Molten Salt Reactors Today Status & Challenges

Workshop on MSR Technologies – Commemorating the 50th Anniversary of the Startup of the MSRE

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MSRs Have Numerous Variants Each With Its Own Advantages and Challenges

- Salt-fueled and salt-cooled are the primary subclasses.
- Both subclasses have fast and thermal spectrum variants (epithermal and flux trap systems also possible).
- Chloride and fluoride coolant and fuel salts are both possible.
- Th/U and U/Pu fuel cycles as well as mixtures are possible.
  - Denatured designs avoid on-site fissile separations.
- Salt-fueled systems (e.g. molten salt in fuel rods) can be cooled by non-fuel salt.
- Salt-fueled systems can employ non-salt coolants.

MSRs are a class of reactors in which a molten salt performs a significant function in core.
MSRE Showed That MSRs are Possible Today’s Efforts Are to Prove They are Practical

• Lower cost power remains the central development challenge
  – Cost and reliability have been Achilles’ heels of advanced reactors
  – High thermal efficiency and low pressure form the foundation for lowering power cost

• MSRs offer increased passive safety at any scale
  – Inherent properties substantially reduce potential source term
  – Modular passive decay heat removal avoids core thermal size limit
  – Lack of cliff-like phenomena relaxes safety system performance requirements

• High temperature broadens applicability of nuclear energy
  – High temperature enables products not economically feasible with LWRs
    • High exergy increases FHR heat delivery compatibility
  – Lower cooling water requirements increases siting flexibility
Liquid Fuels Provide Additional Challenges and Potential Advantages

**Challenges**

- Much higher containment radiation environment
- High neutron and thermal flux on first wall
- More corrosive salt
- Fewer barriers to radionuclide release
- Maintenance and inspections much more difficult
- Unconventional fissile material accountancy required

**Advantages**

- No fuel fabrication
- Minimizes (avoids) in-core material performance limits
- Minimal excess reactivity
- On-line chemistry adjustment
- Breeding
- Potential fuel draining accident response
- Actinide waste production minimization
MSRs Have Substantial Remaining Technology Challenges

- 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 and reflector/shield material temperatures
    - Minimizing ex-core fuel volume necessitates high performance heat exchangers
    - Strengthening alloy microstructures dissipate over time at temperature
- Proper chemistry control is imperative
  - All alkali halide salts can be highly corrosive
  - Ratio of U³⁺/U⁴⁺ 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
Molten Salt Properties and Performance Characteristics Have Large Residual Uncertainties

• Heat transport properties of molten salts are not adequately well known
  – Thermal conductivity
  – Optical absorption, emission, and transmission properties
  – Heat transfer coefficient

• Fission product volatilization is not well quantified
  – Radionuclide source term is key element underlying safety evaluation
  – Semi-noble fission product plate-out has substantial uncertainty

• Long-term waste format remains unproven
  – Solid halide salts are not radiolytically stable
Proliferation Resistance Has Become A Dominant Concern For All Fuel Cycles

- MSRs can be highly proliferation resistant or vulnerable 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
  - Breeders can eventually eliminate need for enrichment facilities

- Liquid fuel changes the barriers to materials diversion
  - Lack of discrete fuel elements 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
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

• 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
Successful Commercial Deployment Depends Upon Resolving Multiple Materials Issues

Control Elements

Test Reactor

Successful Commercial Deployment

Chemical Compatibility

Joinability & Fabricability
MSR Commercialization Will Depend on Risk Informed Licensing

• 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

• Major historic purpose of ASME BPVC is preventing pressure vessel rupture
  – Many MSR designs rely on planned vessel rupture (freeze valves) as a safety response

• Requires well-equipped, knowledgeable regulator
Passive Safety Reduces the Risk Significance of the Components and Instrumentation

- Instrumentation may not be necessary to perform protection functions
  - Reactor shutdown and decay heat removal will be fully passive and cannot be disabled by control system or operator actions
  - MSRs lack heat transfer or temperature threshold phenomena
- Requires a plant specific PRA and validated accident evaluation capabilities to employ 10CFR50.69 for classification
  - Safety related, non safety-significant SSCs do not require Appendix B compliance
  - Goal is to lower costs and improve reliability through greater use of digital instrumentation
  - Substantial development remains to achieve design goal
- Advanced plants will feature increased amounts of safety related monitoring
MSR Potential Remains Substantial and Untapped

- Optimum MSR and fuel cycle depends upon the mission
  - Solid fuel systems minimize deviations from precedent
  - DMSRs build upon prior MSR heritage
  - FS-MSRs avoid requirement for future uranium enrichment
  - TRU fuel reduces amount of existing HLW

- Liquid fuel inherently intimately interconnects the fuel cycle with the reactor

- MSR fuel cycles can be highly proliferation resistant or have substantial proliferation vulnerabilities

- Basic elements of MSR fuel cycles have been identified and demonstrated with varying degrees of sophistication

- Significant research, development, and demonstration remains to enable any MSR