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U-Pu Fast Molten Salt Reactor and its Fuel Cycle

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Abstract – *The recent discovery of extremely high solubility of PuF_3, UF_4 and AmF_3 in the melted LiF-NaF-KF eutectics actually opens a way for developing the fast molten salt reactor (FMSR) with U-Pu fuel. Such a reactor can work in the equilibrium mode, i.e. using ^{238}U only, or in the subcritical mode as the efficient Am burner which does not require the fissile elements (^{235}U and ^{239}Pu) for reactor feeding.*

I. INTRODUCTION

The contemporary nuclear power based on thermal reactors using the rare isotope ^{235}U has no the sustainable future, because it cannot solve its fundamental problems: resources, safety, nonproliferation, radioactive waste handling, economics, etc. In principle the ^{235}U resource problem and the radioactive waste problem can be solved using the fast reactors, but the safety of the sodium fast reactor is questionable, as well as its economics.

It is known that molten salt reactors (MSR) are inherently safe, because their thermal and void coefficients are negative. It was demonstrated during the MSRE program [1,2] which used Th-U fuel and $2LiF\text{-}BeF_2$ (FLiBe) carrier salt. But the thorium based reactor cannot solve the resource and waste problems of the U-Pu fuel cycle, because its neutron spectrum is thermal.

The MSR with fast neutron spectrum and U-Pu fuel was not possible till recently because the solubility of PuF_3 in the all known carrier fluoride salts did not exceed ~ 1 mol.% [3].But in the last two years it was established experimentally, that in the eutectics 46,5LiF – 11,5NaF – 42KF, mol% (FLiNaK) at 700°C the solubility PuF_3, UF_4 and AmF_3 are extremely high (~30, ~45, ~40 mol.% correspondingly) [4-7].This observation opens the way to the development of the fast molten salt reactor (FMSR) with U-Pu fuel cycle [8,9], as well as the subcritical MSR-burner of Am [10].

II. MAIN RESULTS

Tables 1 and 2 present the main properties of the carrier salts FLiBe and FliNaK: all their thermo-physical properties are similar as well as the corrosion properties [11], but the PuF_3 solubility differs drastically. The temperature dependence of the solubility UF_4,PuF_3 and AmF_3 as well as some lanthanide fluorides in FLiNaK are presented at Fig.1 and 2 [9].

TABLE I

Properties of FLiBe and FLiNaKat 700°C

Salt, *mole %r*	Mol. Mass, *g/mol.*	Melting point, °C	Density ρ, *g/cm³*	Vapor pressure 900°C, *mm Hg*	Heat capacity ρc_p, *J/cm³ °C*	ViscositycP, *m²/c*	Thermal conduct., *W/m·K*
$67LiF\text{-}33BeF_2$	33	460	1.94	1.2	4.69	5.6	1.00
46.5LiF-11.5NaF-42KF	41.3	454	2.02	0.7	3.81	2.9	0.92

TABLE II

Solubility of PuF_3 in FLiBe and FLiNaK

Salt, mole %	Melting point, °C	Temperature, °C			
		550	600	650	700
$67LiF\text{-}33BeF_2$	460	0.31	0.45	0.84	–
46.5LiF-11.5NaF-42KF	454	6.8 ±0.6	12.7 ±1.0	21.2 ±1.8	31.1 ±2.5

The neutron spectrum of MSR with FLiNaK as the carrier salt (Fig.3) is very similar to the fast reactor one [9]. (The gap in the FMSR neutron spectrum is explained by the high neutron elastic scattering cross-section on fluoride nuclei [10]). The high PuF_3 solubility in FLiNaK allows developing FMSR operating in the equilibrium mode, i.e. reactor using as a fuel ^{238}U only. The main parameters of such FMSR are presented in Table 3.

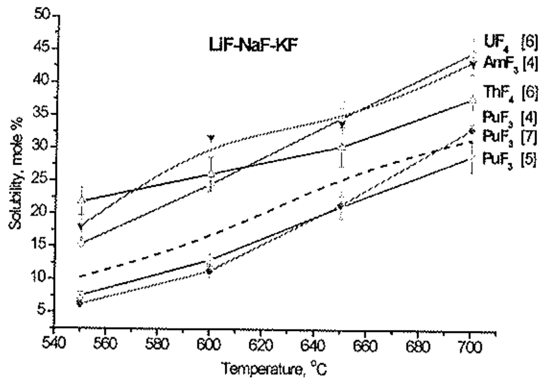

Fig. 1.Solubility of the actinide fluorides in FLiNaK.

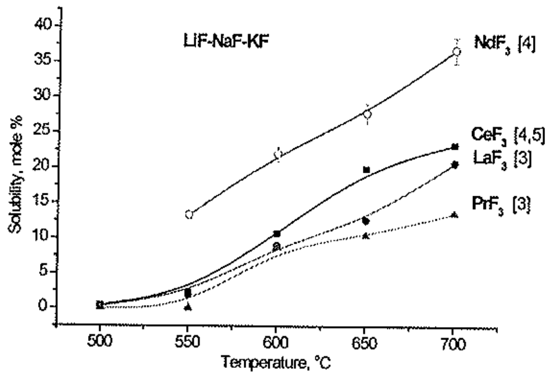

Fig. 2.Solubility of the lanthanide fluorides in FLiNaK

TABLE III

Main characteristics of U-Pu FMSR

Power, *MWth*	3200
Volume, m^3	21.2
Height/radius, *h/r*	1.85
Initial fuel loading U/Pu/TRU, *tons*	68.5/15/-
Specific power, W/cm^3	150
Average neutron flux, $cm^{-2}s^{-1}$	$2{\cdot}10^{15}$
Equilibrium fuel loading U/Pu/Am,Cm, *tons*	68.6/20.9/1.4
Effective fuel density, g/cm^3	3.1
UF_4/PuF_3 equilibrium concentration, *mole* %	21/7
Pu/Am,Cm equilibrium concentration, *mole* %	7/0.5
k_{ef} in equilibrium state	1.008
k_{∞}	1.044
Fraction of the delayed neutrons, β, %	0.34 ~0.15 [a)]
Void coefficient, $dk_{ef}/(d\rho/\rho)$	−0.06
Temperature coefficient, $[dk_{ef}/(d\rho/\rho)]/[(d\rho/\rho)/dT]$, $1/K$	$-2.4{\cdot}10^{-5}$

a) Taking into account the coolant loop.

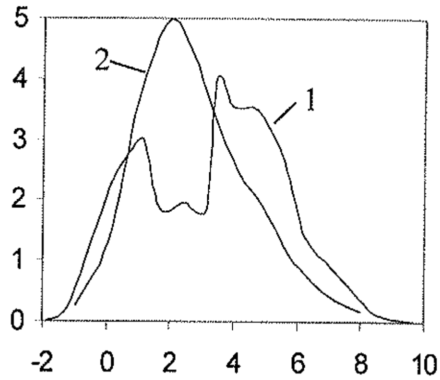

Fig. 3.Neutron spectrum as a function of lethargy[9,10]; $u = \ln E_0/E$, E_0=2 MeV: 1 –UPu-FMSR; 2 –fast reactor.

The closed nuclear fuel cycle of FMSR is not developed yet, but it looks much more cheap and simple in comparison with FR one because it does not need in the fabrication of solid fuel elements from very active spent fuel and utilization of their metal construction elements. The fuel cycle of FMSR can be very much simplified [12], and there is also an idea to improve it using the fractional deposition of the actinide and lanthanide oxides [13].

TABLE IV

Main characteristics of the subcritical FMSR-burner

Power, *MWth*	1650	495
Accelerator power, *MW* [a)]	10	3
Subcriticality, Δk [b)]	0.01	0.01
Average neutron flux, $cm^{-2}{\cdot}s^{-1}$	$2.2{\cdot}10^{15}$	$2.2{\cdot}10^{15}$
Height /radius, *m*	1.74/0.94	1.16/0.63
Fuel salt loading, m^3	8.27	2.48
active core	4.74	1.42
first loop	3.3	1.0
regeneration loop	0.2	0.06
Transuranium part, *mole %*	14	14
Fuel loading, *tons* U/Np/Pu/Am	10.7 0.05/0.01/ /5.26/5.39	3.21 0.014/0.003/ 2.31/1.61
Pu/Am: loading	0.975	1.75
feeding	0	0.59
Rate of Am burning, *kg/year*	520	98
Normalized rate burning, *kg/year·GWth*	~300	~200
Time of the Am initial loading burning τ_{in}, *years*	11	16

a) The neutron production in the target is n ≈ 20.
b) At the subcriticality Δk = 0.03 the accelerator power is 3 times more.

The extremely high solubility of AmF_3 in FLiNaK allows create the high efficiency FMSR-burner of americium, which consumes as a fuel Am only without feeding reactor by the other fissile nuclides (^{239}Pu or ^{235}U). Such a reactor can transmute ~300 kg/year·GWth, i.e. production of ~30 thermal reactors of the same power [9]. Due to the small fraction of the delayed neutrons of Am ($\beta \sim 0.27\%$) this reactor should probably work in the subcritical mode. The main parameters of such reactor are presented in Table 4.

IV. CONCLUSIONS

The first calculations of the FMSR [8,9] manifest that there are no principal restrictions for the development of the fast molten-salt reactor with U-Pu fuel cycle. Its preferences are well known: the negative temperature and void coefficients make impossible the severe nuclear accidents; the absence of the pressure and active chemical substances inside active zone; the small excess of reactivity; it does not need in the fabrication of the solid fuel elements from the high active spent nuclear fuel, it is naturally fitted for closing nuclear fuel cycle and it fulfills the nonproliferation requirements. The five year MSRE experience confirmed the effective MSR maintenance and safety operation.

Of course, there are many unsolved problems, first of all the development of the materials resistant to corrosion under the fast neutron intense irradiation and the systems for the distant reactor maintenance. But the benefits are so serious that these efforts look reasonable and well grounded.

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NOMENCLATURE

MSR -molten salt reactors;
FMSR- fast molten salt reactor;
FliNaK- eutectics46,5LiF–11,5NaF–42KF, mol%;
FLiBe – eutectics 67LiF-33BeF$_2$, mol%.

REFERENCES

1. P. Haubenreich and J. Engel, "Experience with Molten-Salt Reactor Experiment", *Nucl. Appl. and Technol.*, **8**,118 (1970).
2. H. G.MacPherson, "The molten-salt reactor adventure,"*Nucl. Sci. Eng.*, **90**, 374(1985).
3. L.I.Ponomarev, M.B.Seregin, A.P. Parshin et al., "Choice of the fuel salt for the molten salt reactor", *At. Energ.*,**115**,*1*, 6(2013).
4. A.A.Lisin, S.V.Tomilin, O.E. Gnevashov et. al., "Solubility of PuF$_3$, AmF$_3$, CeF$_3$ and NdF$_3$ in the molten-salt LiF-NaF-KF",*ibid.*, 11.
5. N.V.Volozhin, R.Zakirov, P.N. Mushnikov et. al., "Solubility of cerium and plutonium threefluorides in the molten-salt LiF-NaF-KF", *ibid.*, 17.
6. A. A.Lisin, S.V.Tomilin, O.E. Gnevashovet. et al., "Solubility ofUF$_4$, ThF$_4$ in the molten-salt LiF-NaF-KF", *ibid.*, 20.
7. O.Benes and R.Konings, "Actinide burner fuel: potential composition based on thermodynamics evaluation of MF3-PuF3 (M – Li, Na, K, Rb, Cs) and LaF3-PuF3 systems", *J.Nucl.Matter*, 377, 3, 449 (2008).
8. A.M. Degtyarev and L.I., Ponomarev,"Molten-salt reactor with fast neutron spectrum", *At. Energ.*,**112**,*6*, 367(2012).
9. A. M. Degtyarev, A. A.Myasnikov, L. I. Ponomarev, "Molten-salt fast reactor with U-Pu fuel cycle", *Prog. Nucl. Energy*, **82**, 33 (2015).
10. A.M. Degtyarev, O.E.Kolyaskin, A.A.Myasnikov et. al., "Molten-salt subcritical reactor-burner of the transplutonium actinides"*At. Energ.*,**114**, *4*, 183 (2013).
11. L.Olson, J.Ambrosek, K.Shridharan et. al., "Materials corrosion in molten LiF-NaF-KF salt", *J. Fluor. Chem.*,**130**,*1*, 67(2009).
12. L.Mathieu, D.Heuer, E.Merle-Lucotte et al., "Possible configurations for thorium molten salt reactor and advantages of the fast nonmoderated version", *Nucl. Sci. Eng.*,**161**, *1*, 78 (2009).
13. L.I. Ponomarev, Yu.S.Fedorov, A.M.Degtyarev and A.E.Miroslavov, "Nuclear fuel cycle of the fast U-Pu molten-salt reactor", *At. Energ.* (2015), *in press.*