# Module 2: Overview of MSR Technology and Concepts

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# Overview of Liquid-Fuel Molten Salt Reactor (MSR) Key Technologies and Concepts

- Illustrative examples of diverse technologies and configurations intended to support normal operations and accident mitigation
- Conceptual differences from solid-fuel reactors
- MSR technologies and challenges
  - Proliferation resistance
  - Tritium
  - Reactor physics simulation
  - Fission gas management
  - Operations in high dose environment
- Technical maturity and remaining issues

# Diverse MSR Configurations Substantially Complicates Classification – Many Variants Being Pursued

- Normal operations heat transfer from the fuel can occur in the core, in-vessel (ex-core), or in an external heat exchanger
  - In-core heat transfer can be from solid fuel, stationary liquid fuel, or moving liquid fuel
  - Ex-vessel heat transfer may be within a secondary (non fuel salt contacting) vessel that encloses both the reactor and heat exchanger
    - Different layers credited to perform containment under different scenarios

- Decay heat rejection configurations are also diverse
  - Fuel salt cooling may be within reactor vessel or dedicated tanks
    - May employ freeze valve to enable gravity draining
    - May employ active refilling of reactor vessel under normal operation from a continuously drained system
    - May employ accumulator driven fuel salt transfer against gravity
  - Both in- and ex-vessel cooling may be primarily radiative (RVACs), convective (DRACS), or conductive (heat pipes or immersion into large coolant pool)

# Reactor Operating Parameter Comparison

| | MSBR – Single Fluid | MSFR | AP1000 | S-PRISM | IMSR® | Mk1PB-FHR |
|---|---|---|---|---|---|---|
| Inlet temperature (°C) | 566 | 675 | 280 | 363 | 625–660 | 600 |
| Outlet temperature (°C) | 705 | 775 | 322 | 510 | 670–700 | 700 |
| Primary coolant flowrate (kg/s) | 11,820 | 18,920 | 14,300 | 2,992 | 5,400 | 976 |
| Thermal power (MW) | 2,250 | 3,000 | 3,400 | 1,000 | 400 | 236 |
| Core power density (MW/m$^3$) | 22.2 | 330 | 110 | 120 | 9–14 | 22.7 |
| Reactor pressure (MPa) | ~0.1 (cover gas) | ~0.1 (cover gas) | 15.5 (pressurizer) | ~0.1 (cover gas) | ~0.1 (cover gas) | ~0.1 (cover gas) |
| Core structure volume (%) | 63–87 | 0 | ~50 | ~63 | 70–95 | |

# MSR Plant Layouts Will Be Distinctive (1)

- Outermost containment layer primarily provides radiation barrier and external event shielding, not high pressure retention
  - MSR containments will not include large volumes of phase change materials (e.g., water) that could pressurize containment under accident conditions
  - Fuel/coolant salt mixture does not benefit from shielding provided by separate coolant surrounding solid fuel
    - Design option to separate radiation shielding from radionuclide containment function
- Fuel and flush salt storage tanks and transfer systems by necessity will be within containment to enable maintenance
  - Some designs replace the vessel and fuel salt as a whole and are not designed for fuel system maintenance
- All fuel salt system maintenance performed remotely using long-handled tools guided by extremely radiation-hardened vision systems
- Extensive cover gas processing system and fission gas retention beds will be required
  - For aggressively sparged systems significant safety-grade decay heat removal from cover gas will be required
  - Trace fissile material accumulation could eventually become significant (inadvertent criticality potential)
  - Largest quantity of mobile radionuclides are in cover gas
  - Gas line plugging from salt vapor condensation could allow system pressurization

# MSR Plant Layouts Will Be Distinctive (2)

- Passive decay heat removal - key feature of all proposed MSR designs
  - Some designs employ more than one technology [e.g., fuel salt cooled by Direct Reactor Auxiliary Cooling System (DRACS) and fission gas tanks cooled by Reactor Vessel Auxiliary Cooling System (RVACS) type loops]
  - Salt dump tanks, as envisioned for the MSBR, are employed in some designs with fission gases typically used to preheat dump tanks to minimize thermal shock
  - Current designs do not rely upon transferring decay heat through the power cycle loop
  - Major design goal is to reduce safety significance (i.e., lower safety class) of the primary coolant loop [enables use of conventional piping materials and components (rupture disks, bellows, etc.)]
- Salt storage tanks will also require thermal management
  - Flush salt unlikely to contain sufficient radionuclide quantities to self heat
  - Flush salt radionuclide burden: mostly flushed fission products
  - Actinide loading largely unknown

# MSR Plant Layouts Will Be Distinctive (3)

- Primary coolant salt will activate, necessitating shielding and possibly draining for nearby maintenance activities
- Short half-life fission gas decay systems
  - Heat load depends substantially on fission gas (including noble gases) removal strategy
  - Multiple design options remain under consideration
- Longer half-life gaseous fission products will be trapped on series of charcoal beds or scrubber system
  - Fine particulate filters employed to prevent salt egress
  - Safety significance of boundaries decreases as activity decreases
- Fuel salt storage systems
  - Bred fuel – requires both thermal and criticality management
  - Used cores – several designs replace reactor vessel as a whole
- Fuel salt polishing systems
  - Particulate filtering – primarily noble metal fission products
  - Redox condition adjustment

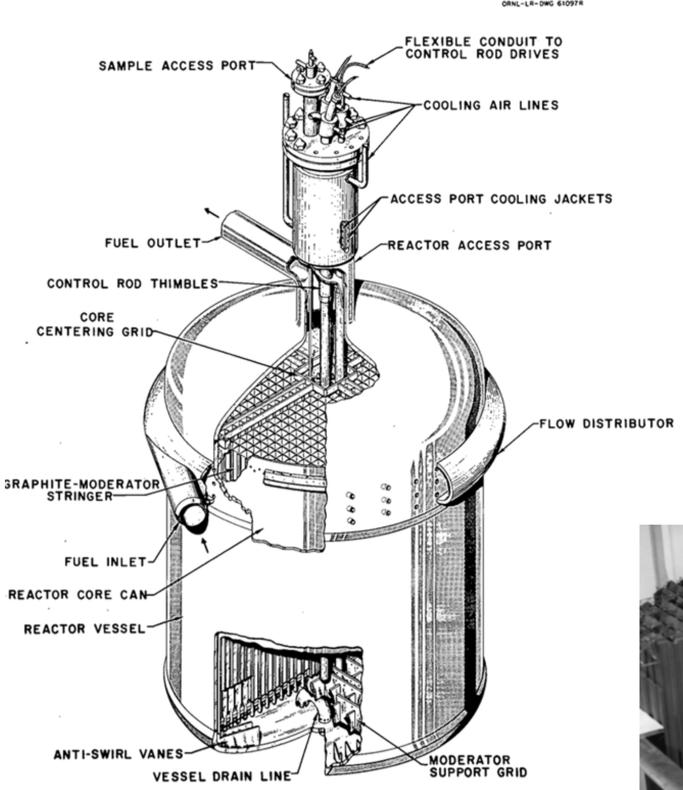
# MSRs Can Transfer Heat From Fuel Salt In-Core, In-Vessel, or Ex-Vessel

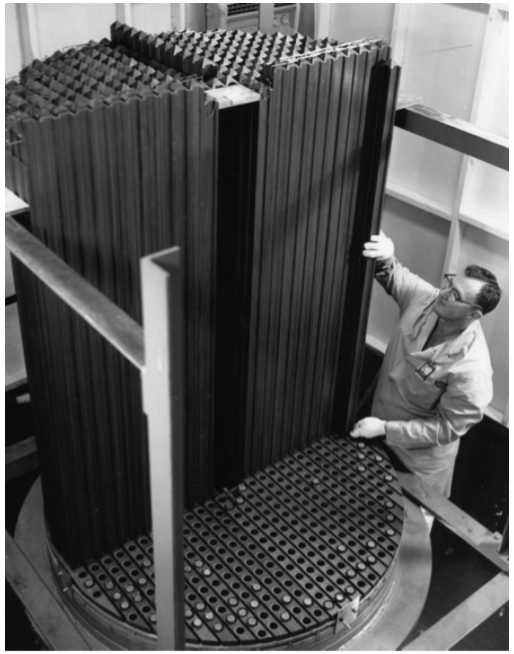
- In-core
  - Fuel salt in rods or tubes
  - Similar to solid fuel reactors with unfueled coolant
  - Coolant can be salt of liquid metal
- In-vessel
  - Integral primary system reactor avoids potential for ex-vessel fuel leaks
  - Requires in-vessel fuel salt pumps
- Ex-vessel
  - Loop type reactor

# Core of Thermal Spectrum MSRs is Largely Graphite with Fuel Salt Channels

- Fast fluence graphite damage is key design issue in setting core power density
  - Increased salt penetration into radiation damaged graphite is key lifetime metric
- Current designs employ interior moderation/shielding to minimize neutron fluence (embrittlement) of reactor vessel
- Most current designs employ integral primary system layout
  - Taller vessel to promote in-vessel natural circulation based decay heat removal alternatives to dump tanks
  - Lower power density enables in-core control elements (typically in thimbles)

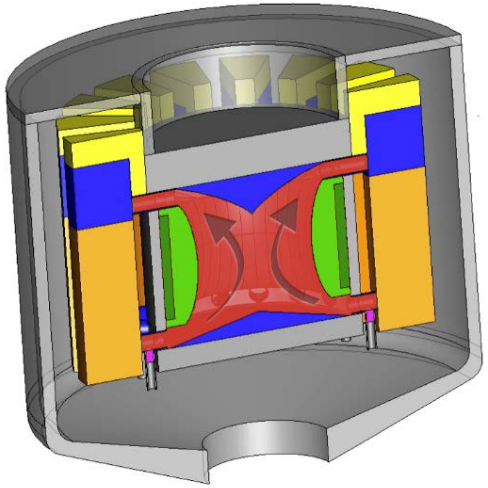
MSRE Vessel and Core





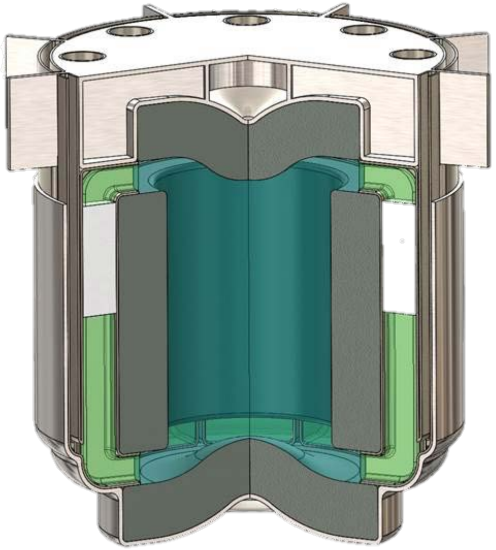
# Fast Spectrum MSRs May Have Open Core or Tube Type Designs

- Open cores have little or no structural material in core
  - Protecting reactor vessel from radiation damage is key lifetime parameter – internal reflectors, shielding, or fertile material layer
- Pin or tube fuel and coolant/reflector configurations are similar to solid-fuel fast reactors
  - Fuel salt flow (including in-pin recirculation) reduces cladding and fuel salt temperature
  - Cladding / tube radiation damage becomes key lifetime parameter
- Core size/geometry is dictated by lower fast spectrum fission cross sections
  - Designs tend to be gigawatt (+) scale
- Fuel salt wetted materials are not a life-of-plant components
- In-core control elements unlikely
  - Reflector geometry change possible
  - Shutdown elements possible (fuel salt displacement)
  - Europeans proposing to employ helium injection as control mechanism
  - Pump speed likely to be principal, normal operation control mechanism



European Fast Spectrum MSR

Source: IAEA ARIS



TerraPower's Molten Chloride Fast Reactor

Image courtesy of TerraPower

# Conceptual Differences for MSRs with Liquid Salt Fuel

- Low intrinsic fuel-salt pressure decreases radionuclide release probability and magnitude
  - Higher coolant salt pressure vs. fuel salt pressure means that primary heat exchanger leaks would be into the fuel salt
- Delayed neutron precursors are mobile
  - Mobile fission gas bubbles also impact reactivity
- Fission products are not all in fuel salt
  - May require cooling of decay heat in additional locations (e.g., fission gas decay tanks)
  - Fewer radionuclides remain to be released in fuel/core accidents
  - Potential for fissile material to be transported with fission products
- Some fission products form stable, low volatility salts (e.g., cesium and strontium)
  - $^{137}$Xe ($t_{½} \approx 3.82$ min) decays to $^{137}$Cs and has low solubility
- High temperature and large salt coefficient of thermal expansion (i.e., density changes) facilitate passive decay heat removal options
  - Higher radiative heat transfer improves RVACS performance
  - Strong natural circulation facilitates DRACS performance
  - Potential for overcooling accidents
- Online refueling minimizes excess reactivity available

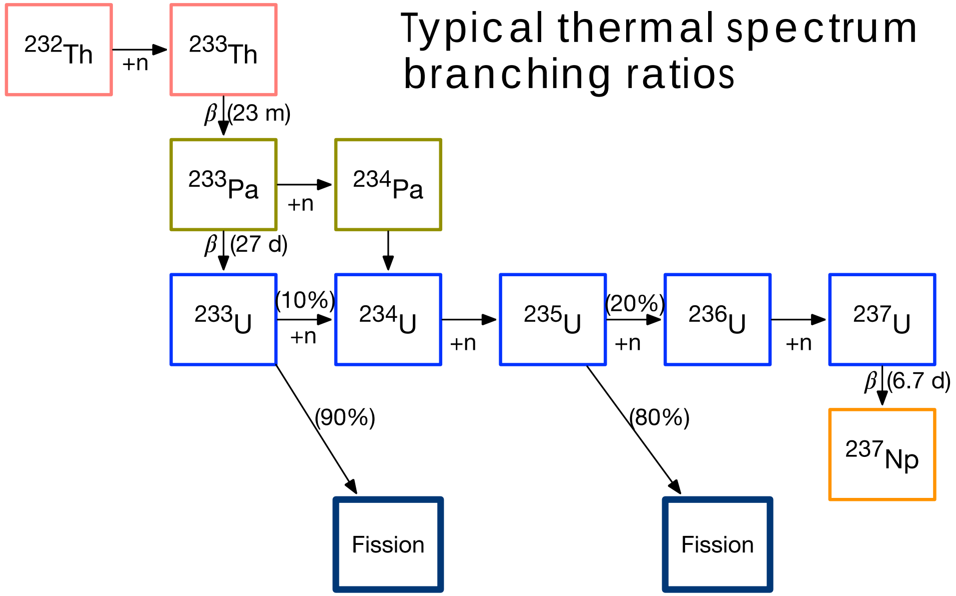
# Conceptual Differences for MSRs with Liquid Salt Fuel (cont'd)

- Fuel composition and chemistry can be continuously adjusted
  - Fuel specification will be based on maintaining composition within an acceptable boundaries based on physical and chemical properties of fuel salt
  - Enables maintaining chemical compatibility with container alloy
- Area surrounding fuel salt will have very high radiation flux
  - Draining and flushing fuel salt required for significant maintenance
  - Solid state electronics would only be possible with substantial shielding
- Core first wall will be subjected to significantly increased neutron fluence
  - Radiation embrittlement and swelling will likely be the first wall limiting phenomena
  - Creep & creep-fatigue will likely remain dominant issues for non-first wall materials
  - Interior vessel shielding (neutron reflectors and/or absorbers) commonly employed
  - All major components (including vessel) are intended for replacement
- Achievable power density is not set by departure from nucleate boiling
  - No cliff-edge phenomena or energetic reactions which liberate radionuclides
  - Limit arises from heat exchanger performance (flow-accelerated corrosion, tube vibration, etc.)
- Fissile material accountability goes well beyond "item counting"

# Proliferation Resistance Has Become a Dominant Concern for All Fuel Cycles

- MSRs can have better or worse proliferation resistance depending on the plant design
  - MSR designs until the mid-1970s did not consider proliferation issues
  - Several current MSR design variants do not include separation of actinide materials
  - Actinide co-separation may result in low attractiveness material
- Liquid fuel changes the barriers to materials diversion
  - Lack of discrete fuel elements combined with continuous transmutation prevents simple accounting
  - Homogenized fuel results in an undesirable isotopic ratio a few months following initial startup (no short cycling)
  - Extreme radiation environment near fuel makes changes to plant configuration necessary for fuel diversion very difficult
  - High salt melting temperature makes ad hoc salt removal technically difficult
  - Low excess reactivity prevents covert fuel diversion
    - Fresh LEU fuel prior to dissolution in fuel circuit is a potential target

# Thermal Spectrum Th/U Breeding Fuel Cycle Presents Distinctive Proliferation Issues



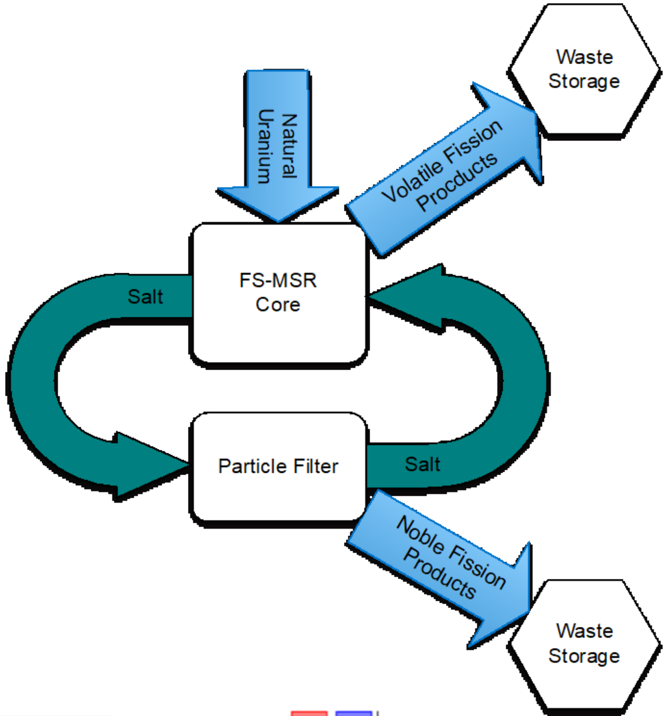
Typical thermal spectrum branching ratios

- $^{232}$Th is not fissile
- A conversion ratio greater than one is only possible if $^{233}$Pa is allowed to decay in a low thermal flux environment
  - $^{233}$Pa has a significant thermal neutron absorption cross-section
  - $^{234}$U is not fissile
- Liquid fuel MSRs can be designed to separate $^{233}$Pa resulting in a separated fissile stream
- Maximizing the Th/U breeding ratio was a significant element of the historic US MSR program prior to the mid-1970s
  - Program focus was on minimizing the amount of the non-renewable resource $^{235}$U required
- US does not have a definition of LEU for uranium isotopes other than $^{235}$U and $^{238}$U
  - Necessary to enable blended Th/U and U/Pu fuel cycles

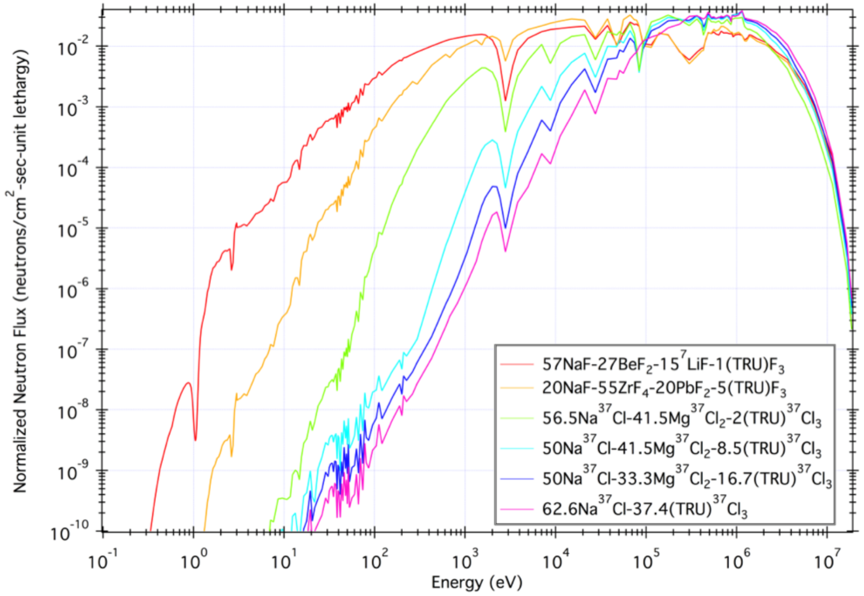
# Denatured MSRs Were Designed in 1970s to Reduce Proliferation Vulnerability

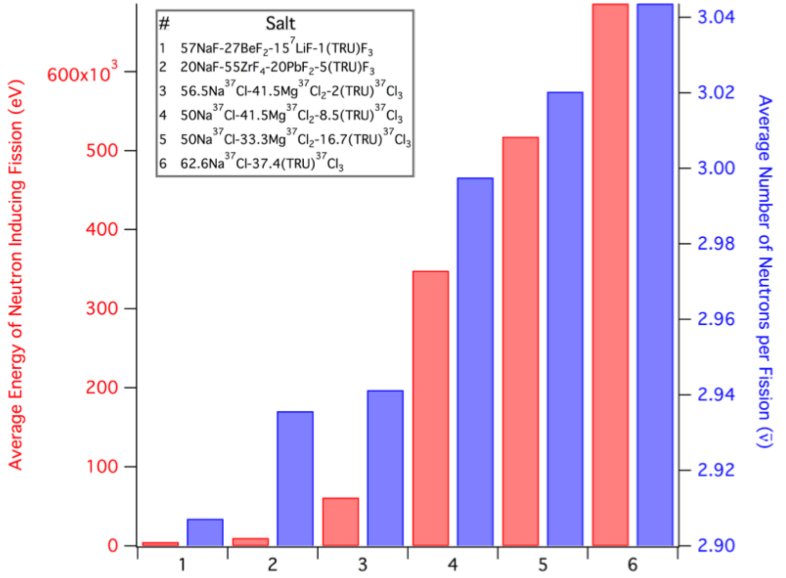
- Online processing is not performed (other than gaseous fission product removal and noble metal filtering)
- LEU for startup and as feed material
  - Conversion ratio < 1 (0.8–0.9 typically)
  - $^{238}$U added as needed to maintain denatured state
  - Thorium only in initial loading
- ORNL 1970s design lowered power density to extend graphite lifetime
- Commercial firms are pursuing DMSR designs
  - Higher power density
  - Integral primary system
  - Replace entire reactor vessel with fuel every 3–10 years
- Fuel salt chemistry has advanced substantially since 1970s

# Fast Spectrum MSRs May Achieve Net Breeding without Actinide Separation



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



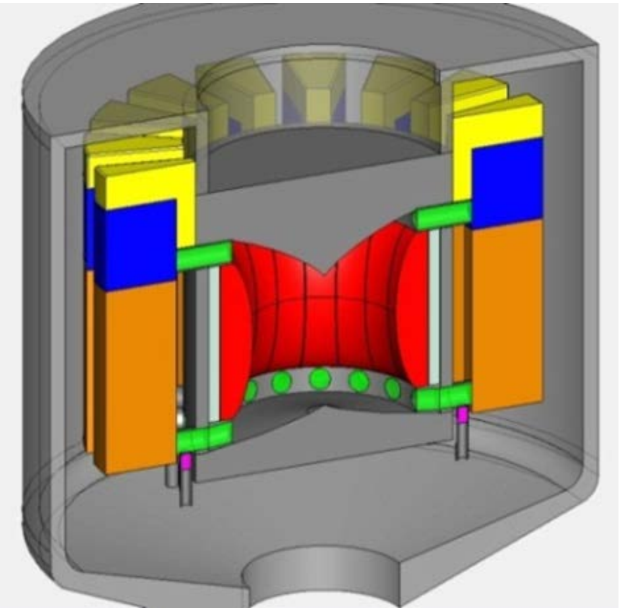


Images from ORNL/TM-2011/105

# European Union and Russian Federation Are Examining Fast Spectrum Fluoride Salt MSRs

## EU MSFR includes both fertile and fissile salts in single fluid

- $LiF$-$ThF_4$-$UF_4$-$(TRU)F_3$ with 77.7-6.7-12.3-3.3 mol%
- U enriched at 13%
- Melting point = 594°C



MSFR Core Cross-Section

Image courtesy Reactor Physics Group LPSC Grenoble and IPN Orsay; IAEA ARIS

## Russian MOSART can be configured as a burner or breeder

| **System** | **Burner /** | **Breeder** |
|---|---|---|
| Fluid streams | 1 | 2 |
| Power capacity, MWt | 2400 | 2400 |
| Fuel salt inlet/outlet temperature, °C | 600 / 720 | 600 / 720 |
| Fuel salt composition, mol% | 72LiF<br>$27BeF_2$<br>$1TRUF_3$ | 75LiF<br>$16.5BeF_2$<br>$6ThF_4$<br>$2.5TRUF_3$ |
| Blanket salt composition, mol% | No | 75LiF<br>$5BeF_2$<br>$20ThF_4$ |

Both designs employ on-site fissile material separations

# First Generation of MSRs Plan to Rely upon Known Component Technology

- Pumps
  - Vertical shaft, cantilever style similar to those used at sodium fast reactors
  - May require pressurization of fuel system to avoid pump cavitation
  - Could be coupled with spray ring to evolve fission gases and tritium
- Heat exchangers
  - Tube and shell remains leading candidate technology
  - Tube vibration and flow-accelerated corrosion appear to be the most significant power density limits
  - Double wall possible for tritium release mitigation
- Vessel
  - Either ASME BPVC code qualified material with redox control, or
  - Modified Alloy N used under a limited term code case
  - Interior shielding to minimize radiation damage is planned by multiple vendors

# Salt Chemistry Is Central to MSR Performance

- All alkali halide salts can be highly corrosive
  - Maintaining mildly reducing conditions key to avoiding significant alloy corrosion
  - Graphite attacked under strongly reducing conditions
  - Presence of electronegative impurities (e.g., $S^{2-}$ or $O^{2-}$) is especially pernicious
  - $U^{4+}/U^{3+}$ serves as a circulating redox buffer
  - Tellurium cracking was largely alleviated by maintaining proper redox conditions

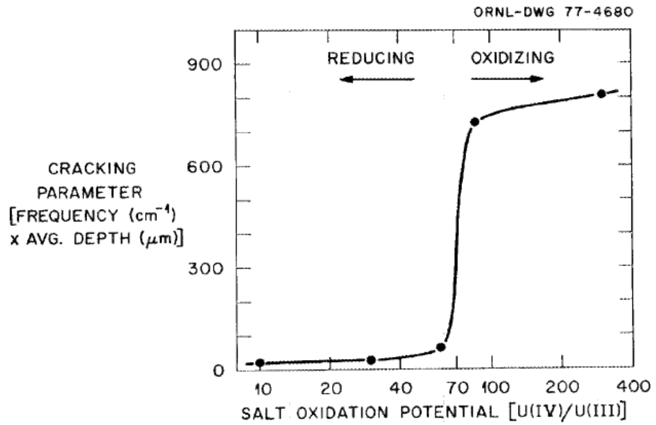


Fig. 12. Cracking Behavior of Hastelloy N Exposed 260 hr at 700°C to MSBR Fuel Salt Containing $CrTe_{1.266}$.

Source: ORNL/TM-6413

- Fast spectrum fluoride salt reactors operate near solubility limits for actinide trifluorides to maintain criticality
  - Chloride salts dissolve significantly larger amounts of actinides
- Fission product distribution is substantially impacted by salt chemistry
  - Important fission products form stable halide salts
  - Volatile, low-solubility compounds may also be formed (e.g., CsI)
  - Chloride salt fission product distribution has never been demonstrated under in-pile conditions
  - Noble and semi-noble (more soluble) fission product distribution has substantial uncertainty

# Replacement Strategy Significantly Alters Structural Materials Requirements

- All salt-wetted components are intended for periodic replacement
  - Key issue is ability to assess remaining useful life
- ASME BPVC is centered around establishing initial fitness for duty with limited accommodation (high temperatures) for in-service degradation
  - Corrosion and neutron induced reduction in fracture toughness are key boundary degradation mechanisms
  - Interior shielding frequently employed in modern designs to minimize fluence on reactor vessel
    - MSRE was approaching end of allowable service life when shut down
  - Establishing appropriate in-service inspections will be key for situations approaching material limits
    - Material coupons
    - Salt composition monitoring for presence of structural alloy elements (e.g., iron, chromium)
- Fuel-salt-wetted components will be both significantly activated and have fission products deposited onto their surfaces

# Liquid Fuel Reactors Require Updating Reactor Physics Simulation Tools

- Mobile delayed neutron precursors decrease stability margin
  - Time constants for feedback mechanisms are key
    - Doppler feedback is prompt
    - Fuel expansion out of critical configuration occurs at speed of sound

- Maximum hypothetical accident approach has been employed to bound the modeling uncertainties

- Fission product bubble formation and collapse cause reactivity burps
  - No significant radiolytic salt decomposition in fluorides or anticipated in chlorides

- Startup of decay heat removal mechanisms
  - No cliff-edge threshold phenomena
  - High power density reactors could experience unacceptable transient heating

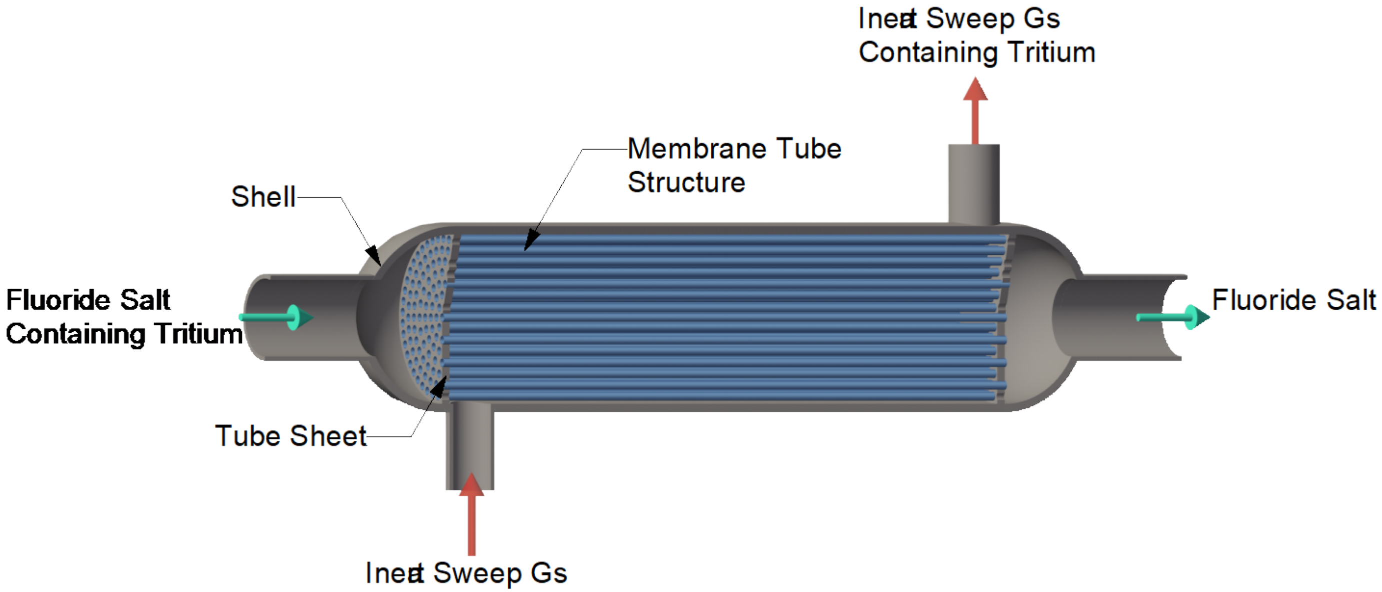
- Cross-section uncertainty will impact fuel cycle modeling
  - Potential significant issue for fissile materials tracking

# Gaseous Fission Products Inherently Evolve from Fuel Salt

- Inert gas sparging and/or fuel salt spraying into an inert gas environment enhances rate of removal
- Evolved fission products (FPs) represent a significant heat load
- Many FPs have Xe or Kr precursors
  - Over 40% of FPs leave core
  - Large fraction of cesium, strontium and iodine end up in offgas
- For 1000 MWe MSR
  - 2 h in drain tank ~20 MW
  - $^{137}$Cs almost all in drain tanks or gas decay tanks
  - Then 47 h delay charcoal beds ~2 MW
  - 90 day long term beds ~0.25 MW
  - 23 m$^3$ of $^{85}$Kr ($t_{½} \approx 10.8$ y) a year

# Tritium Management Is a Key Element to Lithium Fluoride Salt MSRs

- Lithium isotope separation: enabling technology for lithium-bearing fuel salts (avoid $^6$Li)
  - Industrially produced for weapons program in 1950s using mercury amalgam process
  - Substantial modern technology improvements, but no industrial scale demonstration
- Fluoride salt MSRs with lithium-bearing salts generate ~1 Ci tritium / MWt / day
- Above 300°C tritium readily permeates available structural alloys
- Significant advancement in technology for tritium separation from molten salts since 1970s
  - Designing and demonstrating tritium separators are key elements of DOE's solid fuel MSR program at both universities and national laboratories
  - Multiple options for tritium isolation under consideration



# Physics of MSR Accident Progression Is Substantially Different than for LWRs

- Foundation of existing licensing framework is averting core damage and preventing large radionuclide releases
  - Low-pressure, liquid-fueled systems lack analogous accidents
  - Early release of fission gases has large potential consequences
- Safety design requirements need to build from basic phenomena (i.e., quantitative health objectives)
  - Preventing release of radionuclides to the environment remains the central safety metric
  - Relies upon validated accident progression models
- LOCA consequences are significantly different than LWR
  - Low driving pressure and lack of phase change fluids
  - Guard vessels employed on some designs
  - Planned vessel drain down to cooled, criticality-safe drain tanks on some designs

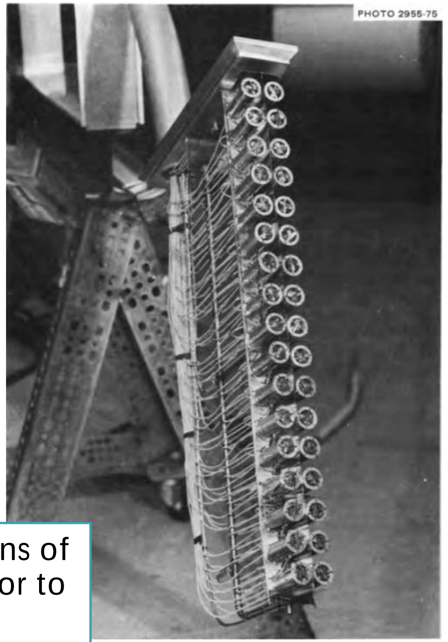
# MSR Characteristics Alter the Risk Significance of the SSCs

- Reduced core source term
- Increased fission gas decay tank source term
- Active systems may not be necessary to perform protection and mitigation functions
  - Capability of bringing the reactor subcritical and decay heat removal will be fully passive and cannot be disabled by control system actions
  - MSRs lack heat transfer or temperature threshold phenomena (e.g., DNB)
  - Reduced safety significance of active components and I&C
- Requires a plant-specific PRA, supplemented by an expert panel, and validated accident evaluation capabilities to employ 10 CFR 50.69 for classification
  - New ANS standard and categorization and classification of SSCs will be an important element of MSR design

# Technology Challenges Remain for MSRs

- Operations and maintenance are much more difficult in an extreme radiation environment
- Nickel-based alloys embrittle under high neutron fluxes at high temperature
  - Refractory, embrittlement-resistant alloys and structural ceramic composites remain at low technology readiness
- High power density reactors challenge heat exchanger material mechanical performance, reflector/shield material temperatures, and startup of passive decay heat removal systems
- Proper chemistry control is imperative
  - Alkali halide salts can be highly corrosive
  - Ratio of $U^{4+}/U^{3+}$ is key to maintaining low corrosivity
- Fluoride salts generate substantial amounts of tritium
  - Especially lithium-bearing salts
- Fast spectrum fluoride salt reactors operate near solubility limits for actinide trifluorides to maintain criticality
- No operational experience with chloride salts

MSRE maintenance used long shafted tools



102 creep test specimens of Nb-modified Alloy N prior to reactor insertion
ORNL-5132

# MSR Technology Maturity Varies Substantially with Reactor Type

- Basic elements of MSRs have been identified and demonstrated with varying degrees of sophistication
- Thermal spectrum fluoride salt-based systems benefit greatly from the earlier MSBR development program, including operation of the MSRE
  - Principal technical challenges identified in 1972 by independent expert reviewers addressed (WASH-1222)
  - Principal remaining technical issues are in commercial viability and system scaling
- Chloride salt-based reactors have significant additional fuel salt in-core performance unknowns that remain to be resolved
  - Undesirable fissile material solid phase formation?
  - Radiolytic instability?
  - Significant increases in evaporation rate?