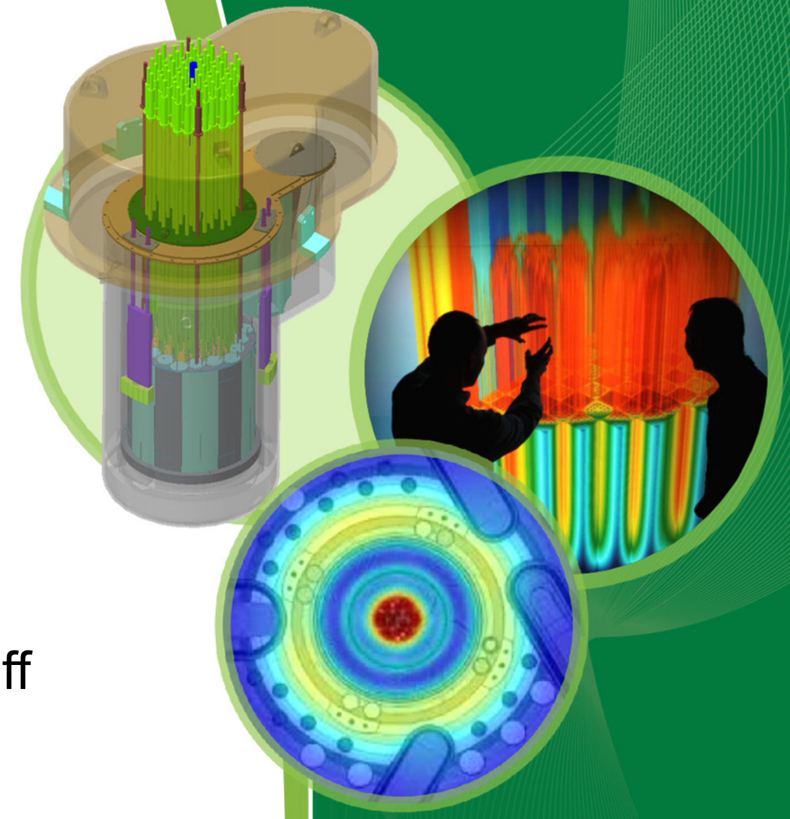
Module 2: Overview of MSR Technology and Concepts



Presentation on Molten Salt Reactor Technology by:
David Holcomb, Ph.D.
Advanced Reactor Systems and Safety
Reactor and Nuclear Systems Division

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Overview of Liquid-Fuel MSR Key Technologies and Concepts

- Configurations
- Conceptual differences from solid-fuel reactors
- System overviews of two representative MSRs
  - Denatured, thermal-spectrum fluoride salt
    - Final system without online processing considered during historic MSR program that is currently being pursued commercially for US deployment
  - Fast-spectrum chloride salt
    - Early system design option not pursued in United States after 1956 due to unavailability of chlorine isotope separation
    - Currently being pursued commercially with US government support
- Technical maturity and remaining issues

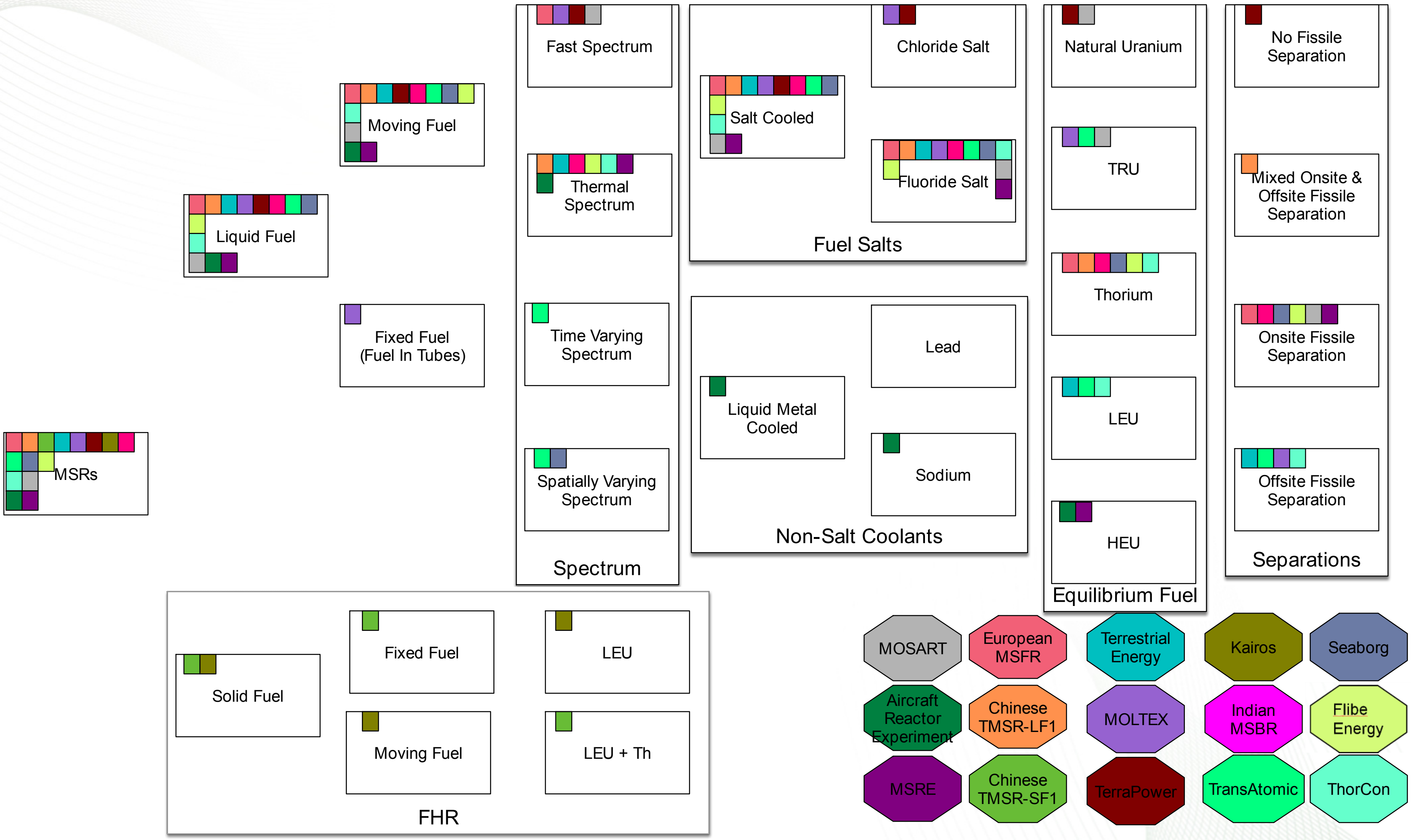
Key Issues Differentiating Molten Salt Reactors from LWRs

- Fuel salt contacting materials are subjected to different stressors (fluence, corrosion, and temperature instead of pressure)
  - Salt chemistry control, structural alloy cladding, internal shielding, and replacement employed to mitigate impact of stressors
- Safeguards and proliferation resistance are conceptually different
  - Fast spectrum, denatured, and thorium cycle issues
- Operations and maintenance need to accommodate a much more severe radiation environment
- Modeling and simulation tools require adaptation
  - Mobile delayed neutron precursors and fission gas bubbles
    - Tritium generation and transport
  - Limited software validation benchmarks available
  - Transient analysis
    - Design margin
    - Location of fission products
    - Startup of decay heat removal in high power density designs

Reactor Operating Parameter Comparison

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

Wide Variation in MSR Concepts



MSRs

Liquid Fuel

Moving Fuel

Fixed Fuel (Fuel In Tubes)

Spectrum

Fast Spectrum

Thermal Spectrum

Time Varying Spectrum

Spatially Varying Spectrum

Fuel Salts

Salt Cooled

Chloride Salt

Fluoride Salt

Non-Salt Coolants

Liquid Metal Cooled

Lead

Sodium

Equilibrium Fuel

Natural Uranium

TRU

Thorium

LEU

HEU

Separations

No Fissile Separation

Mixed Onsite & Offsite Fissile Separation

Onsite Fissile Separation

Offsite Fissile Separation

FHR

Solid Fuel

Fixed Fuel

Moving Fuel

LEU

LEU + Th

MOSART

European MSFR

Terrestrial Energy

Kairos

Seaborg

Aircraft Reactor Experiment

Chinese TMSR-LF1

MOLTEX

Indian MSBR

Flibe Energy

MSRE

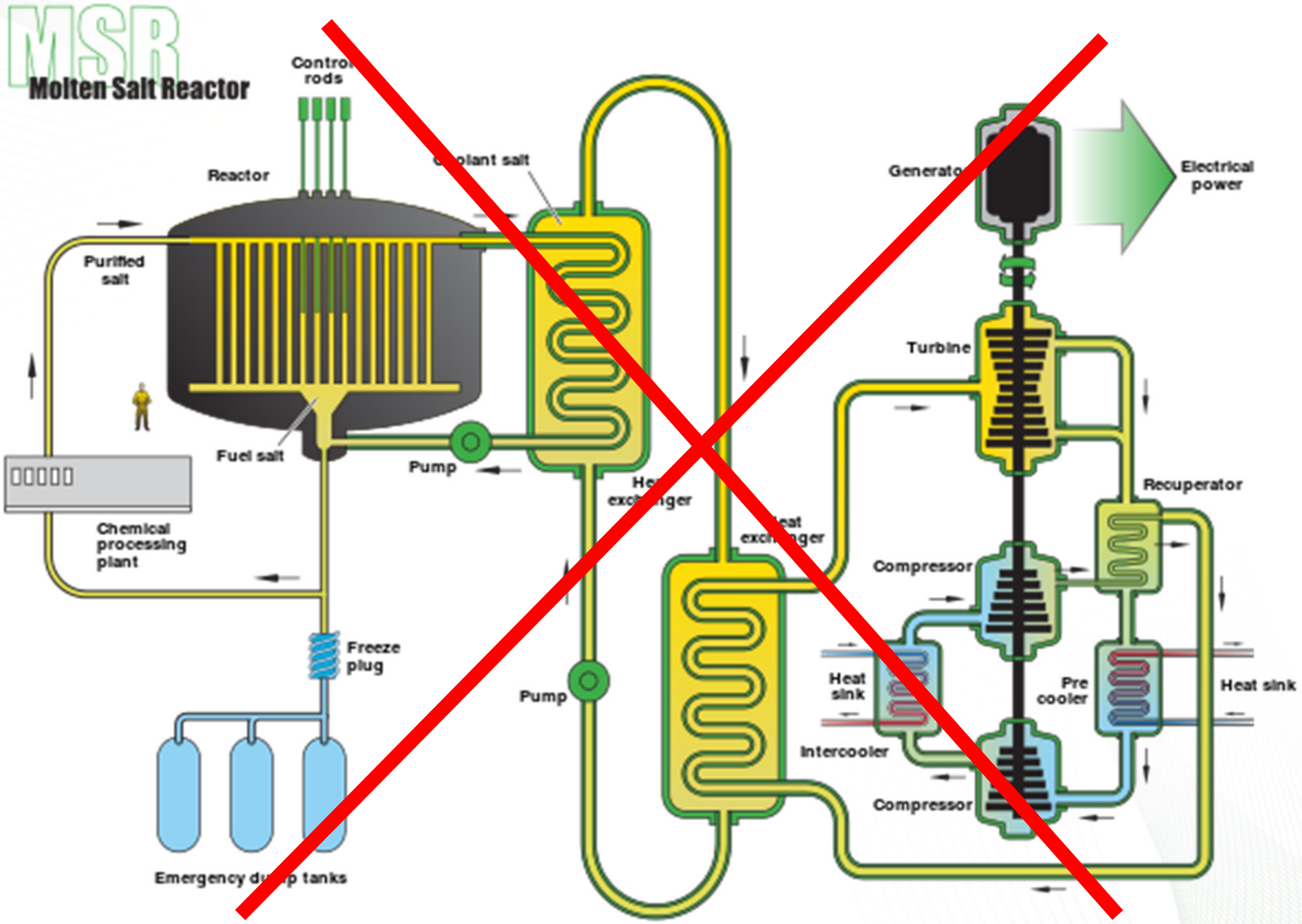
Chinese TMSR-SF1

TerraPower

TransAtomic

ThorCon

The Molten Salt Breeder Reactor Layout is NOT Representative of Modern MSRs



MSR Plant Layouts Will Be Distinctive (1)

- Outermost containment layer primarily provides radiation barrier and external event shielding (e.g., aircraft impact protection), 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 will be necessary 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)

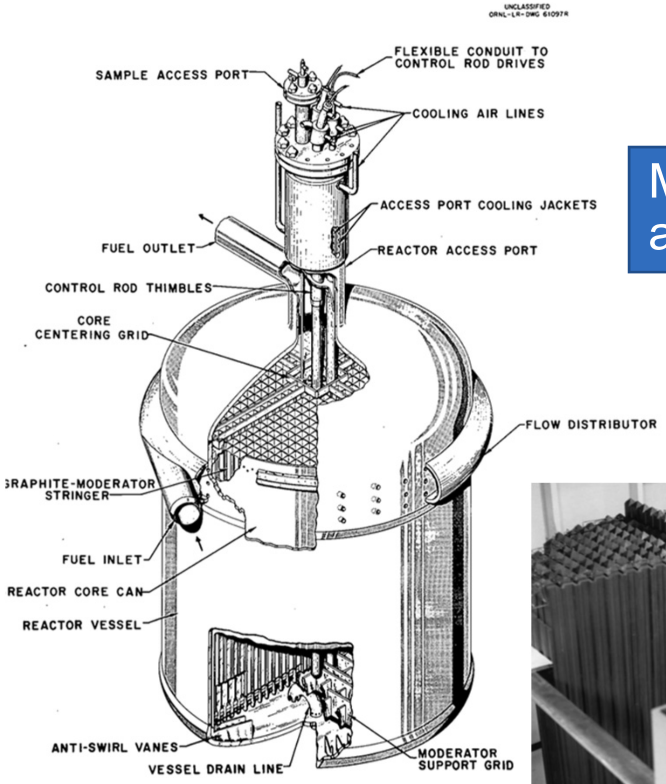
- Passive decay heat removal is a key feature of all proposed MSR designs
    - Some designs employ more than one technology [e.g., fuel salt cooled by Direct Reactor Auxiliary Cooling System (DRACS) and fission gas tanks cooled by Reactor Vessel Auxiliary Cooling System (RVACS) type loops]
    - Salt 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
  - 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

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

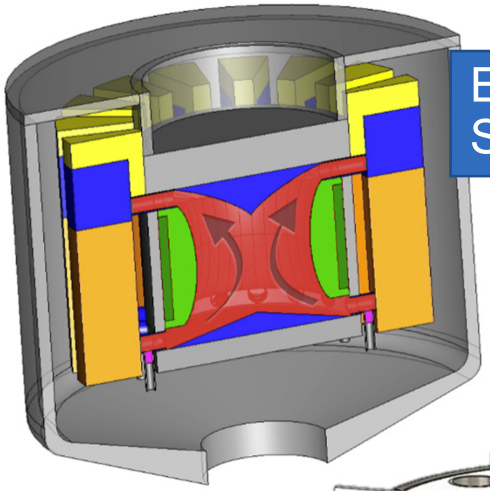
- Fast fluence graphite damage is key design issue in setting core power density
- Current designs employ interior moderation/shielding to minimize neutron fluence (embrittlement) of reactor vessel
- Most current designs employ integral primary system layout
  - Taller vessel to promote in-vessel natural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



MSRE Vessel and Core

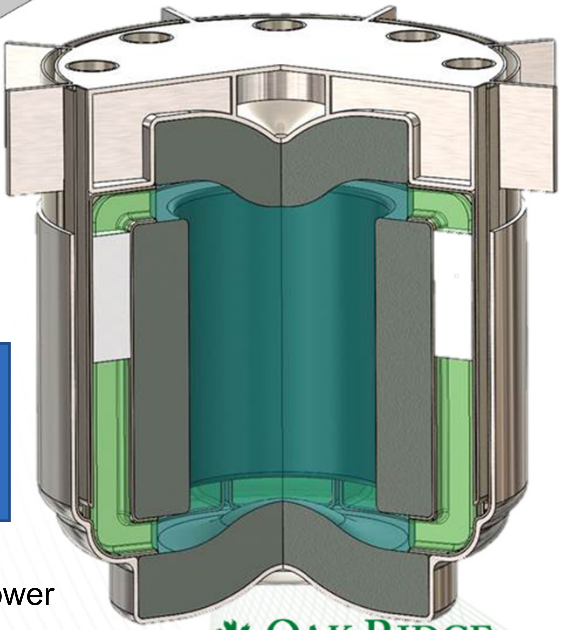
Fast Spectrum MSRs Have Little or No Structural Material In-Core

- Core size/geometry is dictated by lower fast spectrum fission cross sections
  - Designs tend to be gigawatt (+) scale
- Key issue is protecting reactor vessel from radiation environment
  - TerraPower employs reflector
  - European design employs fertile salt
- Reactor vessel is not a life-of-plant component
- 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 Arising from MSRs with Liquid Salt Fuel

- Low intrinsic fuel-salt pressure decreases radionuclide release probability and magnitude
  - Higher primary 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 decay cooling of 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) decreasing their availability for release
- 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 Arising from MSRs with Liquid Salt Fuel (cont.)

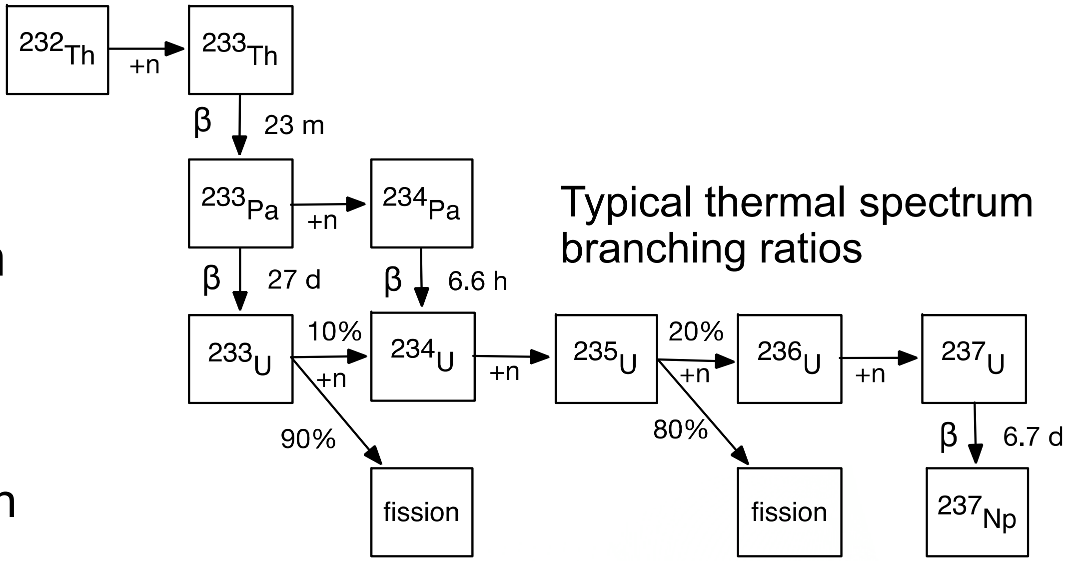
- Fuel composition and chemistry can be continuously adjusted
  - Qualified fuel is likely to be a composition specification based on physical and chemical properties of fuel salt (no time dependence in fuel condition)
  - Enables maintaining chemical compatibility with container alloy
- Area surrounding 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 and 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
- 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

- ^{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



Typical thermal spectrum branching ratios

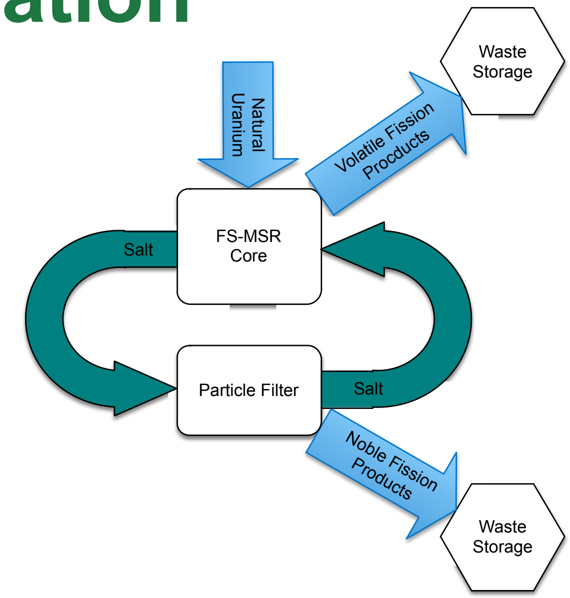
- Liquid fuel MSRs can be designed to separate ^{233}Pa resulting in a separated fissile stream
- Maximizing the Th/U breeding ratio was a significant element of the historic US MSR program prior to the mid-1970s

Denatured MSRs Were Designed 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

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



Natural Uranium

FS-MSR Core

Volatile Fission Products

Waste Storage

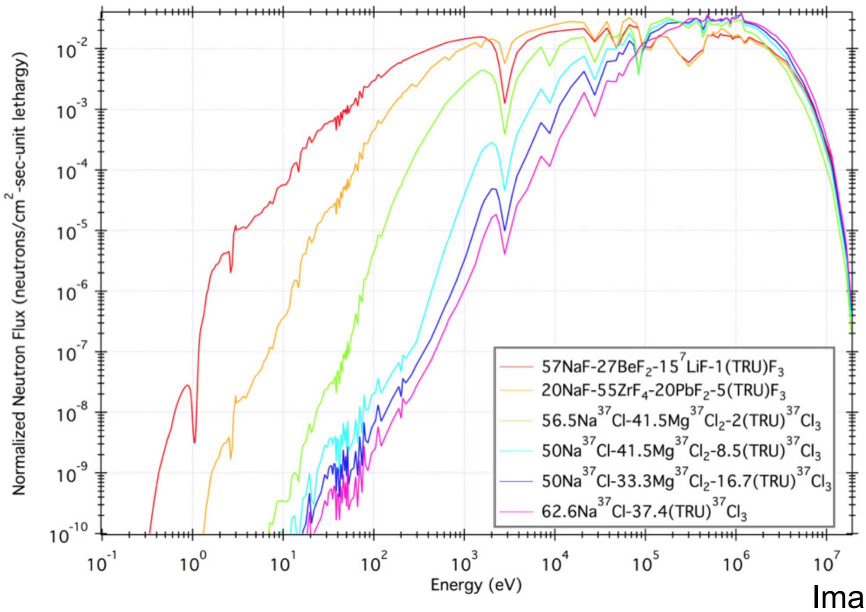
Salt

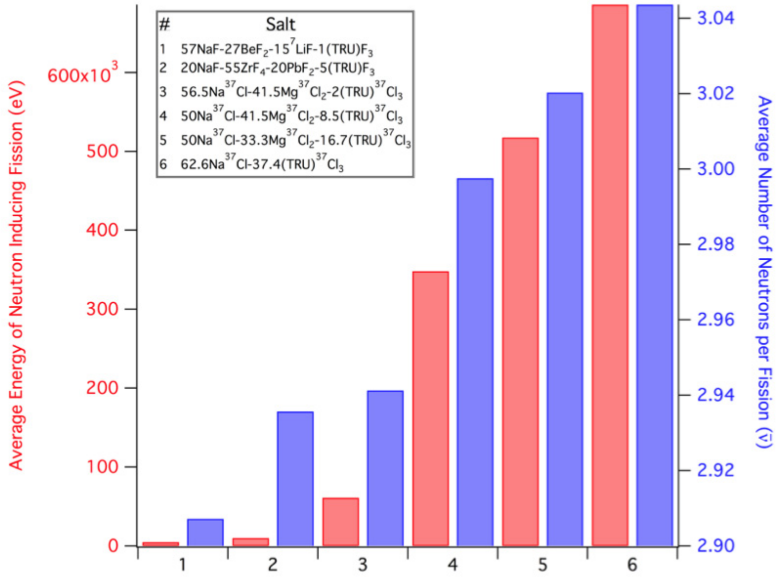
Particle Filter

Salt

Noble Fission Products

Waste Storage



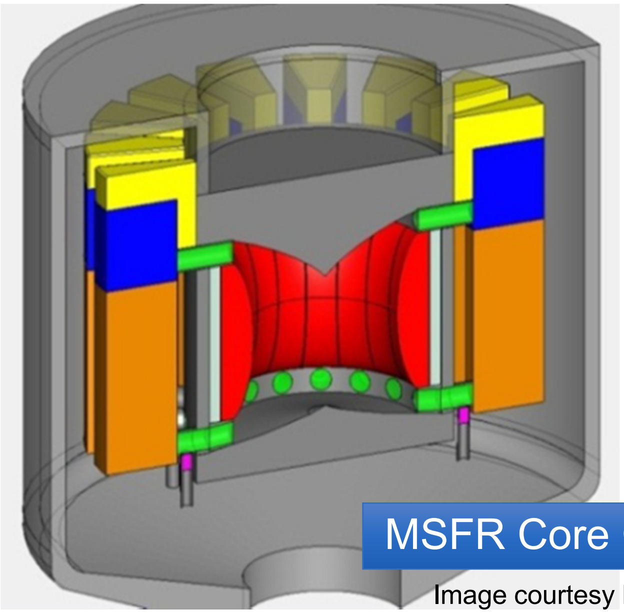


Images from ORNL/TM-2011/105

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

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 $27BeF_2$ $1TRUF_3$	75LiF $16.5BeF_2$ $6ThF_4$ $2.5TRUF_3$
Blanket salt composition, mol%	No	75LiF $5BeF_2$ $20ThF_4$

Both designs employ on-site fissile material separations

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

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 clad ASME BPVC code qualified material, 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 corrosion
  - 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

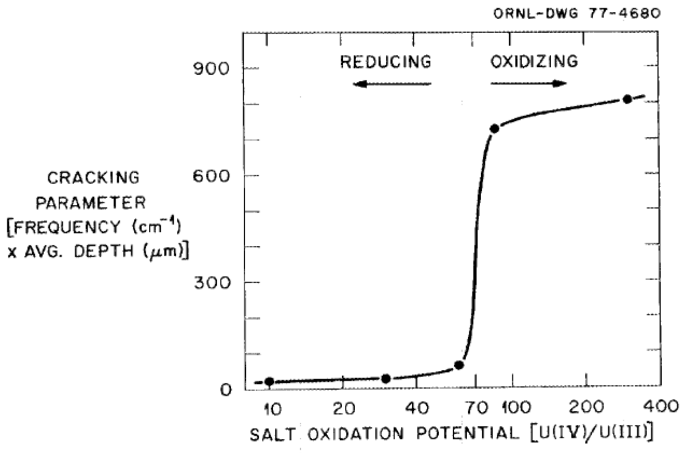


Fig. 12. Cracking Behavior of Hastelloy N Exposed 260 hr at 700°C to MSBR Fuel Salt Containing $CrTe_{1.266}$.

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 (e.g., Cs, I) form stable halide salts
  - 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 impacted into their surfaces

Liquid Fuel Reactors Require Updating Reactor Physics Simulation Tools

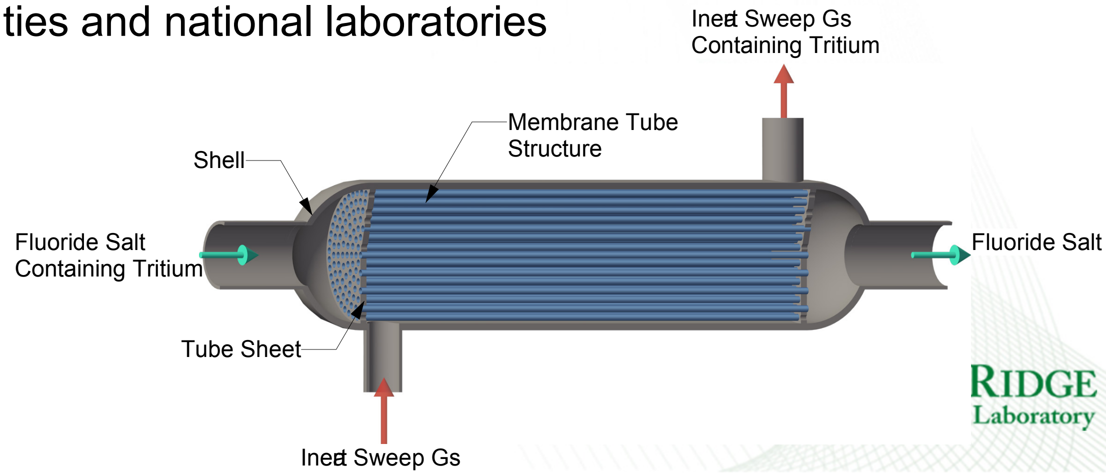
- Mobile delayed neutron precursors decrease stability margin
  - Time constants for feedback mechanisms are key
    - Doppler feedback is prompt
    - Fuel expansion out of critical configuration occurs at speed of sound
- Maximum hypothetical accident approach has been employed to bound the modeling 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 Kr + Xe a year in 8 gas cylinders

Tritium Containment Is Key Element to Lithium Fluoride Salt MSRs

- Lithium isotope separation is an 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



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
- 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

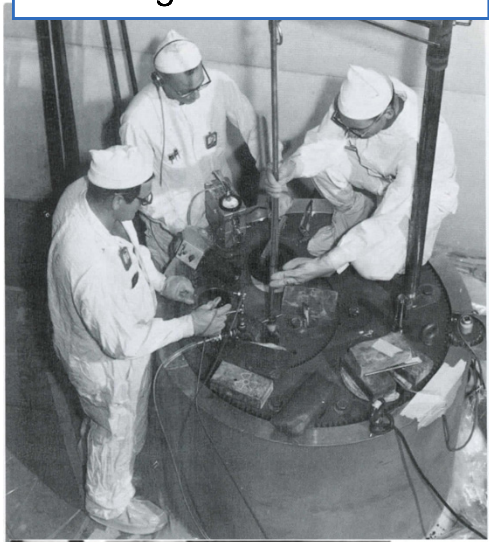
MSR Characteristics Alter the Risk Significance of the SSCs

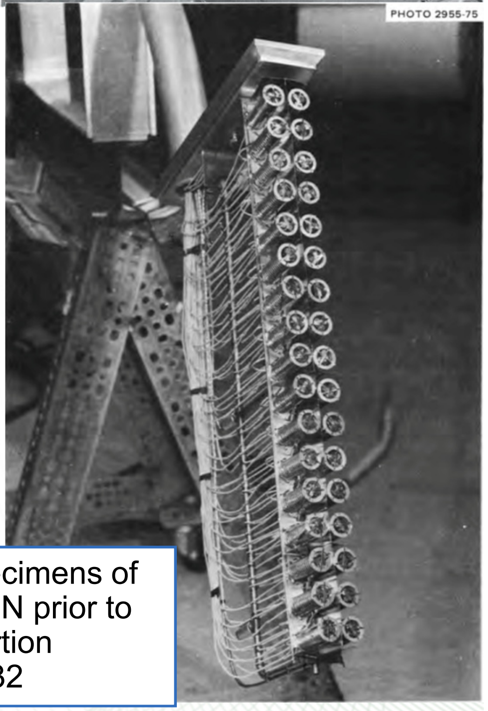
- Reduced core source term
- Increased fission gas decay tank source term
- Active systems may not be necessary to perform protection and mitigation functions
  - The capability of bringing the reactor subcritical and decay heat removal will be fully passive and cannot be disabled by control system actions
  - 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 alloys and structural ceramic composites remain at a low technology readiness levels
- 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?