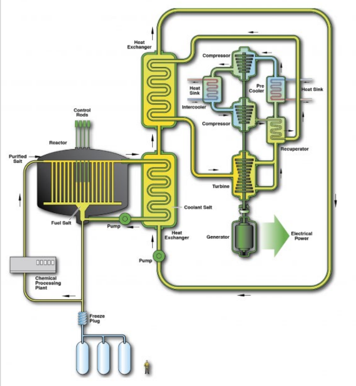
MOLTEN SALT REACTOR RECYCLE OPTIONS



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Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and Waste Aspects of Advanced Nuclear Reactors
National Academy of Sciences Review Panel
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MOLTEN SALT REACTORS

- Molten-salt-fueled reactor can be thermal or fast spectrum
  - Thermal reactors are typically based on fluoride salts, graphite moderated
    - Fuel salts examples include UF_4-BeF_2-LiF, UF_4-BeF_2-NaF
    - Coolant salts examples include FLiBe (LiF-BeF_2 eutectic), FLiNaK (LiF-NaF-KF eutectic)
    - Thorium-fueled variants add ThF_4 to fuel salt or in a second salt loop
  - Fast reactors can be based on chloride fuel salt or fluoride
    - Fuels salt examples include NaCl-KCl-UCl_3
    - Coolant salt examples include NaCl or NaCl-KCl

- Molten salts also used to cool solid-fueled reactors
  - UO_2, TRISO pebbles, molten salt fuel contained in graphite tubes
  - Coolant salt examples include FLiBe and FLiNaK

- Some systems incorporate nitrate salts in secondary heat transfer loops

- Fuel cycles are under development for many of the proposed systems

SALT TREATMENT

- Coolant salt requires periodic cleaning due to build up of fission products in coolant from fuel failures or corrosion products
  - Expected to be infrequent and part of routine maintenance system
    - Filtration or other process to remove insoluble oxides, impurities
  - Salt disposal at end of reactor life

- Fuel salt requires treatment as fission products build up and begin to impact the performance of the reactor
  - On-line or periodic off-line salt treatment to remove fission products

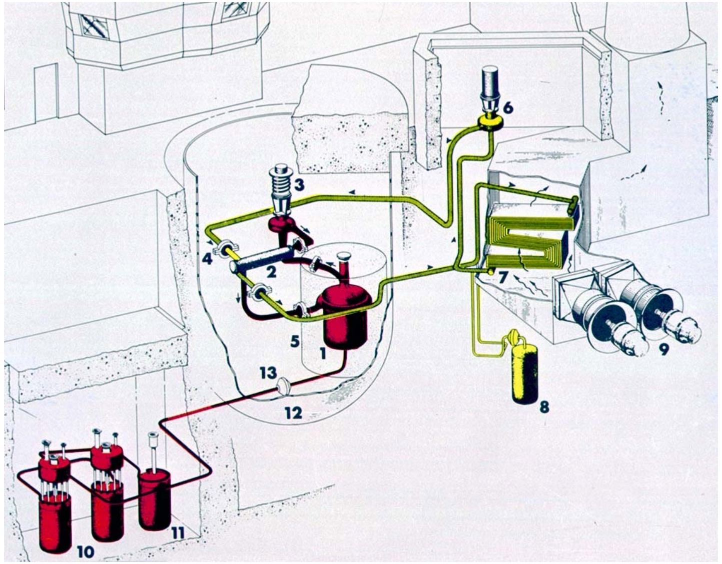
- Fertile salt treated to recover fissile components for recycle to fuel salt

- Dry treatment options
  - Electrochemical processing based on differences in electrochemical reaction potentials between actinides and other fission products
  - Fluoride or chloride volatility process based on volatility of hexavalent actinide halides
  - Reductive extraction based on favored reduction of actinide halides by a reductant metal (e.g., Li)

MSR EXAMPLES

- MSRE
  - Single and dual loop designs
  - Fuel system: UF_4-BeF_2-ZrF_4-LiF and ThF_4-UF_4-BeF_2-LiF in graphite moderated core
  - Breeding using ^{232}Th to produce ^{233}U for recycle
  - On-line salt processing proposed via two methods
    - Volatility for FP removal with U recycle
    - Reductive extraction, Th salt treatment

- Terrestrial Energy
  - Fuel loop, primary coolant, and process salt loops
  - Fuel system: fluoride salt with 5% enriched LEU
  - Swap out entire core for disposition after 7 years
    - No on-line salt processing other than gas sparge



MSRE Layout

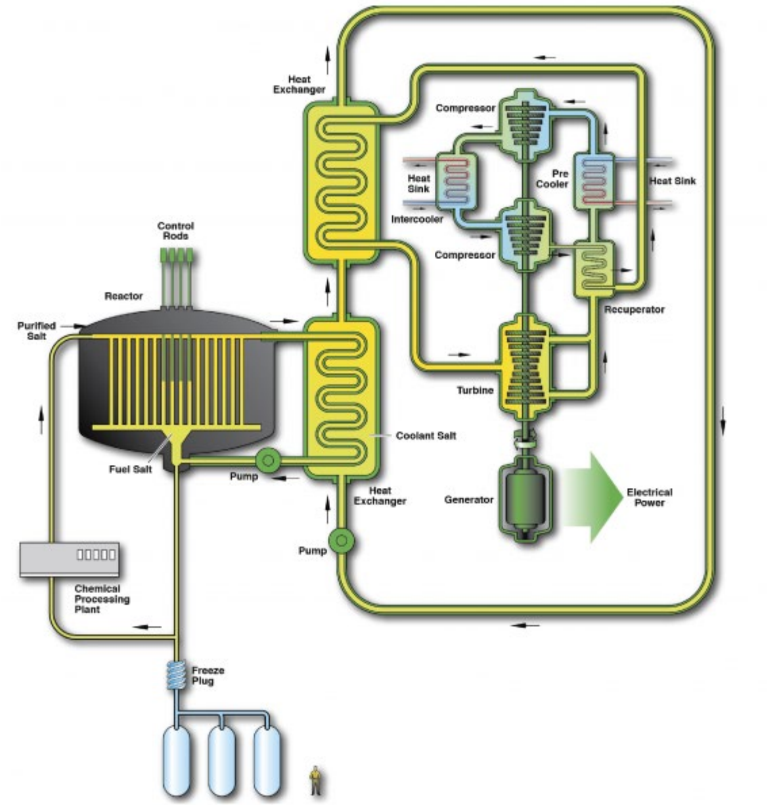
Rosenthal, et al. "Molten Salt Reactors—History, Status, and Potential," *Nuc. Apps. and Tech.*, 8, 1970, 107-117
https://www.terrestrialenergy.com/technology/molten-salt-reactor/

MSR EXAMPLES

- FLIBE Energy
  - Fuel, blanket and primary cooling loops
  - Fuel system: UF_4-BeF_2-^7LiF
  - Breeding using ^{232}Th in blanket
  - Salt processing options
    - FP removal with U recycle
    - U from Th salt treatment

- Elysium Industries
  - Fuel loop, with primary cooling and process heat loop
  - Fuel system: NaCl-KCl-UCl_3 or NaCl-KCl-$(U,Pu)Cl_3$ fuel derived from chlorinated LWR SNF
  - Fuel salt treated periodically to remove FP poisons; actinides remain in fuel salt

https://flibe-energy.com
www.elysiumindustries.com



GenIV MSR Concept

OFF-GAS TREATMENT

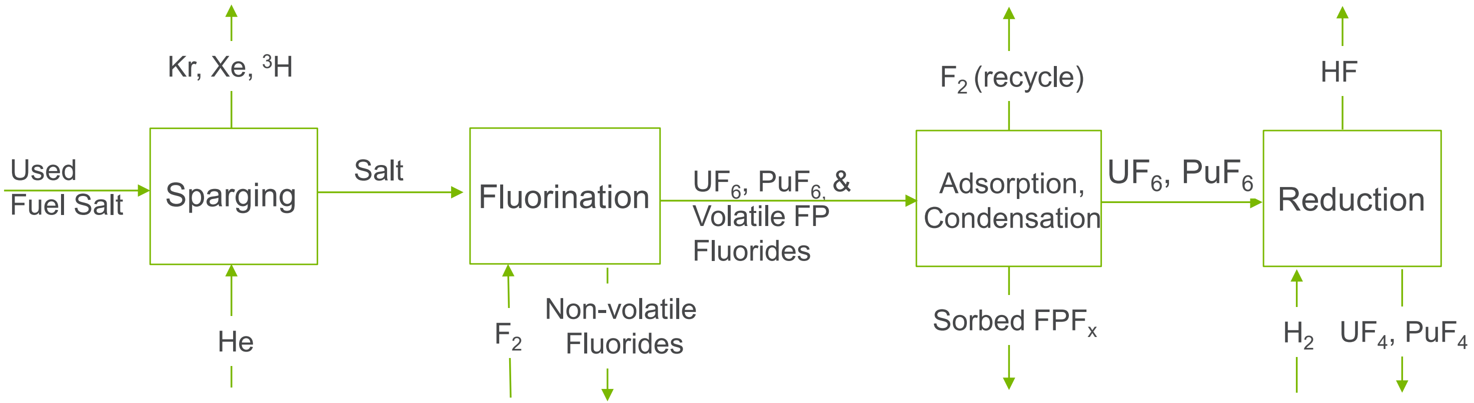
- Volatile fission products will be released via sparging and agitation
  - Xe, Kr, ^{3}H removed up front via sparging with He or Ar
  - Cs, I remain in salt with non-volatile FPs rather than released
  - Some transition metal fission products entrained in sparge
    - Separated by condensation

- Fluorination
  - Fluorination: UF_6 is volatile at ~60ºC; NpF_6 and PuF_6 are also volatile
  - Some transition metal fission products entrained in sparge and F_2
    - Separated from UF_6 by distillation, condensation
  - Fission product capture complicated by the presence of fluorine gas

- Fluoride and chloride salts, particularly the alkali, alkaline earth and lanthanide chlorides, have low volatilities even at elevated temperatures
  - UF_4, UCl_3, $PuCl_3$, etc. volatility is very low at process temperatures

TREATMENT OPTIONS: VOLATILITY

- Volatility process separates U and Pu (and Np) as volatile hexavalent halides for recycle
  - Volatile fission products are evolved in initial sparge step
  - Fluorination generates volatile UF_6, (also PuF_6, NpF_6) which is captured, condensed, and reduced to tetrafluoride for recycle
  - Non-volatile fission product fluorides are collected for disposition
  - For Th options, Pa management required for PaF_4 and PaF_5
  - Chloride volatility follows similar approach



SALT TREATMENT LOOP FOR MSBR (ORNL)

- 2-Loop process
  - Fuel salt
  - Blanket salt
- Volatilization of UF_6 is basis of treatment
- Fission product removal via waste salts, adsorbents

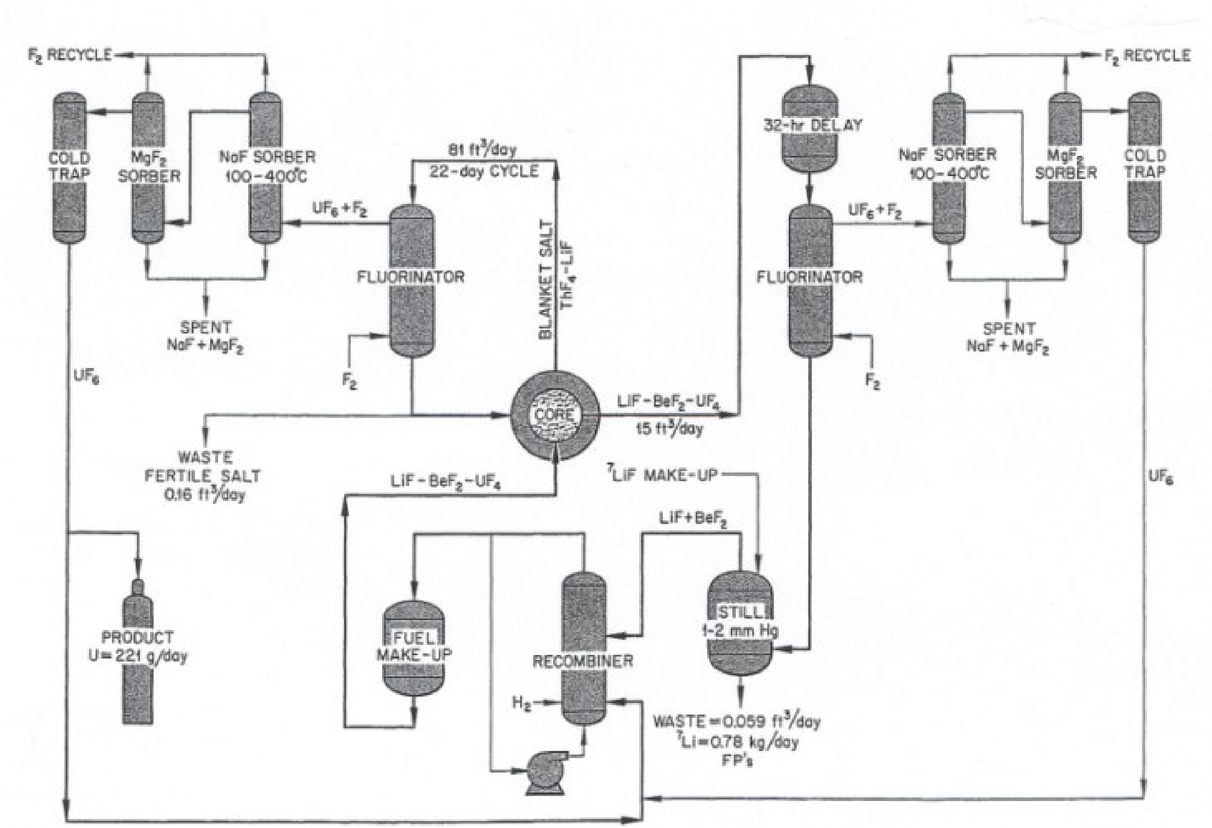
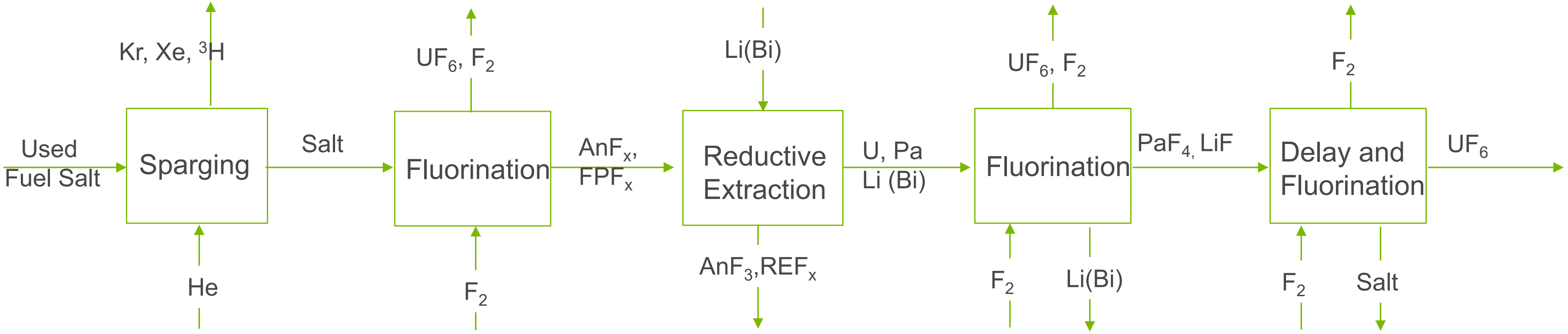


Figure: ORNL-4037

TREATMENT OPTIONS: EXTRACTION

- Reductive extraction based on reduction of UF_4 (and PaF_4) by Li dissolved in liquid Bi
  - Fuel salt is first fluorinated to evolve UF_6 for recycle
  - Residual U is reduced and dissolved into the Bi stream, which is immiscible with salt
  - Less reactive fission products remain in the used fuel salt
  - Pa decays to ^{233}U, is volatilized as UF_6 and recycled
  - U/Li/Bi stream is refluorinated to form UF_6 to regenerate fuel salt for recycle

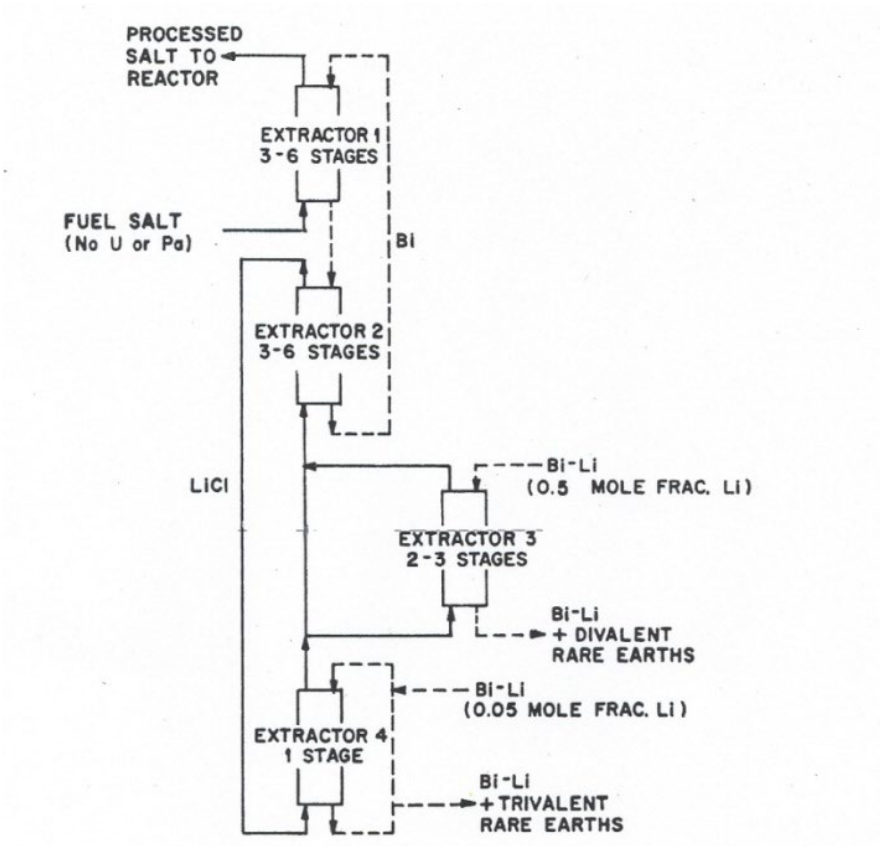


SALT TREATMENT LOOP FOR MSBR (ORNL)

- Extraction process with Li in Bi
  - Fluoride loop to recover residual U and Pa if present
  - Chloride loop to recover lanthanide fission products for disposal

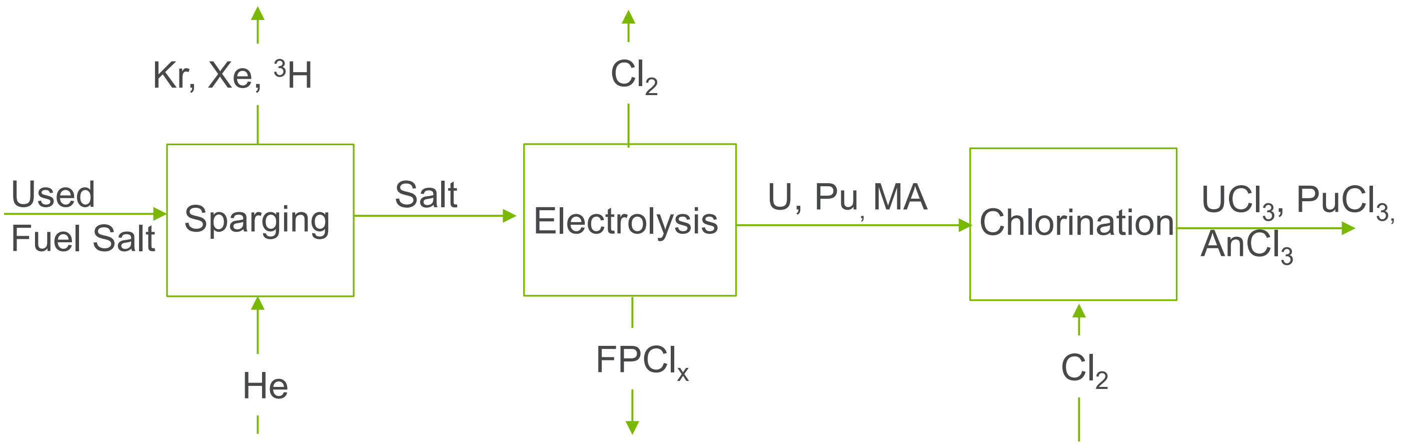
- Used in tandem with UF_6 recovery by volatility differences

Figure: modified from ORNL-4548



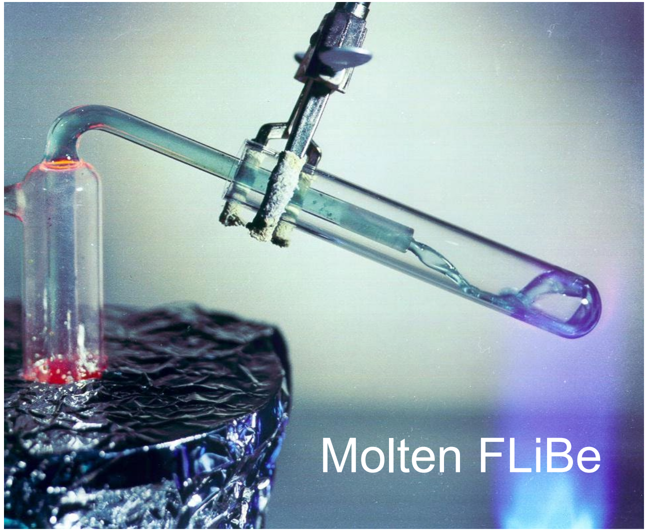
TREATMENT OPTIONS: ELECTROLYSIS

- MSR salt treatment meshes well with technologies being developed for pyroprocessing
  - Electrochemical process collects actinides as metals and fission products remain in the electrolyte salt for disposition
  - Purified uranium or mixed actinides are electrolyzed and collected on cathodes, chlorinated and recycled as liquid fuel salt



SALT WASTE DISPOSITION

- Repository requirements will drive ultimate disposition designs
  – Direct disposal of salt-bearing waste forms most amenable to a salt repository
- Waste forms must retain chlorides or fluorides
  – Several candidates developed for EBRII electrorefiner salt
- Salts may also be dissolved and fission products isolated from halides for placement into glass or ceramic forms



Argonne NATIONAL LABORATORY