THE FUEL CYCLE FOR MOSART: TAXONOMY AND TERMINOLOGY RELATED ISSUES

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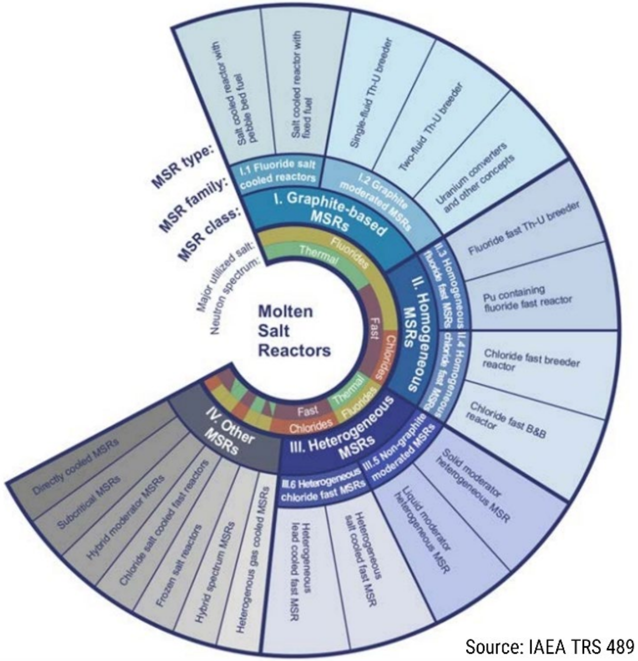
In MSR devices solid fuel elements are replaced by liquids

<u>Chemical engineering device </u>has not only possibilities of general benefits such as unlimited burn-up, easy and relatively low cost of purifying and reconstituting the fuel (fluid), but also there are other specific potential gains:

- Minimum number of parasitic absorbers and as a consequence less loading of fissile materials in the core.
- On-site fuel processing - no temporary storage is required to hold UNF, transportation of UNF and fuel loading for the next transmutation cycle.
- Multiple actinides recycling with minimal losses to waste.
- Flexibility in operation, deployment and product, including the ability to operate: (1) with fuels of various nuclide composition without reactor shutdown and core modifications; (2) in load follow mode; (3) with high thermal efficiency, due to the fuel salt temperature 700°C and more, for electricity and hydrogen production.



Source: IAEA TRS 489

Liquid fuel MSR makes the following possible:

- minimize the initial reactivity excess, which in solid-fuel reactors is compensated by control rods;
- maintain low pressure in the fuel by removing gaseous FP’s from it;
- reduce the amount of fission products and decay heat in the fuel salt.

The radiation safety of MSR is determined by reliable sealing of the actinides and fission products within the reactor circuit and by an effective system for fuel processing. Also playing an important role is the capacity of the fuel salt mixture to retain many dangerous radionuclides in a wide range of the physical parameters, which are characteristic for emergency modes and disruption of normal operation.

MSR offers good option for the long lived waste incineration: fuel cycle flexibility, simplified fuel processing, in-service inspection, no fuel transportation and refabrication, intrinsic safety features:

- Fuel performs cooling function
- Strong temperature negative reactivity feedback
- High boiling point (low pressure)
- Large volumetric heat capacity.

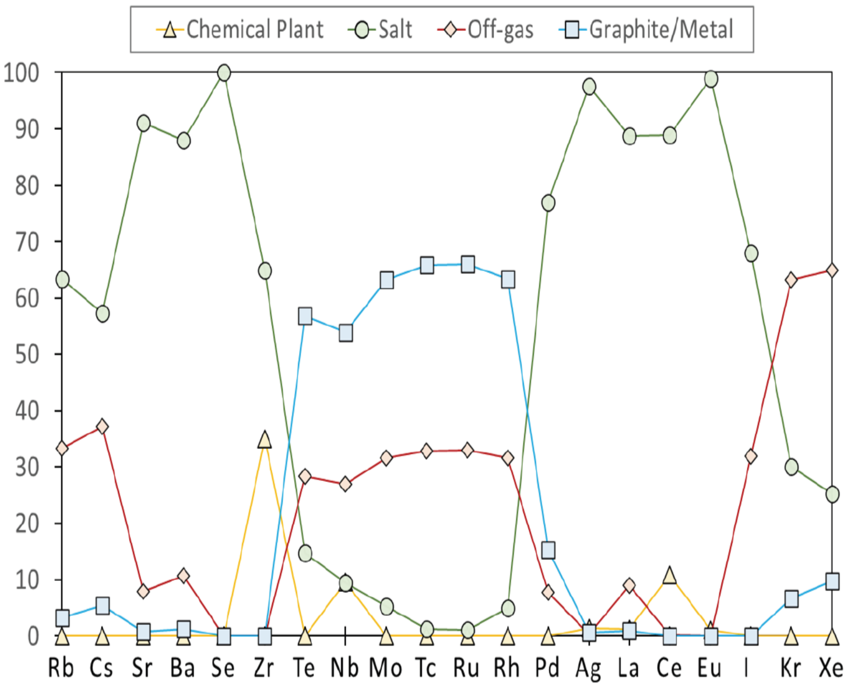
But also some challenges:

- *Potentially highly corrosive behavior*
- *High melting point and solubility limit for fuel addition*
- *Significant quantities of fuel outside the core: heat exchangers, various tanks, pumps, possible associated fuel processing, possible continuous addition / removal of fuel*
- *Distributed delayed neutrons (mobile fuel)*
- *Noble gas FPs evolve out of the salt into cover gas; noble metal FPs plate out onto surfaces; fuel salt retains most other FPs*
- *Salt vapor deposition in cover gas lines*
- *Potential for larger volumes of high activity components (filters and replaced components)*
- *Fuel composition continuously changing*
- *Tritium production (lithium fuel salts)*
- *Presence of bubbles (fission product gasses) passing through the core*

To achieve fuel maintenance: (1) the fuel must be delivered into the reactor in a proper state of purity and homogeneity, (2) the fuel must be sufficiently protected from extraneous impurities, and (3) sound procedures must exist for provision of the required redox potential in the system. They also include:

- addition of fuel to replace that lost by burnup
- continuous removal of Xe and Kr by He sparging
- removal of a portion of the insoluble noble FPs
- recycling of all actinides with min losses to waste
- removal of soluble FPs (principally rare earths)

Element	Time
Kr, Xe	50 s
Zn, Ga, Ge, As, Se, Nb, Mo, Ru, Rh, Pd, Ag, Tc, Cd, In, Sn, Sb, Te	2-4 hrs
Zr	1-2 yrs
Ni, Fe, Cr	1-2 yrs
Pu, Am, Cm, Np, U	1-2 yrs
Y, La, Ce, Pr, Nd, Pm, Gd, Tb, Dy, Ho, Er, Sm. Eu	1-2 yrs
Sr, Ba, Rb, Cs	5-10 yrs



Noble Gas Fission Products

- Kr and Xe form no compounds under conditions existing in a MSR. Moreover, these gases are only very sparingly soluble in molten fluoride mixtures. This low solubility is a distinct advantage because it enables the ready removal of Xe and Kr from the reactor by sparging with helium.
- The transmutation of Li is essential for production of tritium. This tritium should be reduced largely to $^3H_2$, in order to minimize corrosion for container material. Main part of this $^3H_2$ would be removed, along with krypton and xenon, by sparging with helium. However, the extraordinary ability of hydrogen isotopes to diffuse through hot metals will permit a minor fraction of the $^3H_2$ to penetrate the primary heat exchanger to enter the coolant circuit.
- Such a stripping circuit would remove a major fraction of the tritium and a some (probably minor) fraction of the noble and semi noble fission products (FP) as gas-borne particulates.
- In addition, the stripper would remove BF_3 if leaks of secondary NaF-$NaBF_4$ eutectics coolant into the fuel were to occur. None of these removals (except possibly the last) appreciably affects the chemical behavior of the fuel system.

Noble and Semi Noble Metal Fission Products

- Some FP metals (Ge, As, Nb, Mo, Ru, Rh, Pd, Ag, Cd, Sn, and Sb) have fluorides that are unstable toward reduction by fuel mixtures with appreciable concentrations of NpF_3 or UF_3; thus, they must be expected to exist entirely in the elemental state in the MSR. Se and Te were also expected to be present as elements within the reactor circuit, and this behavior was generally confirmed during operation of the MSRE
- Precipitation on the metal surface (most of which is in the HE) will be quite insufficient to impede fuel flow, but radioactive decay of the deposited material contributes to heat generation during reactor shutdown
- Tellurium FP was responsible for the embrittlement of the metal surface exposed in MSRE, and subsequent work has confirmed this. Later work strongly suggest that: (1) if the molten fuels were made to contain as much as 2-5% of the uranium as UF_3, the tellurium would be present as Te^{2-} and (2) in that form, Te is much less aggressive.

Soluble Fission Products

- Rb, Ce, Sr, Ba, Y, the lanthanides, and Zr all form quite stable fluorides that are relatively soluble in fuel salts.
- Bromine and iodine would be expected to appear in the fuel as soluble Br and I, particularly in the case where the fuel contains an appreciable concentration of NpF_3 or UF_3.
- Analyses for ^{131}I showed that a large fraction of the iodine was present in the fuel and that ^{131}I deposited on metal or graphite surfaces in the core region. However, material balances for ^{131}I were generally low. It is possible that some of the precursor, ^{131}Te (25 min), was volatilized and sparged with the krypton and xenon. Further, ^{131}I produced by decay of ^{131}Te in complex metallic deposits (as in the HE) may not have been able to return to the salt.

Reductive extraction

$$MF_{n(salt)} + nLi_{(Bi)} = M_{(Bi)} + nLiF_{(salt)}$$

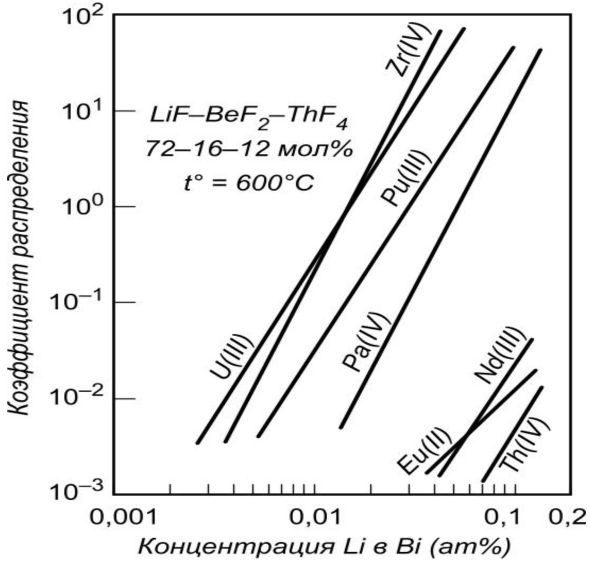
The equilibrium constant of the reaction is determined by the equation:

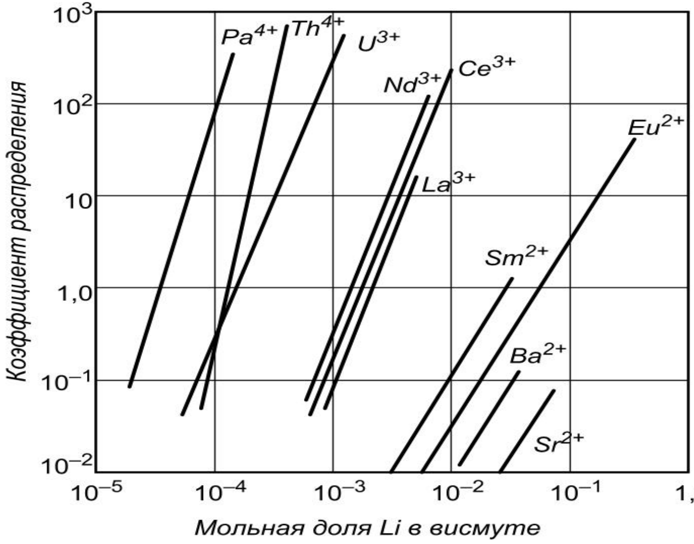
$$K_1 = [(a_{M(Bi)}\ a^n_{LiF})/(a_{MFn}\ a^n_{Li(Bi)})] = [(X_{M(Bi)}\ \gamma_{M(Bi)}\ X^n_{LiF}\ \gamma^n_{LiF})/(X_{MFn}\ \gamma_{MFn}\ X^n_{Li(Bi)}\ \gamma^n_{Li(Bi)})]$$

The equation for the equilibrium constant can be rewritten as

$$\lg D_M = n\ \lg D_{Li} + \lg K'_M,$$ где

$D_M = X_{M(Bi)}/X_{MFn}$ и $D_{Li} = X_{Li(Bi)}/X_{LiF}$ - distribution coefficients of elements; $K'_M = f(T)$



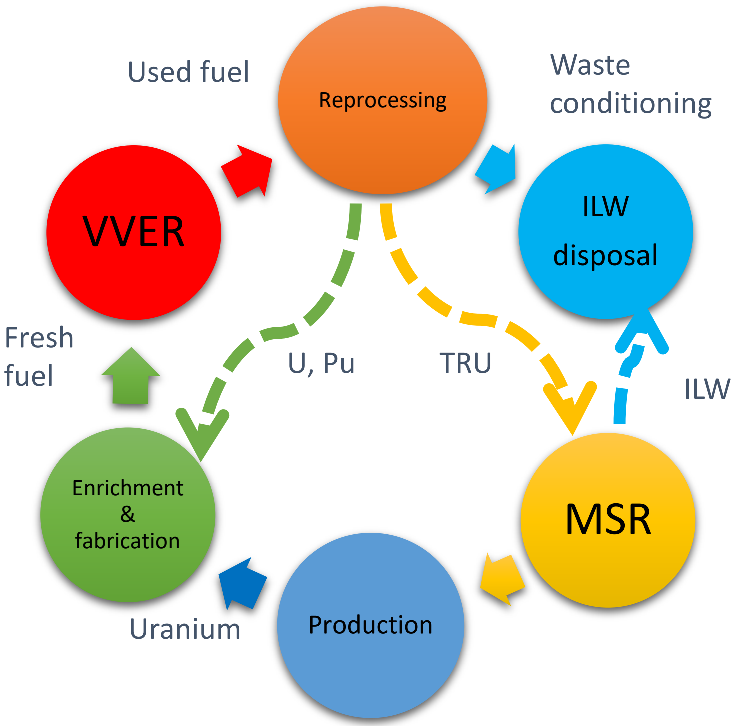


Reductive extraction

Element	Separation Coefficients			
	LiCl-KCl/Cd, 773K	LiCl-KCl/Bi, 773K	$LiF-BeF_2/Bi$, 873K	$LiF-BeF_2-ThF_4/Bi$, 873K
U	1	1	1	1
Np	2	8-10	-	3-4
Pu	2	12	8	12
Am	1-3	23	-	16
Cm	3-4	-	50	90
Nd	40	1000	25000	18000
La	45	2500	190000	27000
Gd	50	10^4	10^6	-
Sm	130	10^6	10^5	$2{\cdot}10^5$
Eu	180	10^7	$4{\cdot}10^7$	$2{\cdot}10^7$

Element	Solubility in liquid Bi, mass.%		
	550°C	600°C	650°C
U	0,86	1,32	1,95
Th	0,11	0,21	0,38
Pa		0,45	
La	1,29	2,27	3,75
Zr	0,5	0,7	0,8
Fe	0,06	0,008	0,01
Pu		3,6	
Sr		12	

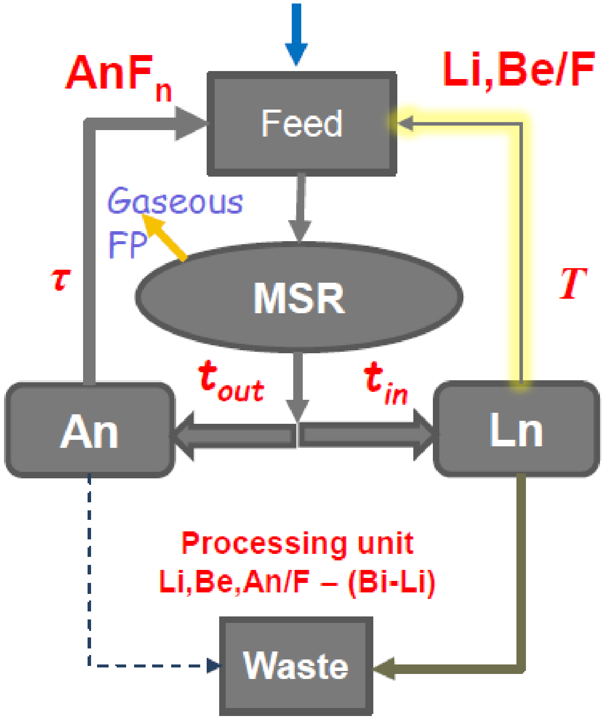
Introduction of 2.4 GWt MOSART into the Russian nuclear power as an integral element help to solve the problem of minor actinides and close the fuel cycle for all actinides



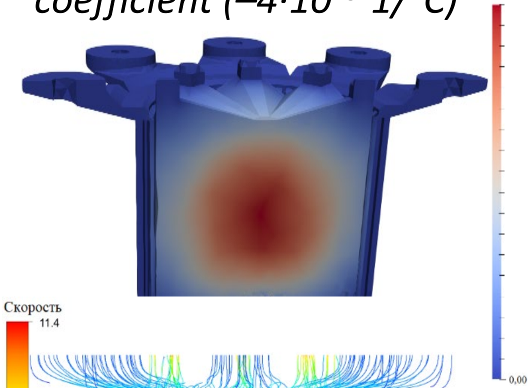
Fuel salt	$LiF\text{-}BeF_2\text{+}TRUF_3$
Temperature, ^{o}C	650-750
Core radius / height, m	1.4 / 2.8
Core specific power, W/cm^3	130
Container material	Ni-Mo-Cr alloy
Removal time for soluble FP, yr	1-3

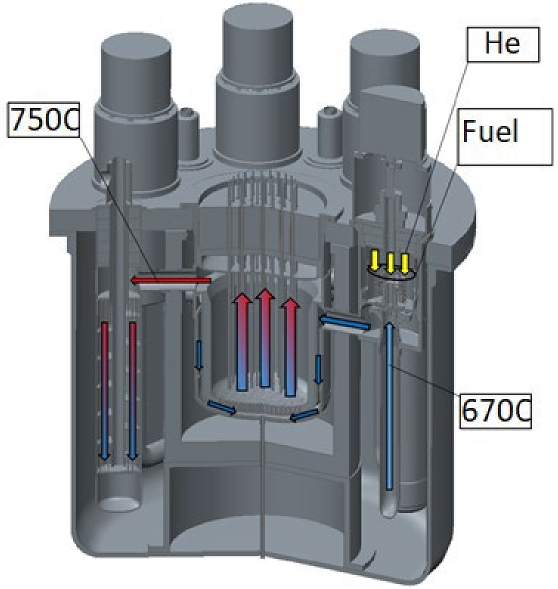
Solvent, mole %	Feed MA/TRU	Loading (EOL), t	TRU/MA, kg/yr
$73LiF\text{-}27BeF_2$	0.1	3.9	730/73
$73LiF\text{-}27BeF_2$	0.35	13.9	730/260
$73LiF\text{-}27BeF_2$	0.45	23.2	730/330

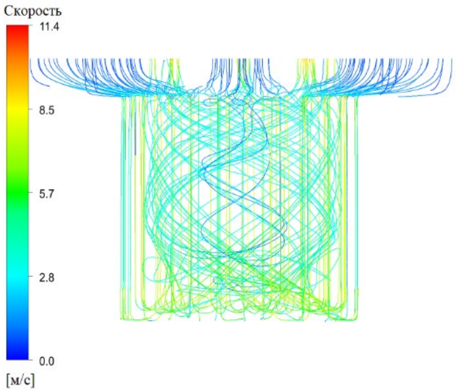
2.4 GWt MOSART design utilize Ni-base alloy as the containment vessel and other metallic parts. Fuel salt will leave the cavity type cyclonic core at a temperatures 750°C and energy will be transferred to a Li,Be/F eutectic coolant salt which in turn is used to produce supercritical steam

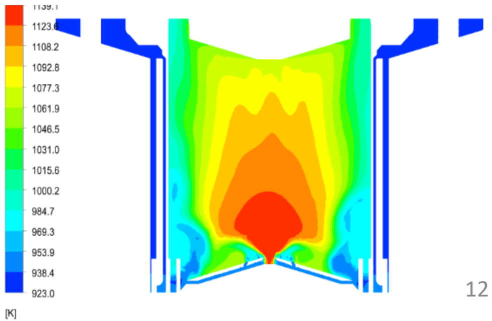


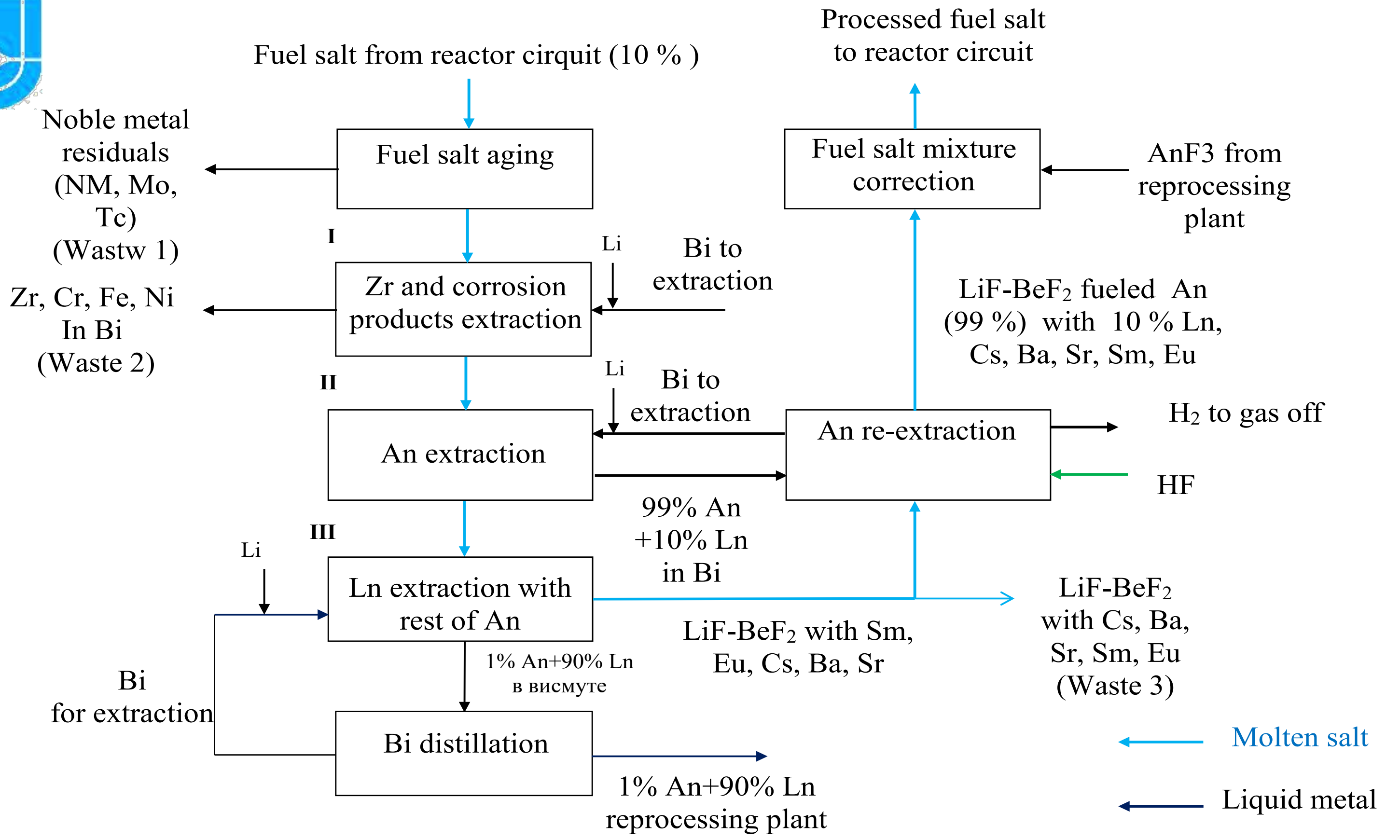
Delayed neutron fraction (the static) $\beta_{eff} = 320{\cdot}10^{-5}$;
Temperature reactivity coefficient ($-4{\cdot}10^{-5}$ 1/°C)







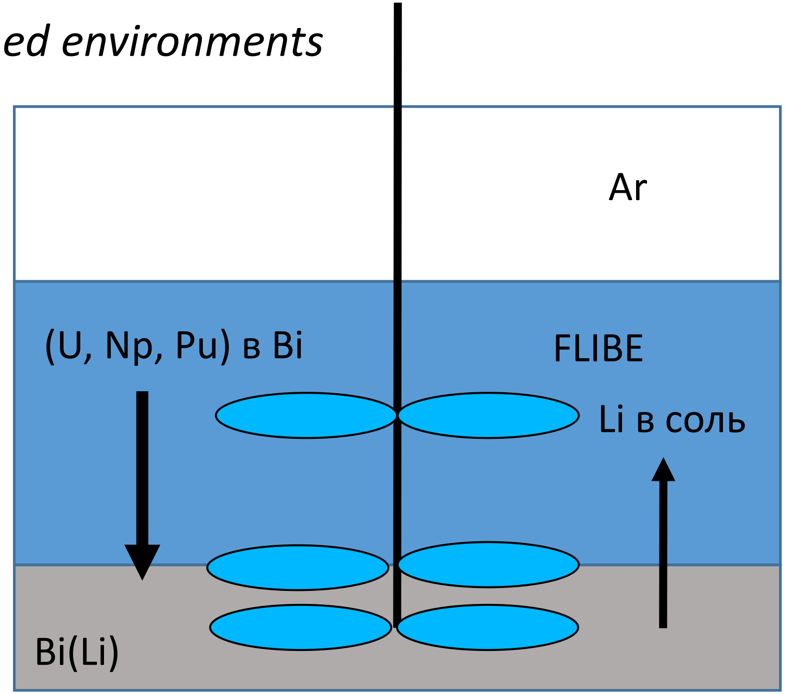




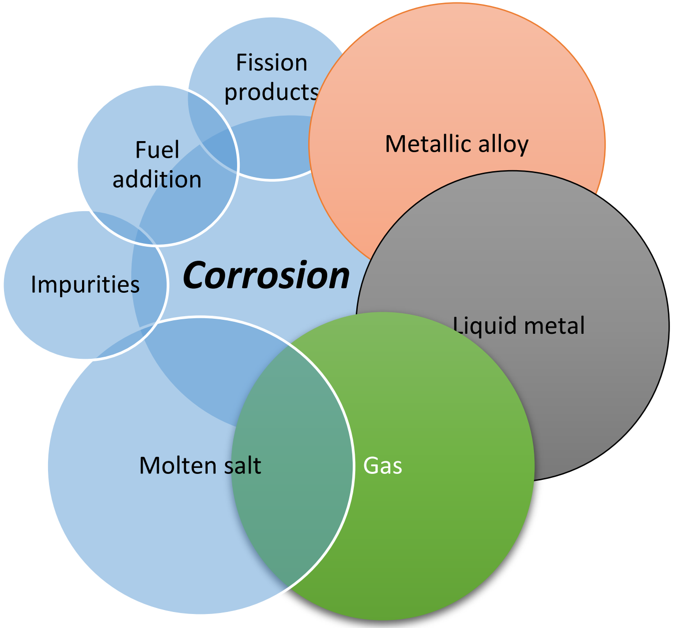
MOSART Processing Flowsheet based on reductive extraction to Bi(Li)

The success of MOSART processing unit is strongly dependent on the compatibility of the materials used with the fuel salt and liquid metal

Combined environments



Corrosion effects



Fuel processing materials development

- It is not necessary that a single material be compatible with all environments anticipated in the processing plant since the system can be designed to allow segregation of particular portions of the plant. It is expected that at least two classes of materials will be required: one for the hydrofluorination and another for the reductive extraction steps.

- Ni, which in some cases must be protected from corrosion by a layer of frozen salt, can be used for those portions of a plant which contain fluorine and HF.

- Materials which have shown good compatibility with Bi solutions during limited tests include graphite and refractory metals such as tungsten, molybdenum, and tantalum. Except for Ta, these materials are difficult to fabricate and join.

Conclusion

- Liquid metal extraction is a promising pyrochemical method for MOSART fuel salt processing.
- To technologically justify this technique application to the MOSART fuel salt processing unit, a series of experimental tests are underway in the Russian Federation.
- This primarily involves studying the key physical - chemical properties of reaction media (melting diagrams of multicomponent systems, solubility of fuel components in fluoride melts and liquid metals) and process parameters (thermodynamic and kinetic parameters of the main chemical reactions).