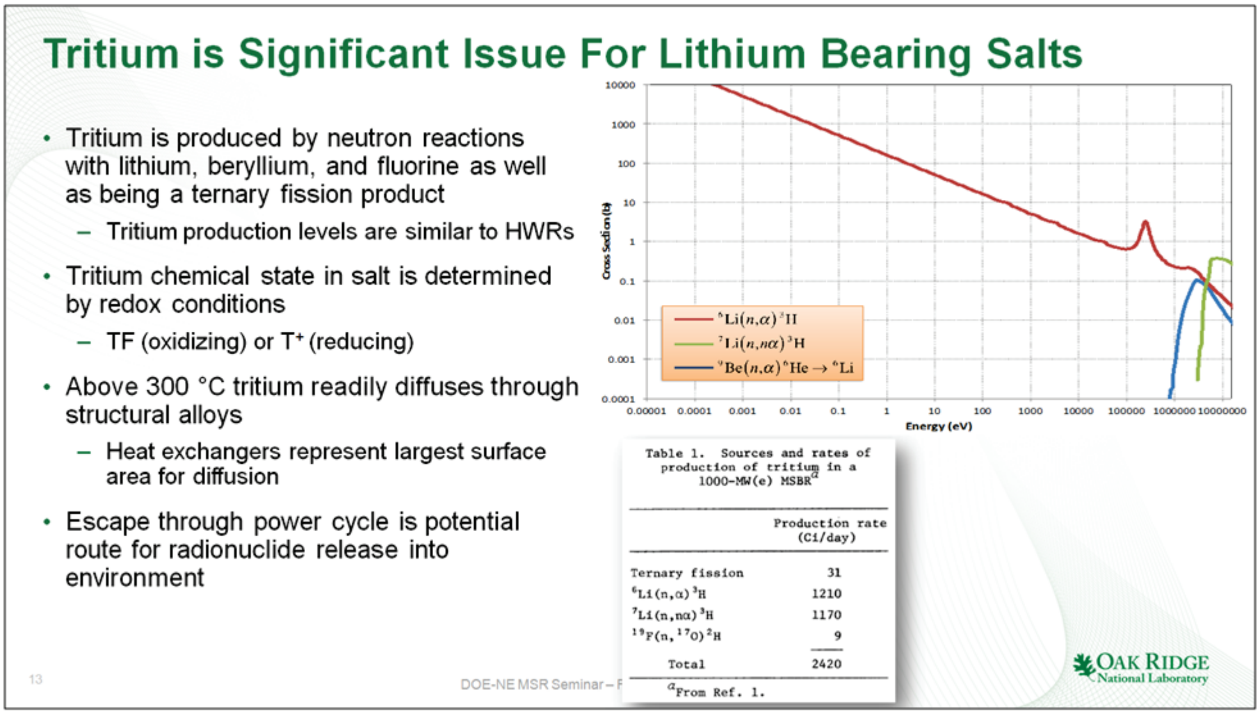
Module 2 – Slide 10. Liquid Fuel MSR Challenges.



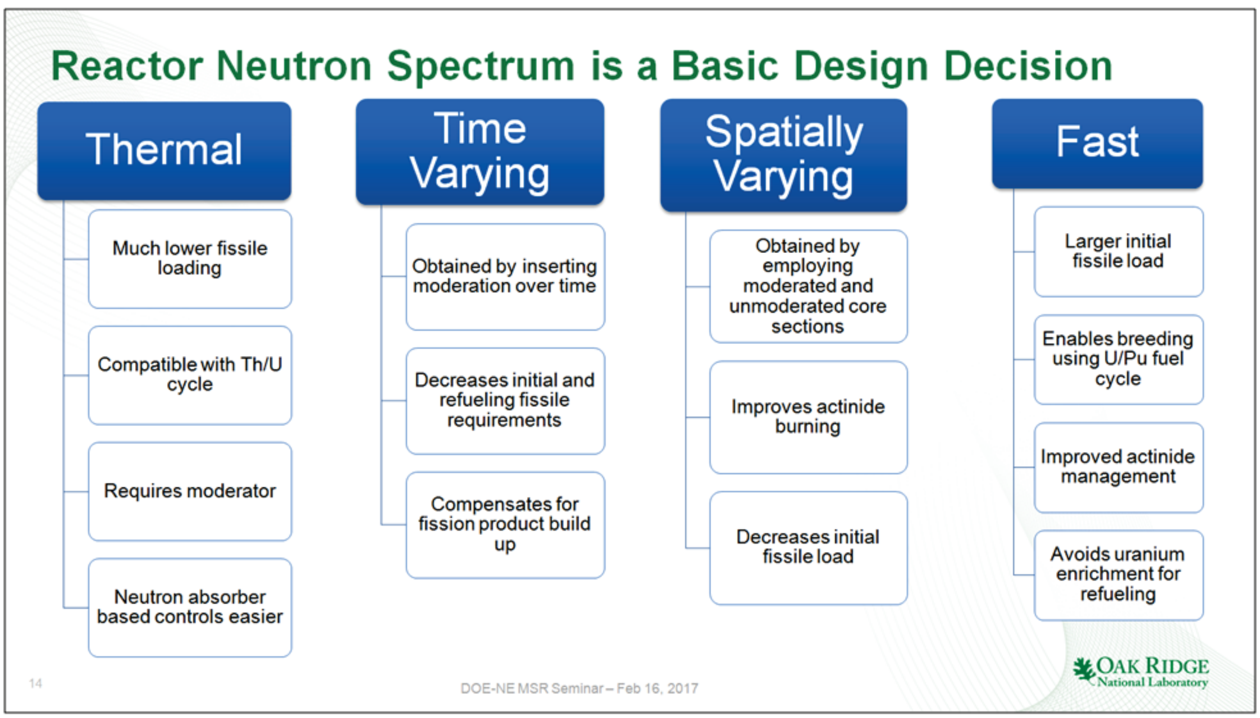
Module 2 – Slide 11. Neutron Fluence will be a Significant Stressor for Container Materials.



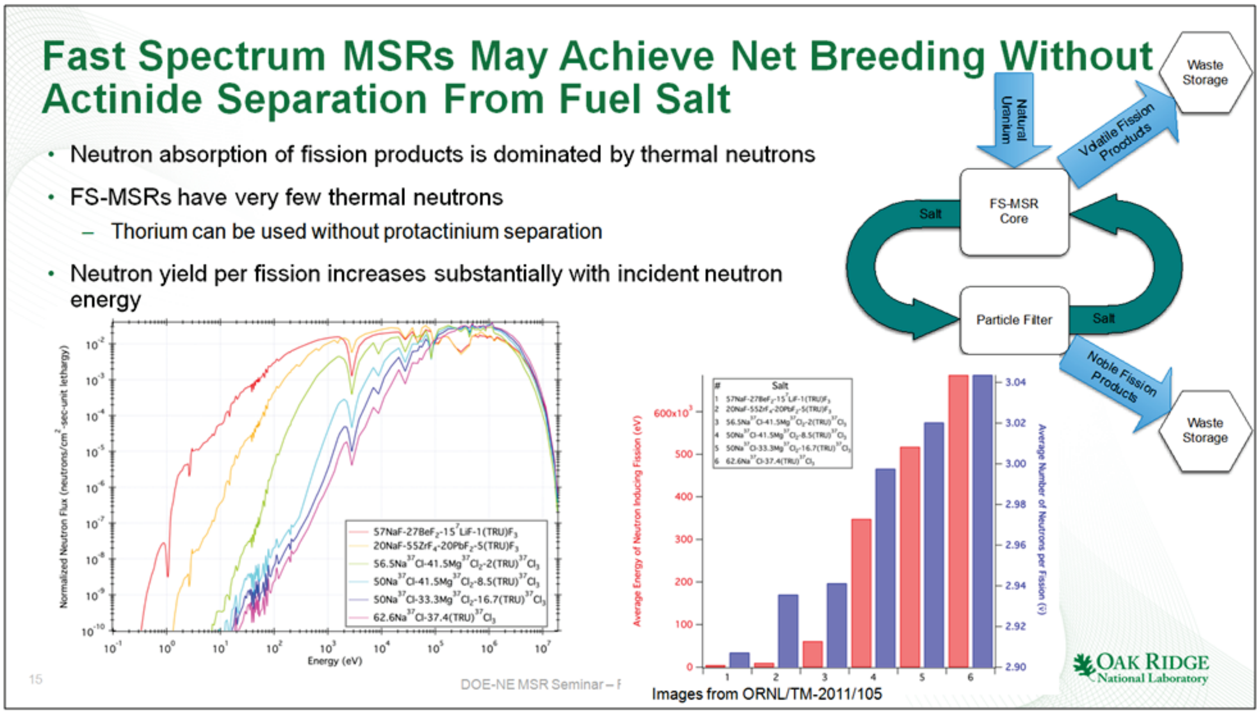
Module 2 – Slide 12. Isotope Separation is a Significant Technical and Cost Issue for Both Fluoride and Chloride MSRs.



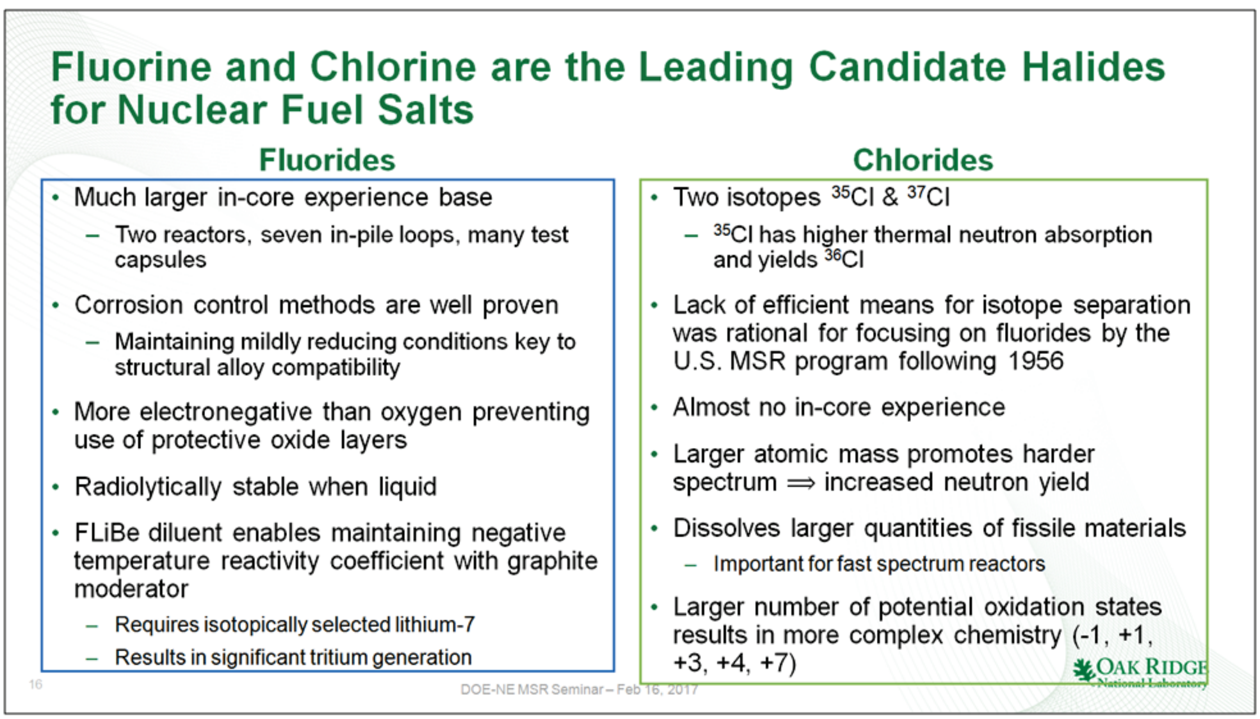
Module 2 – Slide 13. Tritium is a Significant Issue for Lithium Bearing Salts.



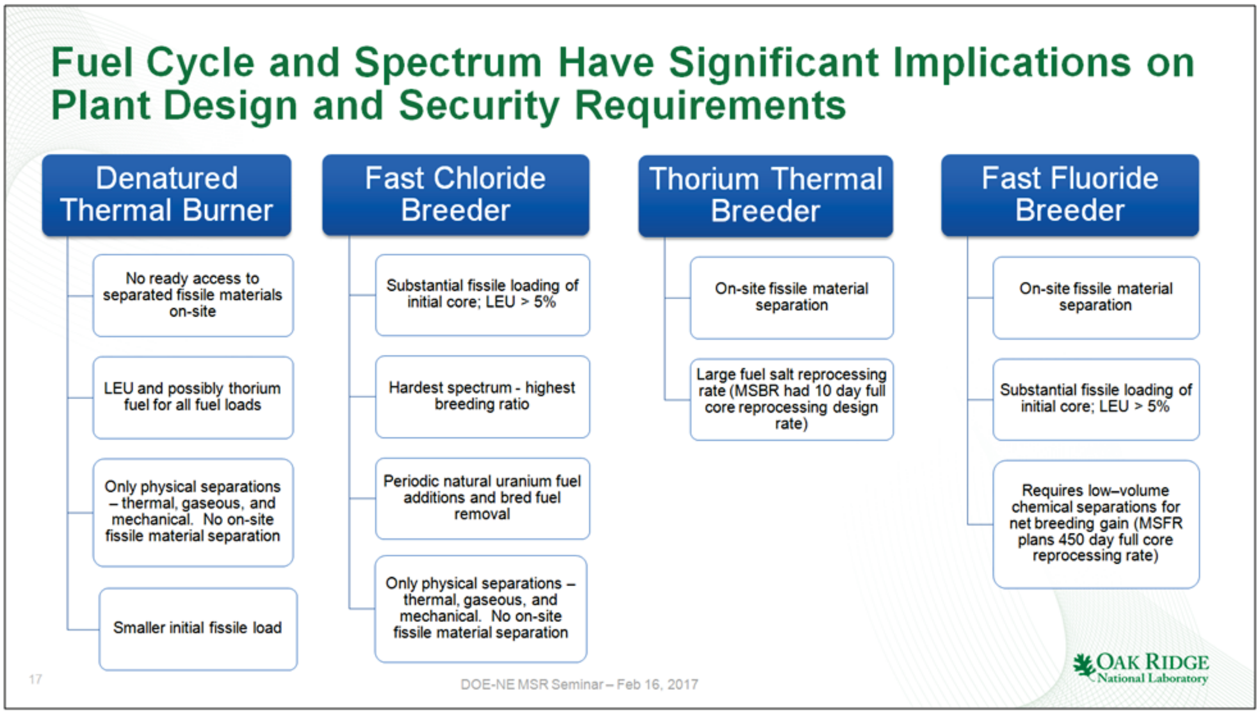
Module 2 – Slide 14. Reactor Neutron Spectrum is a Basic Design Decision.



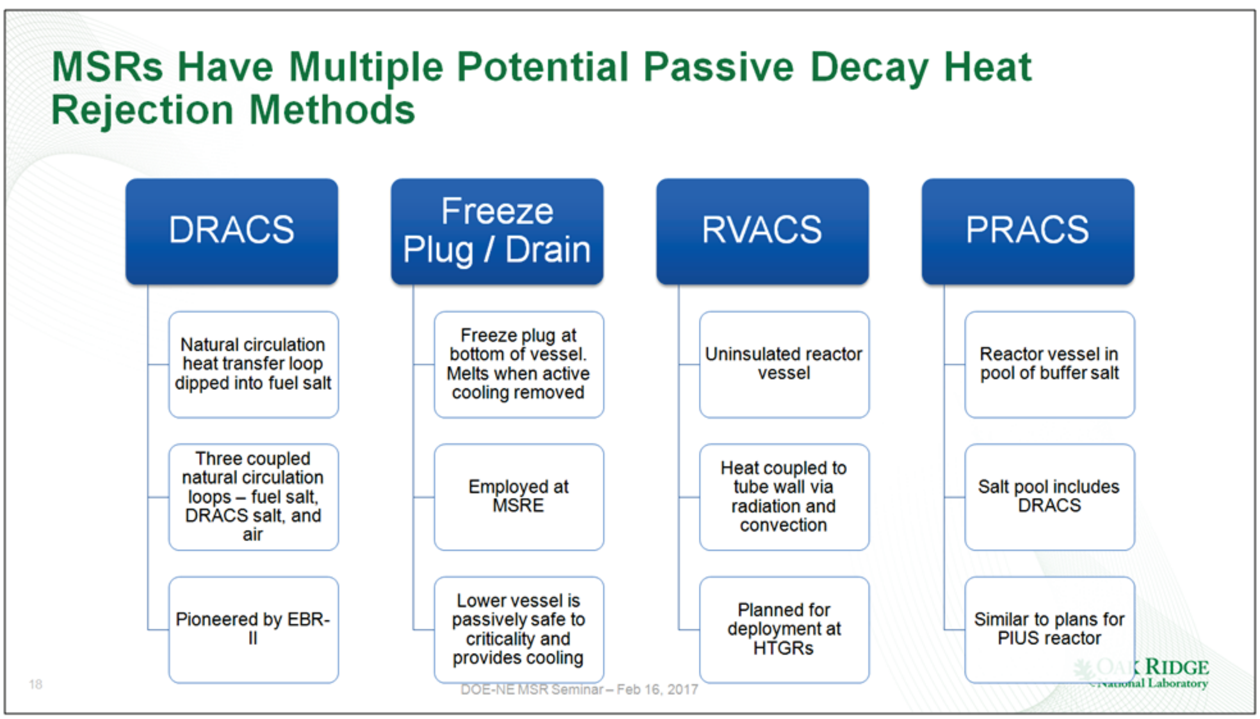
Module 2 – Slide 15. Fast Spectrum MSRs may achieve Net Breeding Without Actinide Separation from Fuel Salt.



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

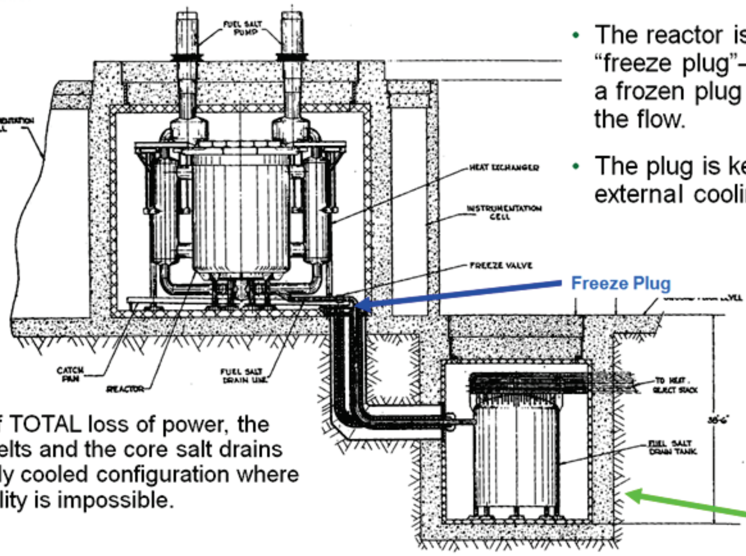


Module 2 – Slide 17. Fuel Cycle and Spectrum have Significant Implications on Plant Design and Security Requirements.



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

MSR Passive Safety: The Freeze Plug



- The reactor is equipped with a "freeze plug"—an open line where a frozen plug of salt is blocking the flow.
- The plug is kept frozen by an external cooling fan.

- In the event of TOTAL loss of power, the freeze plug melts and the core salt drains into a passively cooled configuration where nuclear criticality is impossible.

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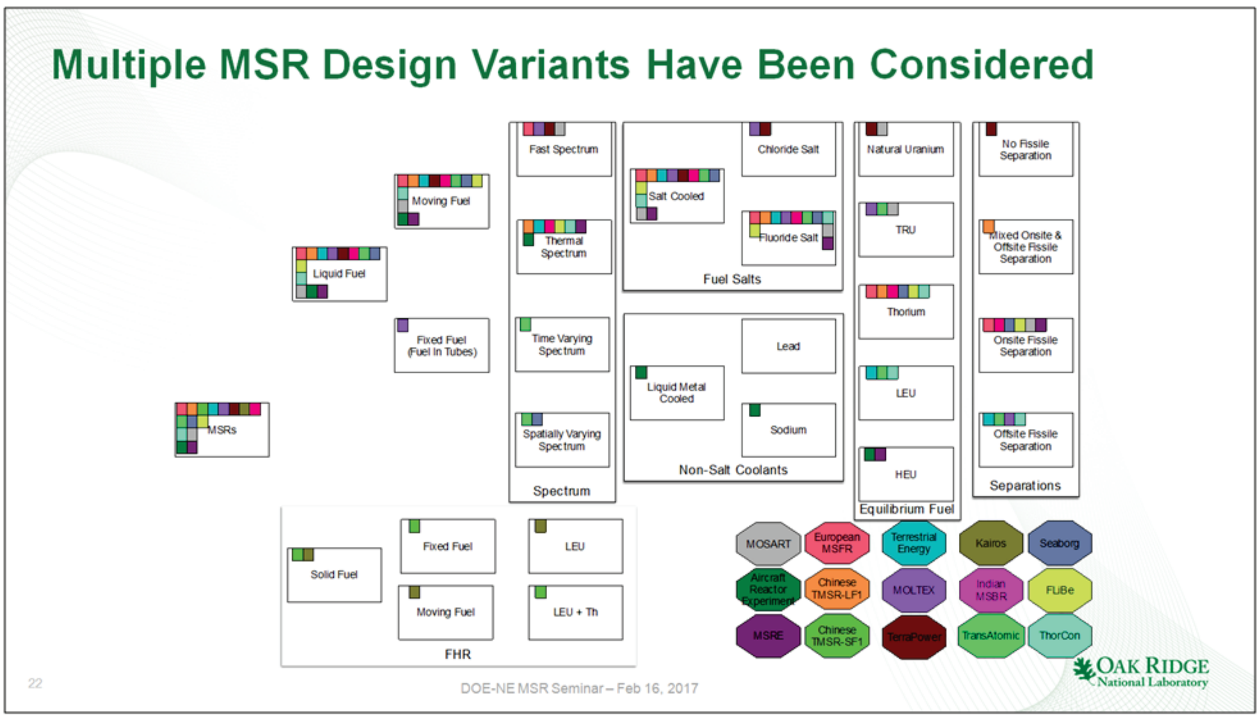
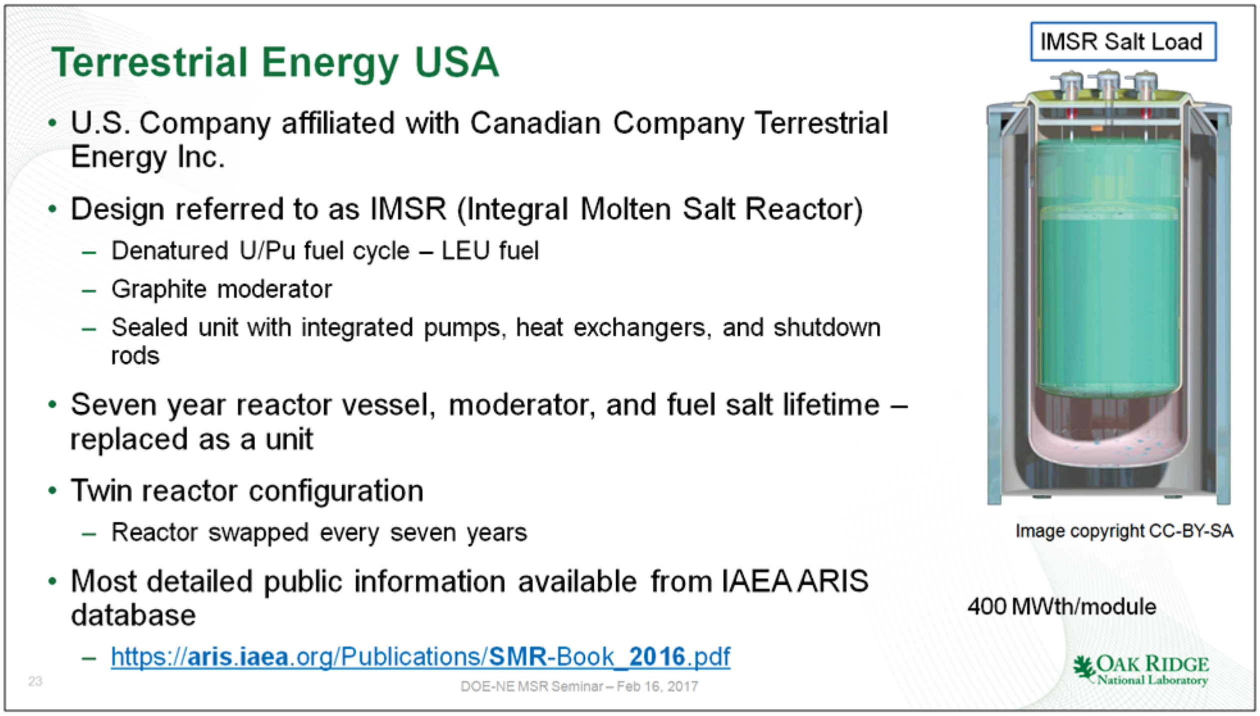
Module 2 – Slide 20. MSRs can be designed with Containerized, Non-Circulating Fuel Salt.

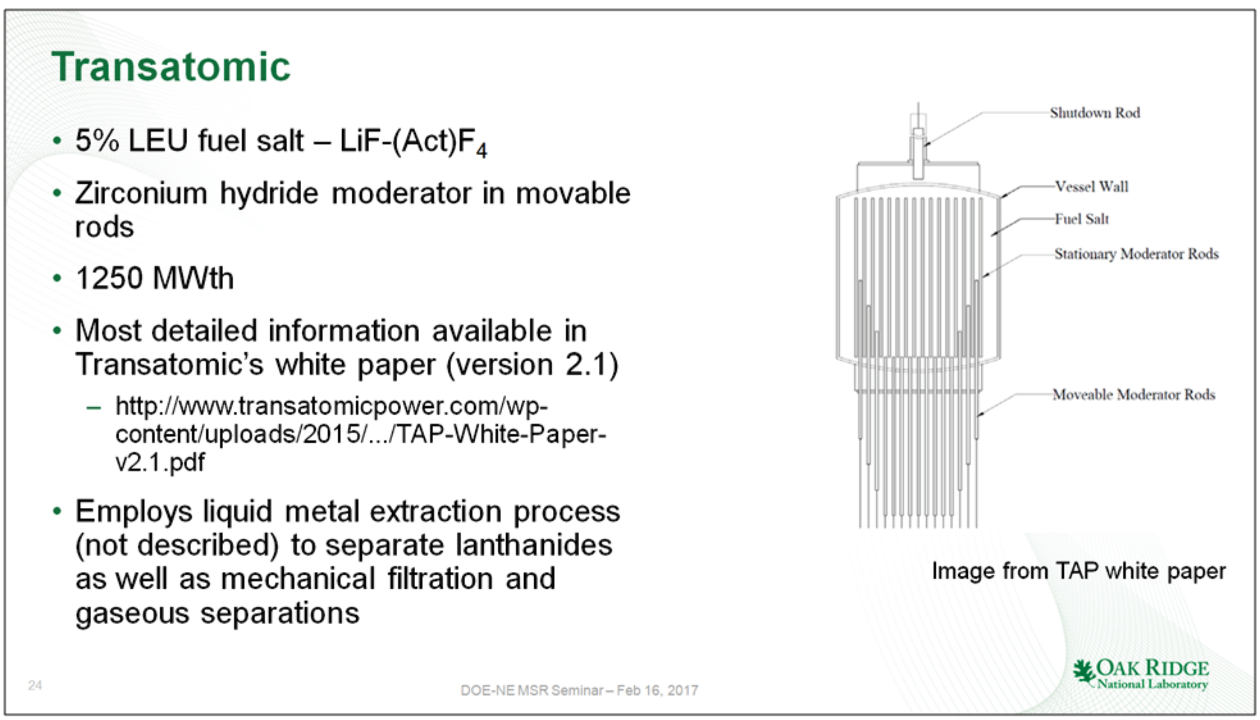
Module 2 – Slide 21. Part 2: Status of Technologies Under Development: Domestic and International.



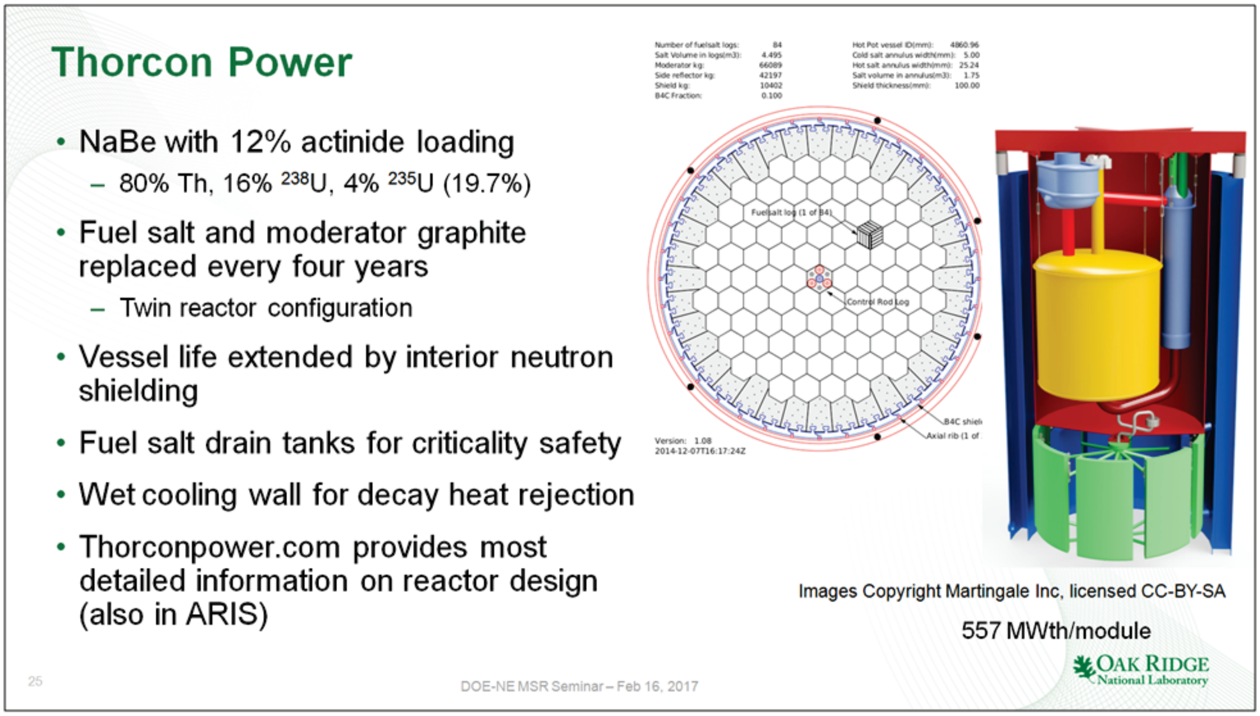
Module 2 – Slide 22. Multiple MSR Design Variants have been considered.



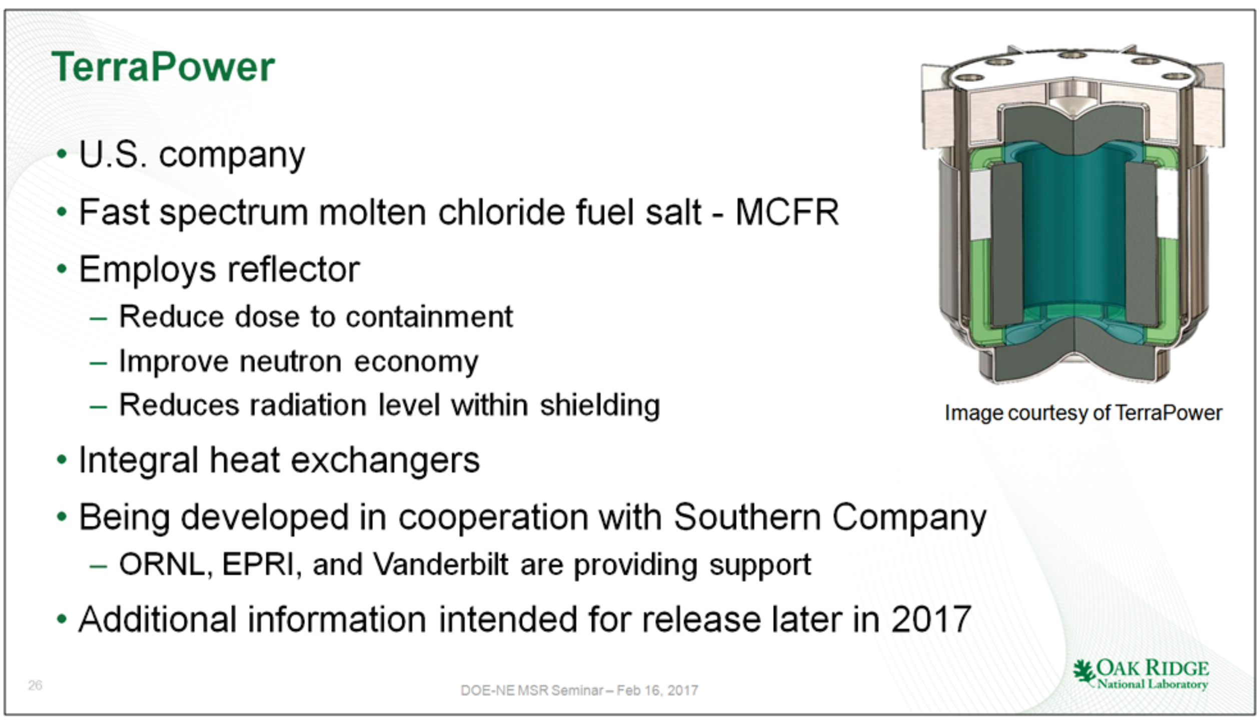
Module 2 – Slide 23. Terrestrial Energy USA.



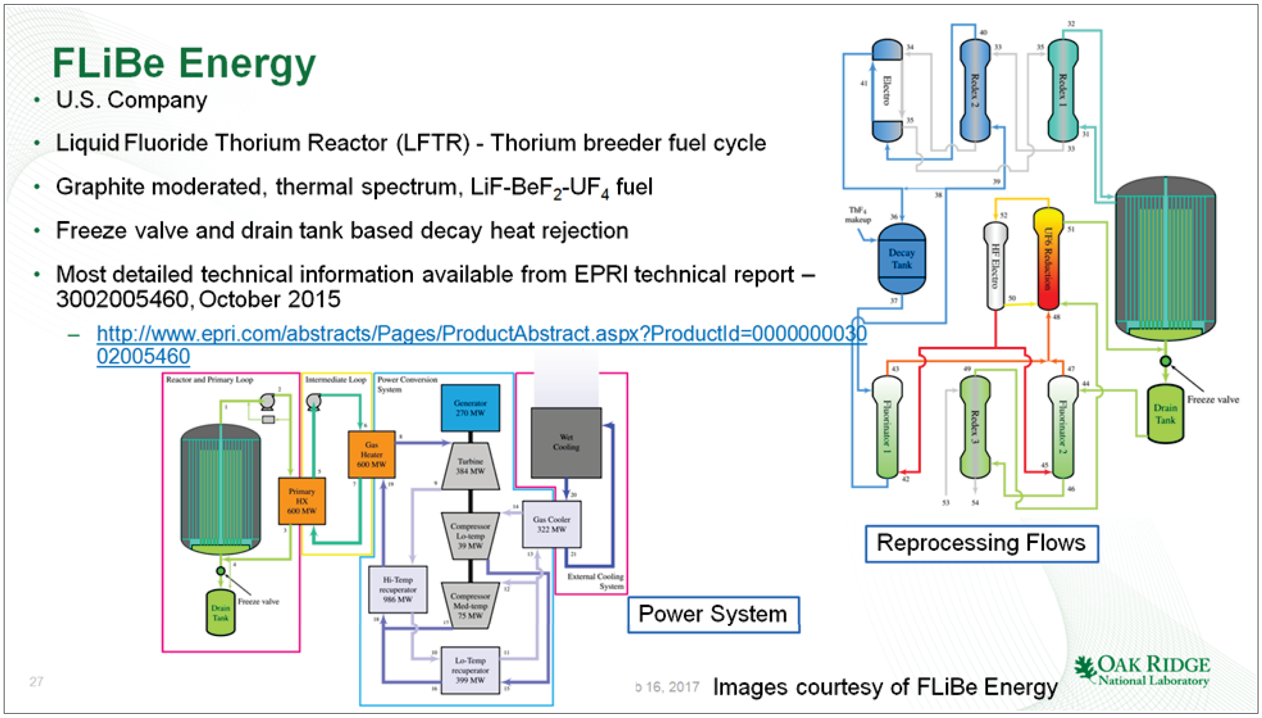
Module 2 – Slide 24. Transatomic.



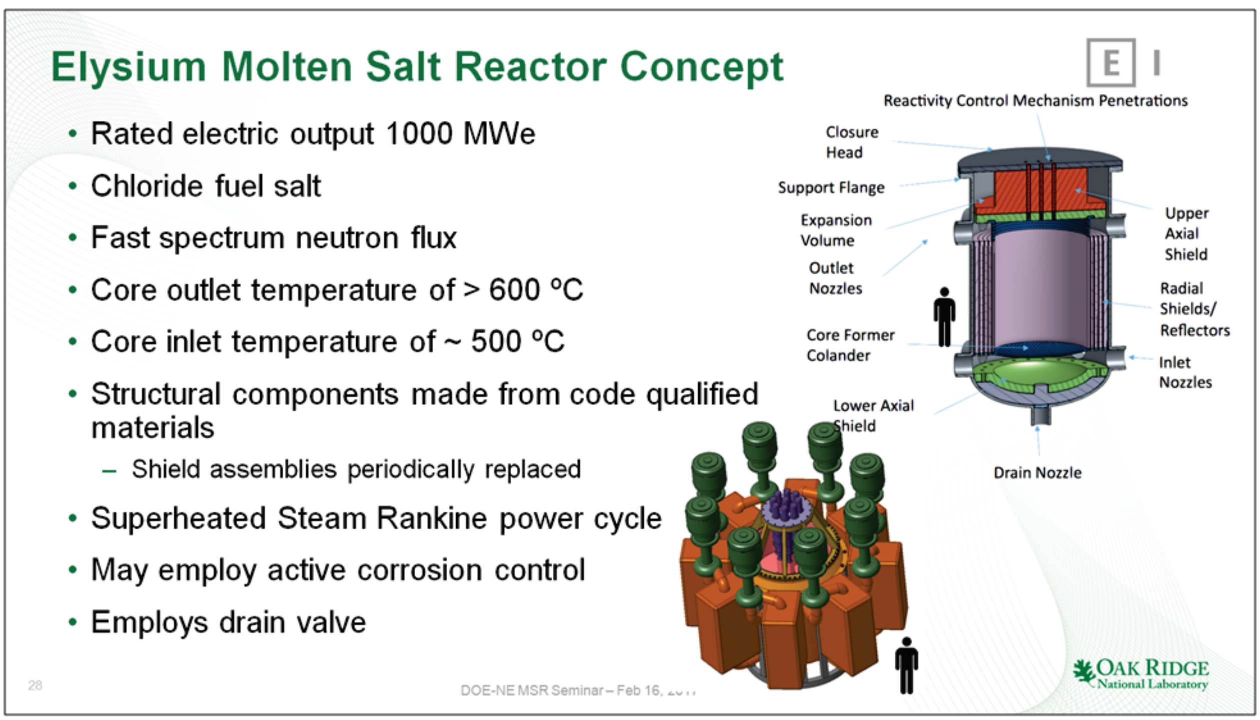
Module 2 – Slide 25. Thorcon Power.



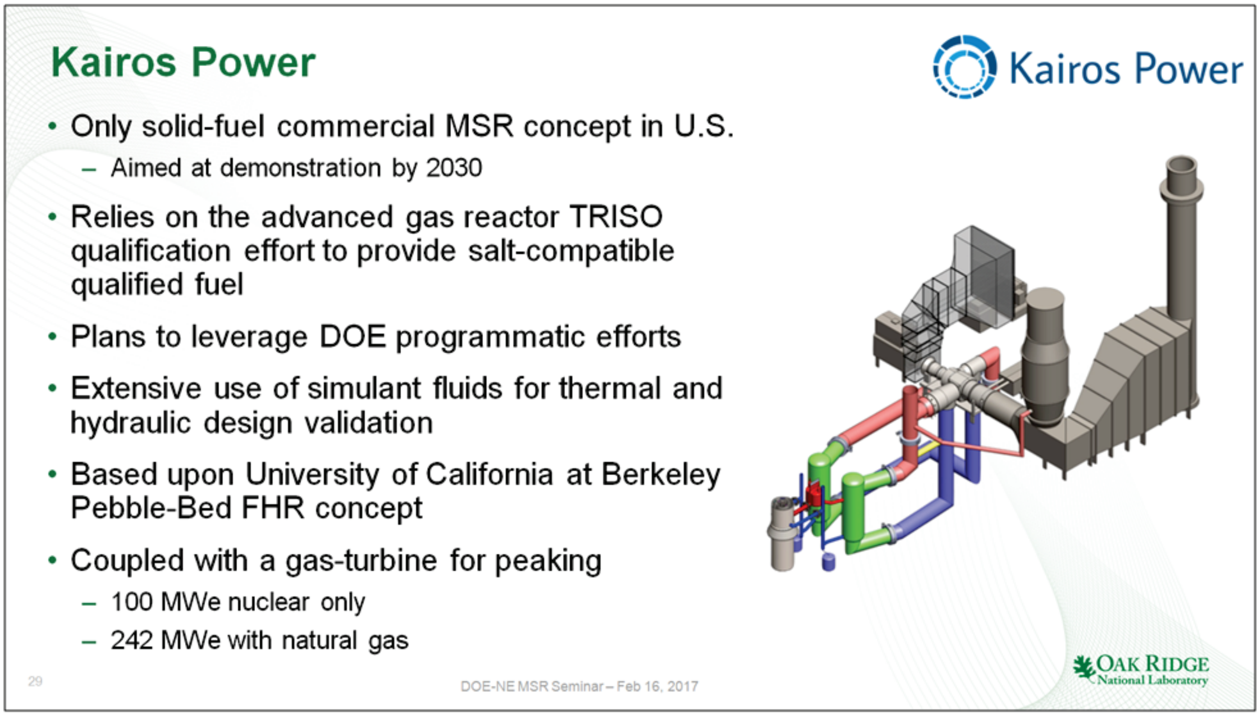
Module 2 – Slide 26. TerraPower.



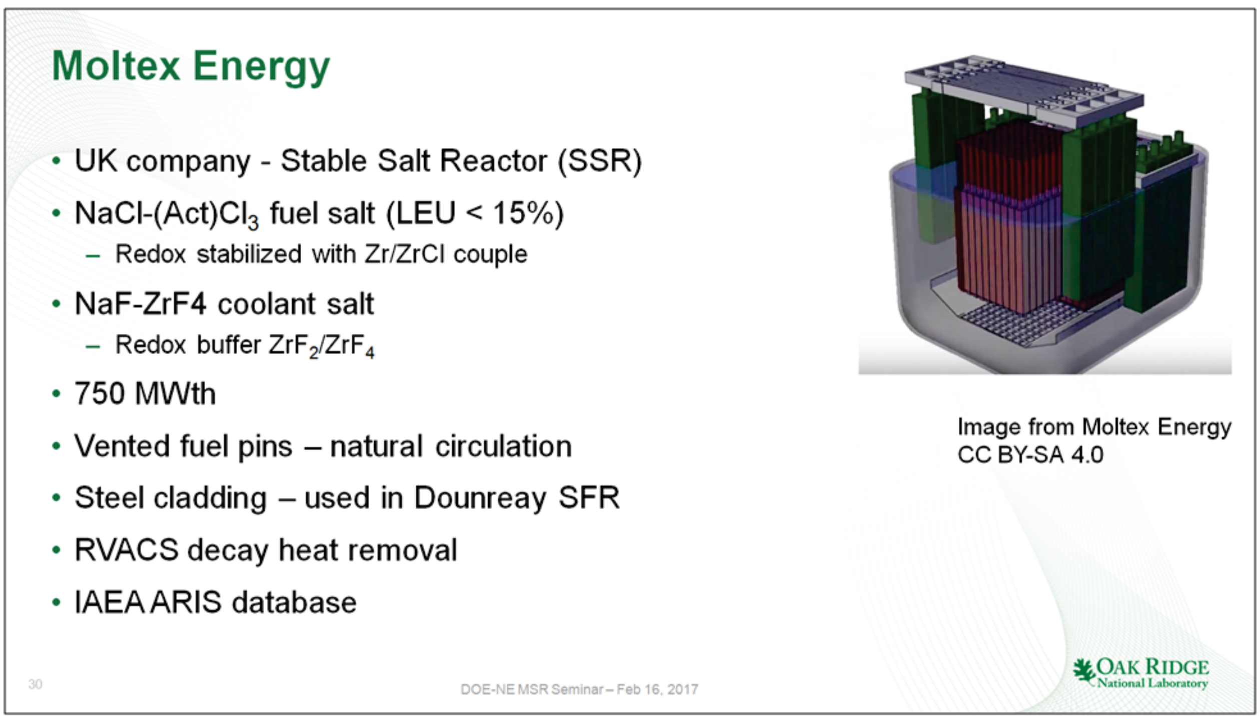
Module 2 – Slide 27. FLiBe Energy.



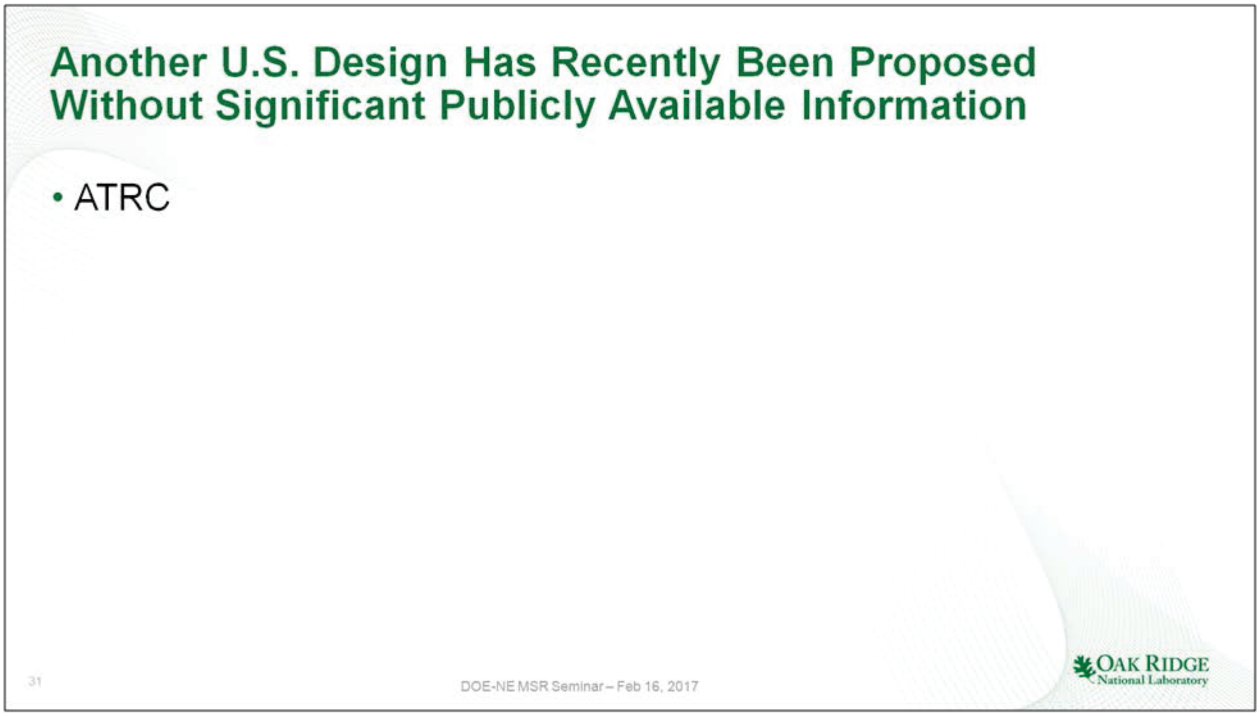
Module 2 – Slide 28. Elysium Molten Salt Reactor Concept.



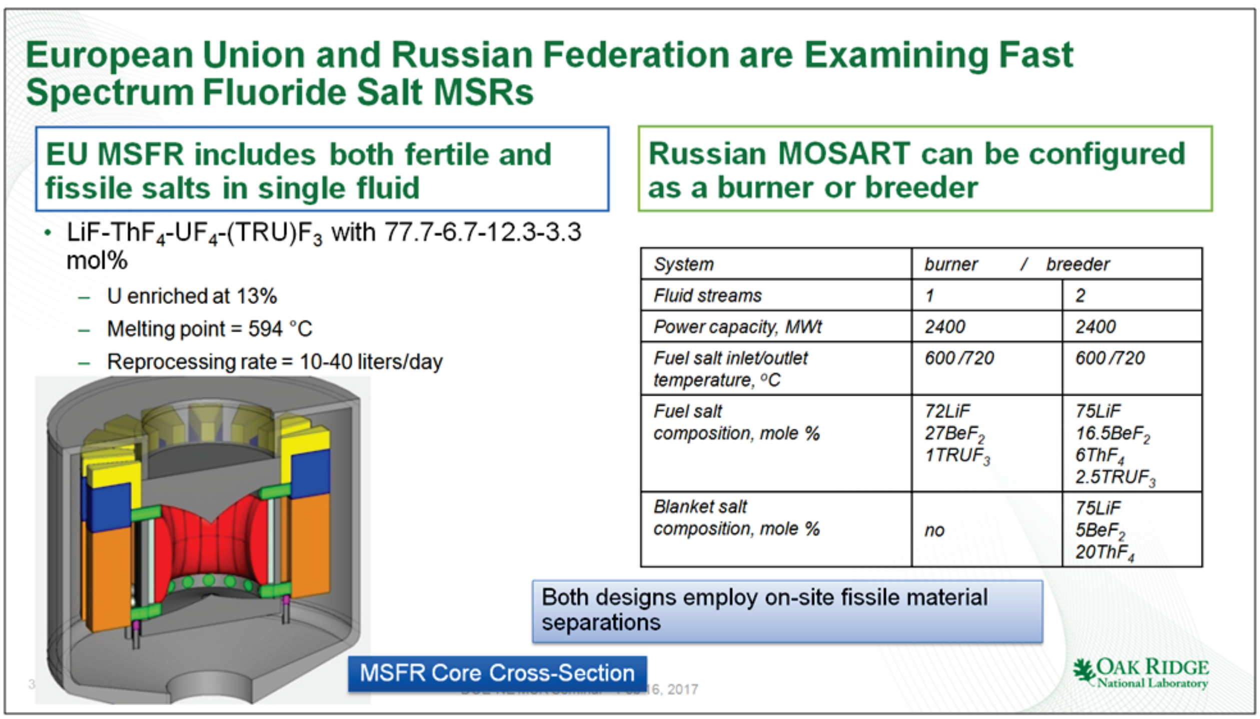
Module 2 – Slide 29. Kairos Power.



Module 2 – Slide 30. Moltex Energy.

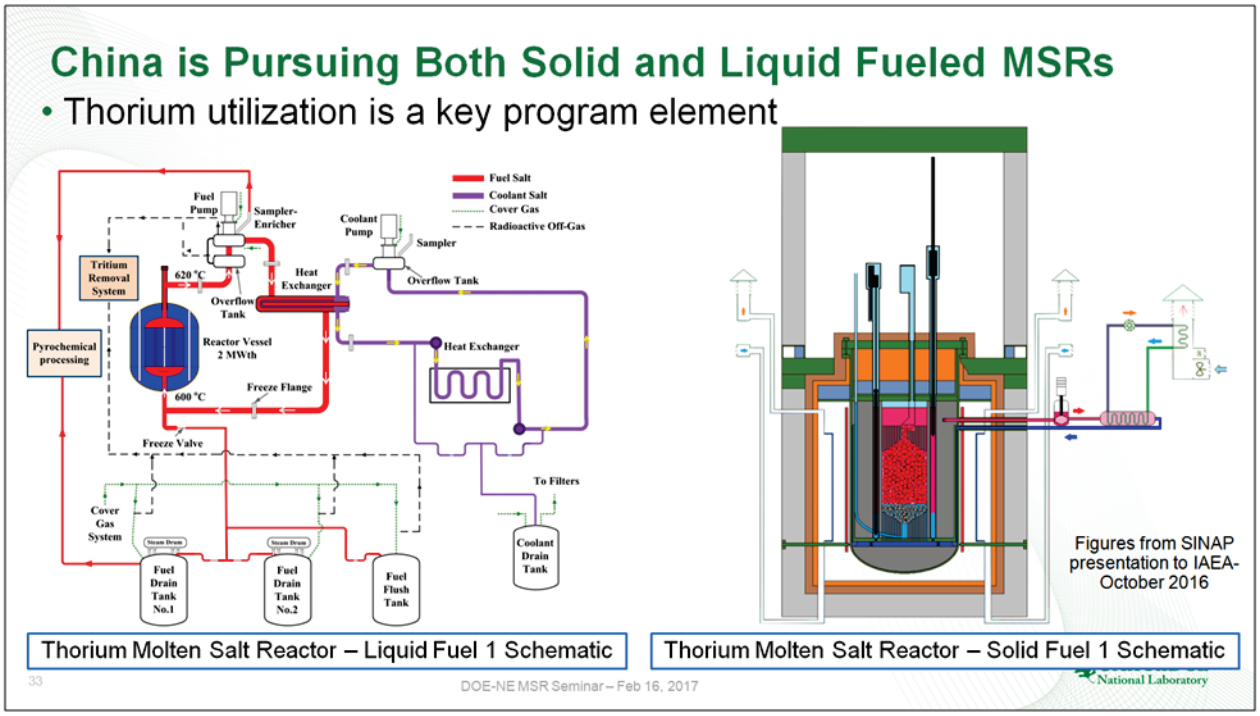


Module 2 – Slide 31. ATRC.



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$_4$

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



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 MSRs. Among the significant points made during the presentation are the following:

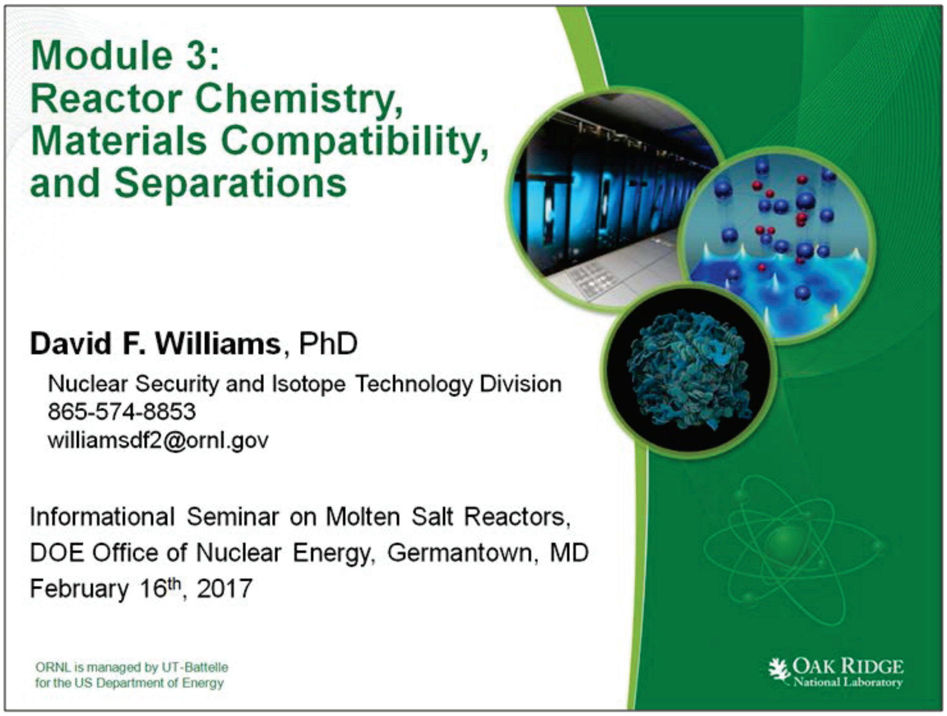
- Many fluoride- and chloride-based salts have been studied for use in liquid-fueled MSRs.
- Choice of salt and the composition can affect properties, including actinide solubility for liquid-fueled MSRs, vapor pressure, and freezing and melting points.
- For liquid-fueled MSRs, fission leads to chemically 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 ^{6}Li (which is why use of ^{7}Li 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

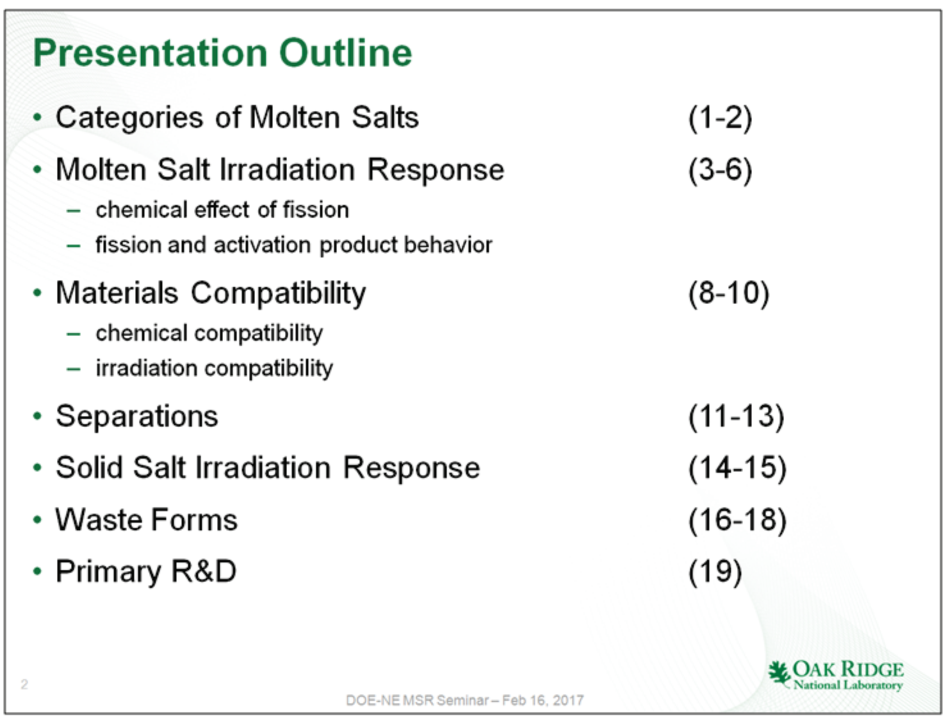
- Remediation activities related to the MSRE have resulted in several findings:
  - Solid halide salts are damaged by radiation and darken, corresponding to the development of metal regions and the release of halide gas.
  - Maintain fuel salts above 150ºC to prevent radiolysis.
  - Some fission products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

Primary Research Issues

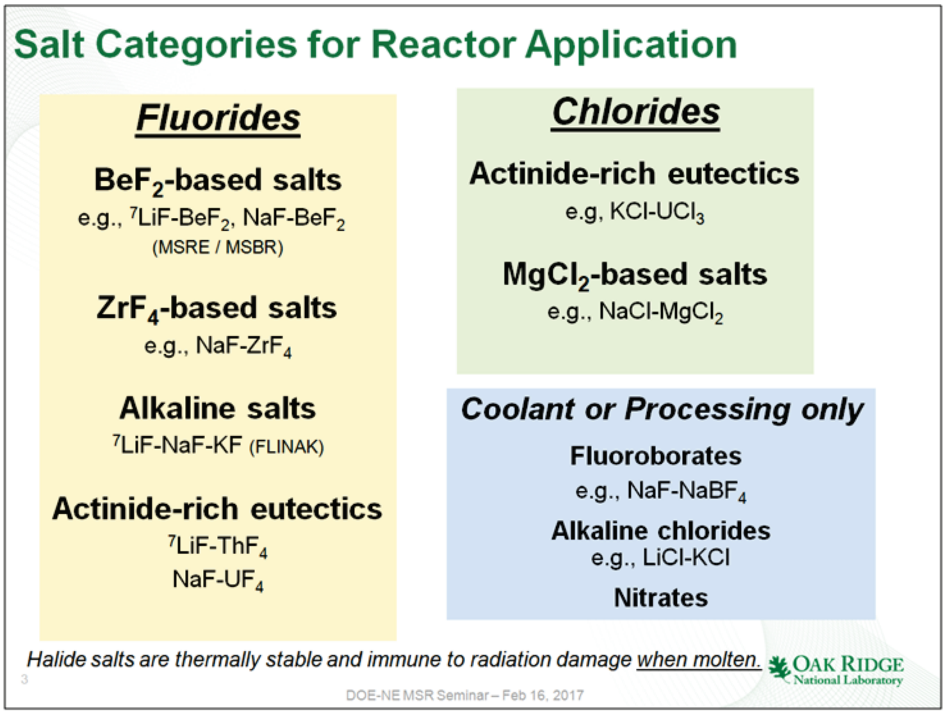
- Understanding and managing salt radiolysis.
- Understanding and managing "noble" fission products, i.e., those fission products that are not soluble in salt, since they have the potential to precipitate from the salt at any location in the circulating liquid-fuel salt loop.



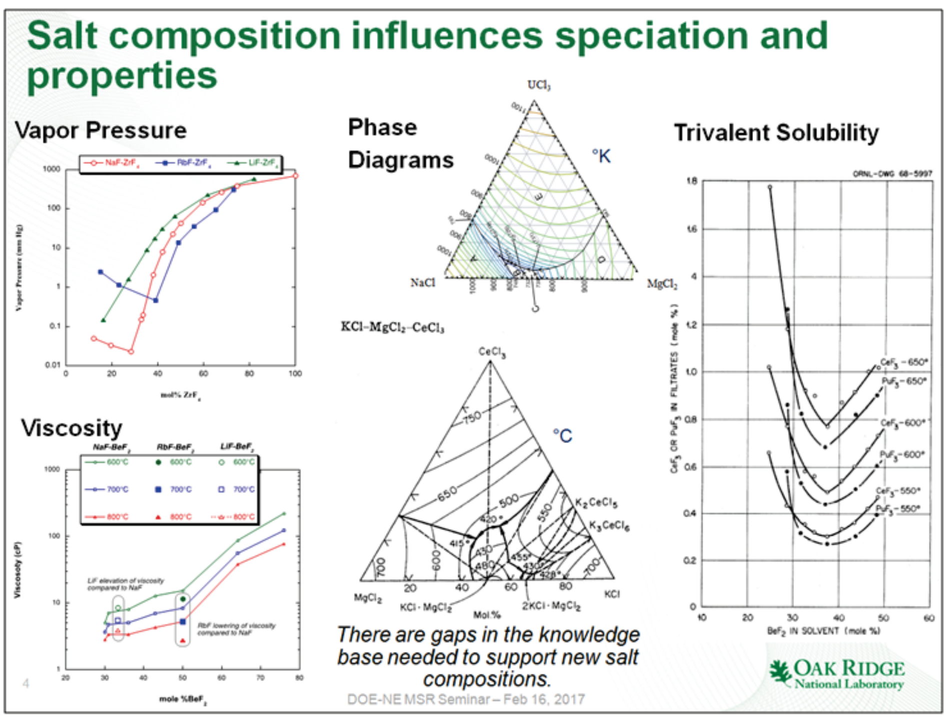
Module 3 – Slide 1. Title Slide



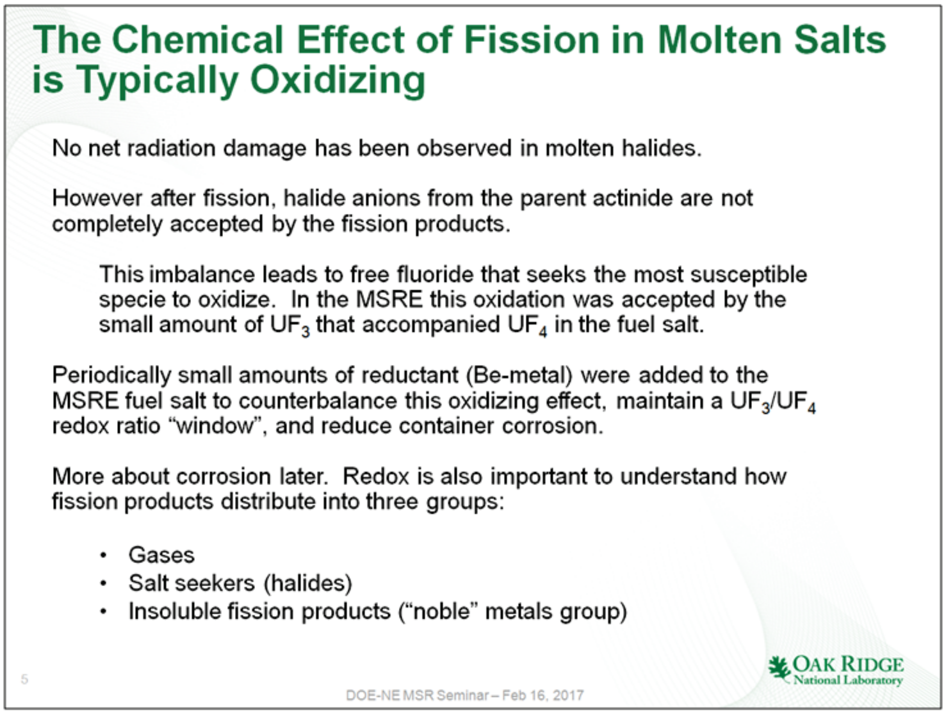
Module 3 – Slide 2. Presentation Outline.



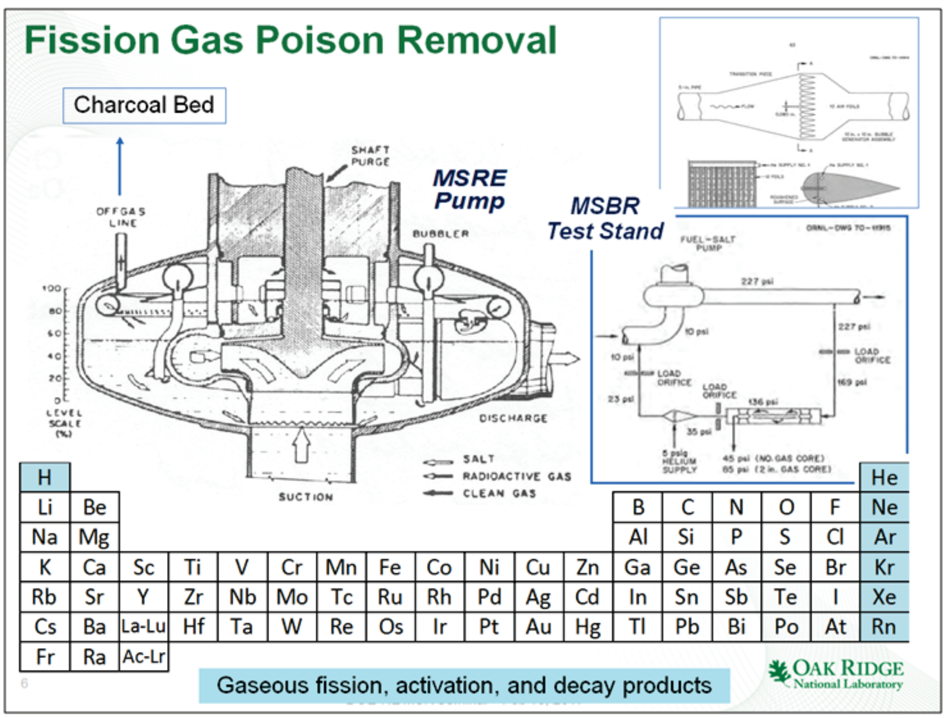
Module 3 – Slide 3. Salt Categories for Reactor Application.



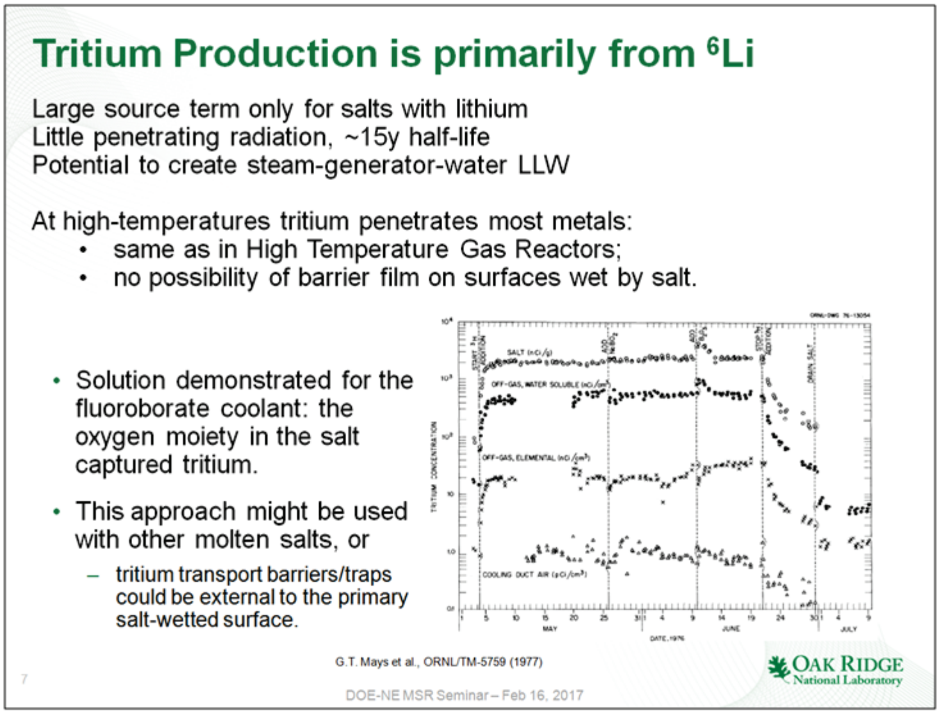
Module 3 – Slide 4. Salt Composition Influences Speciation Properties.



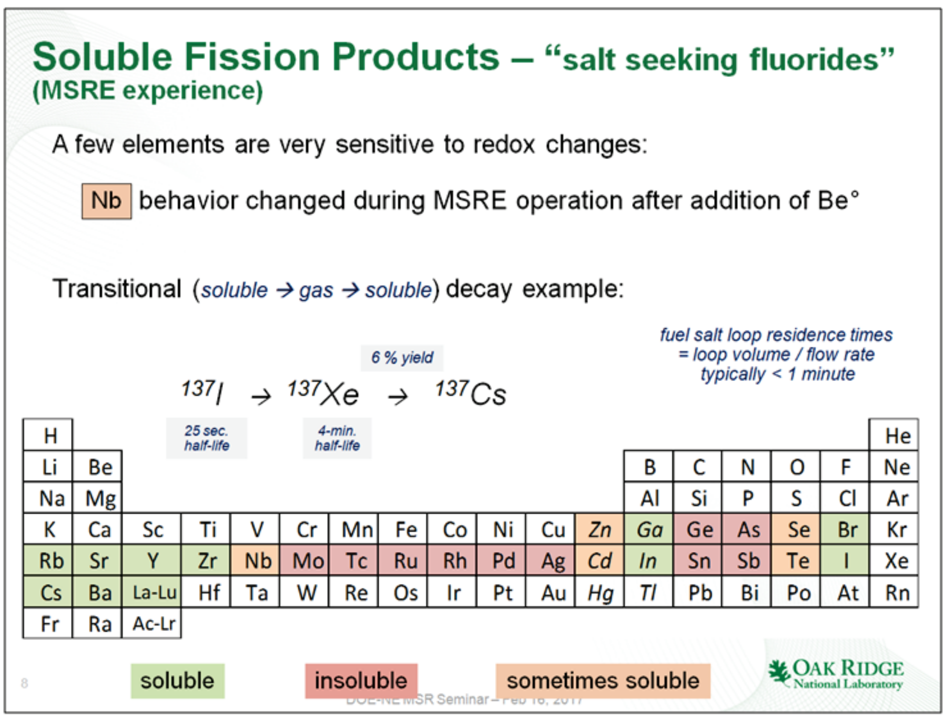
Module 3 – Slide 5. The Chemical Effect of Fission in Molten Salts is Typically Oxidizing.



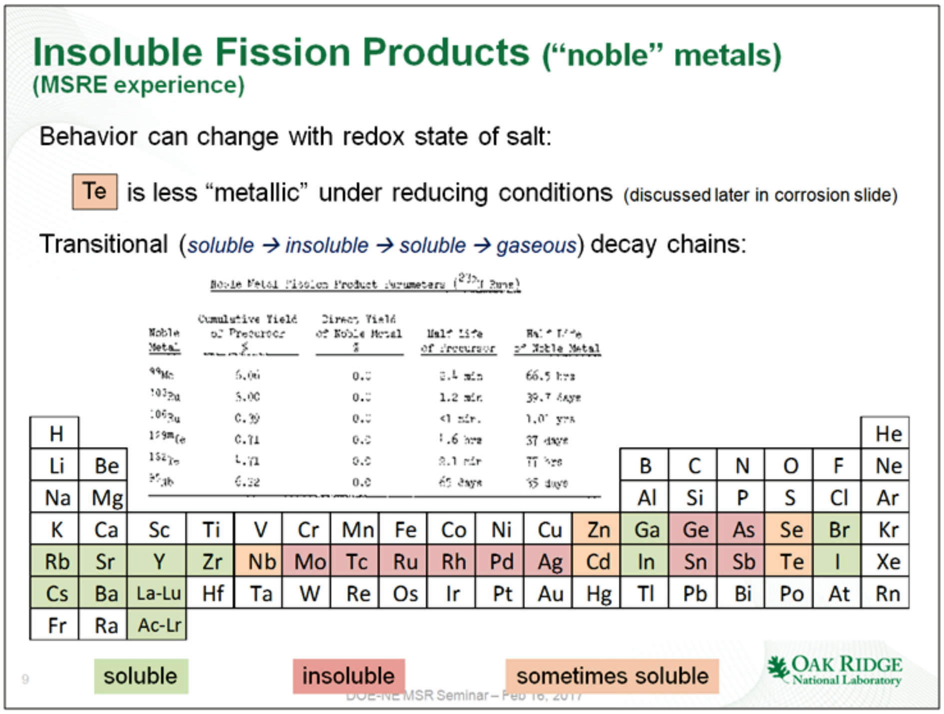
Module 3 – Slide 6. Fission Gas Poison Removal.



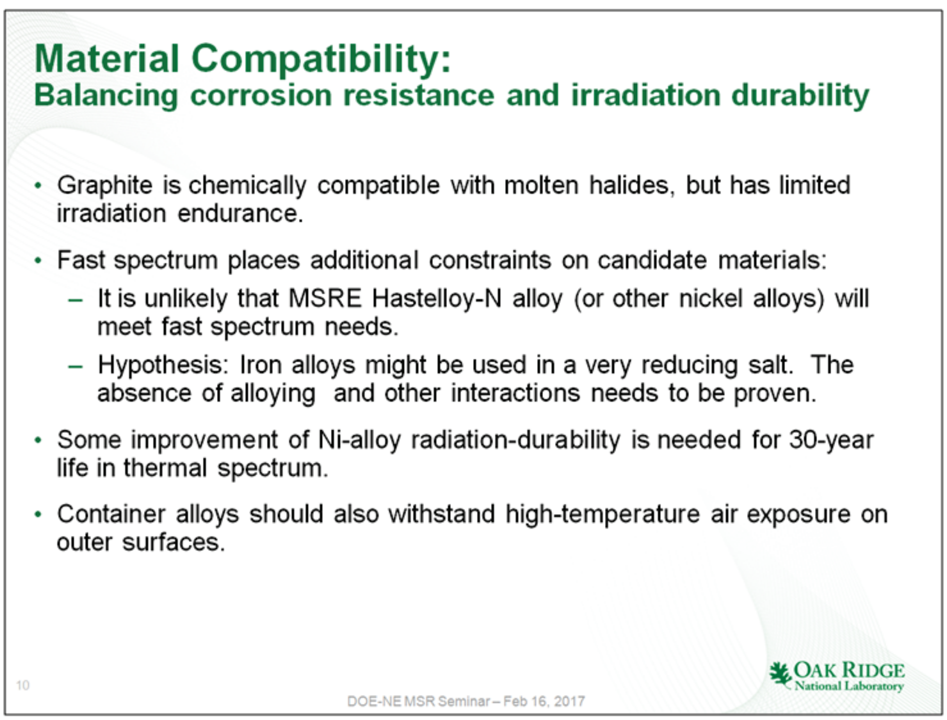
Module 3 – Slide 7. Tritium Production is Primarily from ^{6}Li.



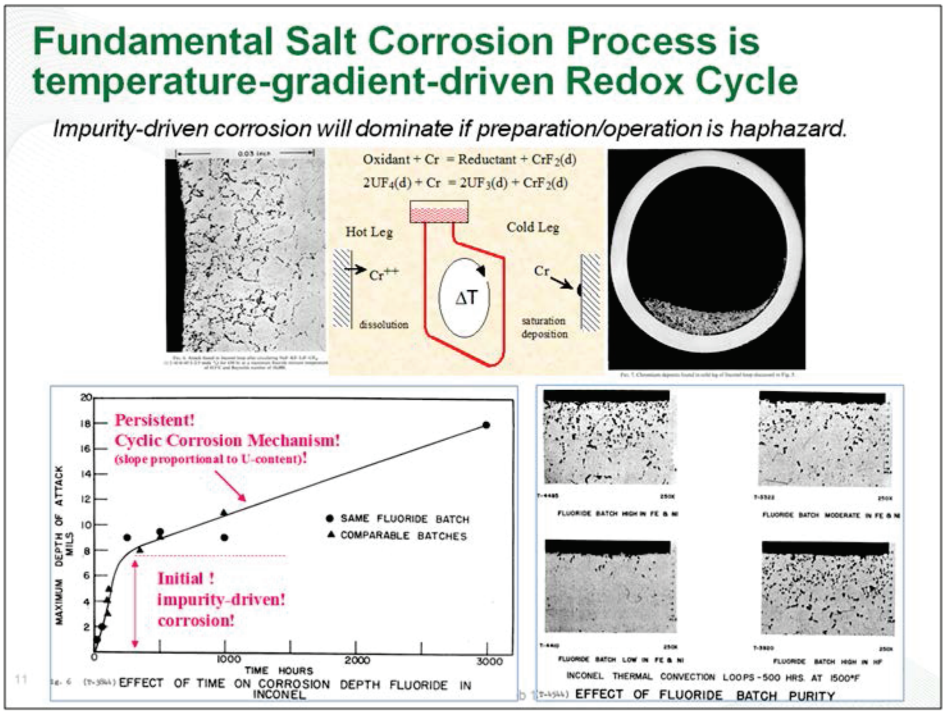
Module 3 – Slide 8. Soluble Fission Products.



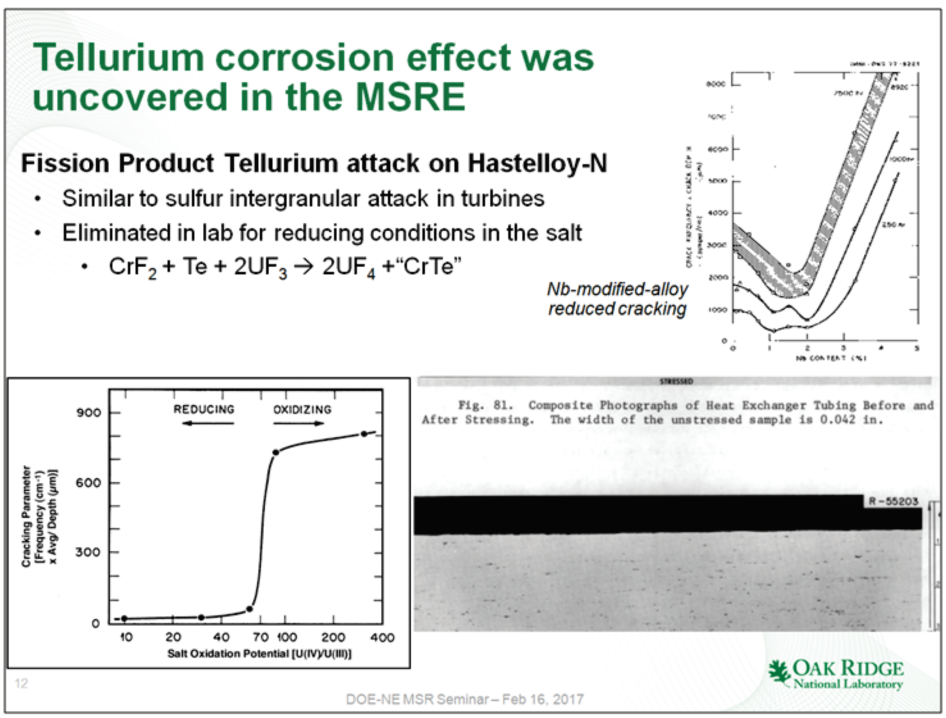
Module 3 – Slide 9. Insoluble Fission Products.



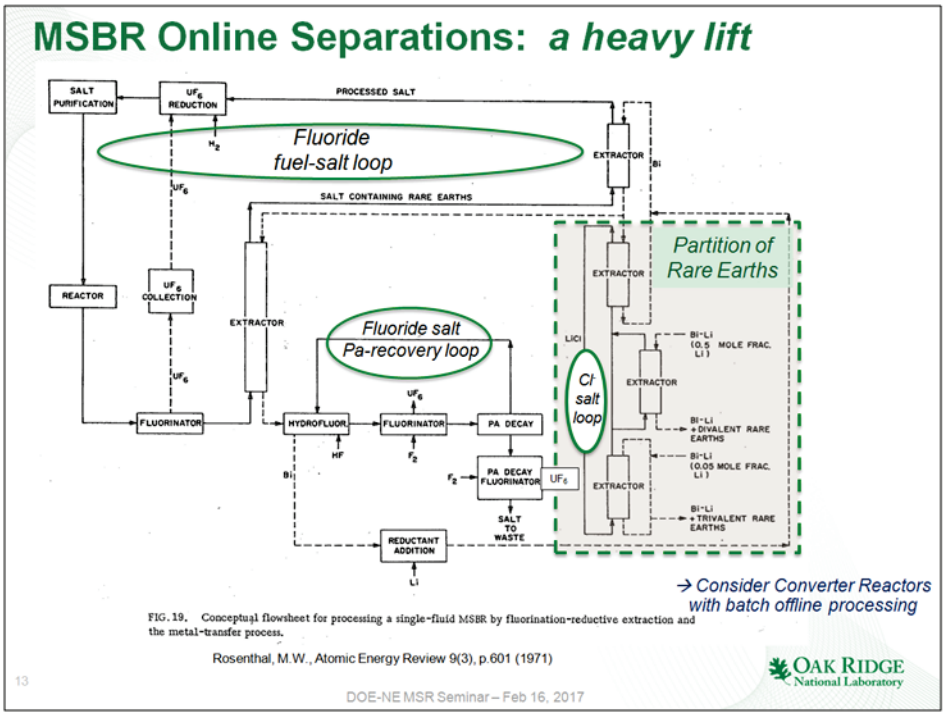
Module 3 – Slide 10. Material Compatibility.



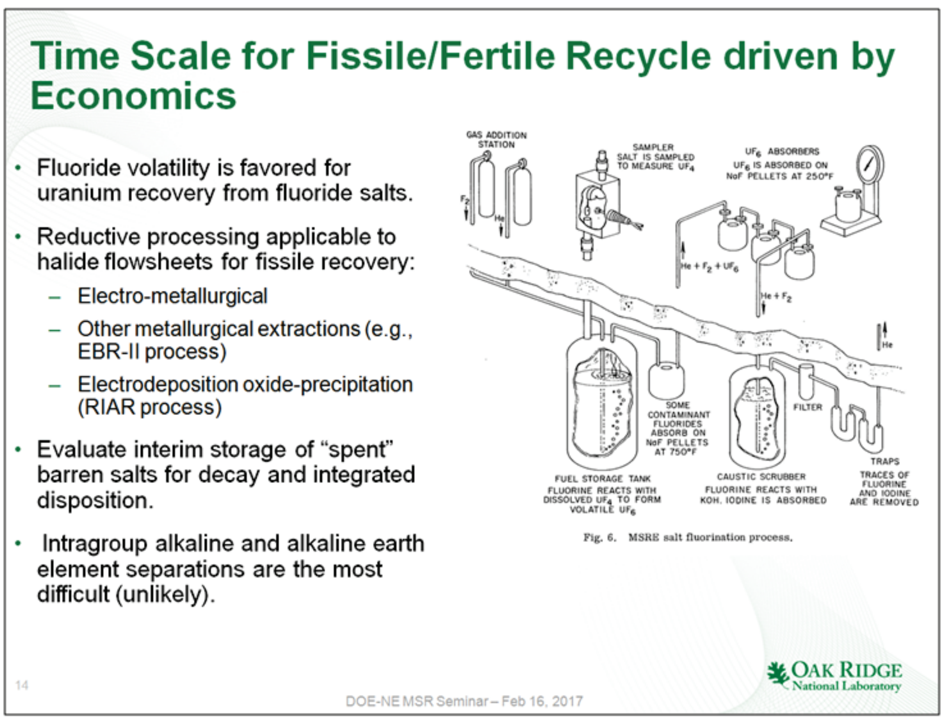
Module 3 – Slide 11. Fundamental Salt Corrosion Process is Temperature-Gradient-Driven Redox Cycle.



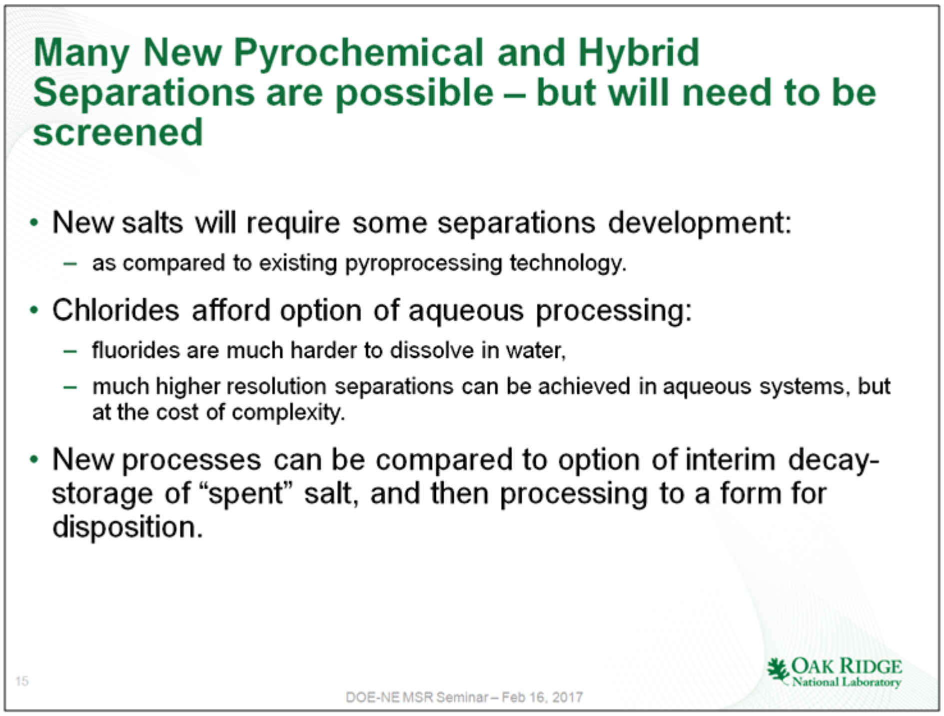
Module 3 – Slide 12. Tellurium Corrosion Effect was Uncovered in the MSRE.



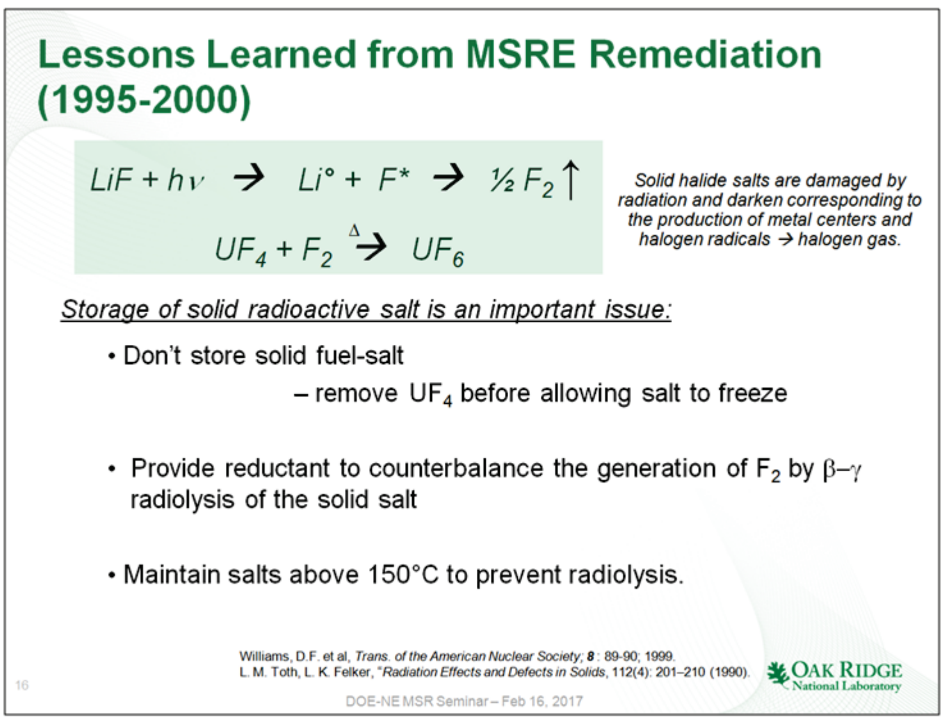
Module 3 – Slide 13. MSBR Online Separations: A Heavy Lift.



Module 3 – Slide 14. Time Scale for Fissile/Fertile Recycle Driven by Economics.

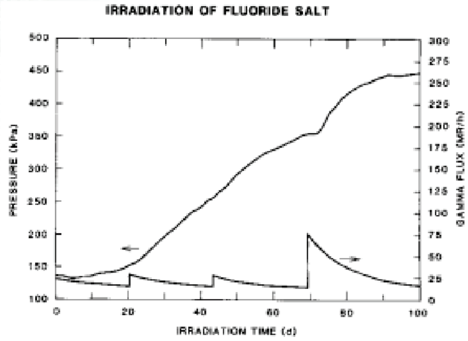


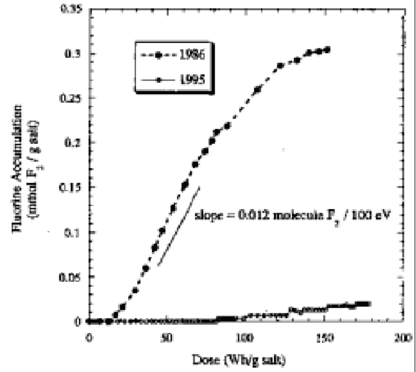
Module 3 – Slide 15. Many New Pyrochemical and Hybrid Separations are Possible.



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

Solid Salt Irradiation Response – cont'd





	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]

[a]For example, zirconium tends to accumulate with protactinium holdup in reductive extraction processing.
[b]Particulate observations suggest appreciable percentages will appear in processing streams.
[c]Substantial iodine could be removed if side-stream stripping is used to remove I-135.

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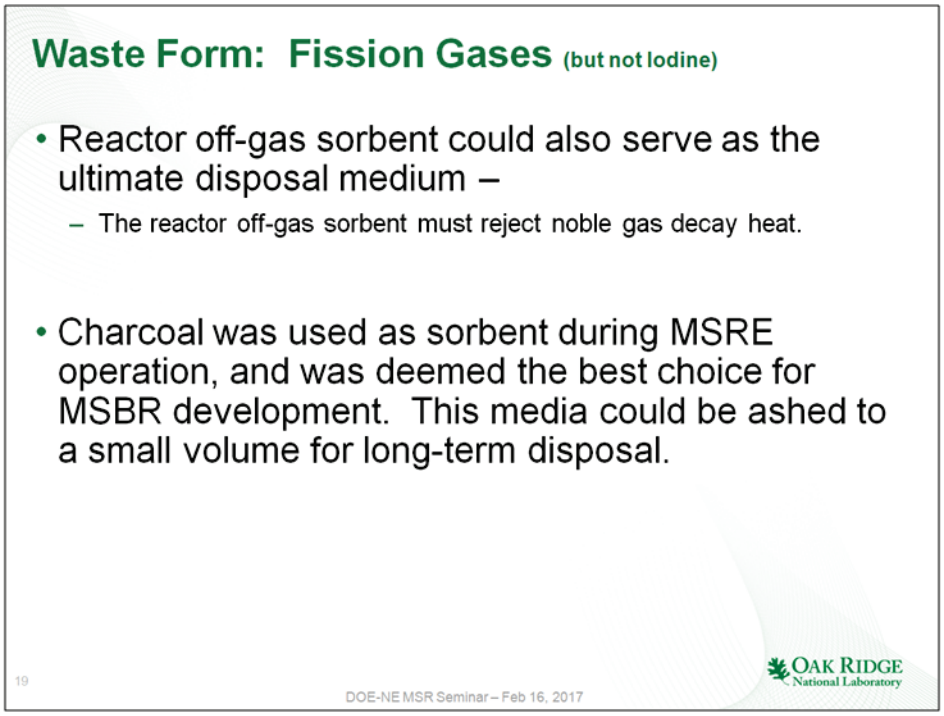
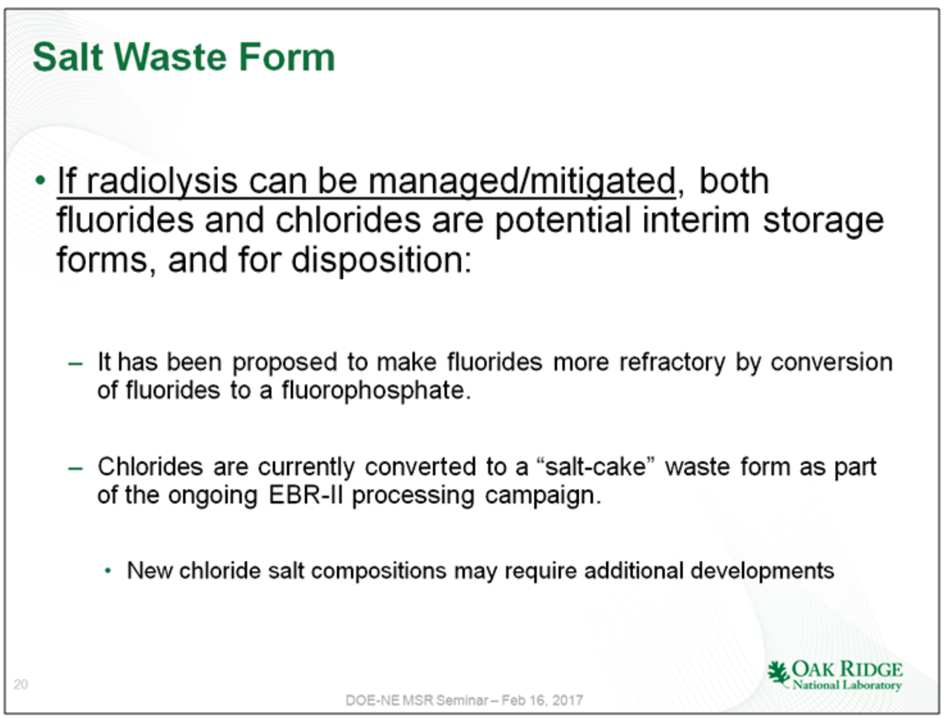
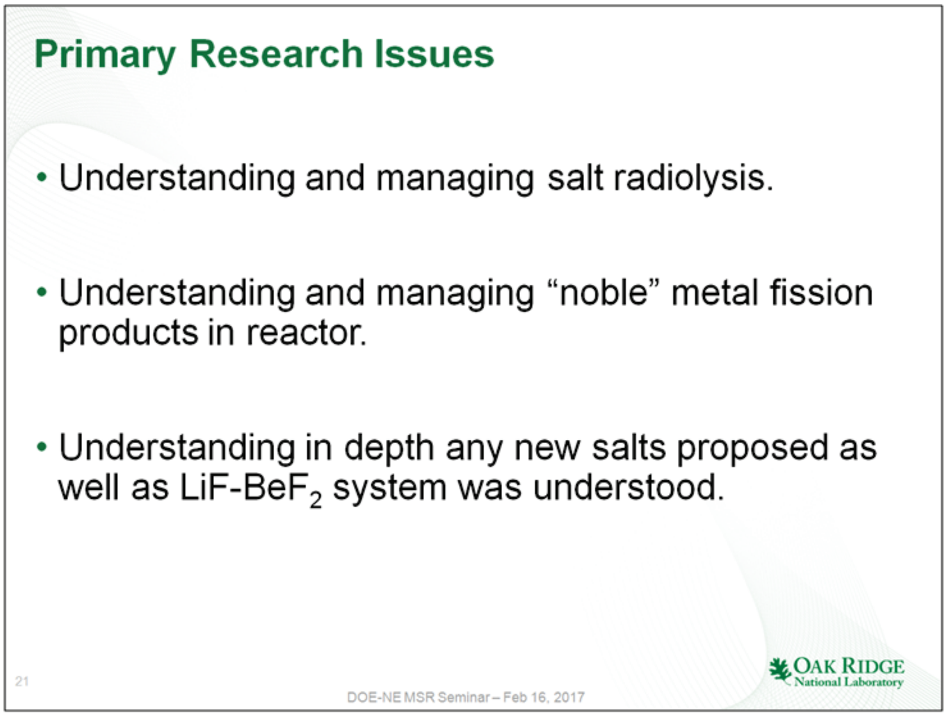
Module 3 – Slide 18. Waste Form: Reactor Internals.



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



Module 3 – Slide 20. Salt Waste Form.



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 MSRs, 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

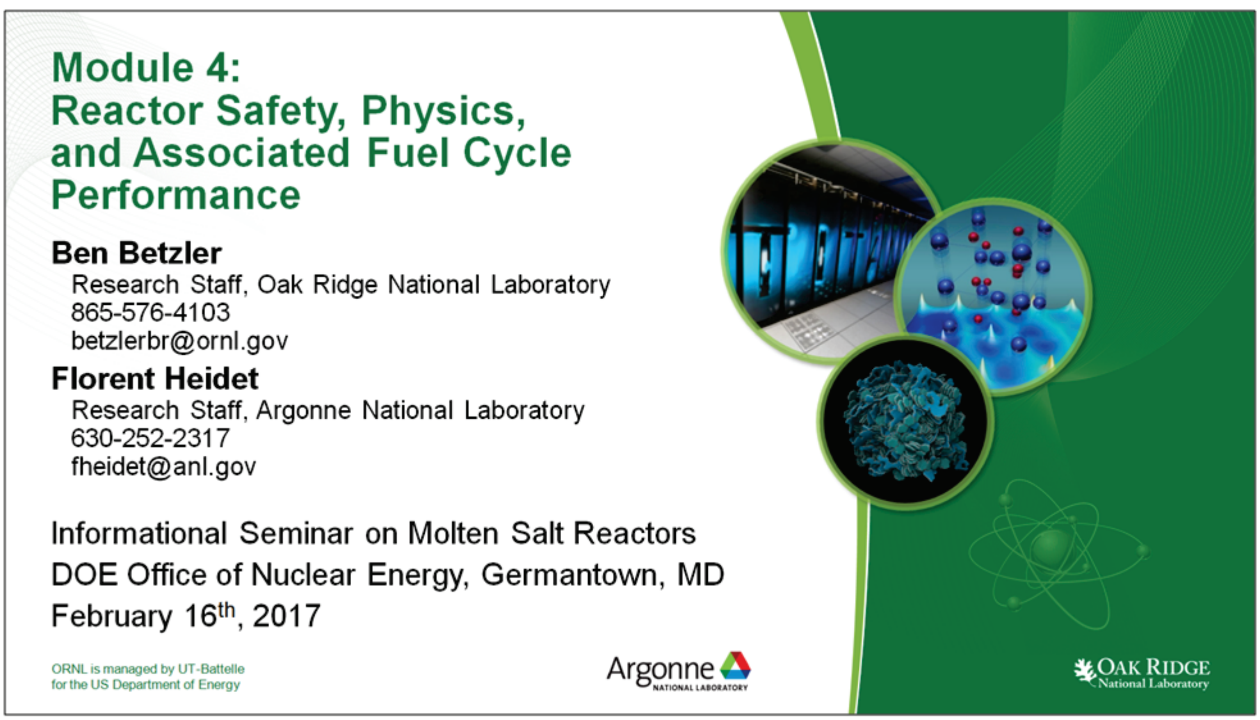
- Undesired freezing of the salt must be prevented.
- Managing waste forms from fission product and other material removals, since there are multiple radioactive source terms in multiple locations.
- Remote maintenance required due to high radioactivity of fuel salt flowing through the fuel loop.
- A 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.

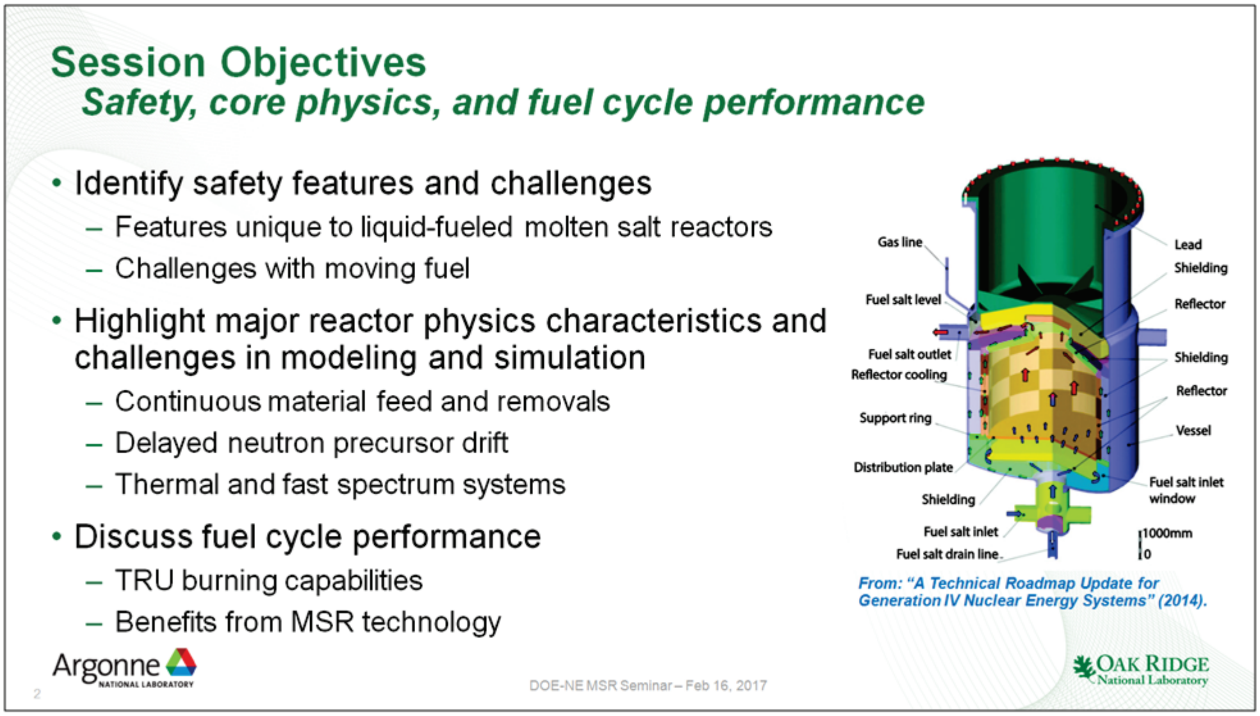
– Analysis of the reactor physics is different than for solid-fueled reactors.

  - 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.

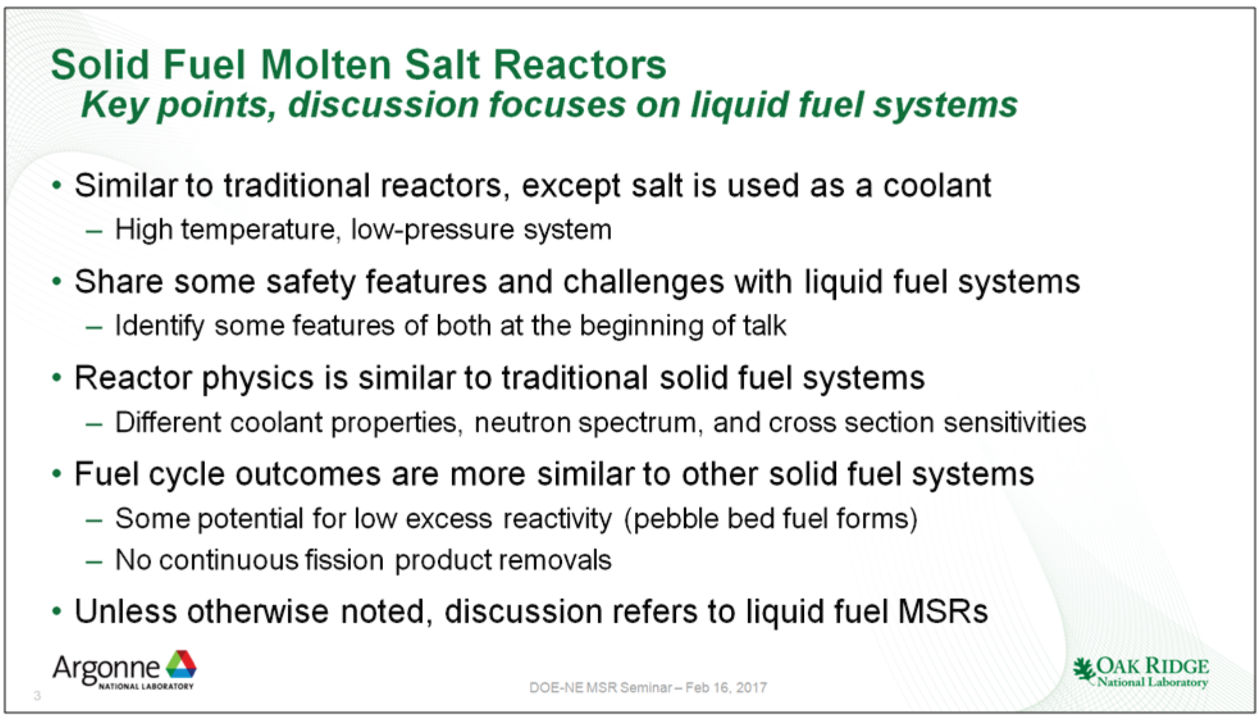
– Fast neutron spectrum MSRs may need to use chloride-based salts instead of the historical fluoride-based salts used in thermal neutron spectrum MSRs to reduce the neutron moderating effect. Much less is known about chloride-bases salts in MSR applications.



Module 4 – Slide 1. Title Slide.



Module 4 – Slide 2. Session Objectives.



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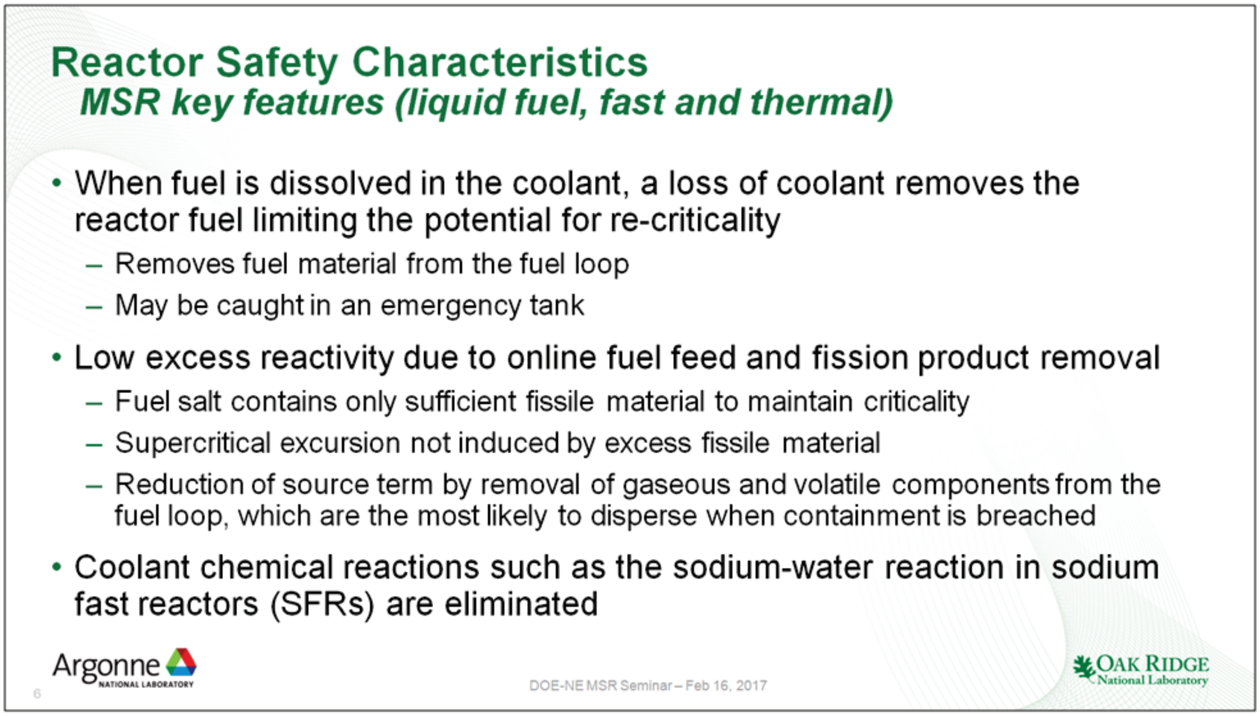
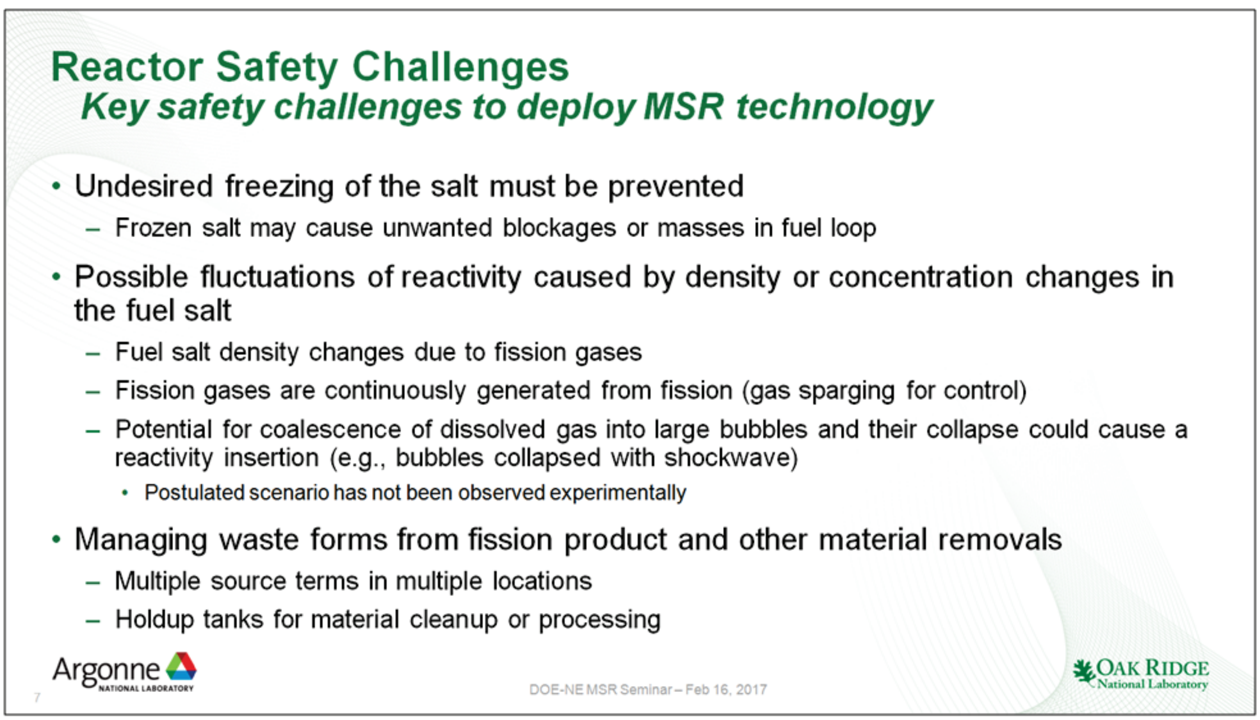
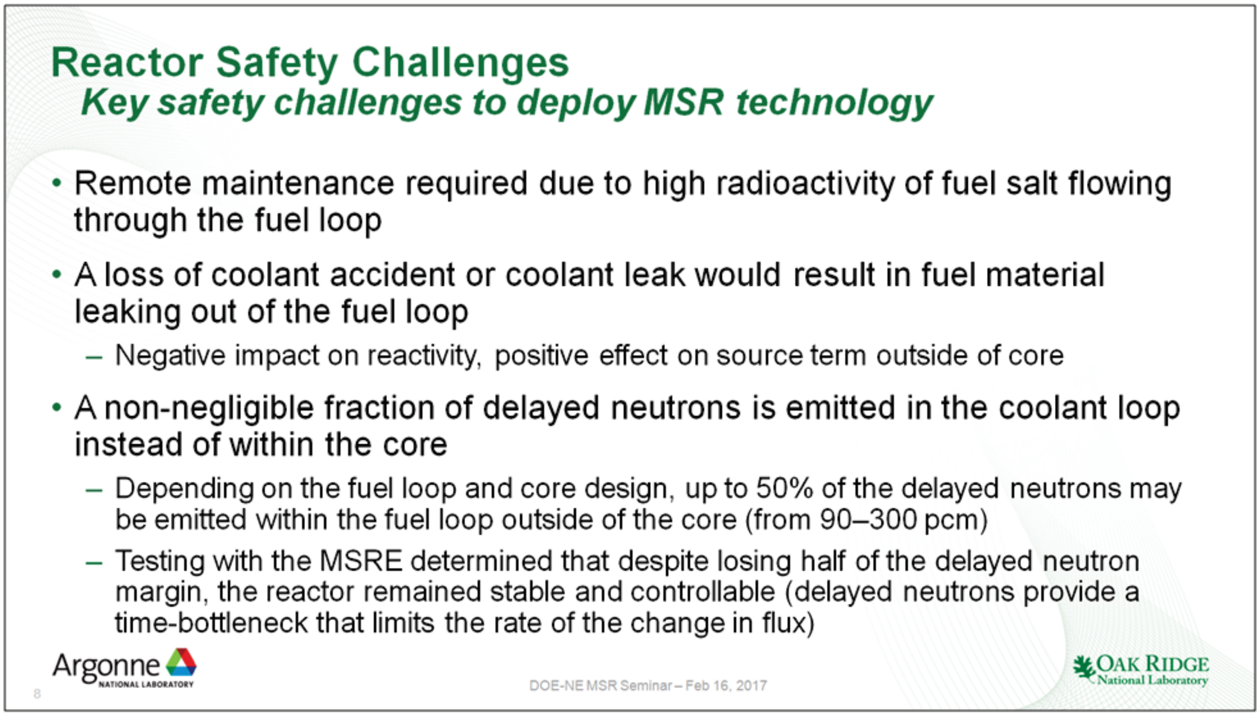
Module 4 – Slide 5. Reactor Safety Characteristics – MSR Key Features (Liquid Fuel).



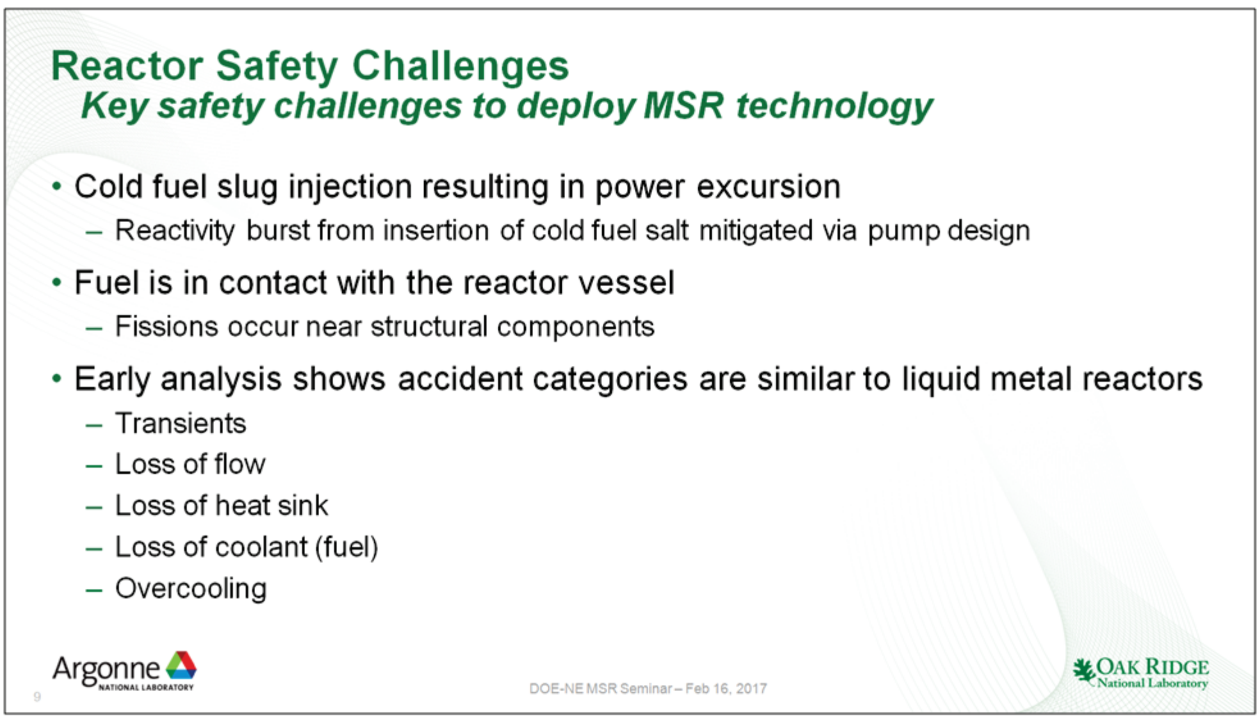
Module 4 – Slide 6. Reactor Safety Characteristics – MSR Key Features (Liquid Fuel).



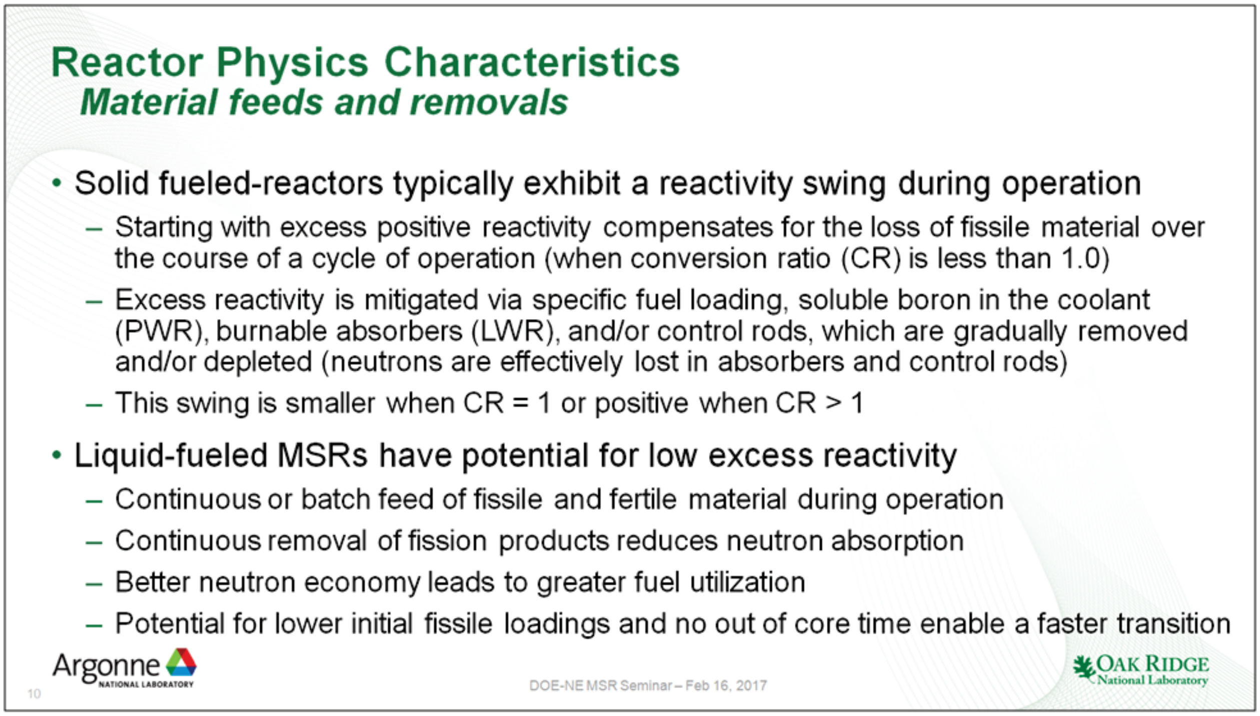
Module 4 – Slide 7. Reactor Safety Challenges – Key Safety Challenges to Deploy MSR Technology.



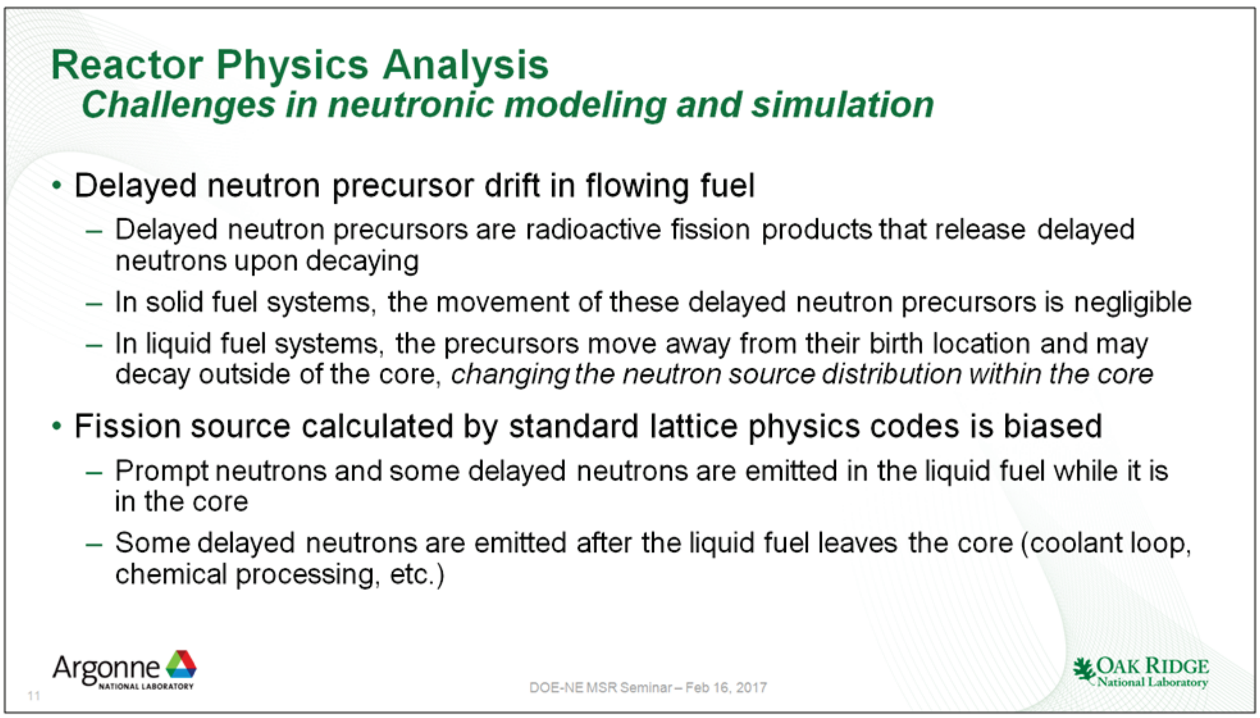
Module 4 – Slide 8. Reactor Safety Challenges – Key Safety Challenges to Deploy MSR Technology.



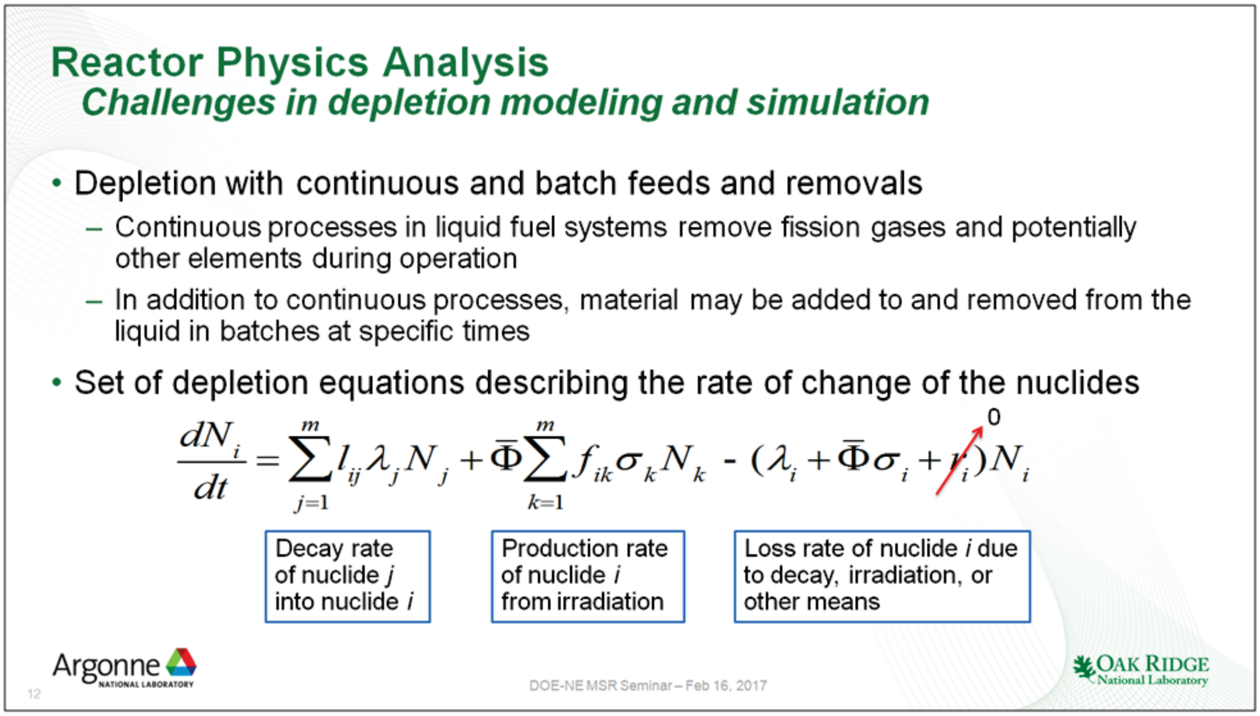
Module 4 – Slide 9. Reactor Safety Challenges.



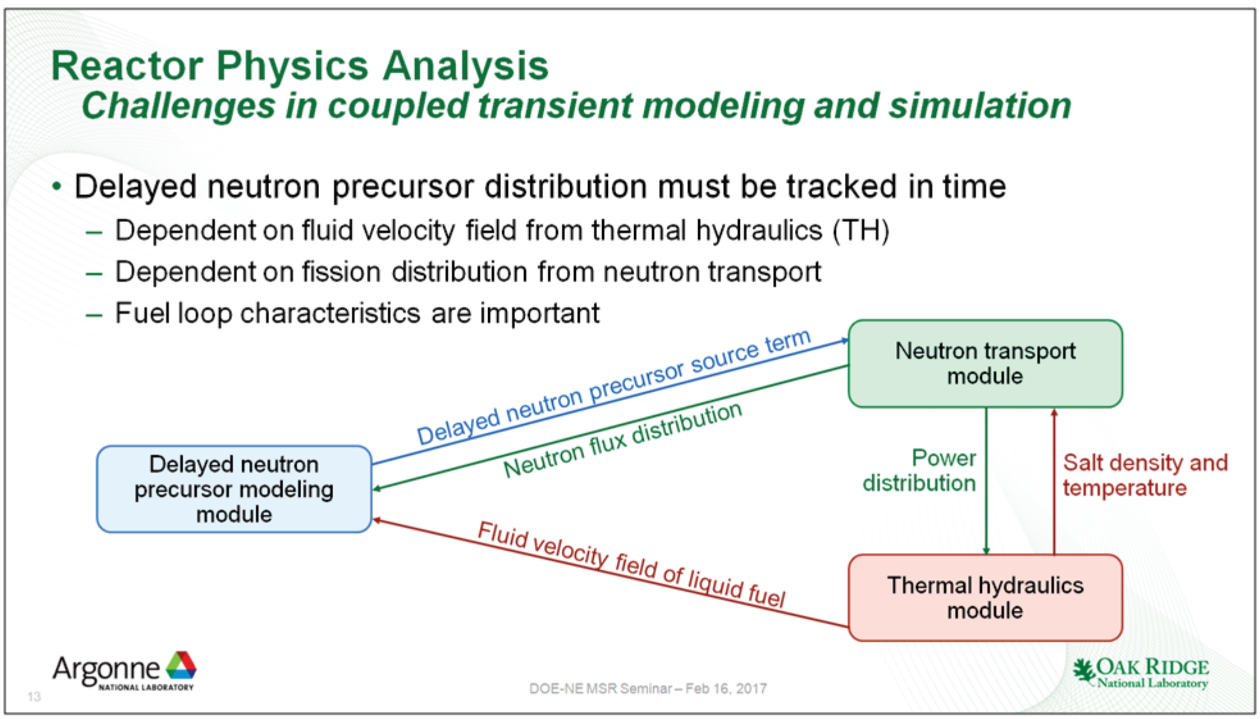
Module 4 – Slide 10. Reactor Physics Characteristics – Material Feeds and Removals.



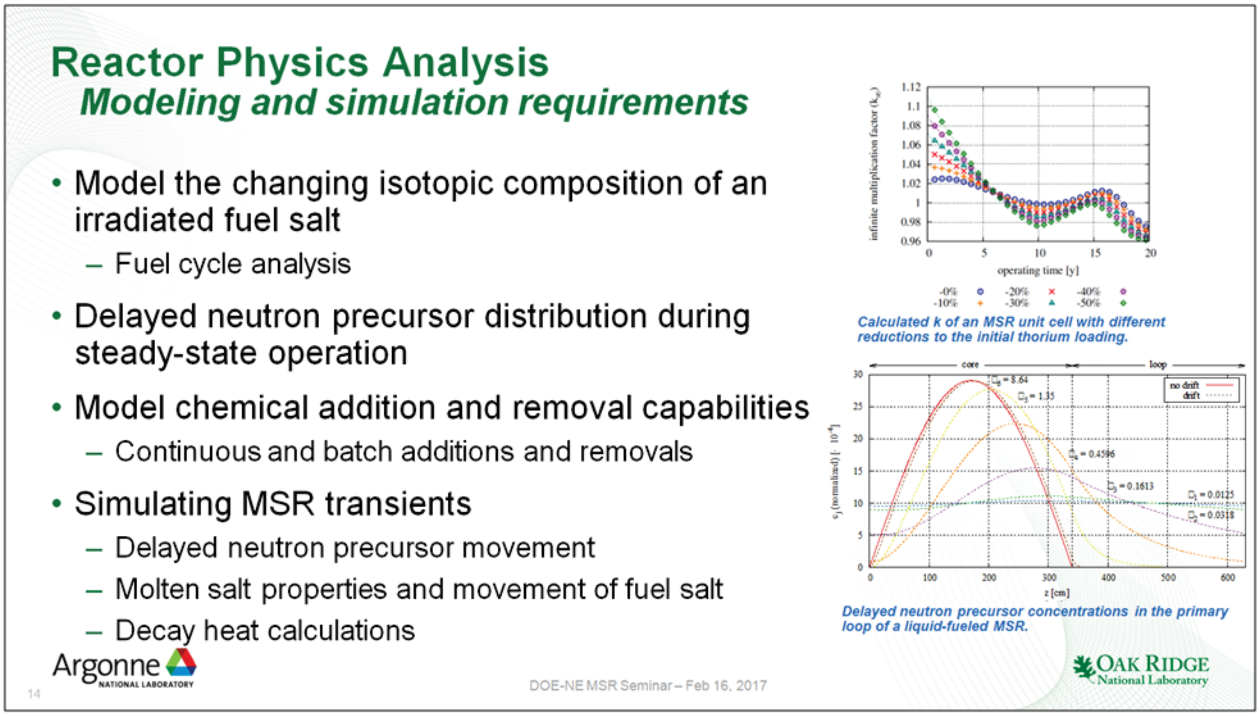
Module 4 – Slide 11. Reactor Physics Analysis – Neutronic Modeling and Simulation.



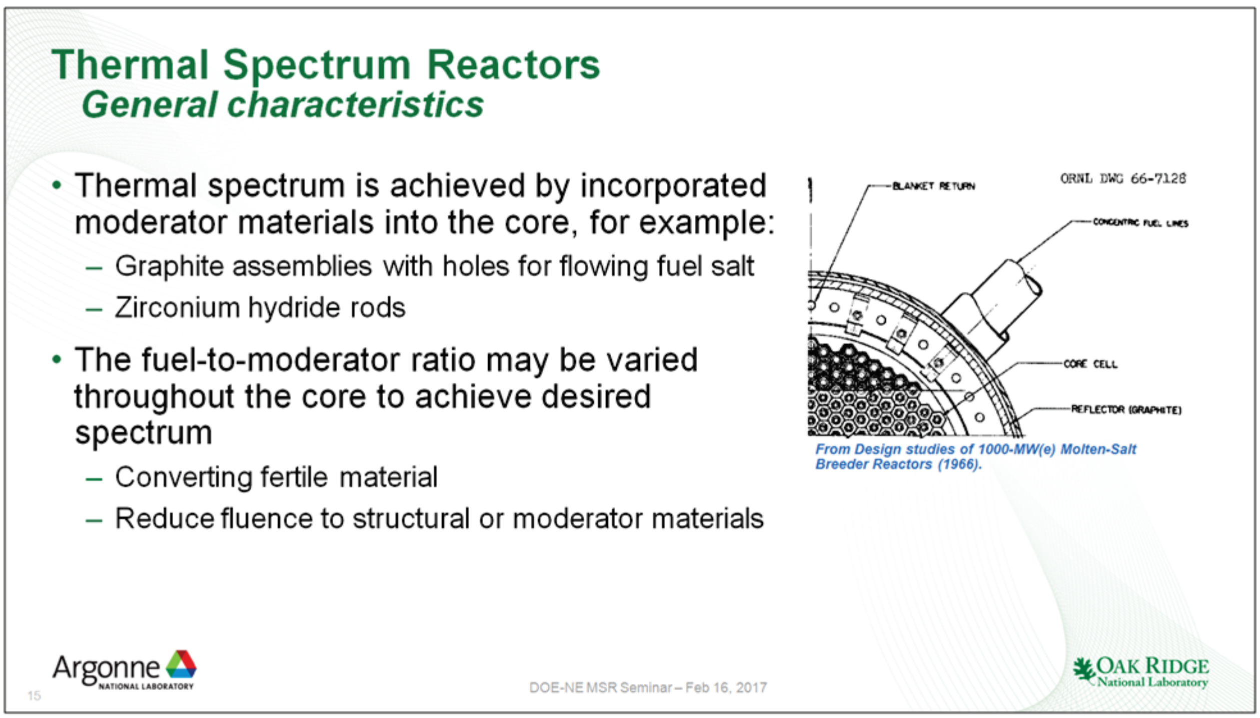
Module 4 – Slide 12. Reactor Physics Analysis – Depletion Modeling and Simulation.



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



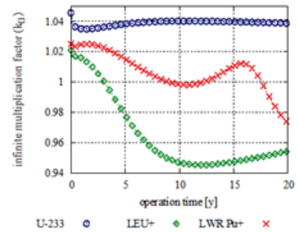
Module 4 – Slide 14. Reactor Physics Analysis – Modeling and Simulation Requirements.



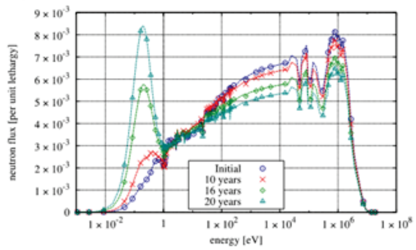
Module 4 – Slide 15. Thermal Spectrum Reactors – General Characteristics.

Thermal Spectrum Reactor Performance
Effect of initial startup composition

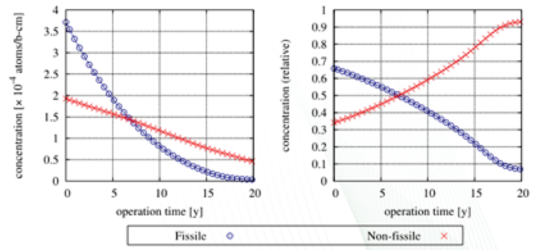
- Composition of the initial (startup) fuel salt has a significant effect on the viability of an MSR
  - Non-fissile heavy metals loaded at startup reside in the reactor for long periods of time
  - Neutron spectrum softens during operation



MSR reactivity with different initial fissile materials.



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



Fissile and non-fissile plutonium concentrations during operation.

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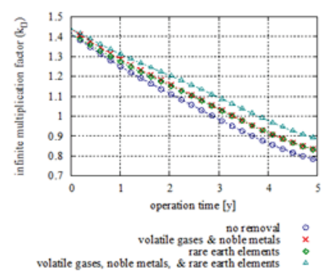
Module 4 – Slide 16. Thermal Spectrum Reactor Performance – Effect of Initial Startup Composition.

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



Calculated k of a unit cell with different removal groupings.

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

Removals	Core lifetime time [y]	Core lifetime 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

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	50 d
	Eu	500 d
Discard	Rb, Sr, Cs, Ba	3435 d

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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

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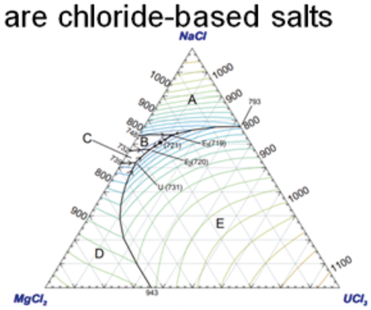
Module 4 – Slide 18. Fast Spectrum MSRs – Basic Physics Differences.

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



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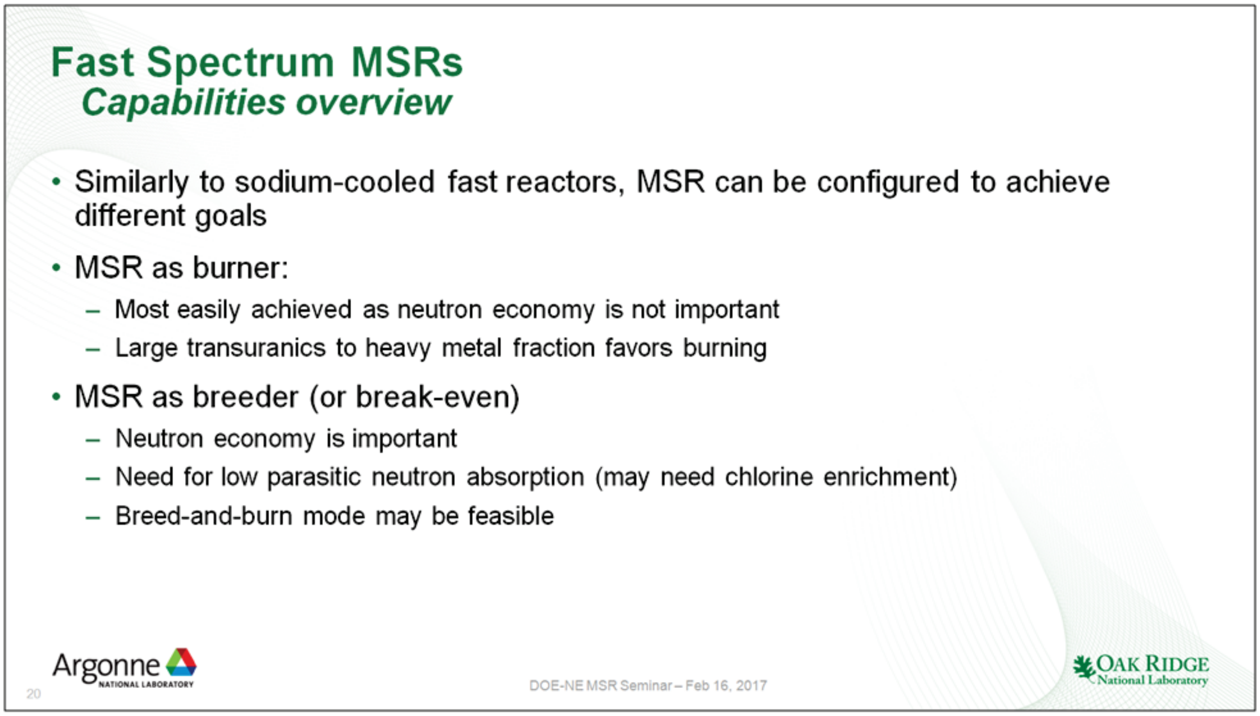
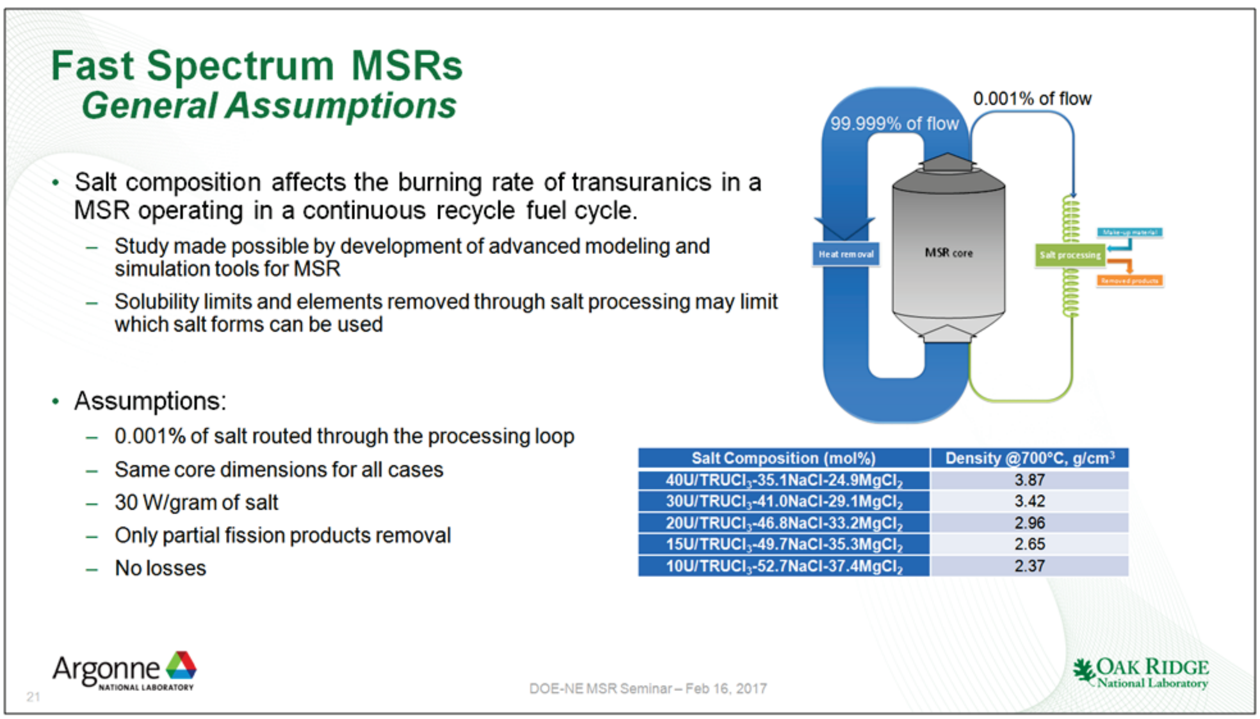
Module 4 – Slide 19. Fast Spectrum MSRs – Chloride Salt.



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

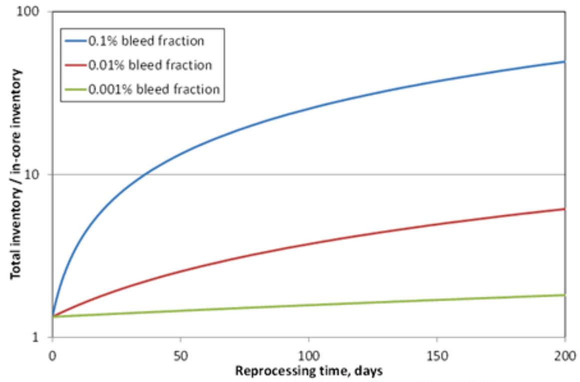


Salt Composition (mol%)	Density @700°C, g/cm^3
40U/TRUCl$_3$-35.1NaCl-24.9MgCl$_2$	3.87
30U/TRUCl$_3$-41.0NaCl-29.1MgCl$_2$	3.42
20U/TRUCl$_3$-46.8NaCl-33.2MgCl$_2$	2.96
15U/TRUCl$_3$-49.7NaCl-35.3MgCl$_2$	2.65
10U/TRUCl$_3$-52.7NaCl-37.4MgCl$_2$	2.37

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



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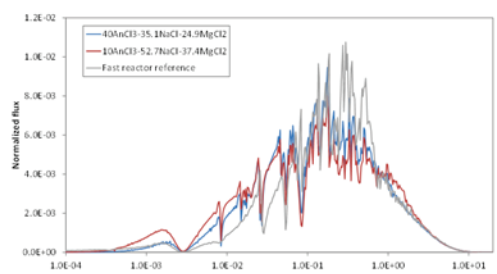
Module 4 – Slide 22. Fast Spectrum MSRs – Material Inventory.

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}

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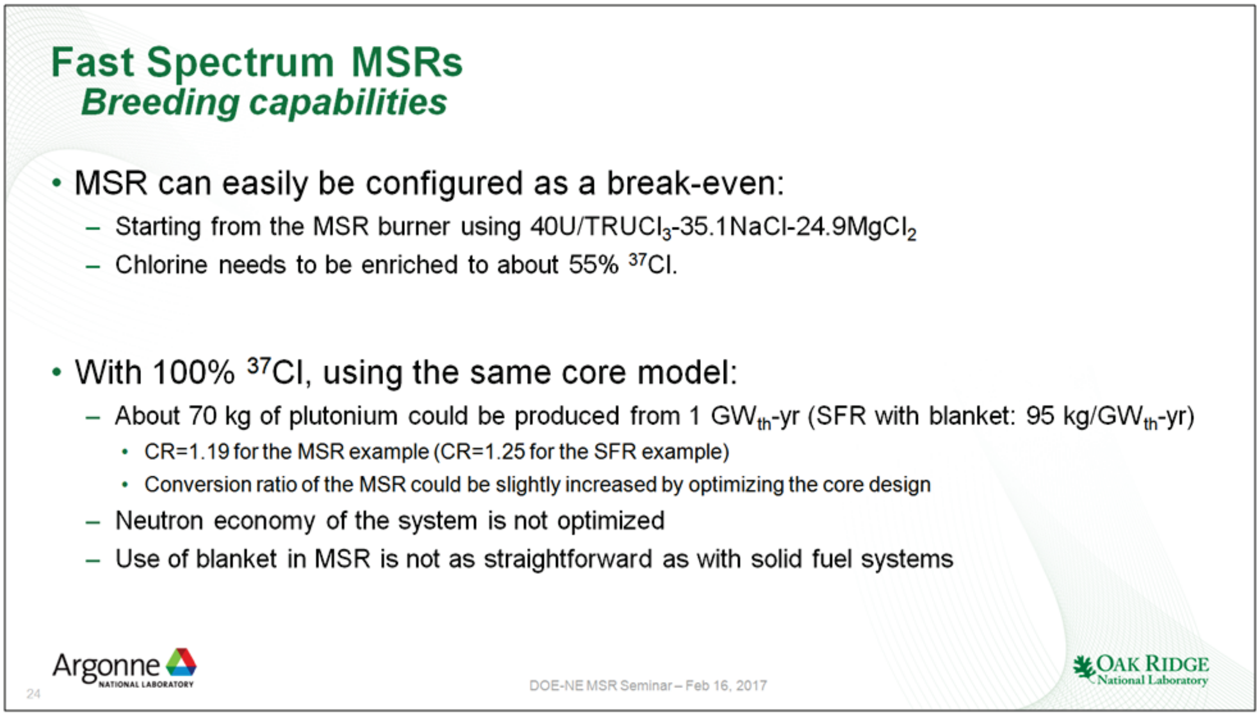
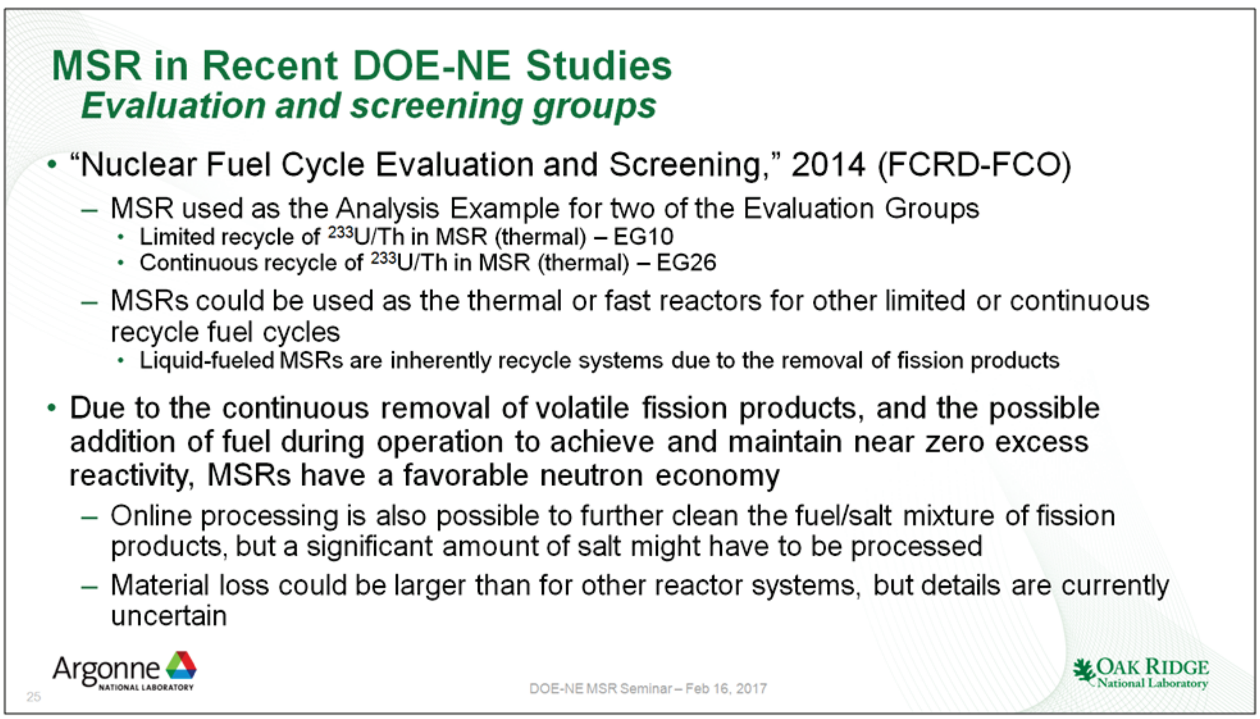
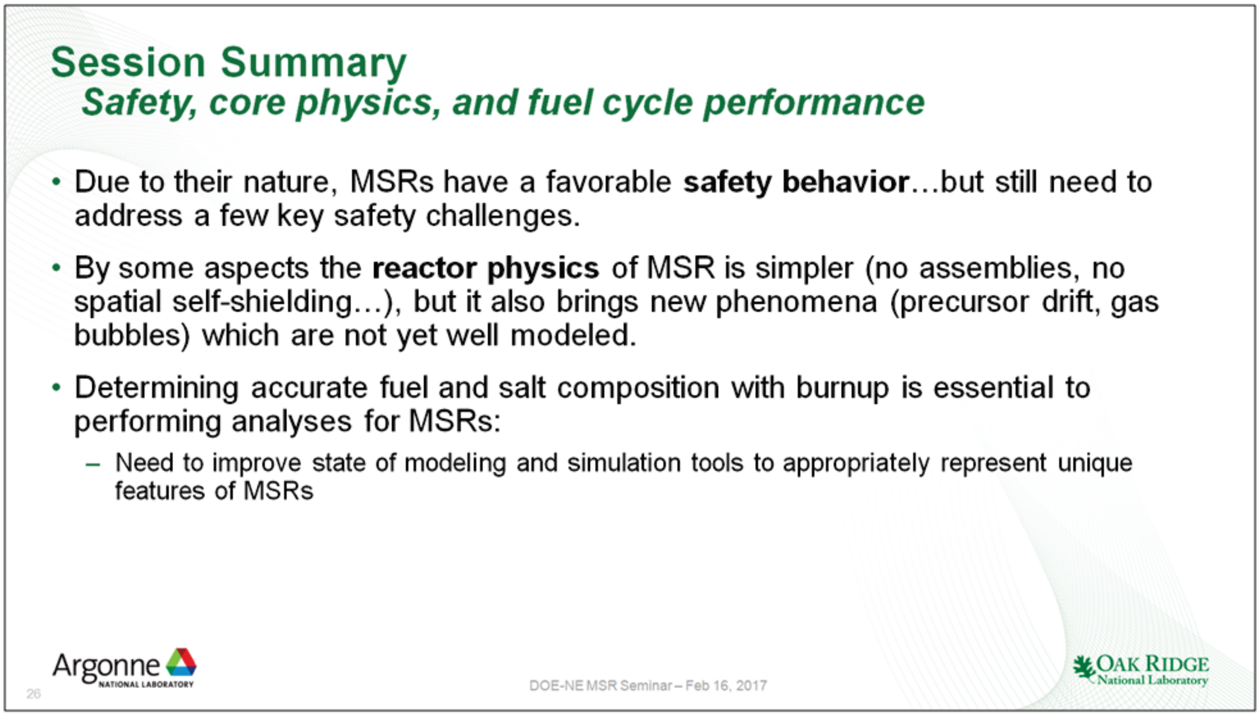
Module 4 – Slide 23. Fast Spectrum MSRs – TRU Burner Designs.



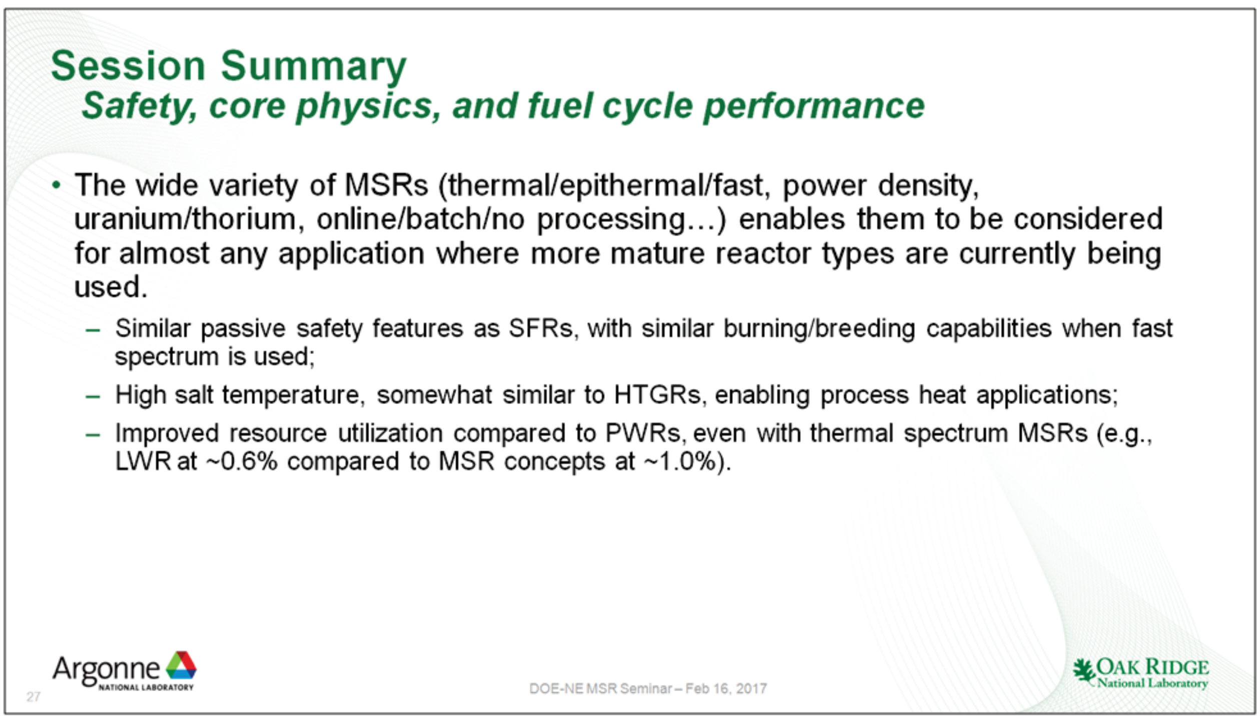
Module 4 – Slide 24. Fast Spectrum MSRs – Breeding Capabilities.



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



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

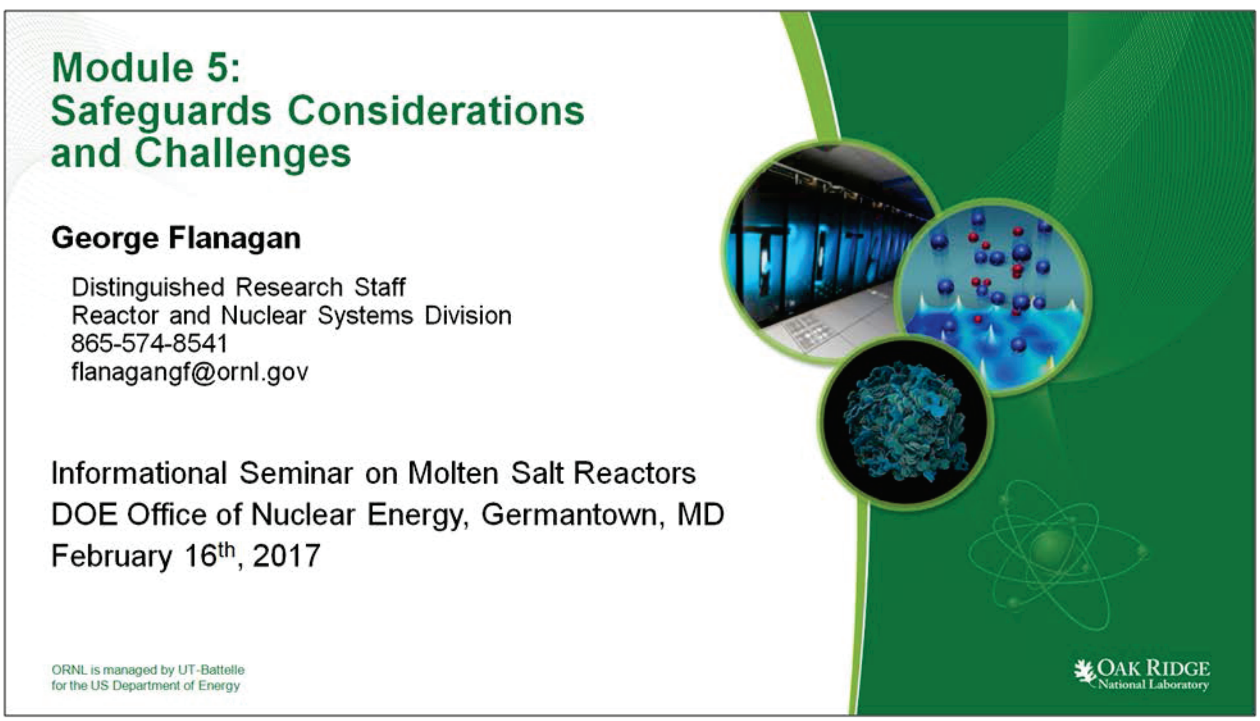


Module 4 – Slide 27. Session Summary – Safety, Core Physics, and Fuel Cycle Performance.

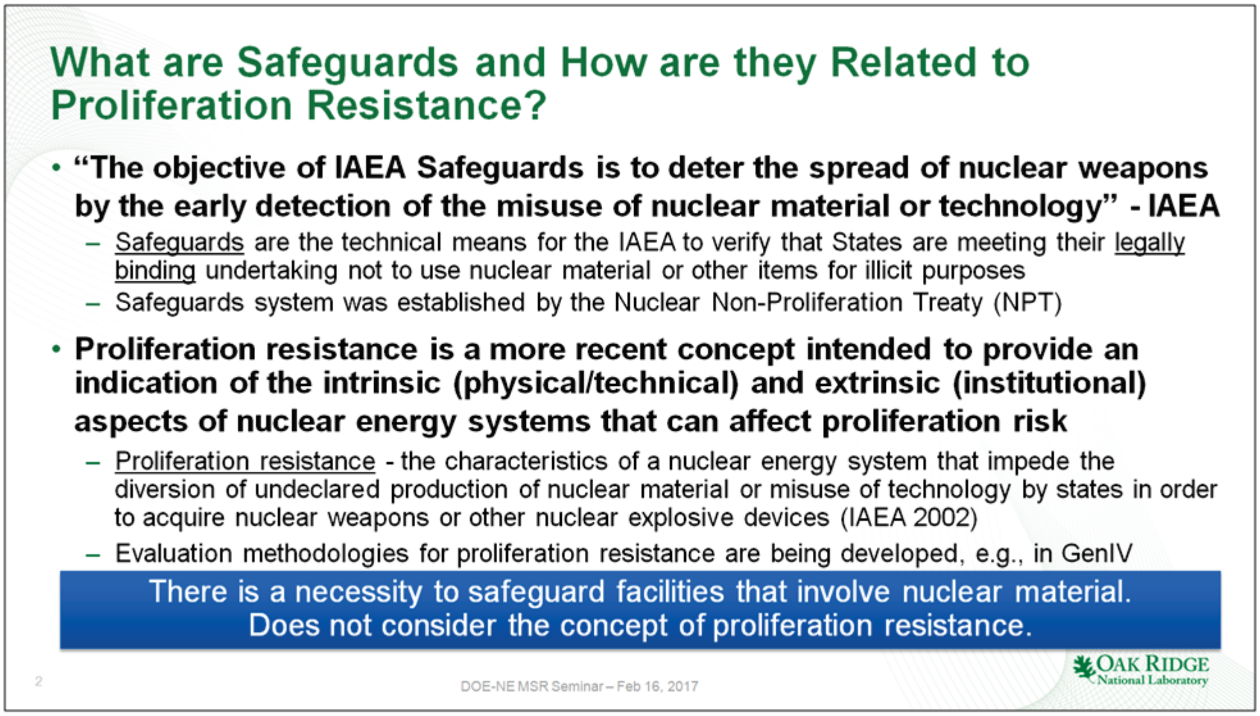
2.6 Module 5 – Safeguards Considerations and Challenges

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:

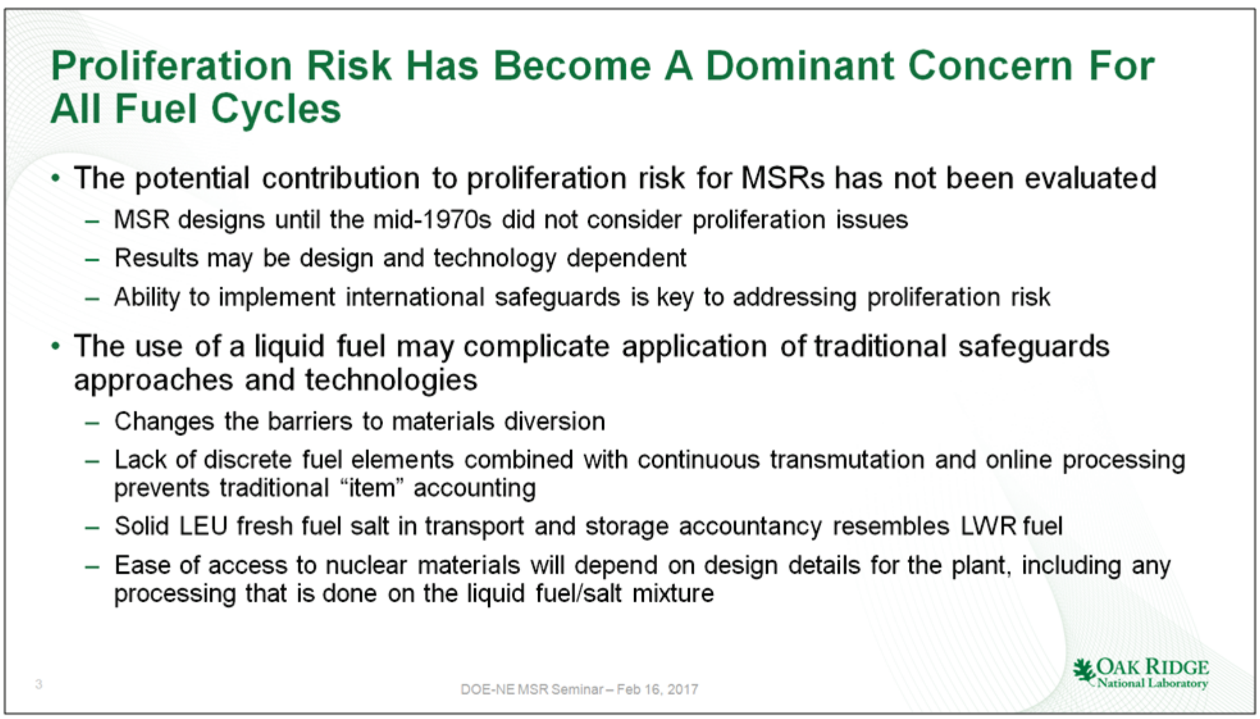
- Proliferation risk is the risk that a state would obtain nuclear weapons. As stated by the IAEA, "The objective of IAEA Safeguards is to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology."
- Proliferation risk has become a dominant concern for 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.



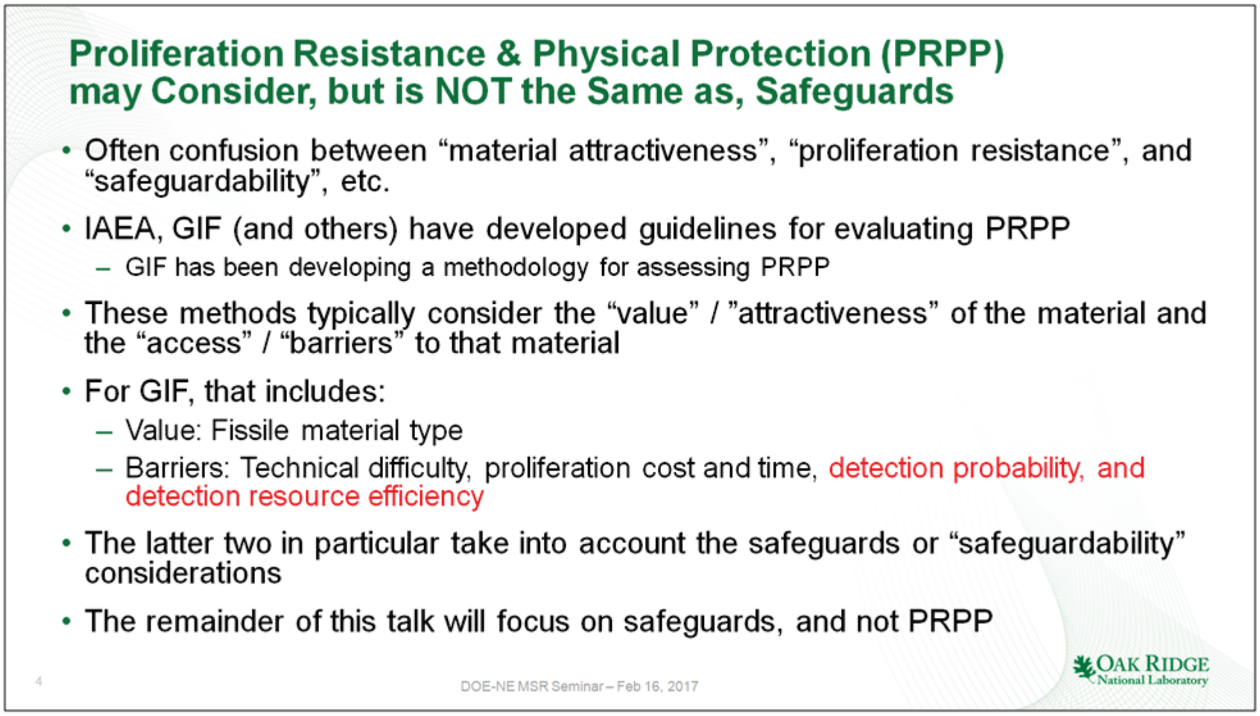
Module 5 – Slide 1. Title Slide.



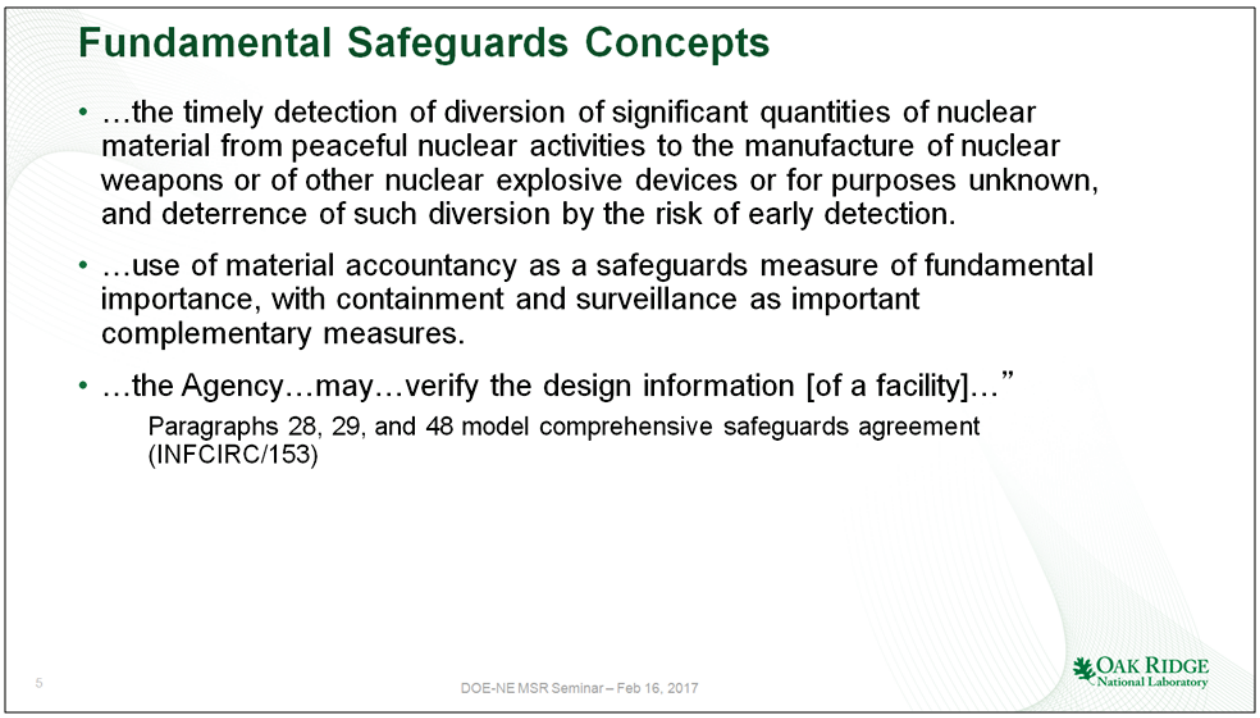
Module 5 – Slide 2. Safeguards and How are They Related to Proliferation Resistance?



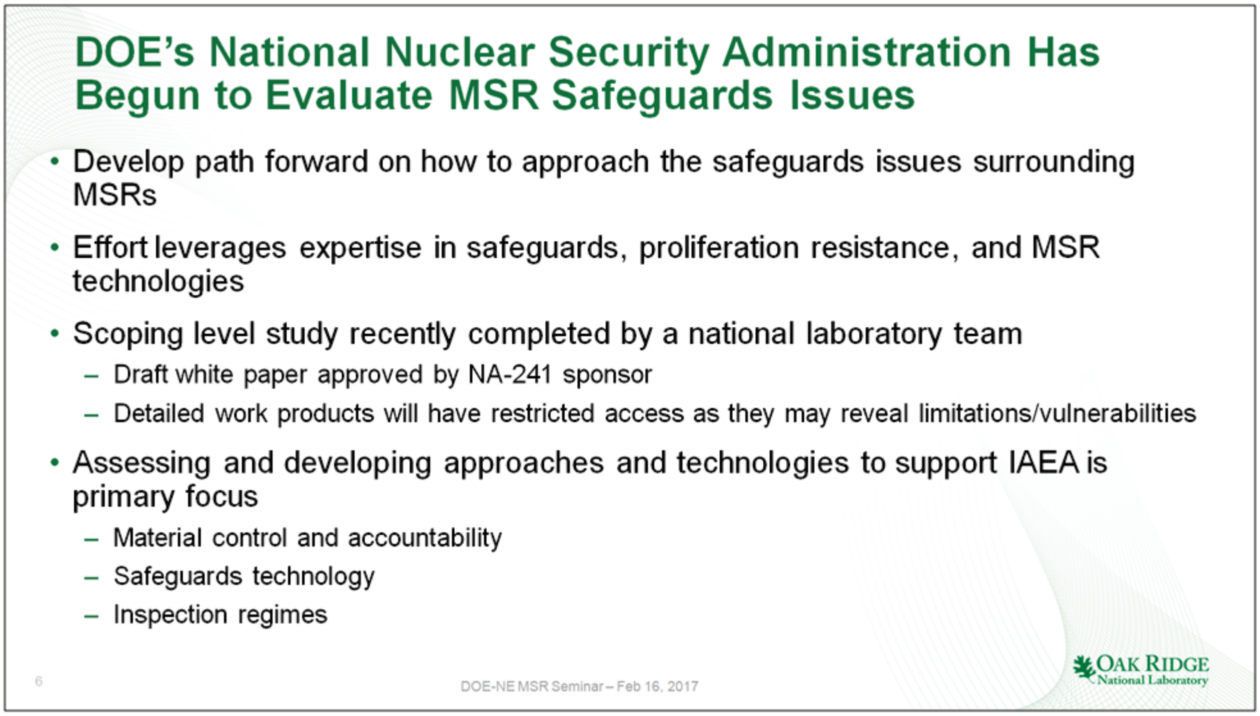
Module 5 – Slide 3. Proliferation Risk has become a Dominant Concern for All Fuel Cycles.



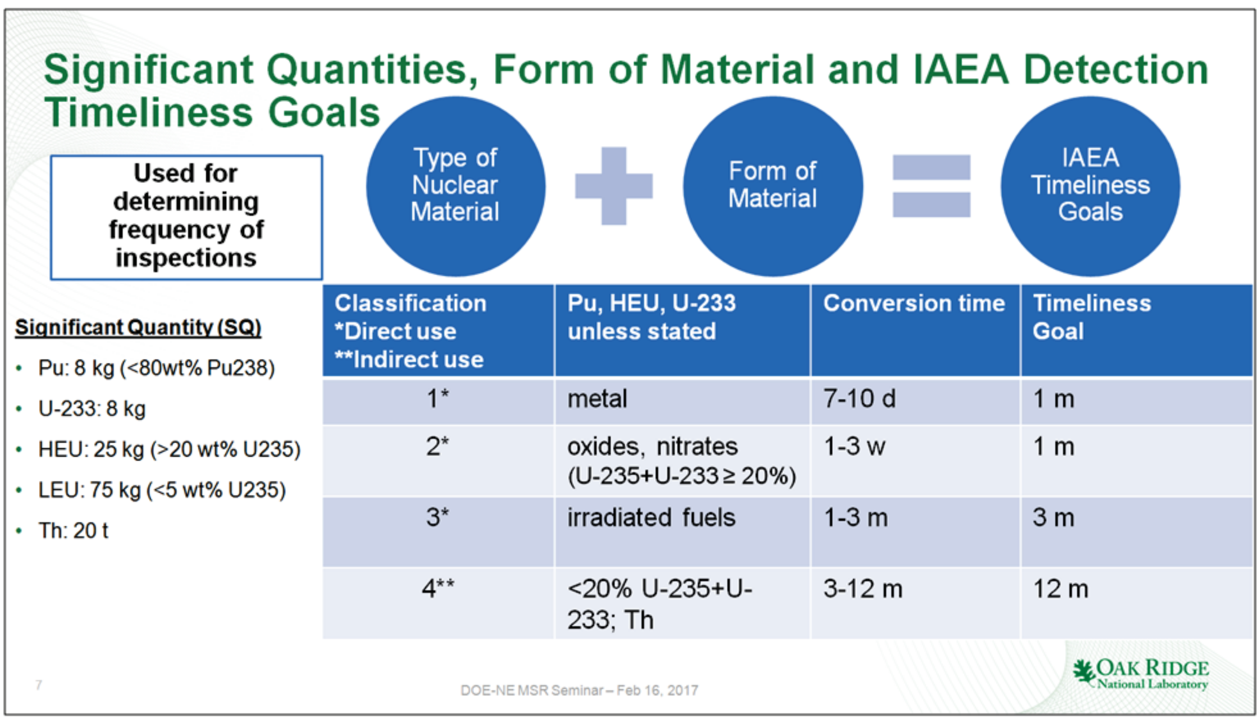
Module 5 – Slide 4. Proliferation Resistance & Physical Protection (PRPP).



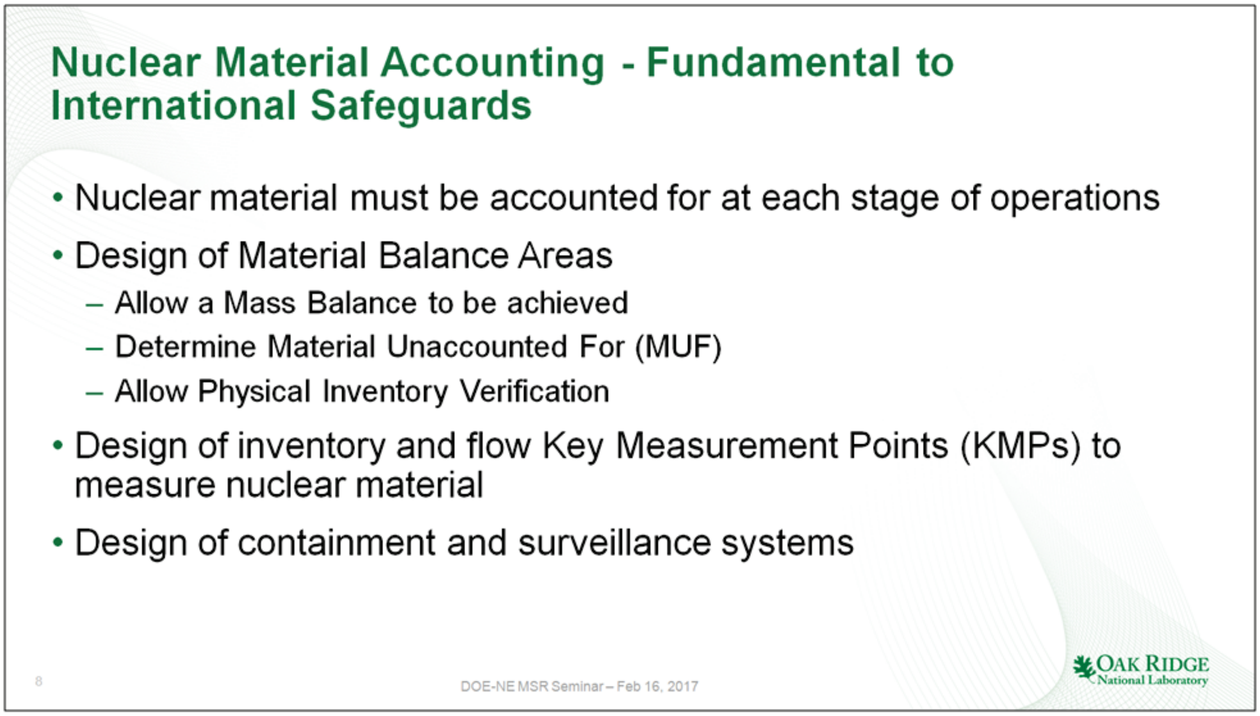
Module 5 – Slide 5. Fundamental Safeguards Concepts.



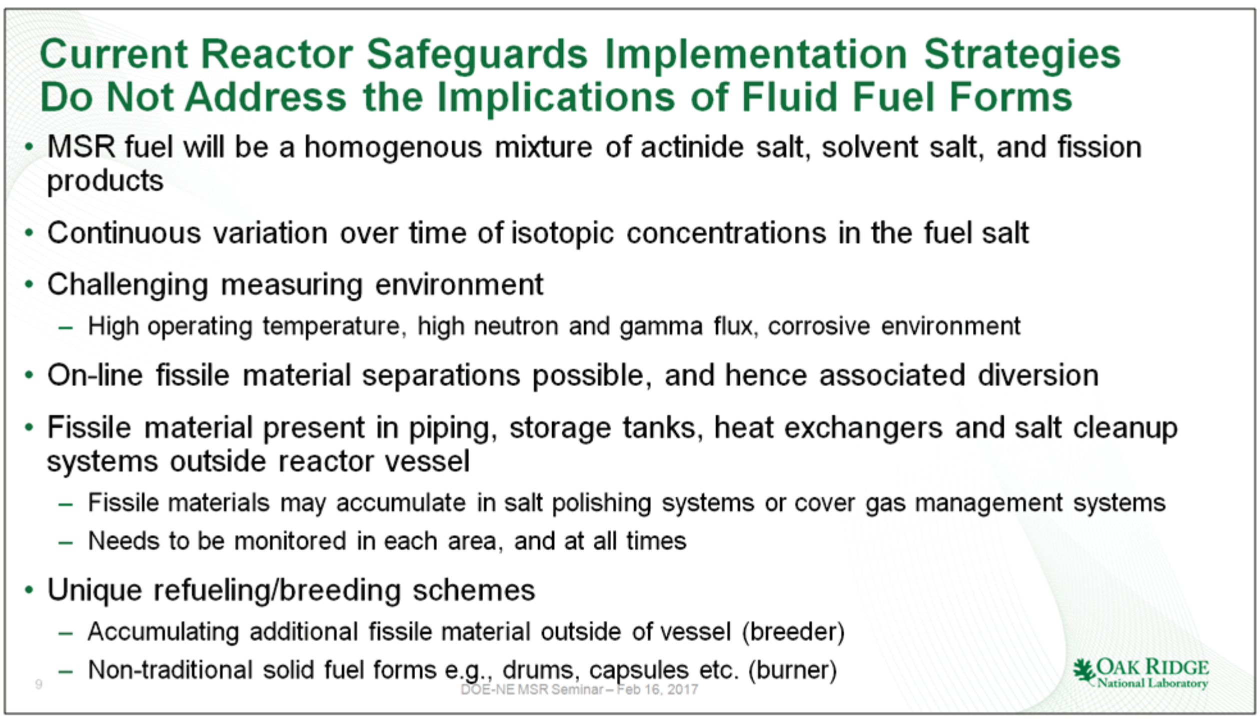
Module 5 – Slide 6. DOE's National Nuclear Security Administration has begun to Evaluate MSR Safeguards Issues.



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



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



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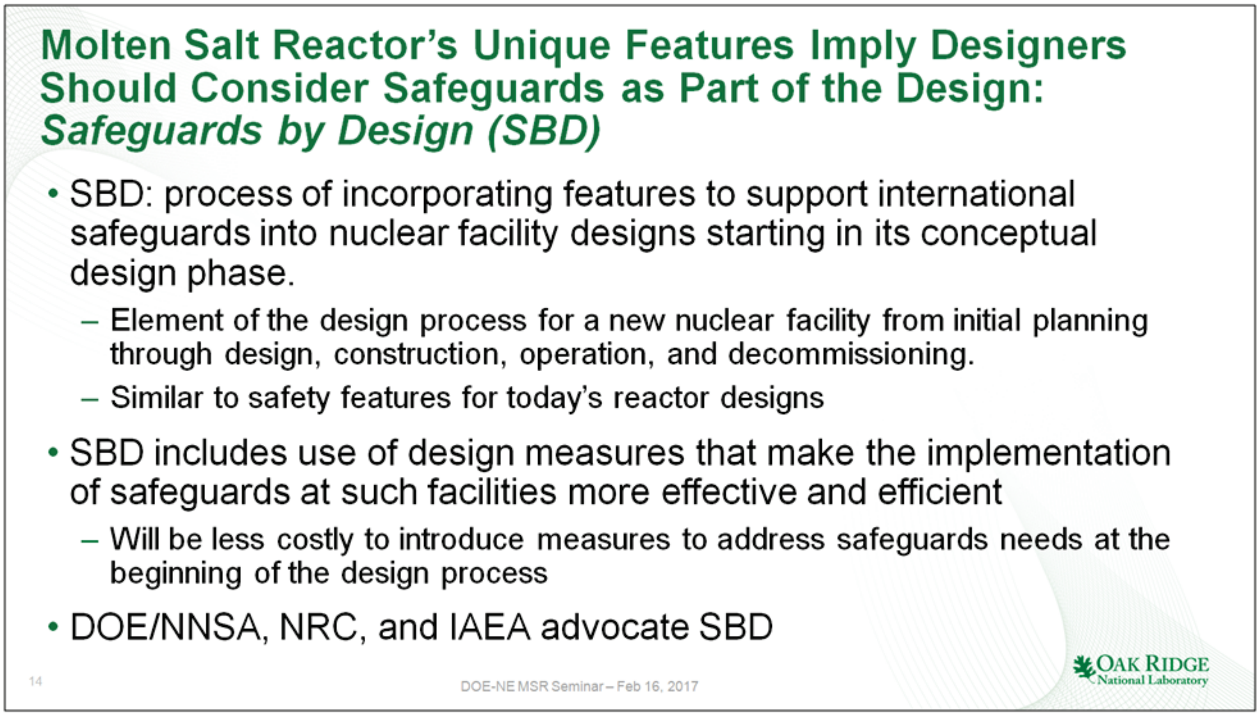
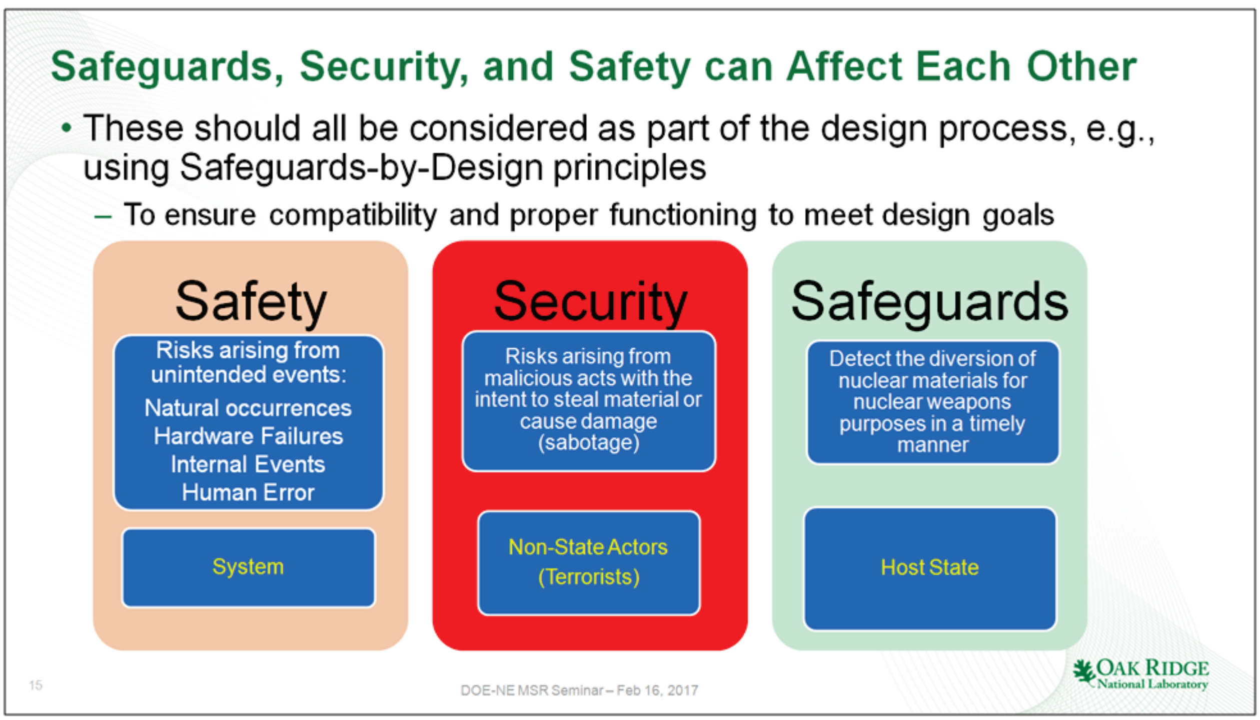
Module 5 – Slide 13. Several Technical Factors will shoe Departure from Conventional Safeguards for Liquid Fueled MSRs.

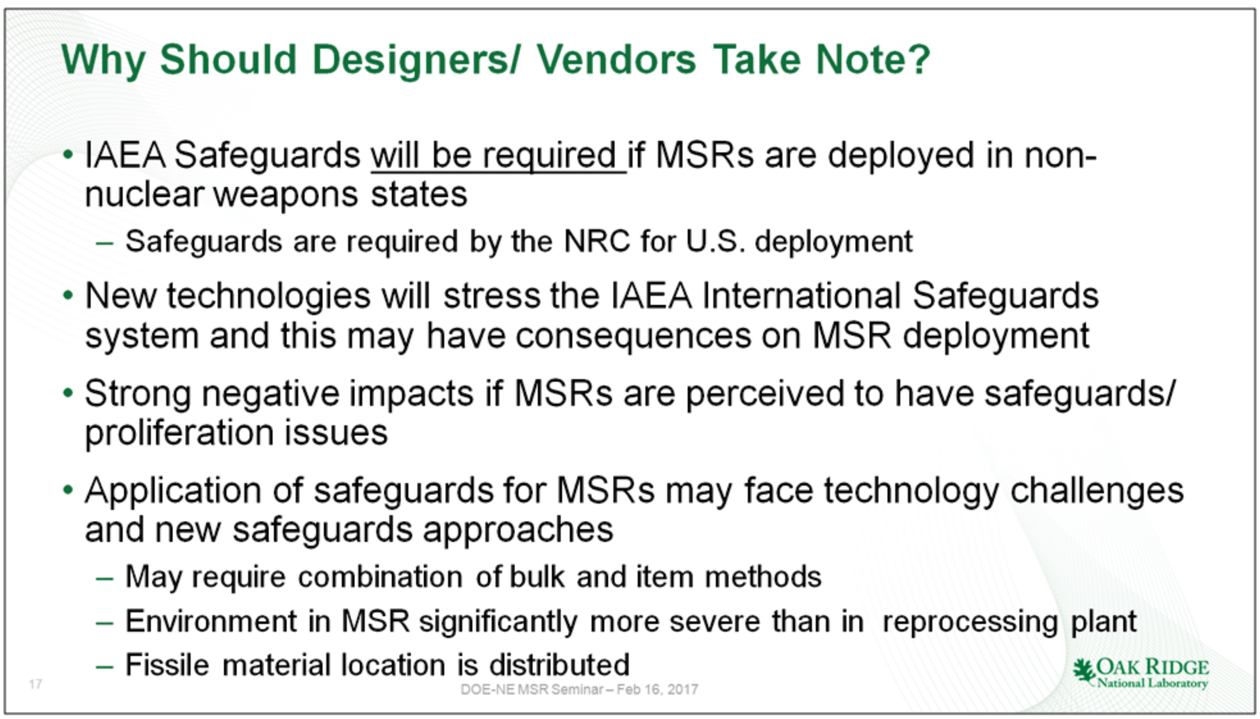


Module 5 – Slide 14. Molten Salt's Unique Features imply Designers should consider Safeguards as Part of the Design.

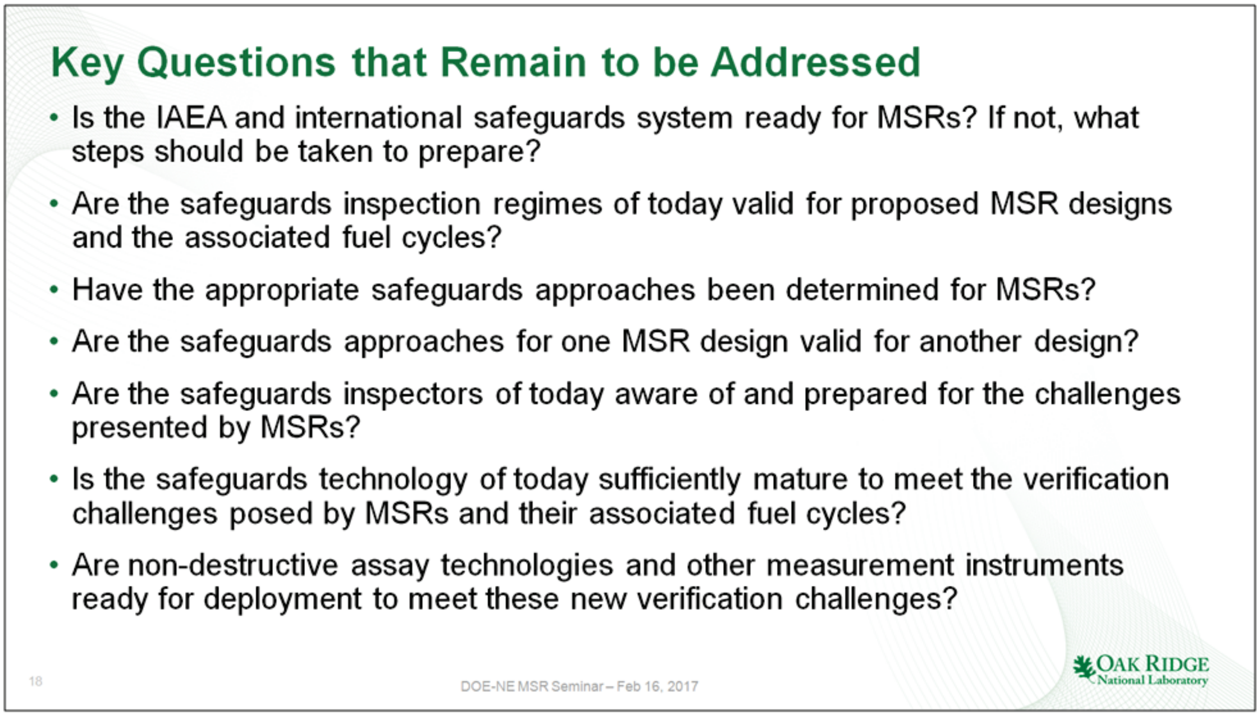


Module 5 – Slide 15. Safeguards, Security, and Safety can affect each other.

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



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

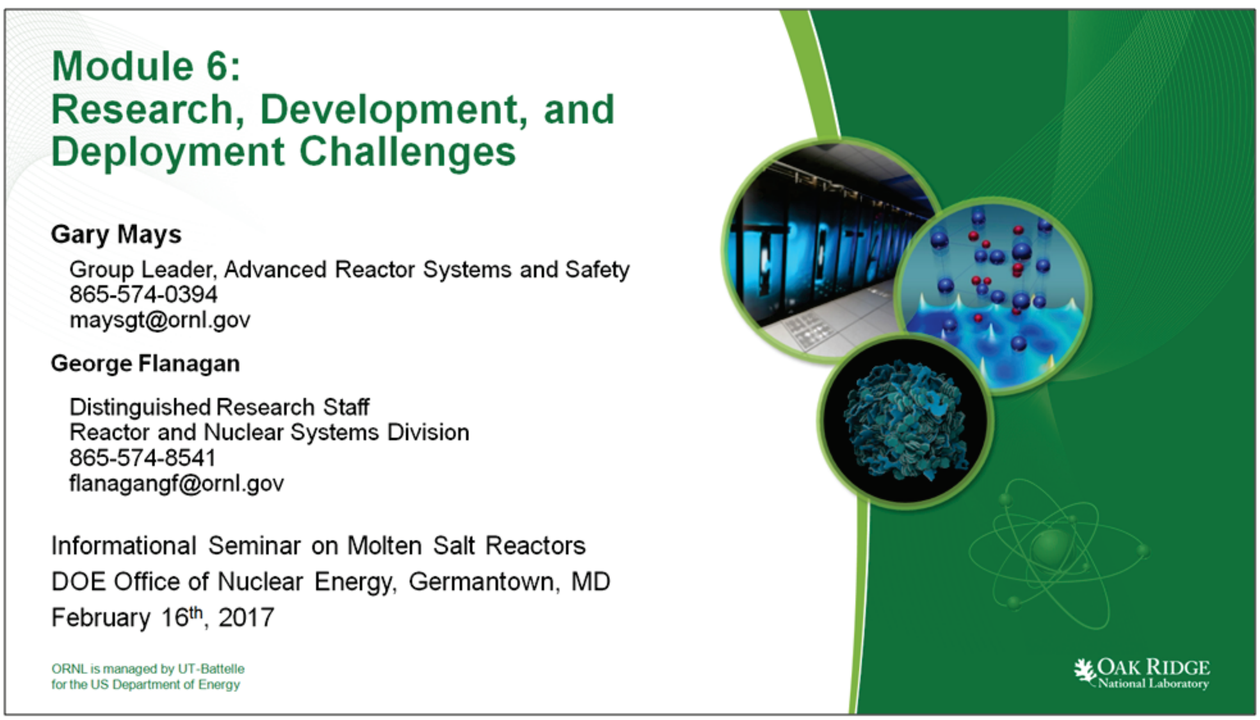


Module 5 – Slide 18. Key Questions that Remain to be Addressed.

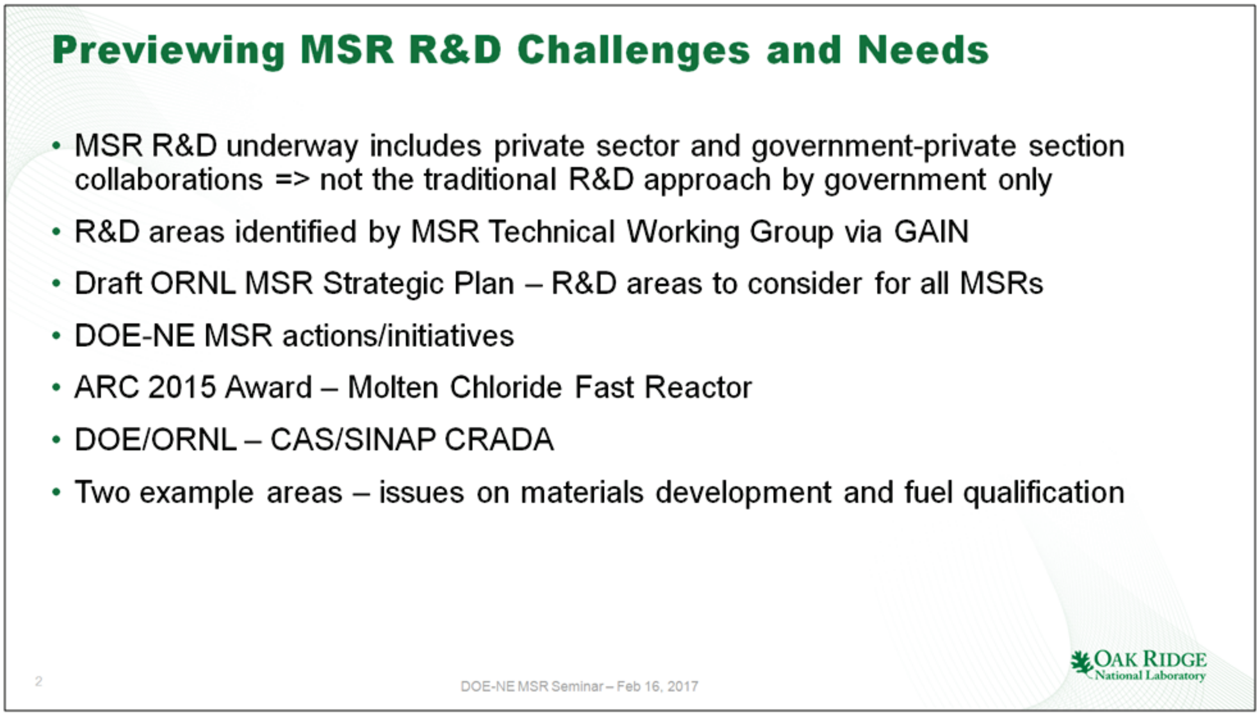
2.7 Module 6 – Research, Development, and Deployment Challenges

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:

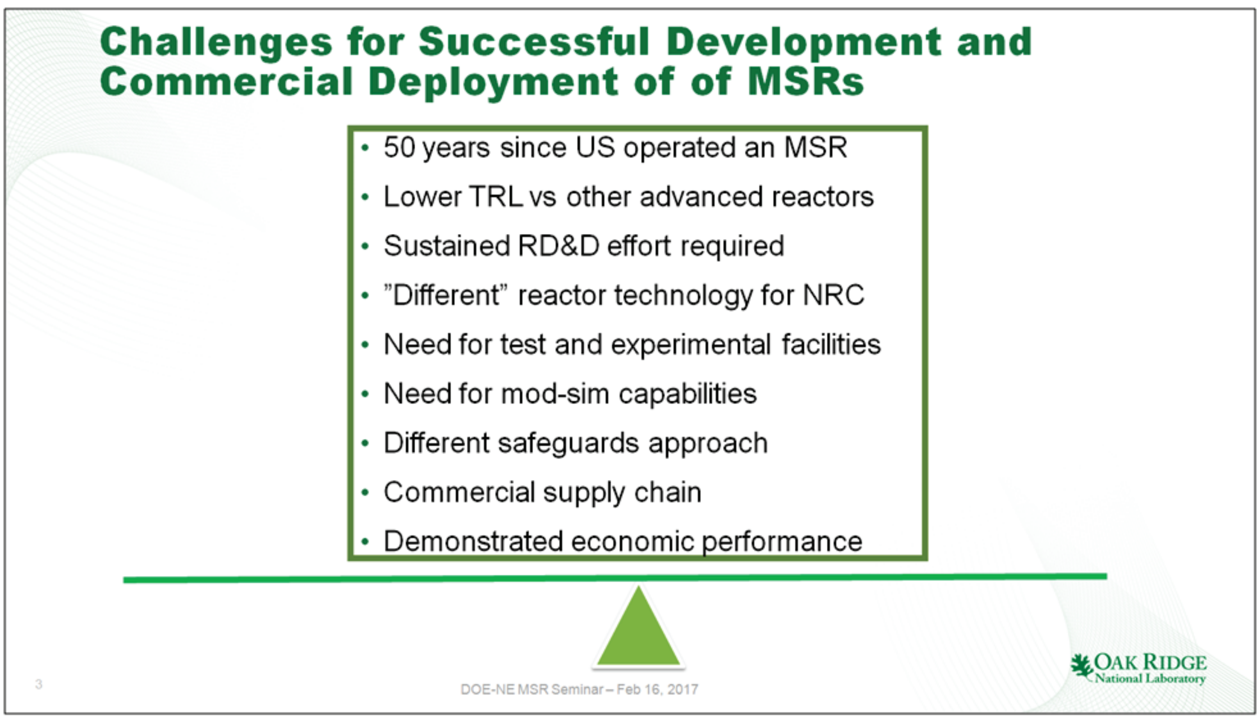
- MSR R&D needs have been identified by a task force representing developers in industry, as well as by DOE laboratory researchers.
- ORNL has prepared a draft MSR strategic plan and provided the plan to DOE/NE as input for MSR R&D moving forward.
- ORNL identified 7 strategic objectives to support MSR 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.



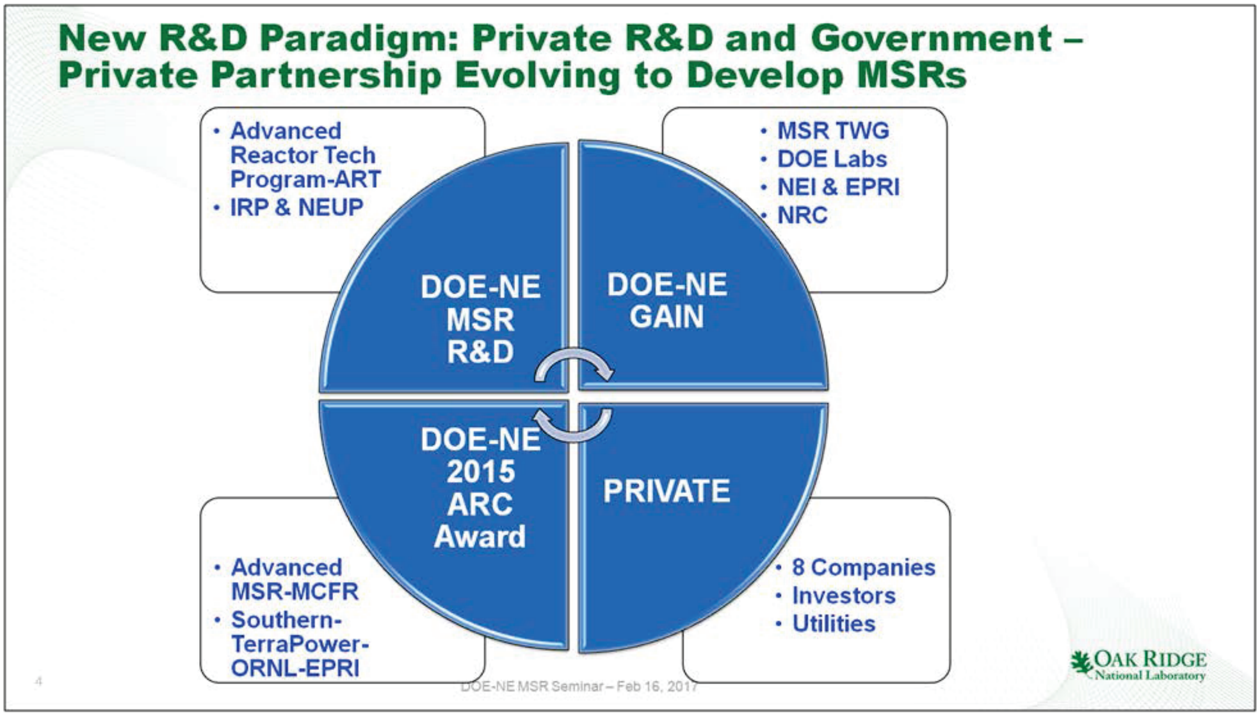
Module 6 – Slide 1. Title Slide.



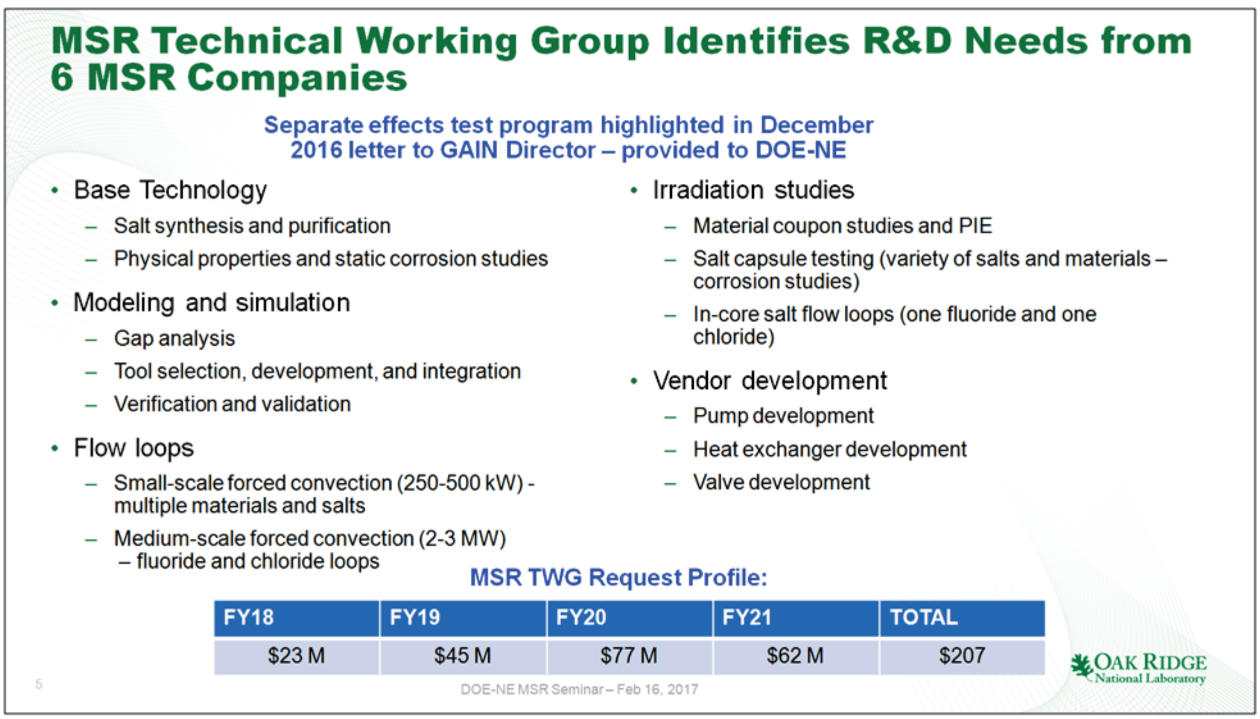
Module 6 – Slide 2. Previewing MSR R&D Challenges and Needs.



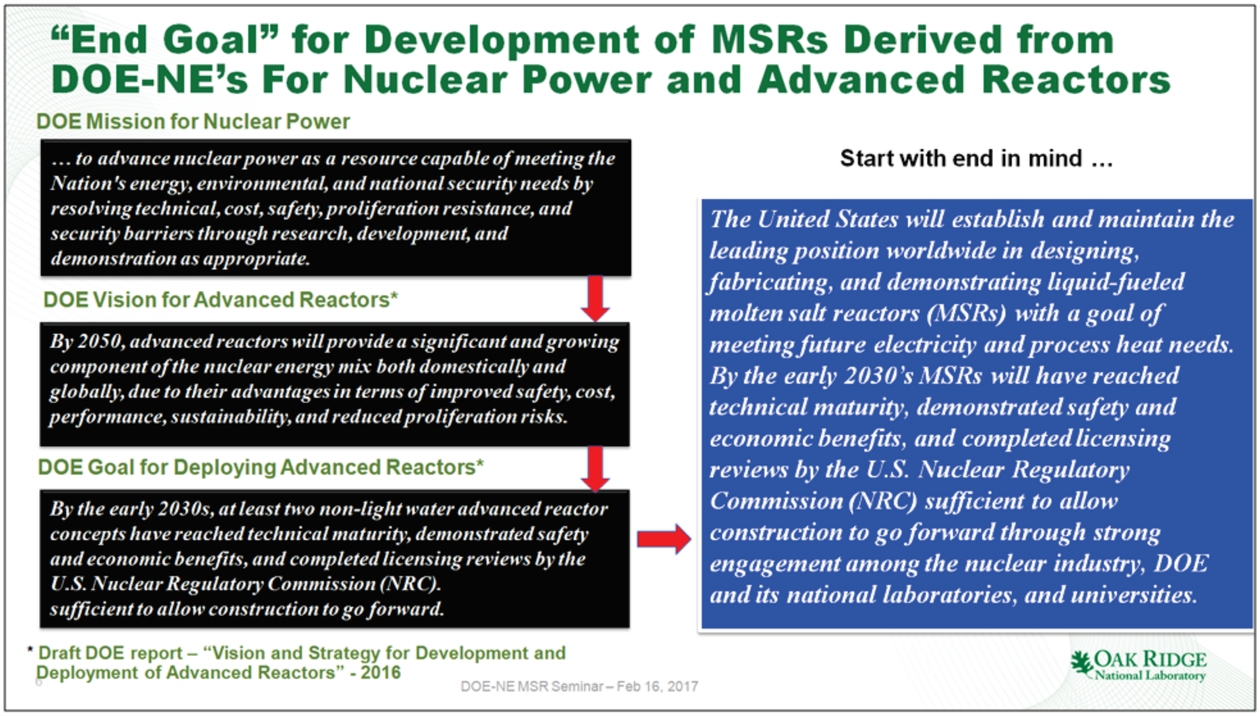
Module 6 – Slide 3. Challenges for Successful Development and Deployment of MSRs.



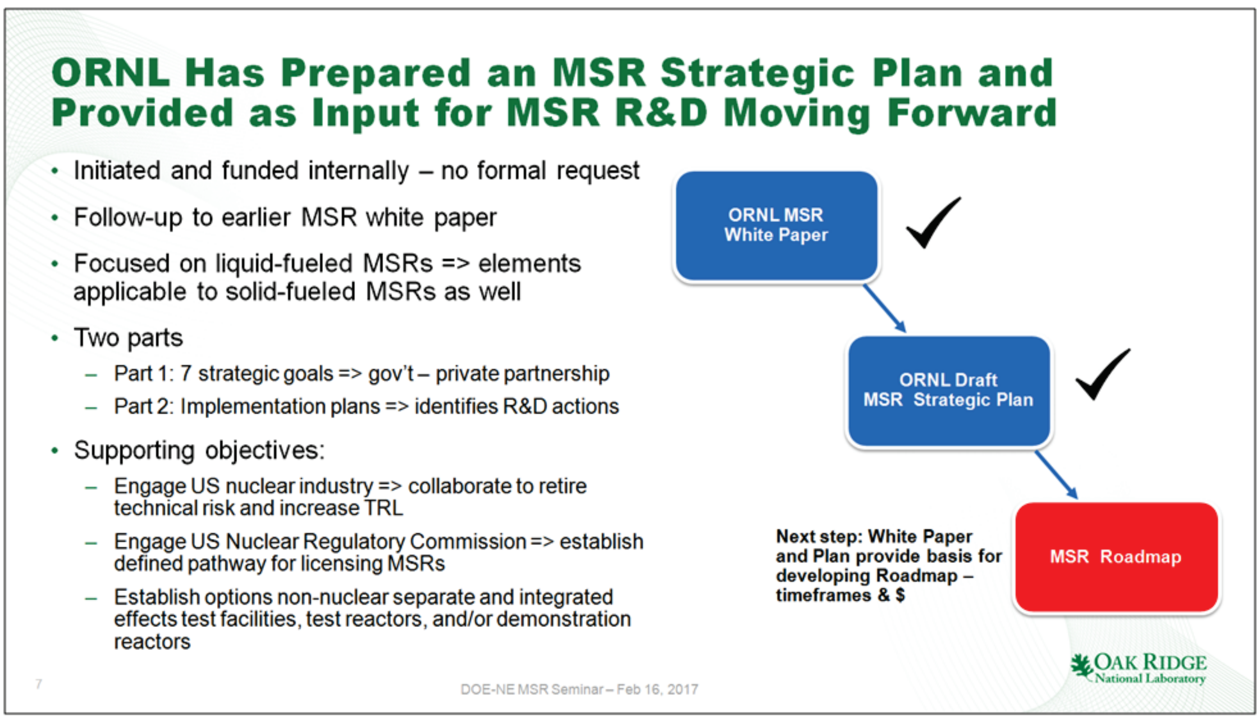
Module 6 – Slide 4. New R&D Paradigm.



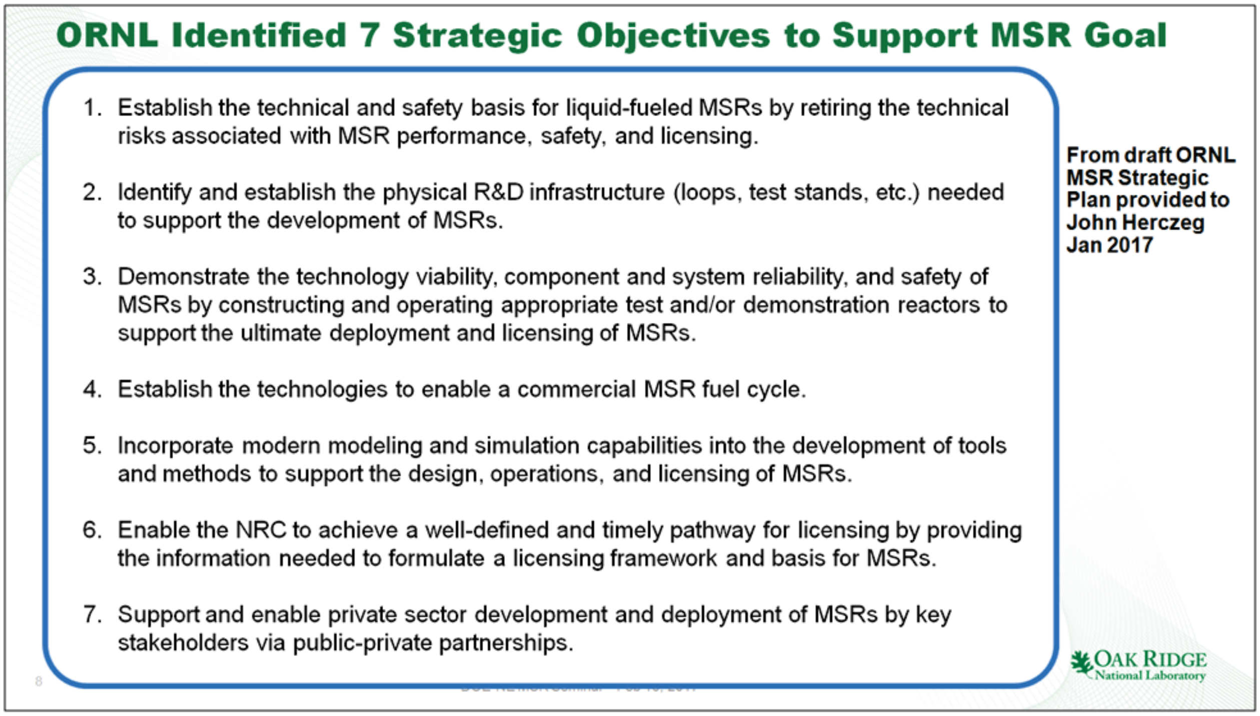
Module 6 – Slide 5. MSR Technical Working Group Identifies R&D Needs.



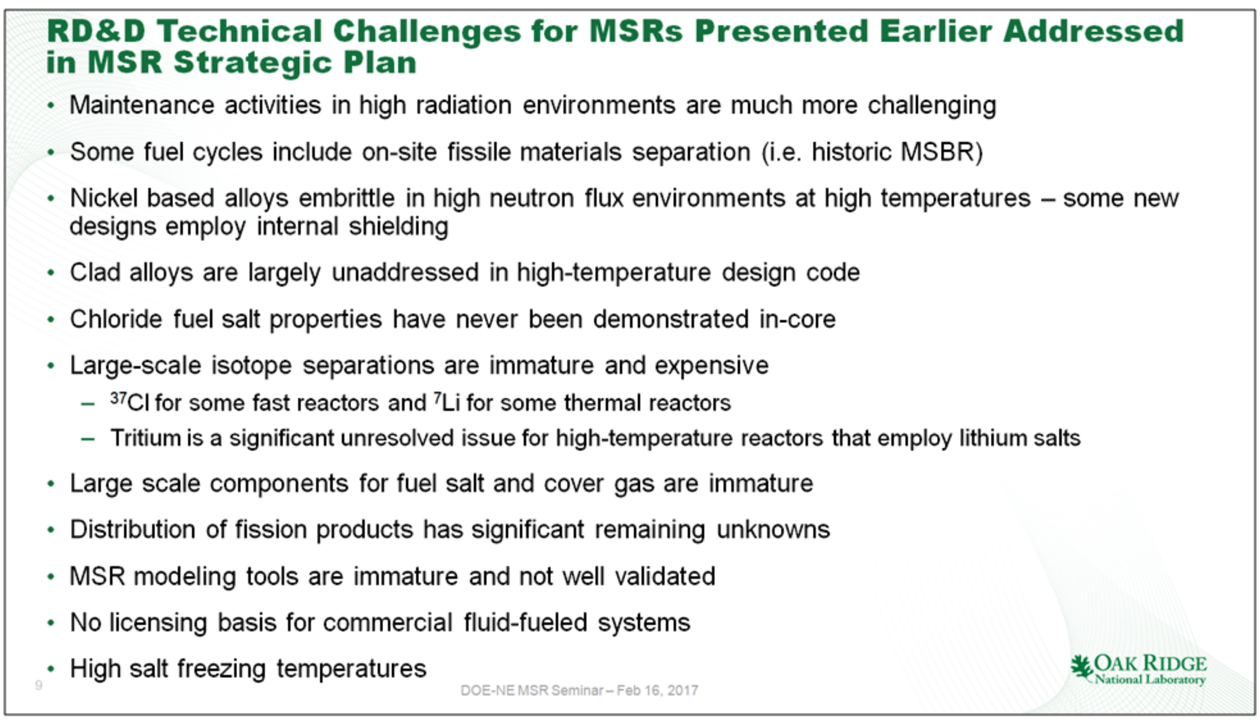
Module 6 – Slide 6. "End Goal" for Development of MSRs.



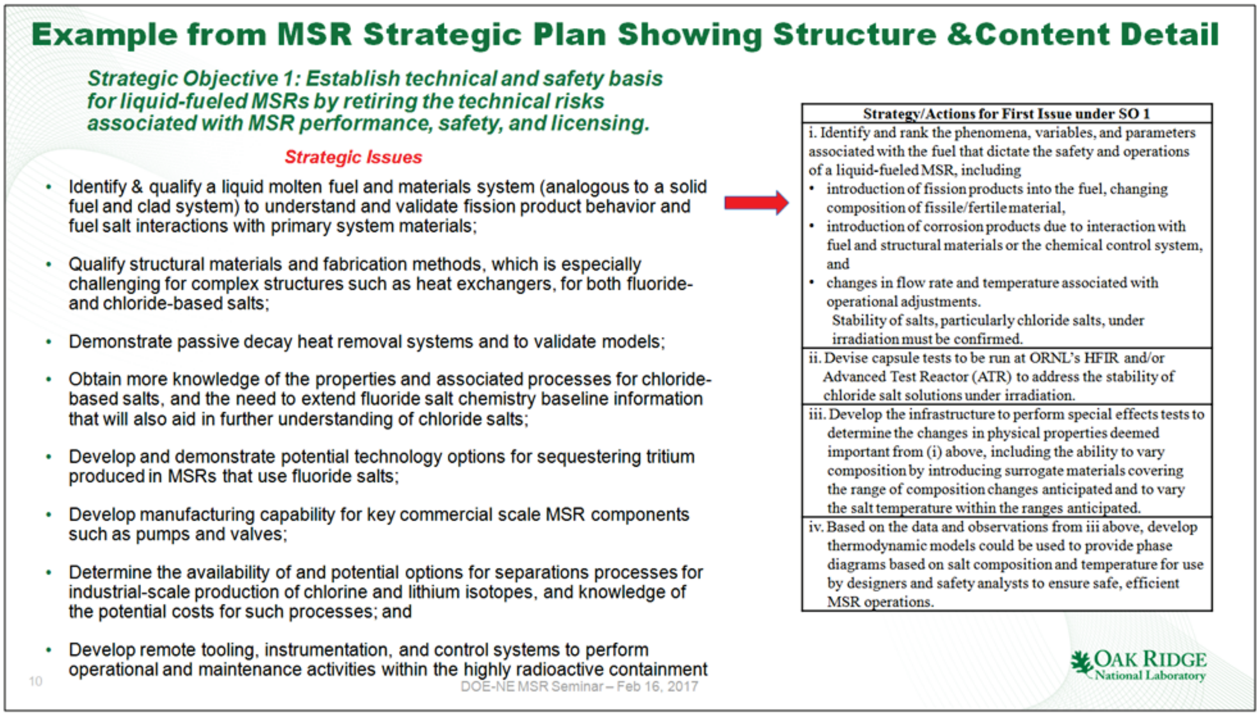
Module 6 – Slide 7. ORNL has prepared an MSR Strategic Plan.



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

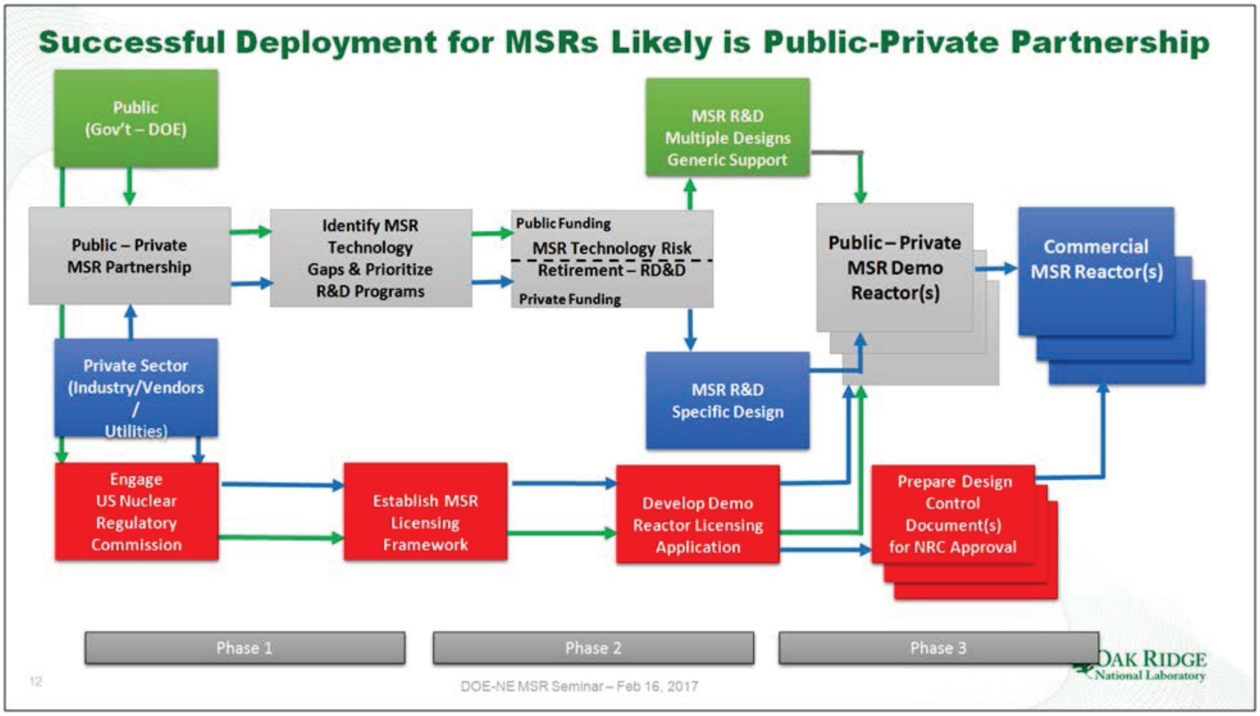


Module 6 – Slide 9. RD&D Challenges for MSRs Presented Earlier Addressed in MSR Strategic Plan.

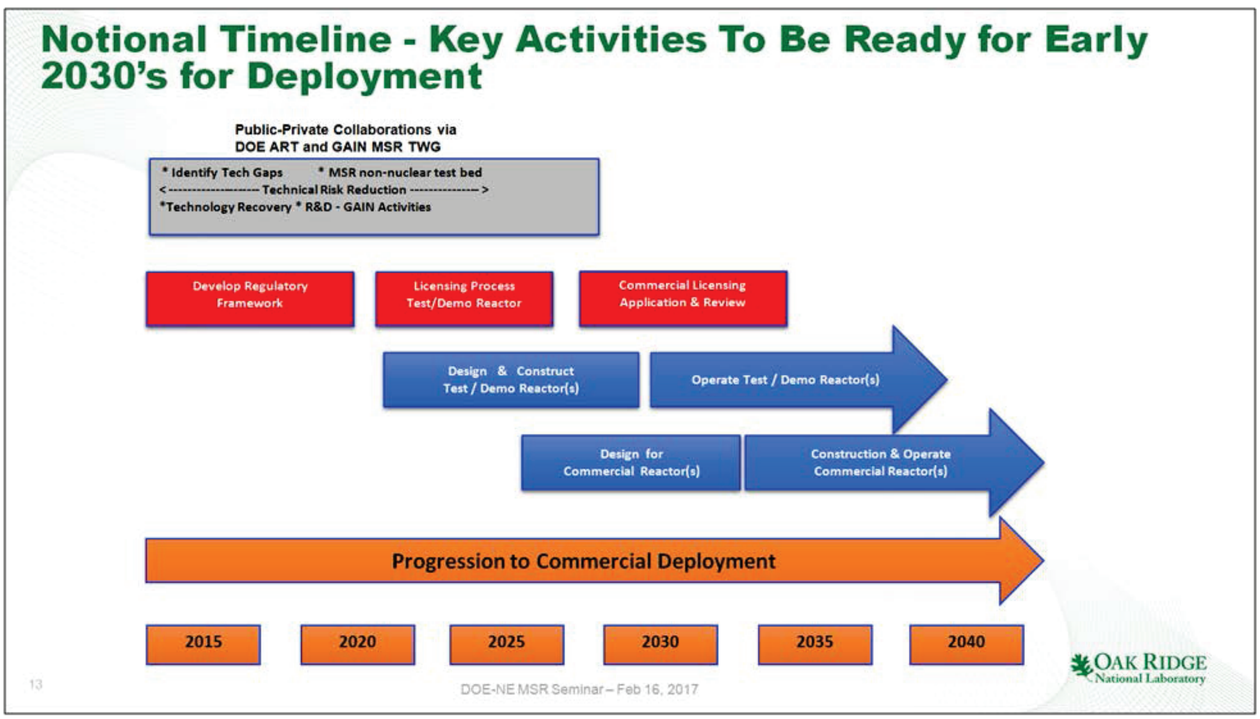


Module 6 – Slide 10. Example from MSR Strategic Plan Showing Structure and Content Detail.

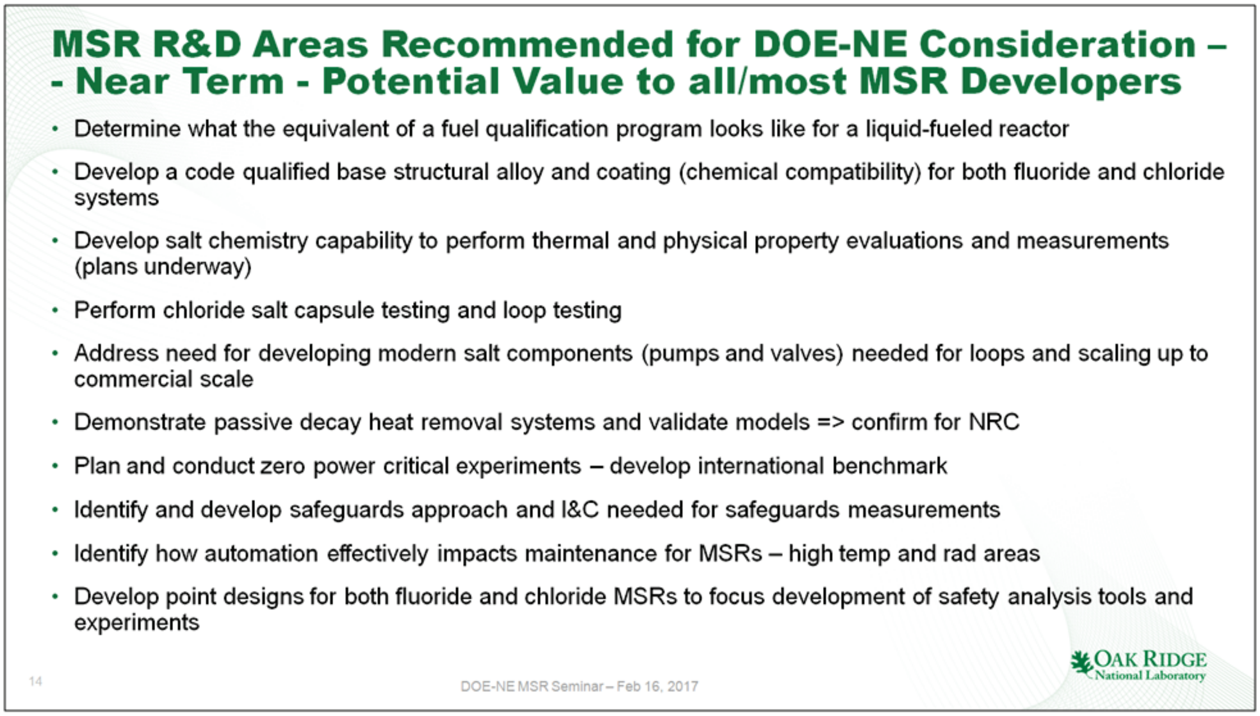
Module 6 – Slide 11. Supporting MSR Goals to Aid Commercial Deployment Complement Strategic Objectives.



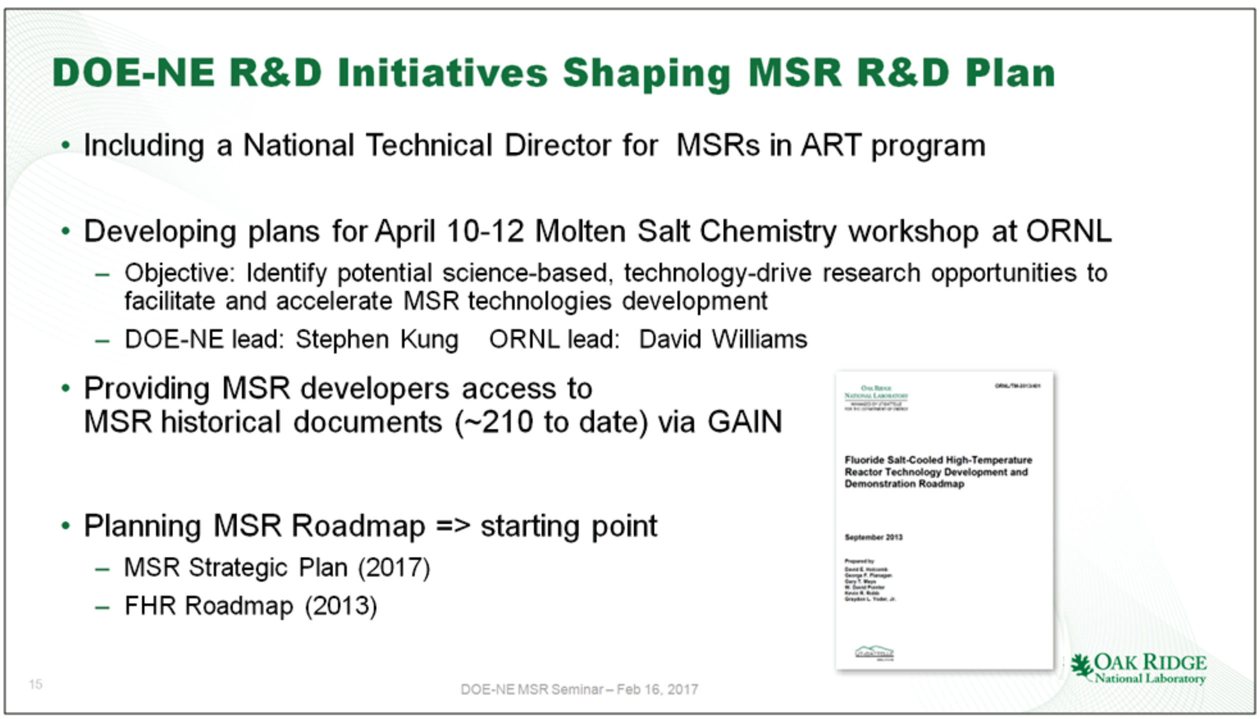
Module 6 – Slide 12. Successful Deployment for MSRs Likely is Public-Private Partnership.



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

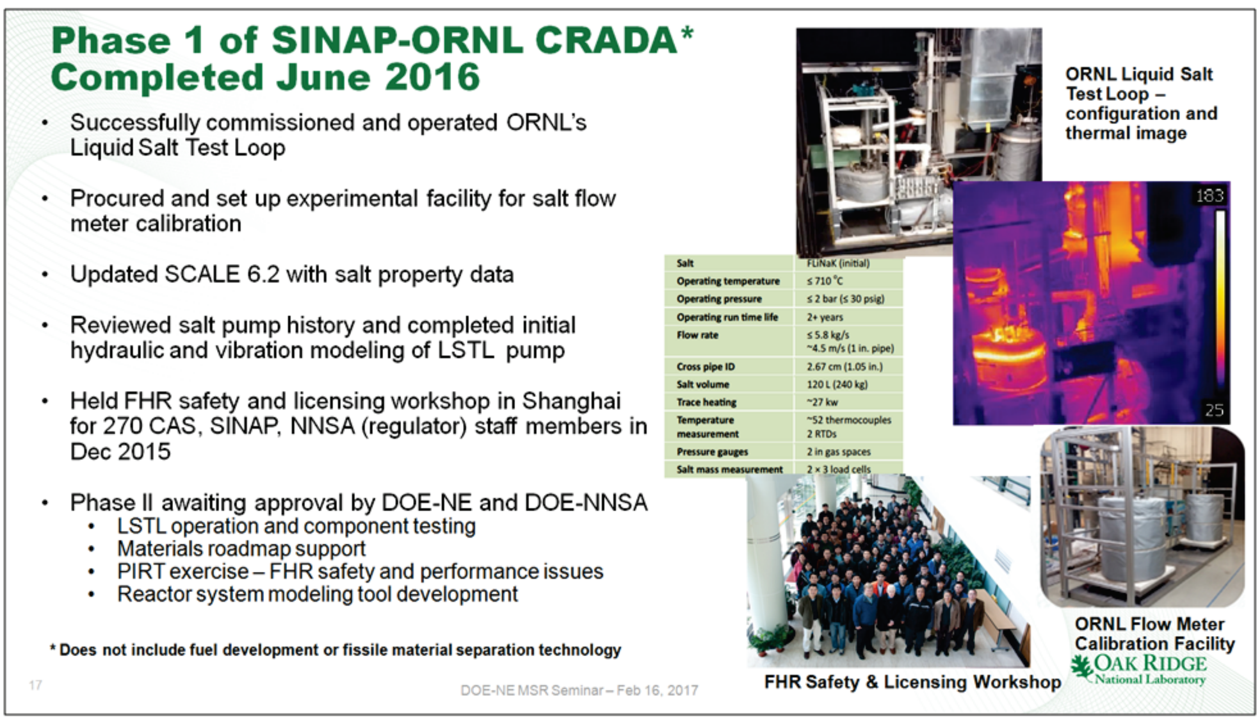


Module 6 – Slide 14. MSR R&D Areas Recommended for DOE-NE Consideration.

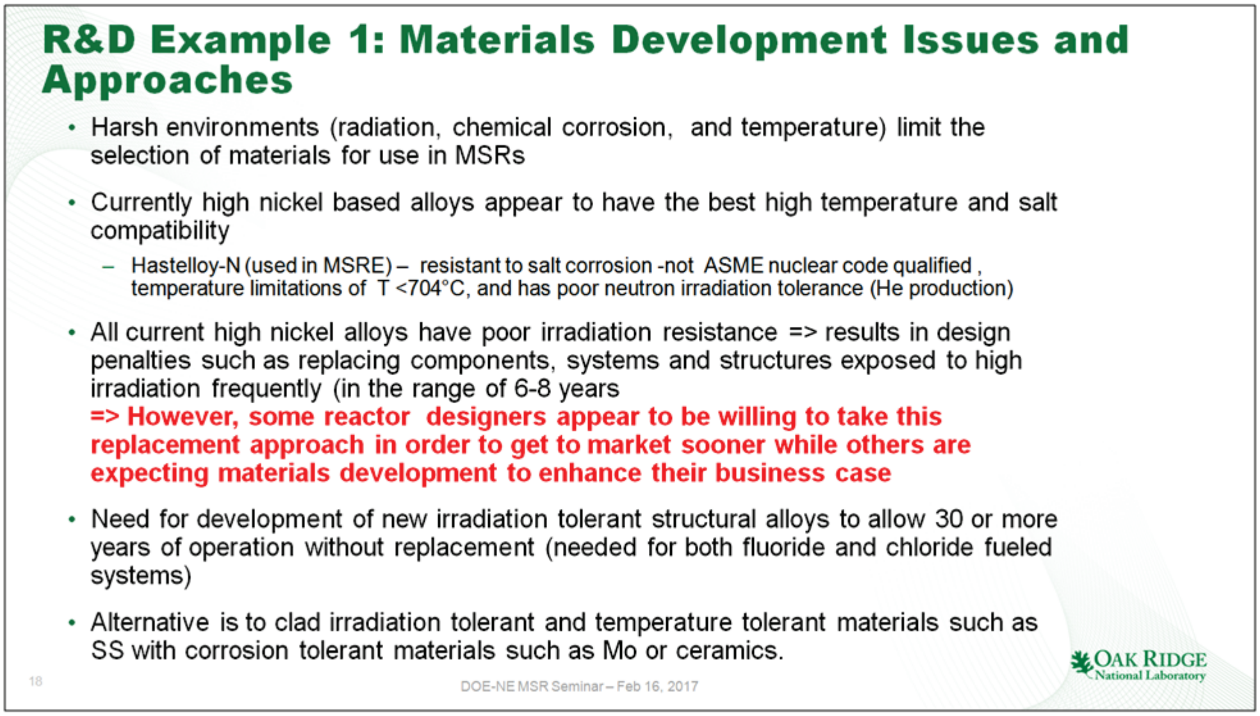


Module 6 – Slide 15. DOE-NE R&D Initiatives Shaping MSR R&D Plan.

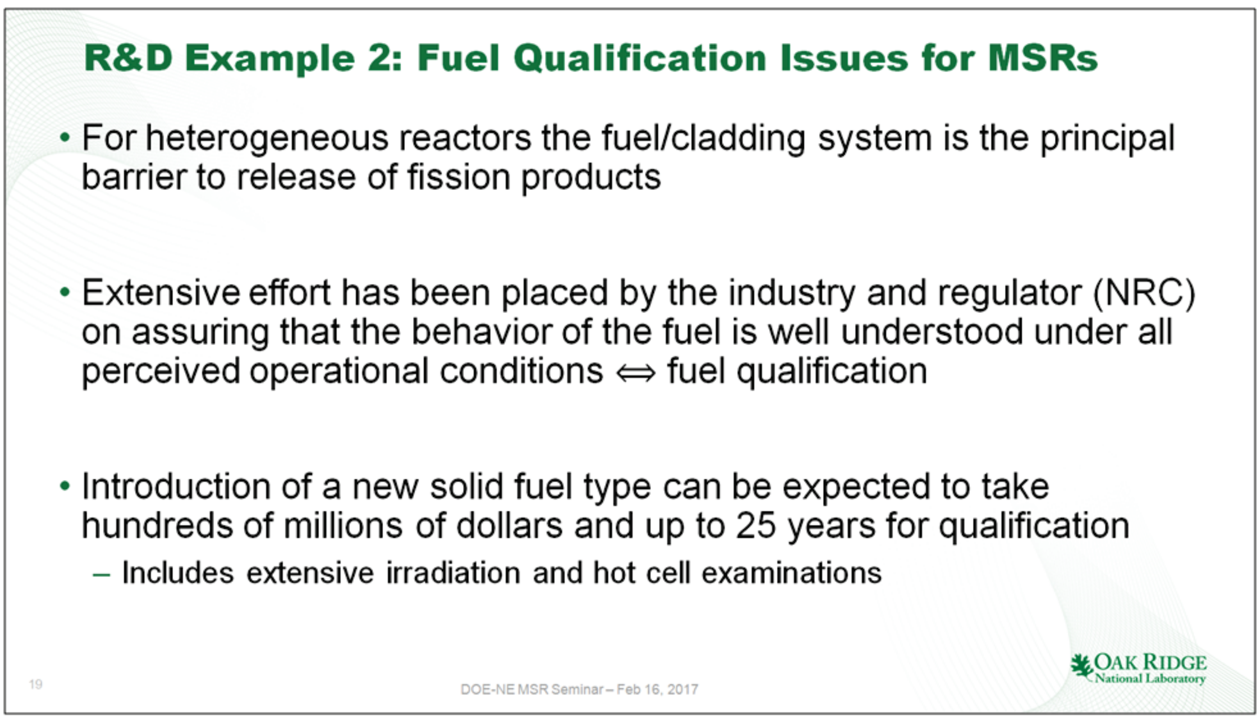
Module 6 – Slide 16. DOE ARC 2015 Awards – 2 New Investments in Advanced Reactors Announced in 2016 – One is an MCFR.



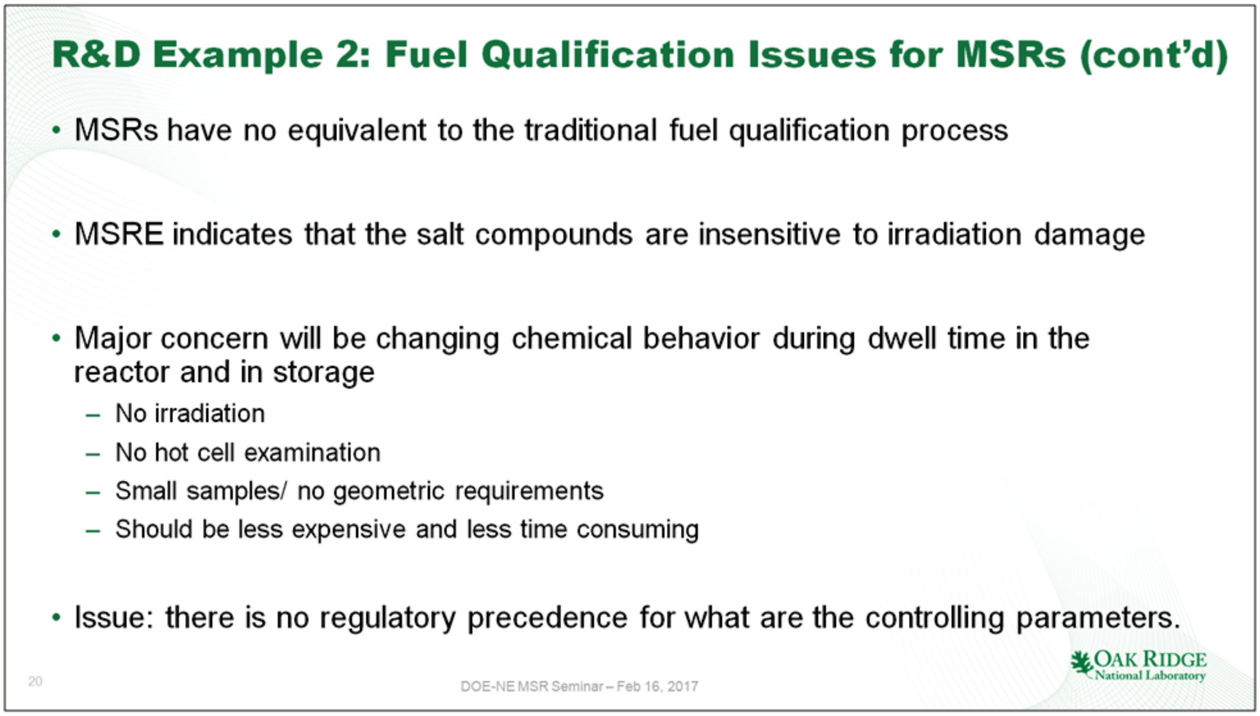
Module 6 – Slide 17. Phase 1 of SINAP-ORNL CRADA Completed June 2016.



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



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

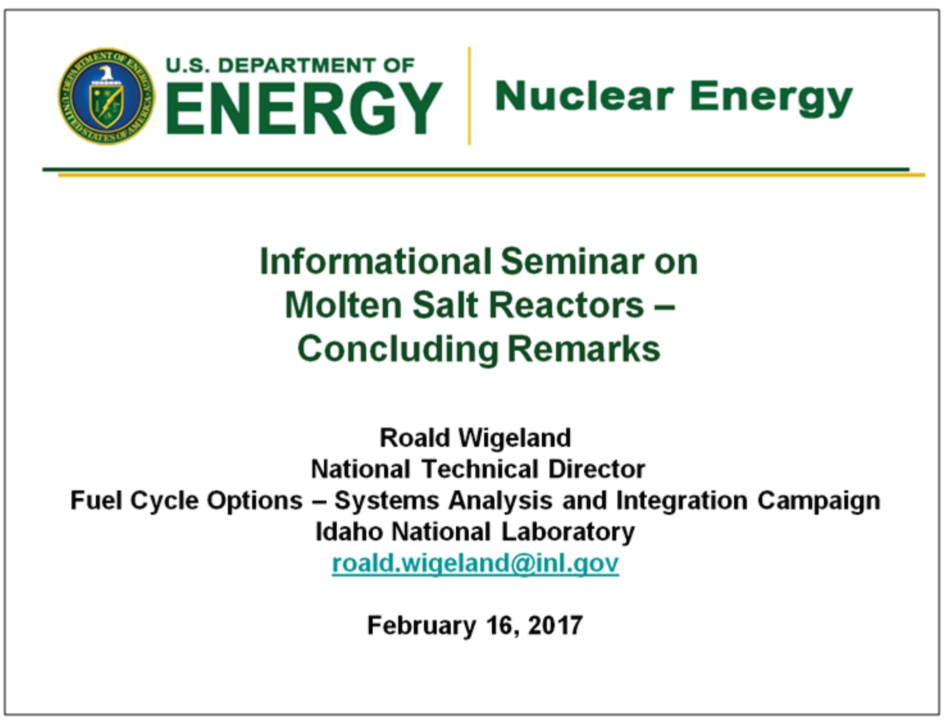


Module 6 – Slide 20. R&D Example 2: Fuel Qualification Issues for MSRs (cont'd).

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.



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.