OAK RIDGE
National Laboratory

Module 9: Fuel Cycle and Safeguards

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U.S. DEPARTMENT OF
ENERGY

Liquid Nature of MSR Fuel Enables Highly Diverse Fuel Cycles

- Fuel salt is a synthesized chemical not a fabricated structure substantially decreasing production cost and complexity
  - MSRs operate with fuel salt within a composition window based upon its resultant nuclear, thermophysical, and thermochemical properties
- MSRs are currently being pursued with almost every possible combination of fissile and fertile materials as equilibrium feedstock
  - Initial core load must include sufficient fissile materials to achieve criticality
- Safeguards and proliferation resistance concerns have increased over time
  - Historic MSR program gave little attention to safeguards or proliferation resistance
  - Modern design objectives include avoiding generating material more attractive than LEU and making fissile material diversion both difficult and readily apparent
- Fuel salt chemical processing technologies and reactor conceptual designs continue to advance
  - Several currently proposed reactor systems would not have been possible historically

Nuclear Material Properties Provide the Foundation for the Fuel Cycles

- Three major groupings of nuclear fuel materials
  - 1) Used fuel derived TRU, 2) U/Pu, and 3) Th/U
  - Mixed fuel compositions are common
- Neutron spectrum interacting with the fuel materials determines their response (i.e., nuclear fuel materials have energy dependent cross-sections)
  - Different fuel salts are optimal for different spectra
- Key nuclear material technical issues are
  1. Producing the needed number of neutrons in each generation to accomplish the fuel cycle objective
  2. Achieving the desired neutron energy spectrum at the location of the fuel material

MSR May Be a Breeder, Converter, or Burner of Nuclear Materials

- Breeder reactors produce more fissile materials than they consume
- Converter reactors balance nuclear fuel consumption and production
- Burner reactors consume more fissile material than they consume
- Same MSR core can be a breeder, converter, or burner depending on the fuel salt processing and composition
  - Liquid fuel facilitates composition adjustment (on-line or nearby)
    - Removing parasitic neutron absorbers, adding or removing nuclear materials

Most Common Burner Reactor Fuel Cycle is the Thermal Spectrum, U/Pu Once-Through

- Neutron efficiency improved by providing a soft neutron spectrum at the locations of the fuel
  - Maximizes fission to capture ratio
  - Heterogeneous cores with substantial moderation
- Fluorine has lower absorption and improved moderation than chlorine
- Cores larger than an equivalent power LWR due to the lower moderation density of graphite
- Th may be added as a supplement – generally parasitic unless neutron flux is very low
  - Low neutron flux extends graphite lifetime
- May achieve initial criticality with slightly enriched uranium (<5% enrichment), but will need higher enrichments (LEU or HA-LEU) as parasitic absorbers (fission products) build up
- Similar burn-up achievable in small MSRs as with large LWRs
  - Neutron losses are a combination of leakage and parasitic absorption

Appendix M to Part 110—Categorization of Nuclear Material Provides Current Material Attractiveness Rules

Material	Form	Category I	Category II	Category III[3]
Plutonium[1]	Unirradiated[2]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less by more than 15 g
Uranium-235	Unirradiated[2]			
	Uranium enriched to 20% ^{235}U or more	5 kg of more	Less than 5 kg but more than 1 kg	1 kg or less but more than 15 g
	Uranium enriched to 10% ^{235}U but less than 20% ^{235}U		10 kg or more	Less than 10 kg but more than 1 kg
	Uranium enriched above natural, but less than 10% ^{235}U			10 kg or more
Uranium-233	Unirradiated[2]	2 kg or more	Less than 2 kg but more than 500 g	500 g or less by more than 15 g
Irradiated Fuel			Depleted or natural uranium, thorium or low enriched fuel (less than 10 percent fissile content)[4, 5]	

[1] All plutonium except that with isotopic concentration exceeding 80 percent in plutonium-238.

[2] Material not irradiated in a reactor or material irradiated in a reactor but with a radiation level equal to or less than 1 Gy/h (100 rad/h) at 1 m unshielded.

[3] Quantities not falling in Category III and natural uranium, depleted uranium and thorium should be protected at least in accordance with prudent management practice.

[4] Although this level of protection is recommended, it would be open to States, upon evaluation of the specific circumstances, to assign a different category of physical protection.

[5] Other fuel which by virtue of its original fissile material content is classified as Category I or II before irradiation may be reduced one category level while the radiation level from the fuel exceeds 1 Gy/h (100 rad/h) at one meter unshielded.

Same as IAEA INFCIRC/225/Revision 5

US Currently Lacks Rules that Reflect the Impact of Isotopic Dilution on ^{233}U Nuclear Properties

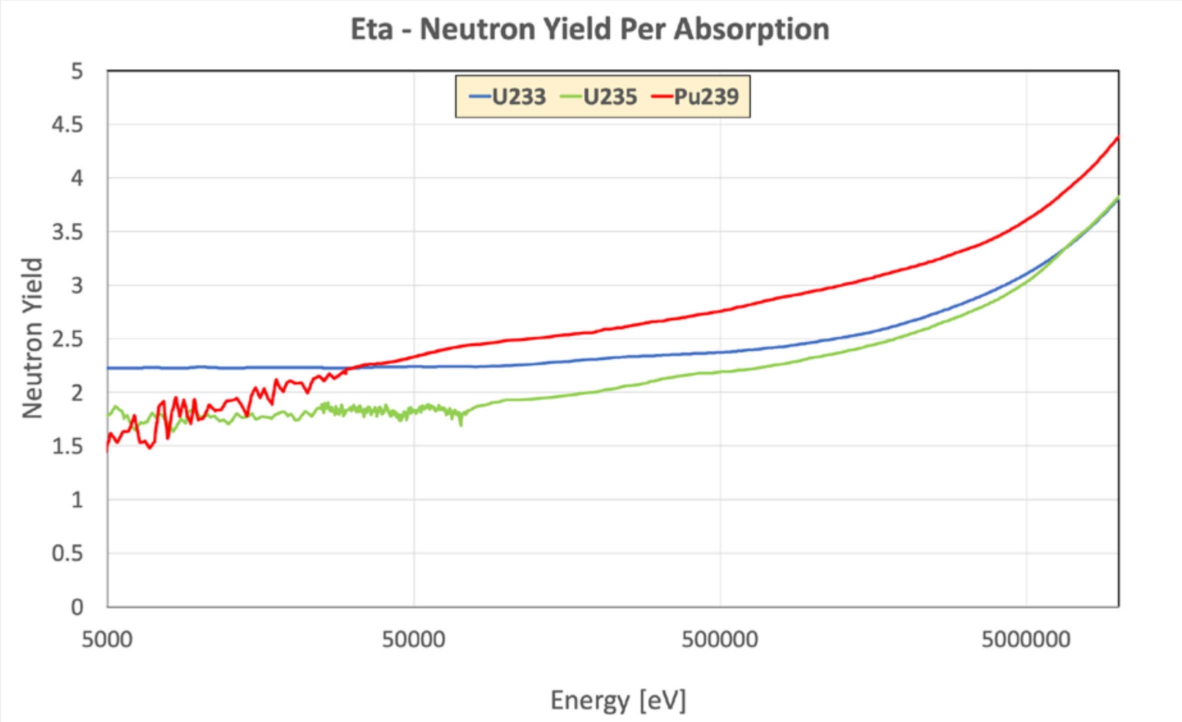
- LEU is defined solely in terms of ^{235}U weight percentage
  - 10 CFR 50.2 - *Low enriched uranium (LEU) fuel means fuel in which the weight percent of U-235 in the uranium is less than 20%*
  - Uranium-233 rules are currently more restrictive than those for Pu which can be denatured by dilution with 80% ^{238}Pu
  - Uranium-233 (at any isotopic fraction) must be irradiated to lower its category
- Current ^{233}U rules do not align with the Atomic Energy Act (Section 103) requirement that proposed activities serve a useful purpose proportionate the the quantities of special nuclear material or source material utilized

MSRs Can Be Configured as Either Thermal Spectrum Th/U or Fast Spectrum Breeder Reactors

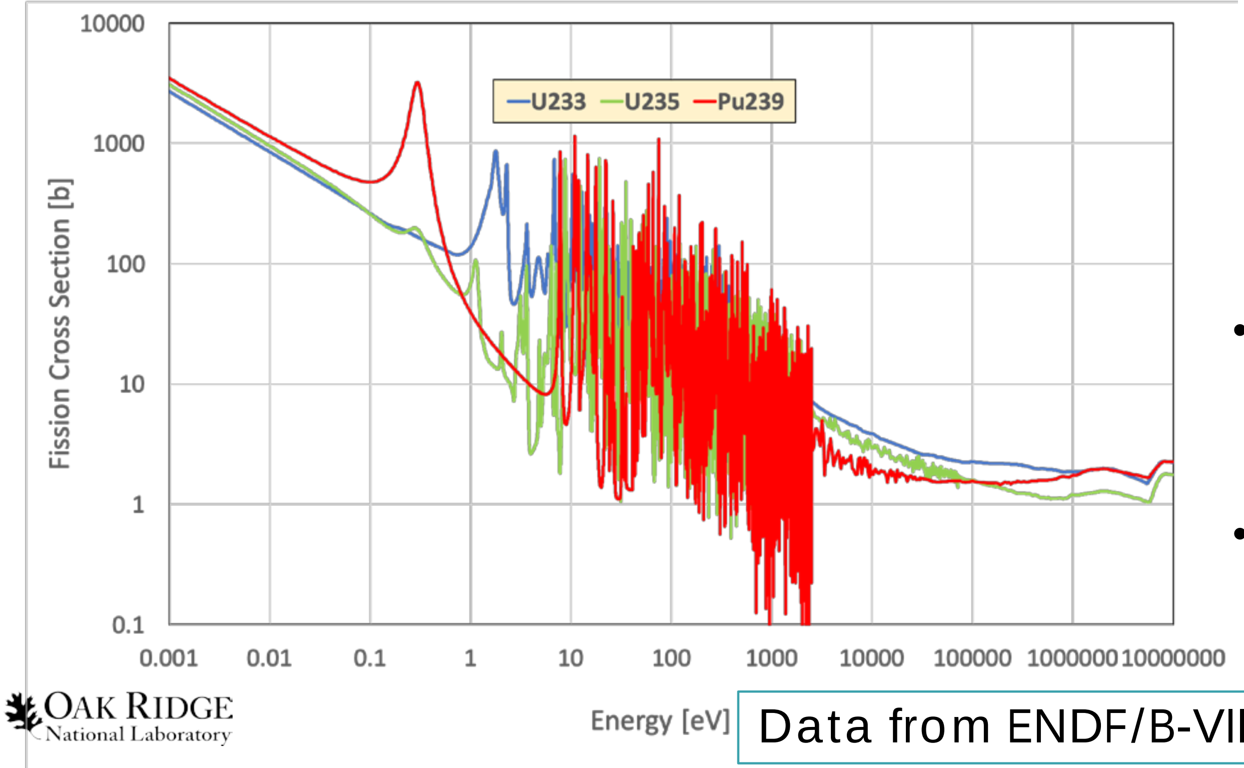
- Key proliferation resistance objective is to avoid creating materials that are more attractive than LEU
  - Thorium breeding blankets are likely to be problematic as without denaturing (including sufficient quantities of non-fissile uranium) the bred fuel would be unacceptably attractive
    - Likely to provide much less radiation dose than needed for self protection
  - Uranium breeding blankets raise similar issues in that bred Pu outside of used fuel salt would be unacceptably attractive
    - Key issue is to lower the material attractiveness category via dilution and sufficient dose rate for the material to be considered irradiated fuel
      - < 10% fissile content and > 1 Gy/h at 1 m (unshielded)
- Maximizing breeding requires maximizing neutron production which requires tailoring neutron spectrum and selecting fissionable isotope
  - Fast spectrum breeding is maximized by hardening neutron flux and maximizing ^{239}Pu content
  - Thermal spectrum breeding is maximized by avoiding resonance absorption (via core heterogeneity) and using ^{233}U

Hardening Neutron Spectrum is Key Consideration to Maximize Breeding in Fast Spectrum Reactors

- ^{239}Pu has highest neutron yield in fast neutron spectrum
- ^{233}U neutron yield per absorption is also high enough to breed
  - Thorium frequently has higher solubility in fuel salts



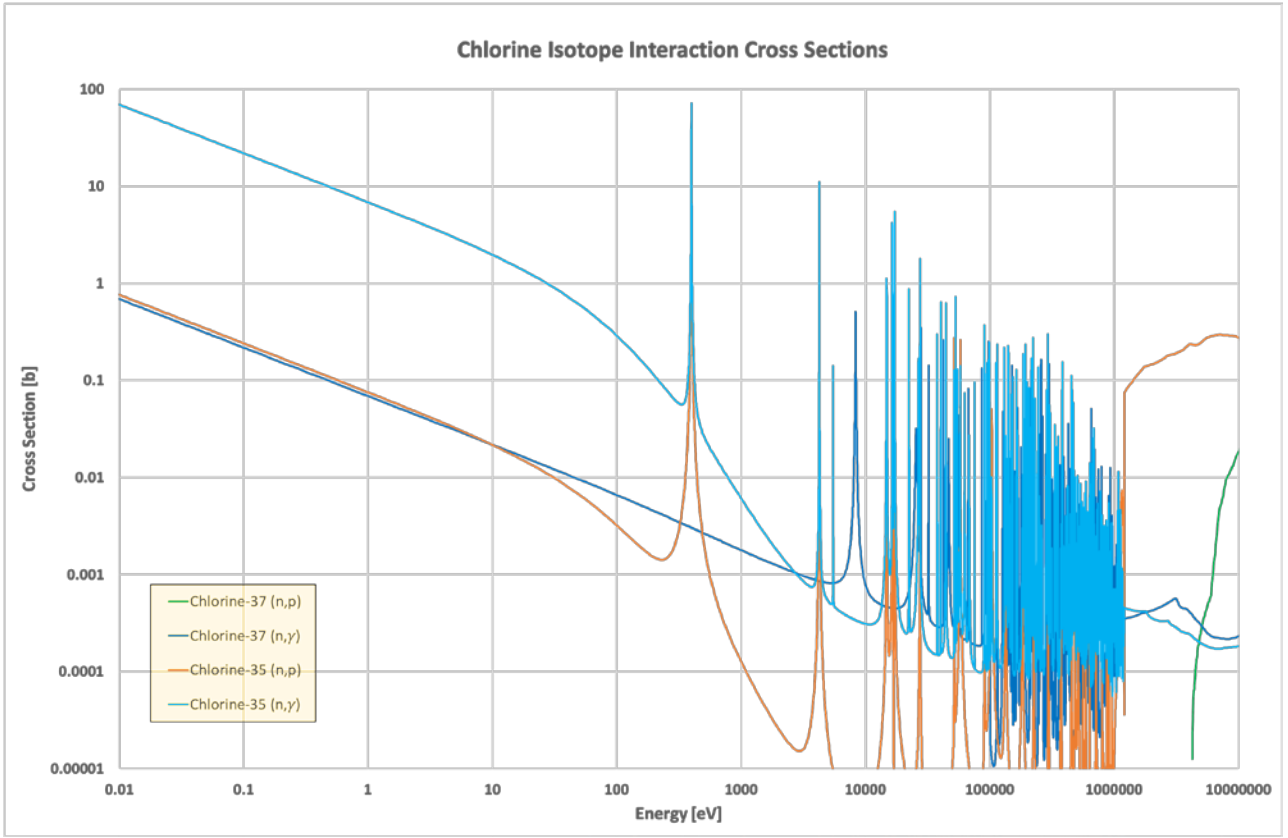
- Fission cross sections are much lower in fast region requiring more fissile material to maintain criticality
- Minimizing low atomic mass materials in core is key to hardening neutron spectrum
  - Low atomic mass materials employed to lower fuel salt melting point



Data from ENDF/B-VIII.0

Chloride Fuel Salts May Require Isotopic Enrichment For Breeding

- Chlorine has two stable isotopes
  - ^{35}Cl - 76%
  - ^{37}Cl – 24%
- Chlorine-35 has higher neutron absorption
- Chlorine cross section data uncertainty has significant impact on fast spectrum designs
  - Identified as issue by multiple developers
- ^{35}Cl(n,p)^{35}S cross section currently being reexamined
  - Details of abrupt transition at ~1.2 MeV would be important to fast spectrum designs



Data from ENDF/B-VIII.0

Taylor et al, “Sensitivity to Chlorine Nuclear Data in Molten Chloride Fast Reactors” provides detailed explanation

MSRs Fuel Cycles Can Be Configured to Improve Resource Utilization and Reduce Waste Generation

- Determining accurate fuel and salt composition with burnup is essential to performing analyses for MSRs
  - Need to improve state of modeling and simulation tools to appropriately represent unique features of MSRs
- The wide variety of MSRs (thermal/epithermal/fast, power density, uranium/thorium, online/batch/no reprocessing, etc.) enables them to be considered for almost any application where solid-fueled reactor types are currently proposed to be used
  - Similar passive safety features as SFRs, with similar burning/breeding capabilities when fast spectrum is used
  - High salt temperature, similar to HTGRs, enabling process heat applications
  - Improved resource utilization compared to PWRs, even with thermal spectrum MSRs

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)
  - Implemented by 10 CFR Part 75
- 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 STR-332, 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.**

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 will 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
  - Large volumes of materials being used at any one time in reactor
  - Access for measurements difficult
  - Correlation between current instrument signals and presence/quantity of fissile material not understood

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

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 49 model comprehensive safeguards agreement (IAEA INFCIRC/153)

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 (reactors and fuel cycles)
- 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

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 (<80 wt% ^{238}Pu)
- ^{233}U: 8 kg
- HEU: 25 kg (>20 wt% ^{235}U)
- LEU: 75 kg (<5 wt% ^{235}U)
- Th: 20 t

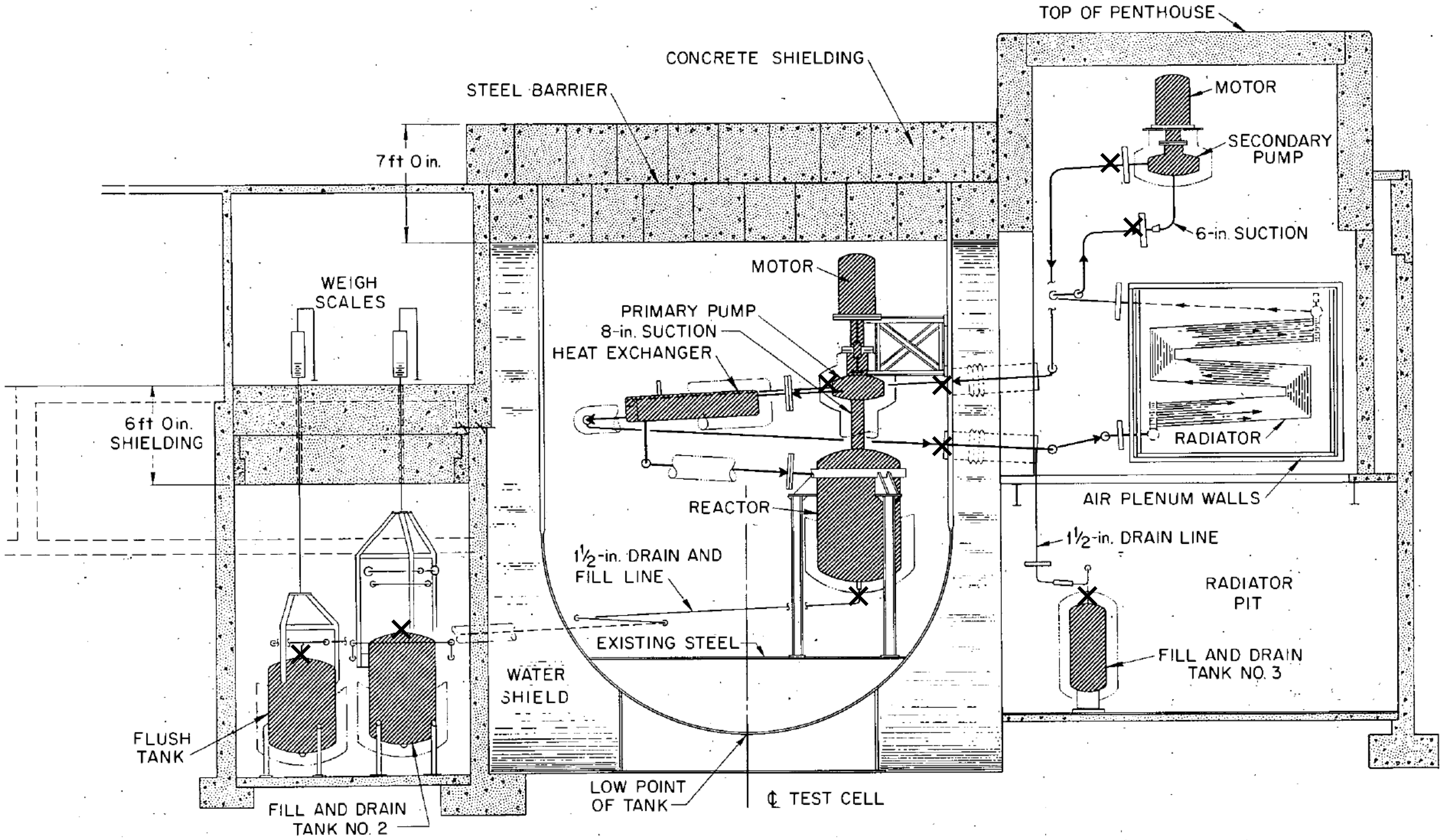
Classification	Pu, HEU, ^{233}U unless stated	Conversion time	Timeliness goal
1*	metal	7-10 d	1 m
2*	oxides, nitrates (^{235}U + ^{233}U ≥ 20%)	1-3 w	1 m
3*	irradiated fuels	1-3 m	3 m
4**	<20% ^{235}U + ^{233}U; Th	3-12 m	12 m

*Direct use
**Indirect use

Nuclear Material Control and 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

“Simple” Example



Early MSRE Elevation Schematic (~1961)

Informs on:

- **Where** to measure/monitor
- **What** to measure/monitor
- **How** to measure/monitor
- **If** we can measure/monitor

Leads to:

- Instrumentation development?
- Accuracy of measurement
- Frequency of measurement
- Design modifications needed?

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
- Online 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 continuously
- Unique refueling/breeding schemes
  - Accumulating additional fissile material outside of vessel (breeder)
  - Nontraditional solid fuel forms, e.g., drums, capsules, etc. (burner)

Safeguards Technology and 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 and radiation environment, remote and 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 and supporting software
- Extensive assessment of current safeguards technology required
  - Applicability to MSR safeguards and what further development, modifications, and upgrades should occur

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 other existing 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

MSRs Will Require Nontraditional Safeguards Approaches

LWR (Traditional)	MSR (Nontraditional)
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 ID 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

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

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 the 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

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

Safety

Risks arising from unintended events:

Natural occurrences

Hardware Failures

Internal Events

Human Error

System

Security

Risks arising from malicious acts with the intent to steal material or cause damage (sabotage)

Non-State Actors

(Terrorists)

Safeguards

Detect the diversion of nuclear materials for nuclear weapons purposes in a timely manner

Host State

It Is Important that Safeguards and Security Be Considered Early in the Design of MSRs

- 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 that have 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, continually changing material)
    - 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.

Key Questions that Remain to be Addressed

- Is the IAEA safeguards system ready for MSRs? 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 nondestructive assay technologies and other measurement instruments ready for deployment to meet these new verification challenges?