



Progress in ISTC-1606 phase 2

Participating Institutions: VNIITF, RRC KI, IHTE, VNIikHT

Foreign Collaborators: BNFL, CEA, CEC RTD, EdF, FZK, IAEA, KTH, NRI

Phase 2 Duration: November 2004 – April 2007

Presented by Victor Ignatiev

[RRC-Kurchatov Institute, ignatiev@quest.net.kiae.su](mailto:ignatiev@quest.net.kiae.su)

for ISTC CEG meeting, Brussels, EC, January 30-31, 2006



Task#1606 Objectives

- ❖ To examine and demonstrate the feasibility of different molten salt systems: actinide burner and thorium system to reduce long lived waste toxicity and to produce efficiently electricity in closed fuel cycle
- ❖ Focus is placed on the experimental and theoretical evaluation of single stream transmuter system fuelled with different compositions of TRU trifluorides from LWR spent fuel without U-Th support



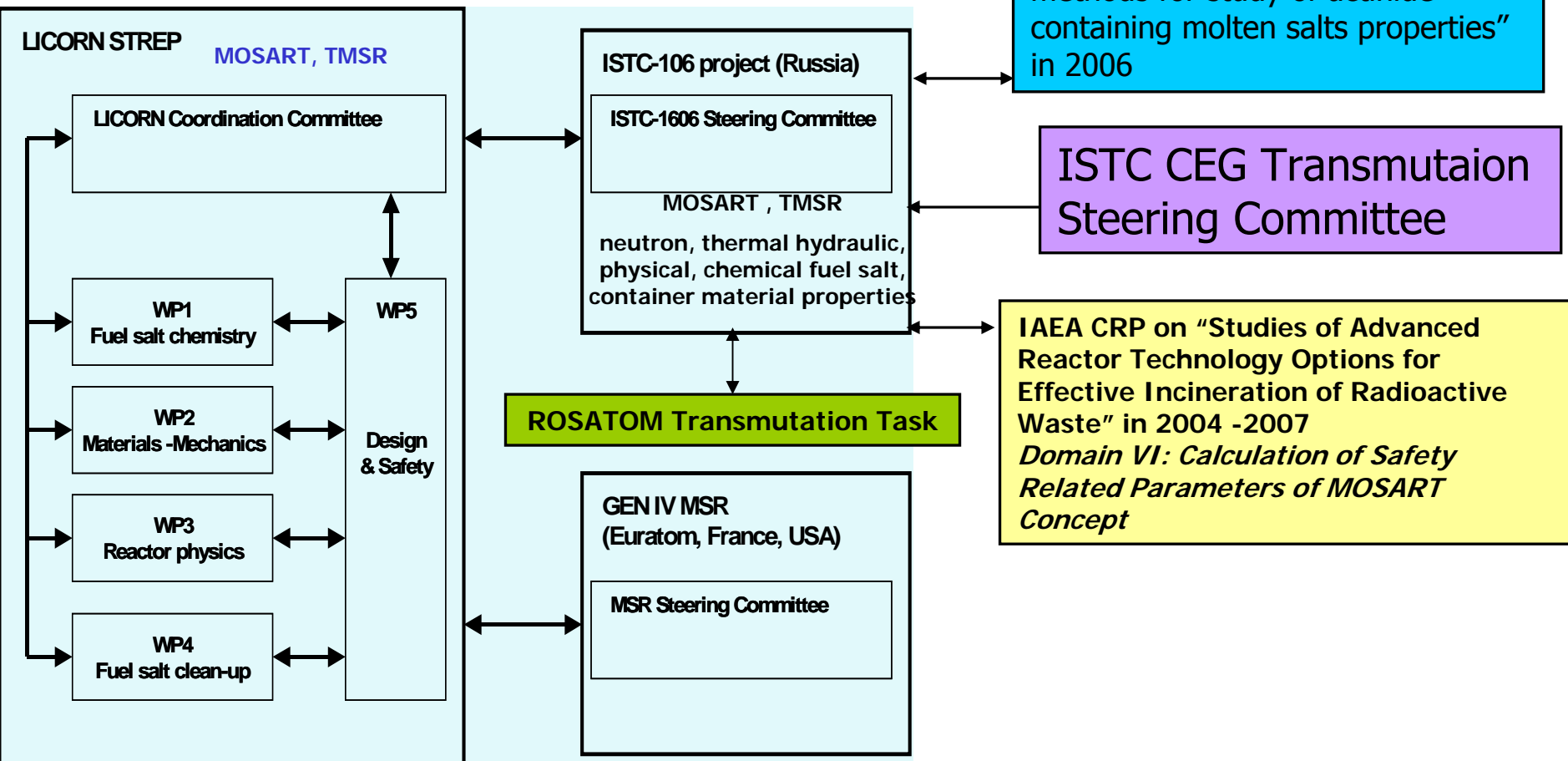
Task#1606 work packages

- WP 1: Study on neutronic and thermal hydraulic properties of cores, of selected MOSART and MS thorium systems operated in forced convection mode, accounting for technology constrains
- WP 2: Measurement of selected fuel salts key physical and chemical properties
- WP 3: Experimental verification of Ni-Mo alloys for fuel circuit in corrosion facilities with on-line redox measurement

New experimental data received in our studies feed into conceptual design efforts, which also fit to the need of EU partners

Co-operation with EU partners

MOST project, Euratom 5th FP in 2002-2004
LICORN proposal, Euratom 6th FP in 2007-2010

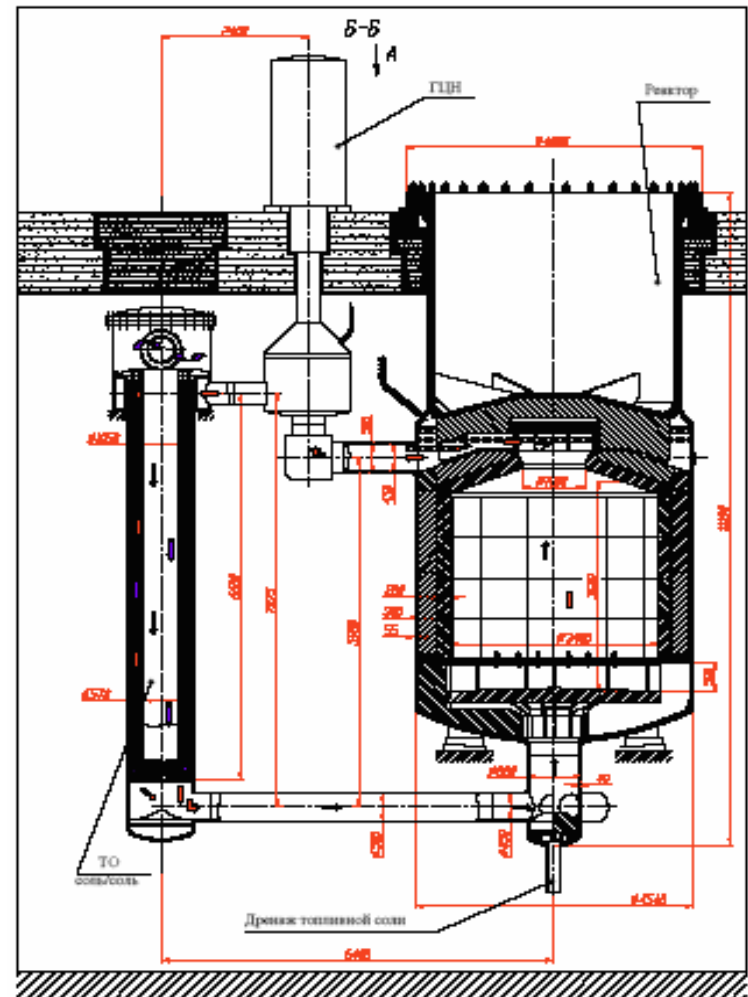
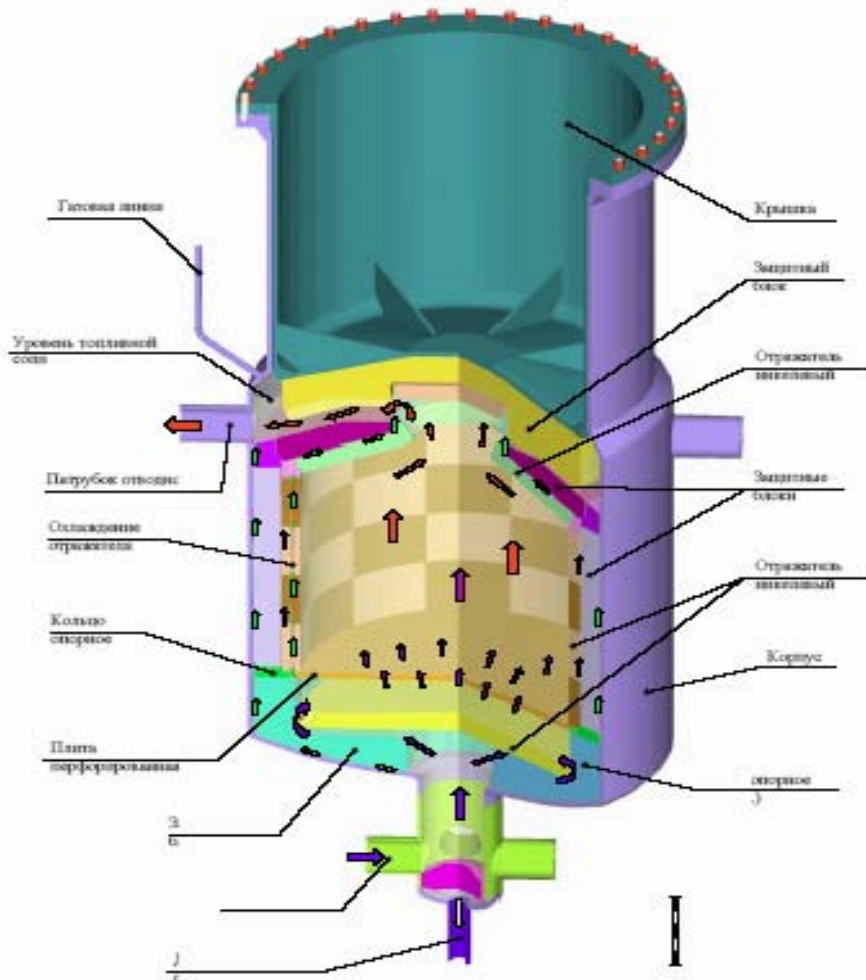




2500MWt MOSART concept

- 2500MWt MOSART system has homogeneous cylindrical core with 0.2 m graphite / nickel reflector
- Fuel salt is molten 58NaF-15LiF-27BeF₂ (mole%) fuelled by TRUF₃ from UOX / MOX PWR spent fuel
- The removal times for soluble fission products (rare-earth trifluorides) is considered as 1 year
- Diameter / height of the core are 3.4 m / 3.6 m
- The salt inlet temperature is assumed as 600°C
- The fuel salt specific power is about 47 W/cm³
- The effective flux is near $1 \cdot 10^{15}$ n/cm²/s
- Salt volume out of the core is 18.4m³

2500MWt MOSART Sectional View

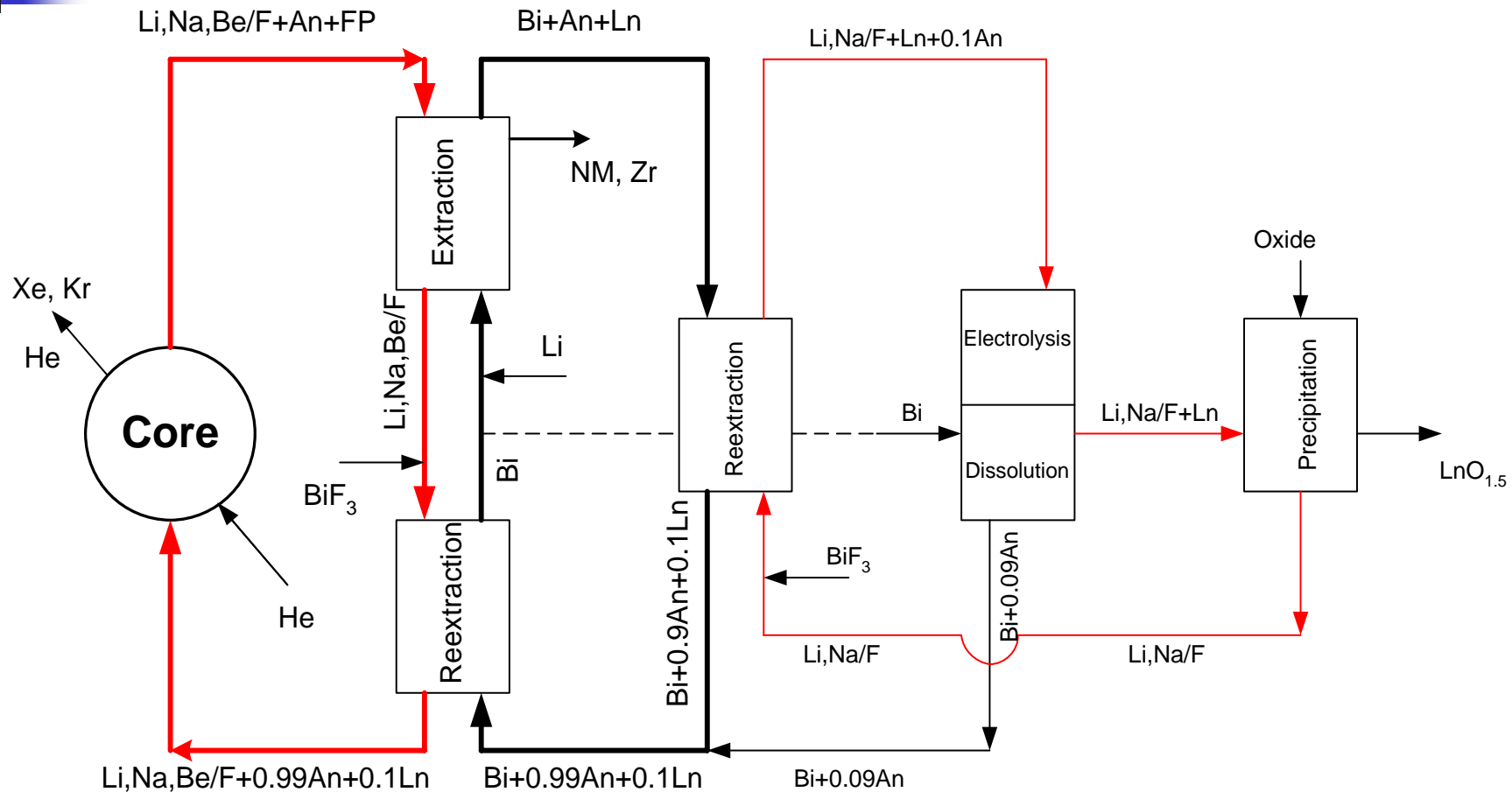


Na,Li,Be/F MOSART fuel and its clean up

Start up and feed material compositions, in mass %.

Scenario	1	2	3	Component	Cycle times	Removal operation
Np	6.42	6,51	0,84	Kr, Xe	50 sec	Sparging with He
Pu238	3.18	2,77	6,34	Zn, Ga, Ge, As, Se,Nb,Mo, Cd,In,Sn,Sb,Te, Ru,Rh,Pd.Ag,Tc	2.4 hr	Plating out on surfaces + To off gas system
Pu239	43.93	48,36	8,44	Zr	1 -3 yrs	Reductive extraction, Oxide precipitation, Electrodeposition
Pu240	21.27	19,97	34,89	Ni, Fe, Cr		
Pu241	13.52	8,30	9,33	Np, Pu, Am, Cm		
Pu242	7.88	6,25	18,7	Y, La, Ce, Pr, Nd, Pm, Gd, Tb, Dy, Ho, Er, Sm, Eu		
Am241	0.55	5,56	1,4	Sr, Ba, Rb, Cs	>30 yr	Salt discard
Am243	2.33	1,69	4,65	Li, Be, Na		
Cm	0.92	0,59	5,07			

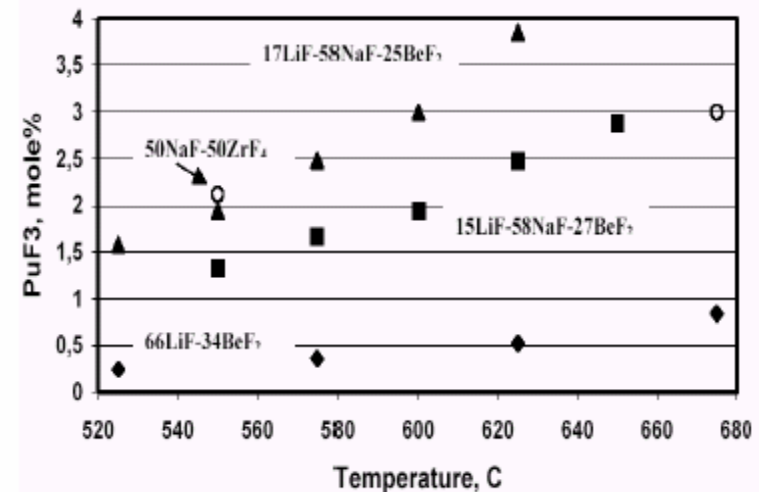
Na,Li,Be/F MOSART fuel clean up



Na,Li,Be/F Transport properties

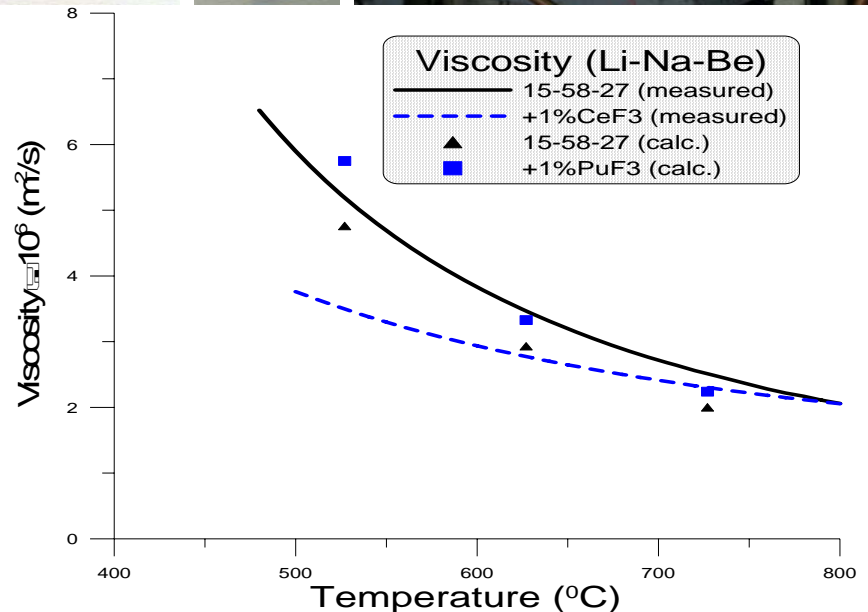
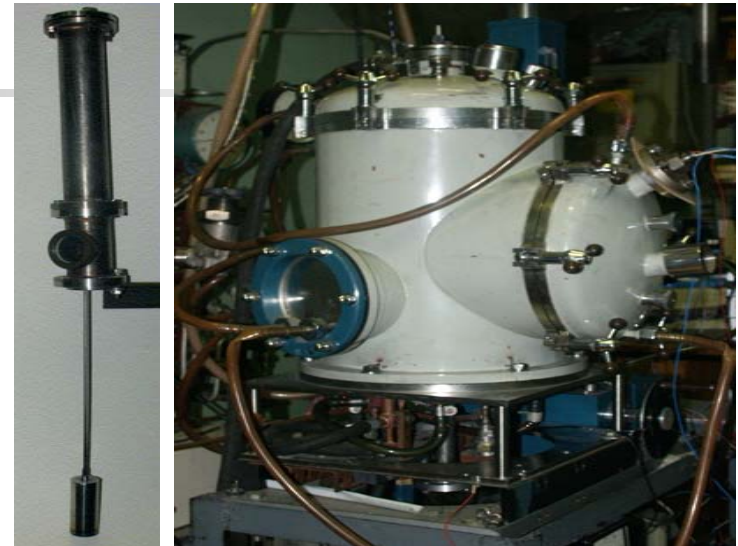
Composition, mol%	58NaF-15LiF-27BeF ₂	479 C
Solubility of PuF ₃ , mole%	$\ln P = -6334/T [K] + 8.38$	1.94
Viscosity, m ² /s	$\nu = 0.136 \cdot \exp\{2914/T[K]\}$	3.75
Heat capacity, J.kg ⁻¹ .K ⁻¹	$C_p \neq f(T) = 2090$	2090
Thermal conductivity, W/(m.K)	$\lambda = 0.838 + 0.0009([C] - 610.3)$	0.837
Density, g/cm ³	$2.163 - 0.406(t[C] - 601.4)$	2164
Prandtl number	$Pr = \eta * C_p / \lambda$	11.6
Reynolds number	$Re = 4G/D/\eta/\pi$	706930
Vapor pressure, Pa	$\ln p = 18.920 - 1.469 * 10^4 T(K) - 25283/T + 0.9819 \ln(T)$	
Temperature, C	500-800	600

LiF	NaF	BeF ₂	T _{melt} / °C
7	64	29	515-536
13	58	29	486-500
15	58	27	479
17	58	25	494-496
22	57	21	570



Transport properties studies: Phase 2

- Measurement of viscosity for molten 15LiF-58NaF-27BeF₂ (mole%) mixture fuelled by actinide trifluorides simulators (CeF₃)
- Measurement of density for molten 17LiF-58NaF-25BeF₂ (mole%) mixture
- Selection of the Th containing fuel composition for the further studies
- Evaluation of properties for Th-containing solvent selected

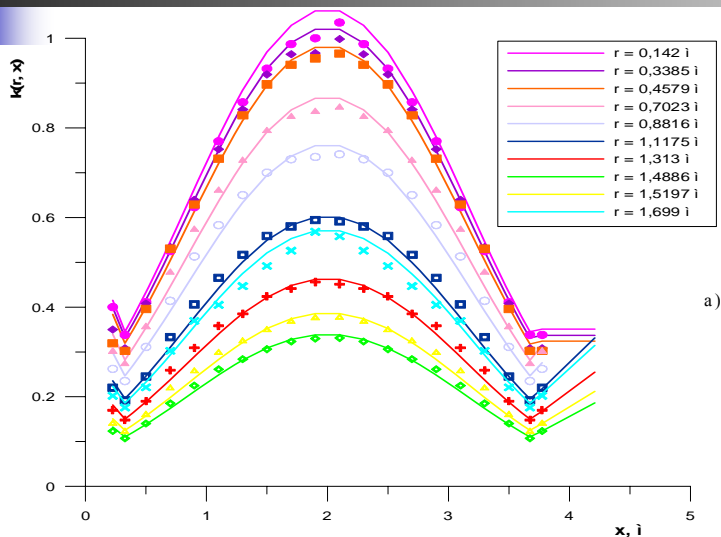


Neutronic & thermal hydraulics

Coupling MCNP / MCU with material evolution code

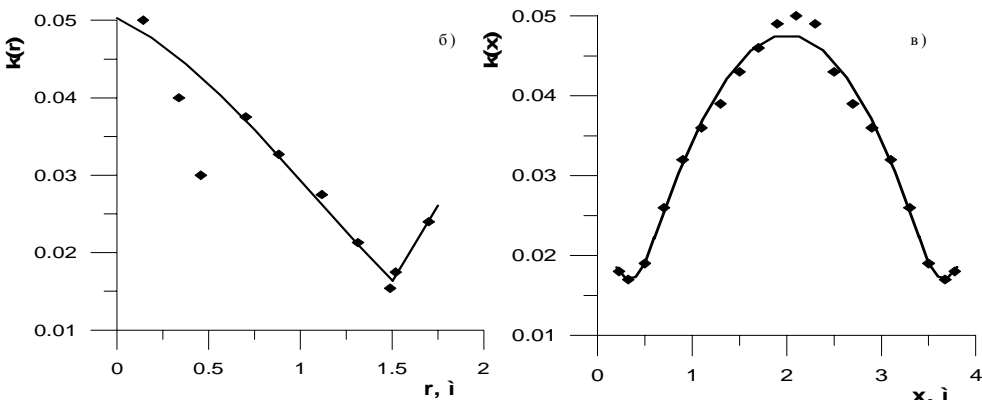
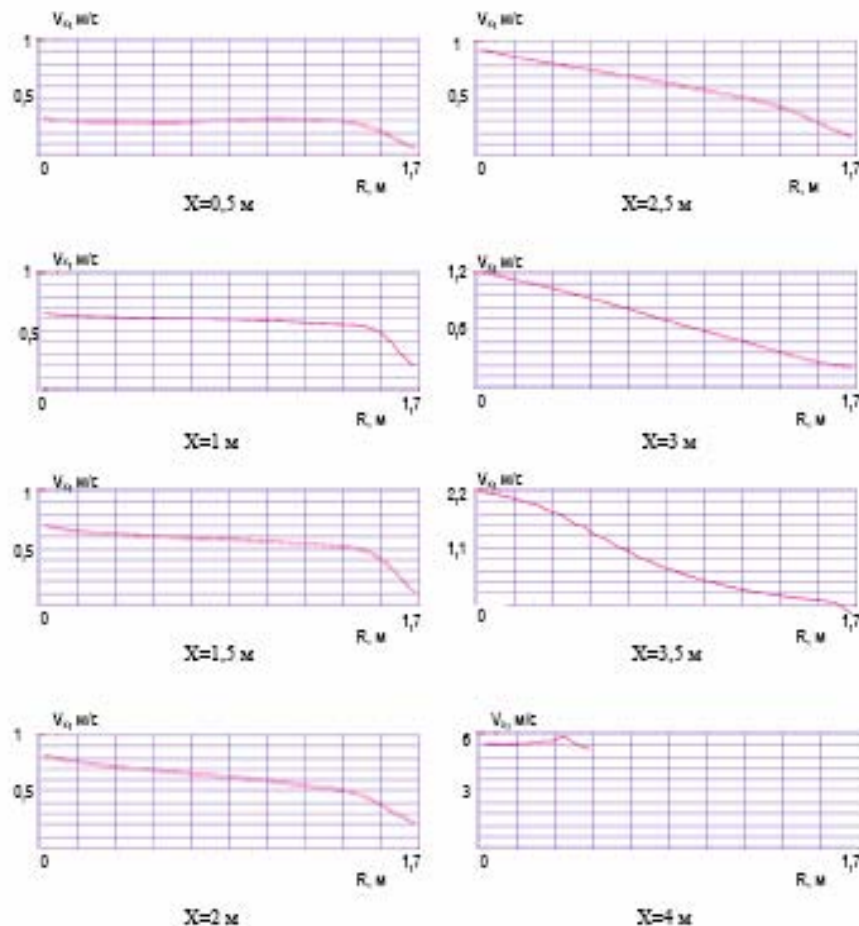
3D Power distributions: MCNP and MCU codes up to 6 millions histories

3D Thermal hydraulics: Flow Vision code with > 80000 working cells



a)

Velocity V_x along reactor height X for different radius R , m/s

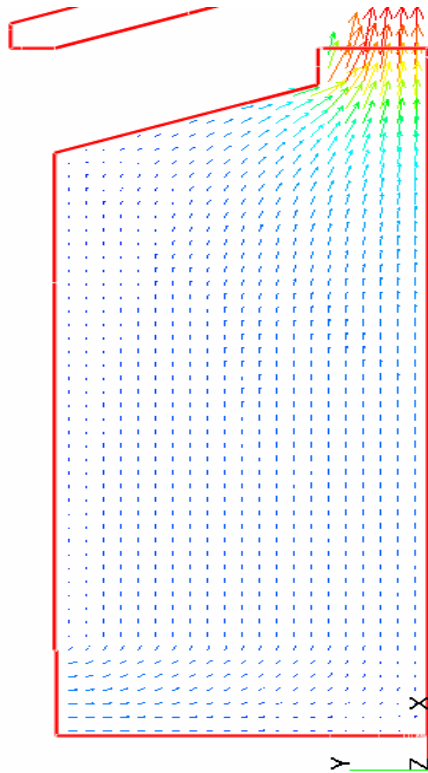


a – core with graphite reflector; b,c – axial/ radial reflectors

Reflectors power due to $n+\gamma$ radiation is 2.2% of total

Velocity and temperature distributions in core with 20cm graphite reflector:

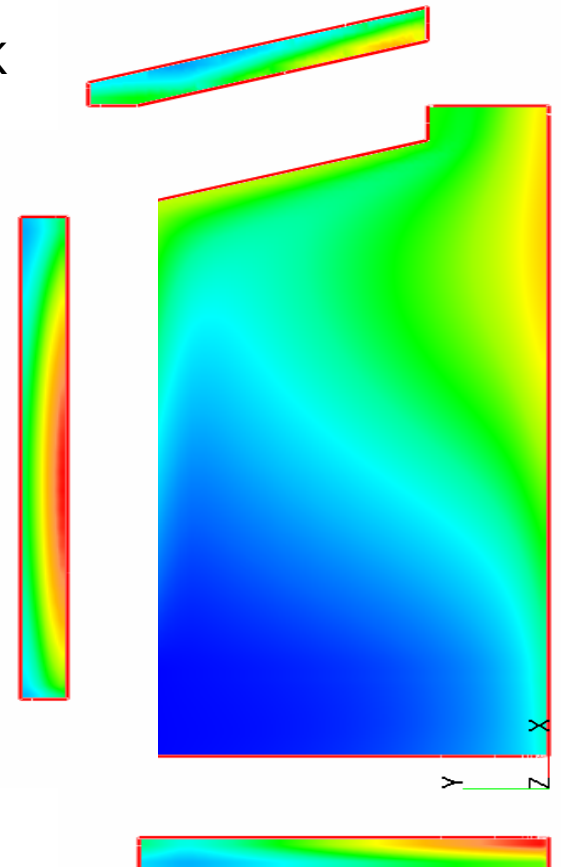
Conic Reflector, Salt Inlet at Bottom Periphery ($H_t=50\text{cm}$), Distribution Plate (porosity 0.32)



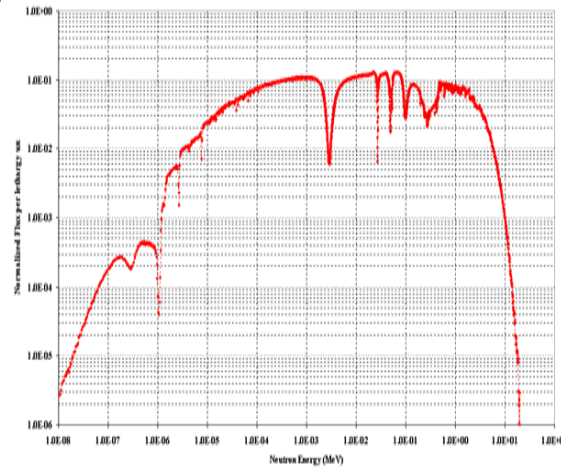
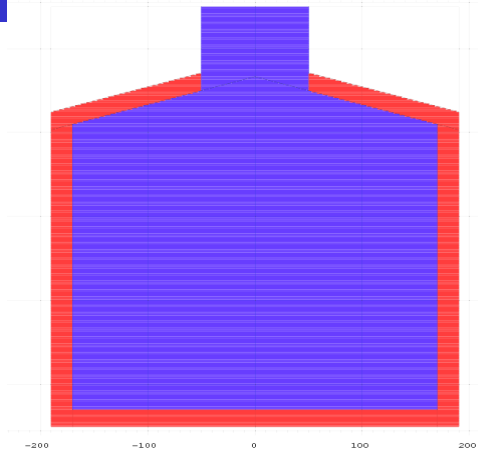
Цвет	Значение
Red	7
Orange	6.3015
Yellow	5.603
Light Green	4.9045
Green	4.206
Light Blue	3.5075
Cyan	2.809
Blue	2.1105
Dark Blue	1.412
Very Dark Blue	0.7135
Black	0.015

$T_f \text{ max} = 1036\text{K}$
 $T_r \text{ max} = 1087\text{K}$
 $\langle T_f \rangle_{\text{out}} = 988\text{K}$

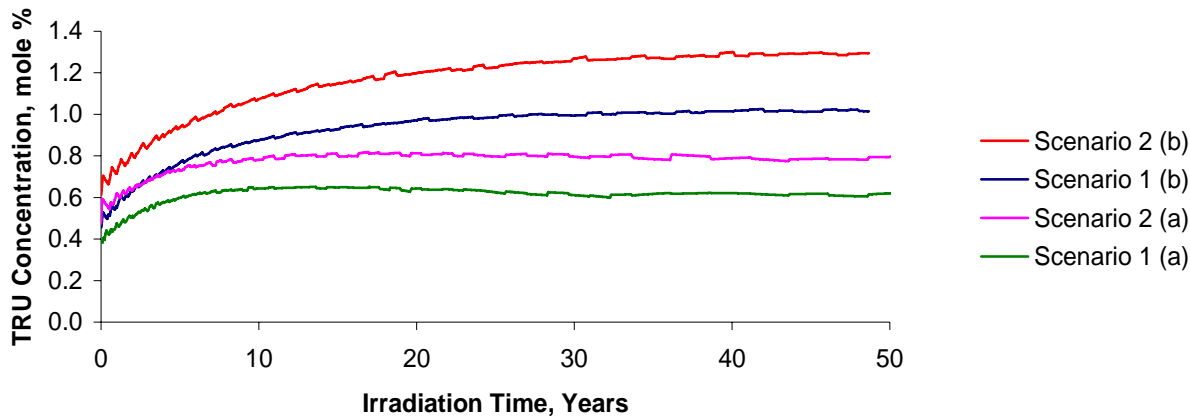
Цвет	Значение
Red	1087
Orange	1066
Yellow	1044
Light Green	1023
Green	1002
Light Blue	979
Cyan	958
Blue	937
Dark Blue	916
Very Dark Blue	894
Black	873



MOSART core benchmark



Molar Concentration of TRU



Library	k-eff
Feynberg	RRC-KI
ENDFB V,VI	0.99791
MCUDAT-2.2	0.98930
Rineski	FZK
JEFF 3.0	0.99285
JENDL 3.3	1.01023
ENDF 6.8	0.98474
Malambu	SCK-CEN
JEFF 3.1	1.00905
Da Cruz	NRG
JEFF 3.0	0.99335
JEFF 3.1	1.01210



Reactivity coefficients for Na,Li,Be/F MOSART core

T_{salt} K	T_{ref} K	ρ_{salt} g/cm ³	Doppler $\Delta K_{\text{eff}}/(T_t-900)$, pcm/K	Total $\Delta K_{\text{eff}}/(T_t-900)$, pcm/K
900	950	2.15261		
1000	1050	2.11201	-1.178 (-2.054*)	-3.225 (-4.237*)
1100	1150	2.07141	-1.222	-3.279
1200	1250	2.03081	-1.152	-3.333
1300	1350	1.99021	-1.134	-3.322
1400	1450	1.94961	-1.137	-3.356
1500	1550	1.90901	-1.093	-3.408
1600	1650	1.86841	-1.068	-3.449

MCU with DLC/MCUDAT-2.2: 6 mln histories
for isothermal core and for 8 radial and 10 axial zones

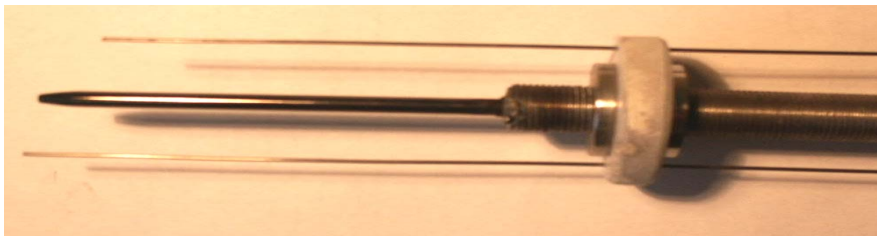


Primary heat exchanger

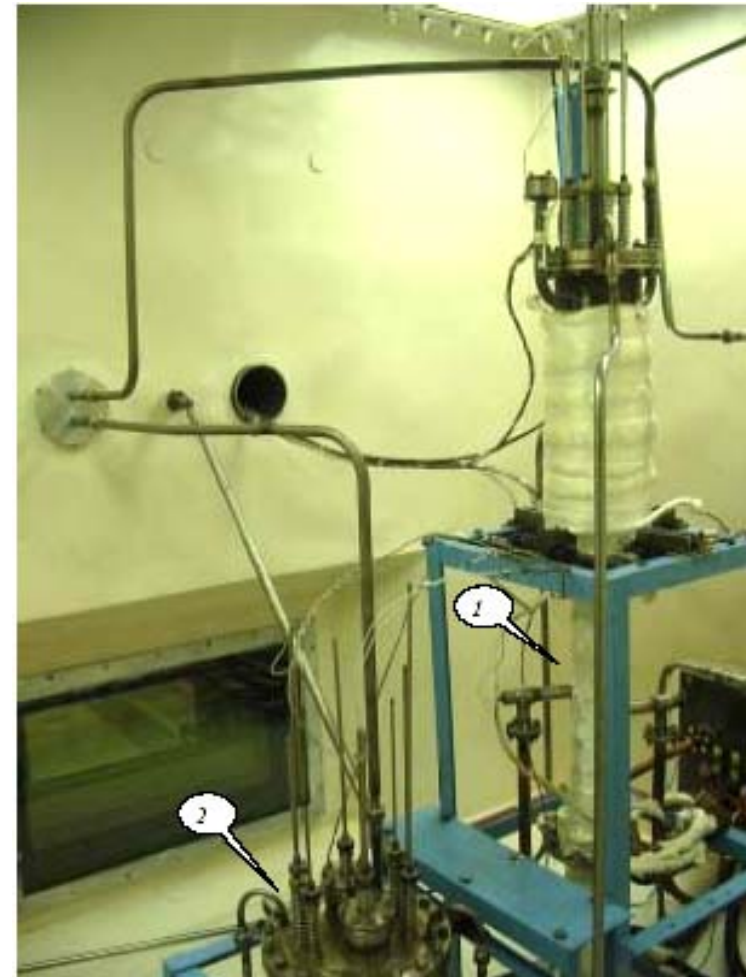
Configuration	Vertical
Fuel salt (tube), inlet / outlet temperature, C	600/ 715
Coolant salt (shell) inlet / outlet temperature, C	450/ 620
Fluid velocities ($v_1=v_2$), m/s	5
Tube OD, mm	Ø10x1
Tube pitch, S_i , mm	12.2
Down flow tube ID D_1 , m	0.57
Heat exchanger OD, D_2 , m	1.05
Tube number for 4 heat exchangers, N	18591
Heat exchanger length, L , m	6.6
Total heat transfer coefficient K_{Σ} , W/m ²	5700
Pressure drop, ΔP_{Γ} , MPa	0.66
Total fuel salt volume in tubes, V , m ³	6.2

Corrosion studies: Phase 2

- Compatibility test (1200hrs) between 15LiF-58NaF-27BeF₂ salt and Ni - based alloys in loop with redox potential measurement
- 200hrs test on effect of PuF₃ addition in 15LiF-58NaF-27BeF₂ salt on compatibility with Ni - alloys
- Te corrosion study between 15LiF-58NaF-27BeF₂ salt and Ni - Mo alloys



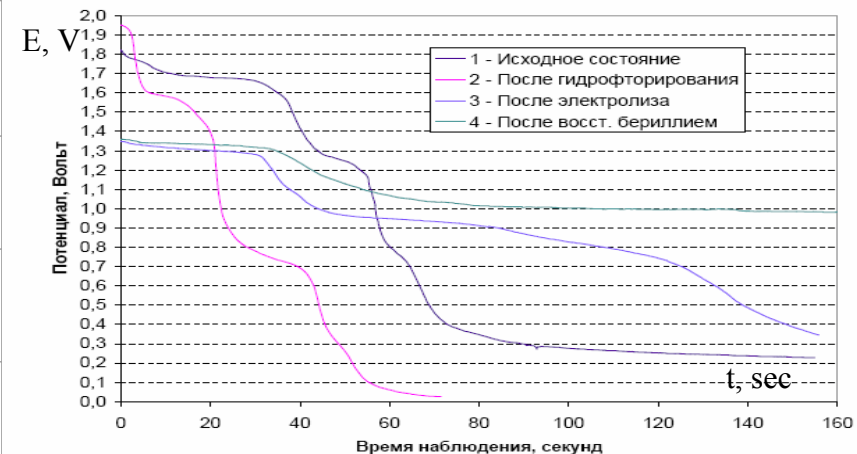
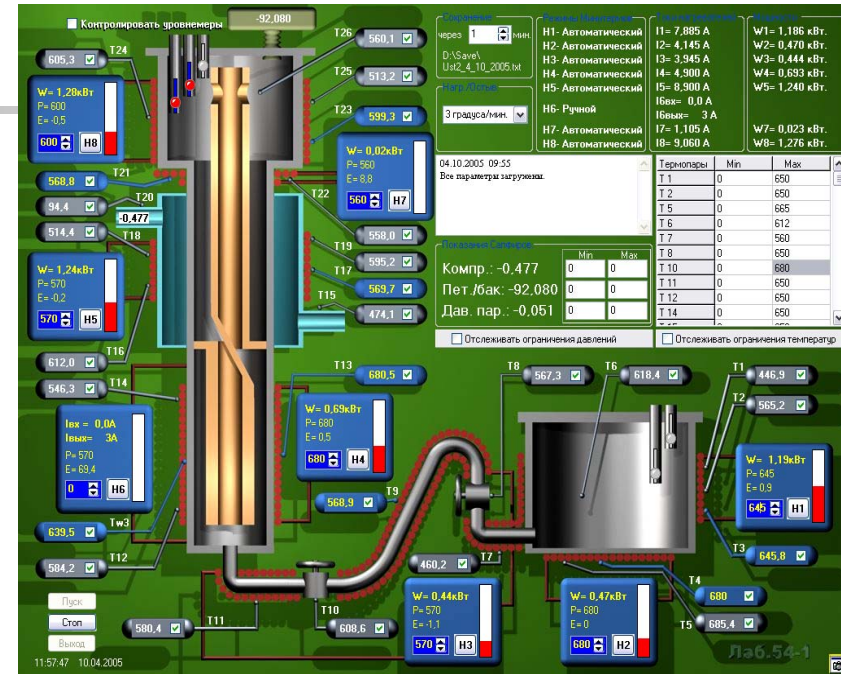
Diaphragm-free meter with dynamic berillium reference electrode for redox potential measurement in BeF₂ / PuF₃ containing melts



Na,Li,Be/F Salt purification procedure

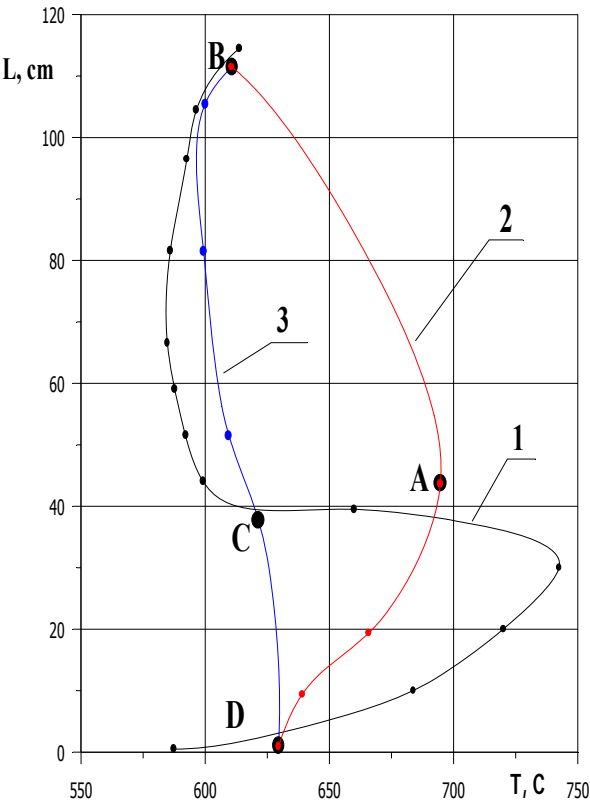
1. Hydrofluorination by a HF –He mixture in order to remove solid and dissolved oxides
2. Electrolysis to remove dissolved nickel
3. Treatment by metallic beryllium in order to remove rest of nickel and iron ions

Salt charge after clean up procedures	T _s , °C	Impurities in salt, mass. %			Red Ox, V
		Ni	Fe	O	
100 hrs in drain tank	650	0.39	0.057	0.3	1.58
75 hr circulation in loop + 3 hrs of He bubbling in drain tank	590	1.01	0.042	0.34	1.78
14 hrs of HF-He +3 hours of He sparging	580	0.57	0.047	0.08	1.95
34 hrs of electrolysis + He sparging	575	0.038	0.001	0.06	1.34
12 hrs of metallic Be treatment	580	0.014	0.017	0.08	1.3



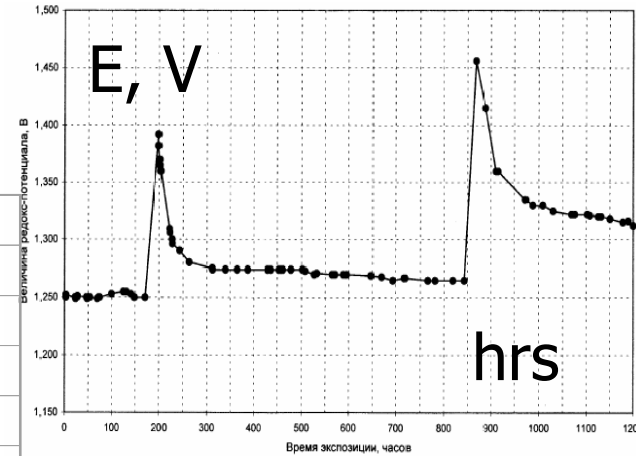
Thermal convection corrosion test

Specimens of HN80M-VI, HN80MTY and MONICR from loop hot leg exposed 1200 hrs at temperatures from 620°C till to 695°C showed uniform corrosion rate from 2 μm/year to 4 μm/year



Analysis of salt impurities, mas. %

hrs	0	1200
Ni	0.0030	0.0019
Fe	0.0165	0.0040
Cr	0.0026	0.0037
Mo	-	<0.0002
Nb	-	<0.0001
Al	-	0.0049
Ti	0.0099	0.0005
Ba	-	<0.0001
Mg	0.0041	0.0040
Mn	0.0006	0.0003
Ca	0.0300	0.0070
Cu	-	<0.0001
Si	-	-
Sr	0.0005	0.0004

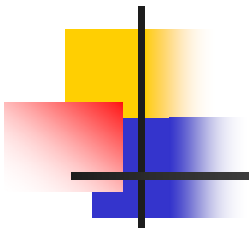


Examination of specimens:

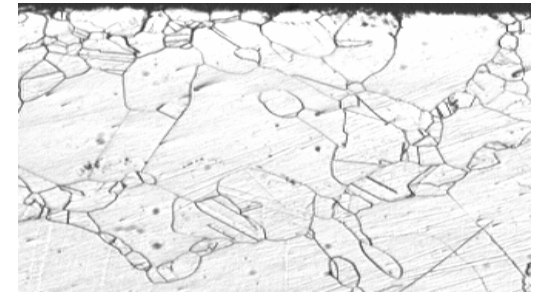
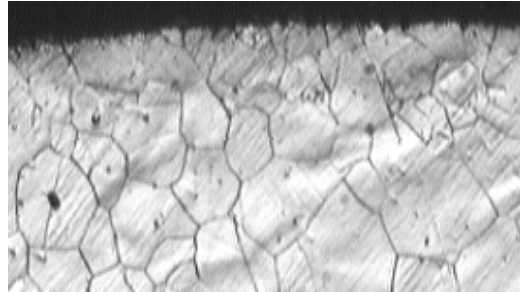
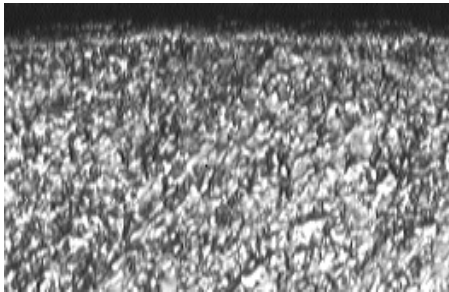
HN80M-VI,
1.5% Nb

HN80MTY,
1% Al

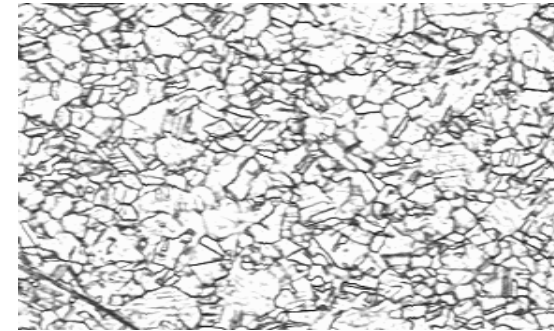
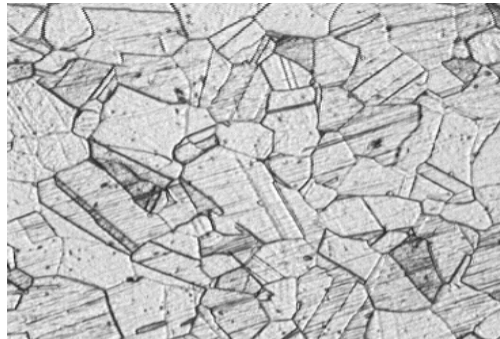
MONICR
2.3% Fe



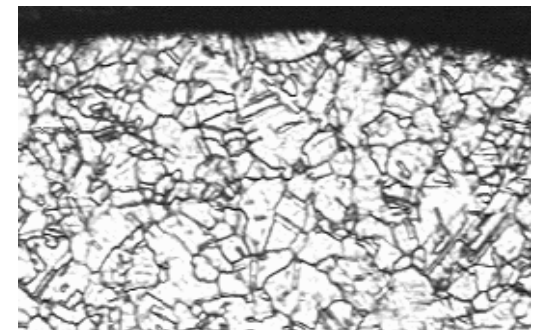
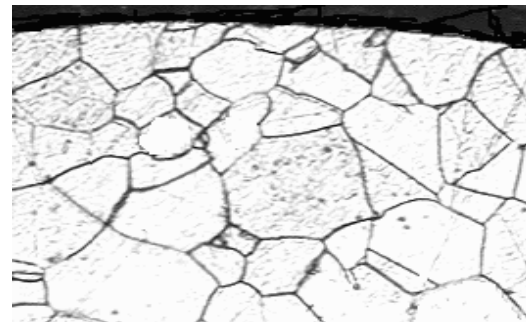
After 100hrs
exposure in
flash salt at
650C, E=1.6E



After
preliminary
thermal
treatment

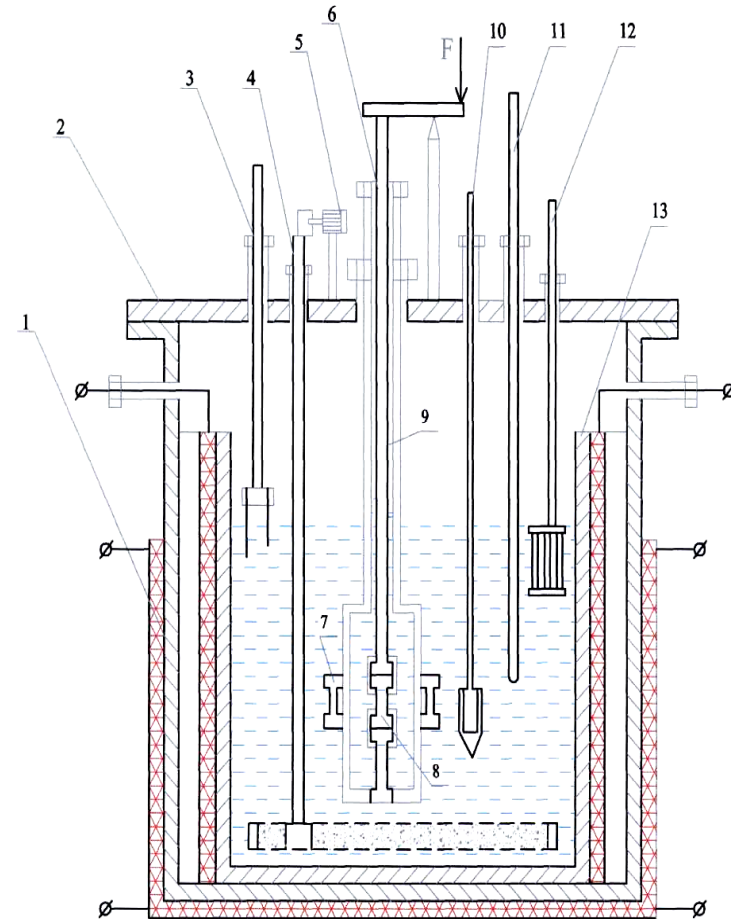


After 1200 hrs
exposure in
loop, E=1.2V



Studies on interaction of tellurium with Ni - Mo alloys

- Interaction of specimens with Te vapor (capsule, source – Cr_3Te_4)
- Interaction of specimens with Te in Na,Li,Be/F salt (capsules with pure solvent and additions of NiF_2 / FeF_2 , source – Cr_3Te_4)
- Tests of specimens under stress in salt – tellurium environment (T=750C, t=250hrs, source – Cr_3Te_4 , redox potential control, salt mixing)

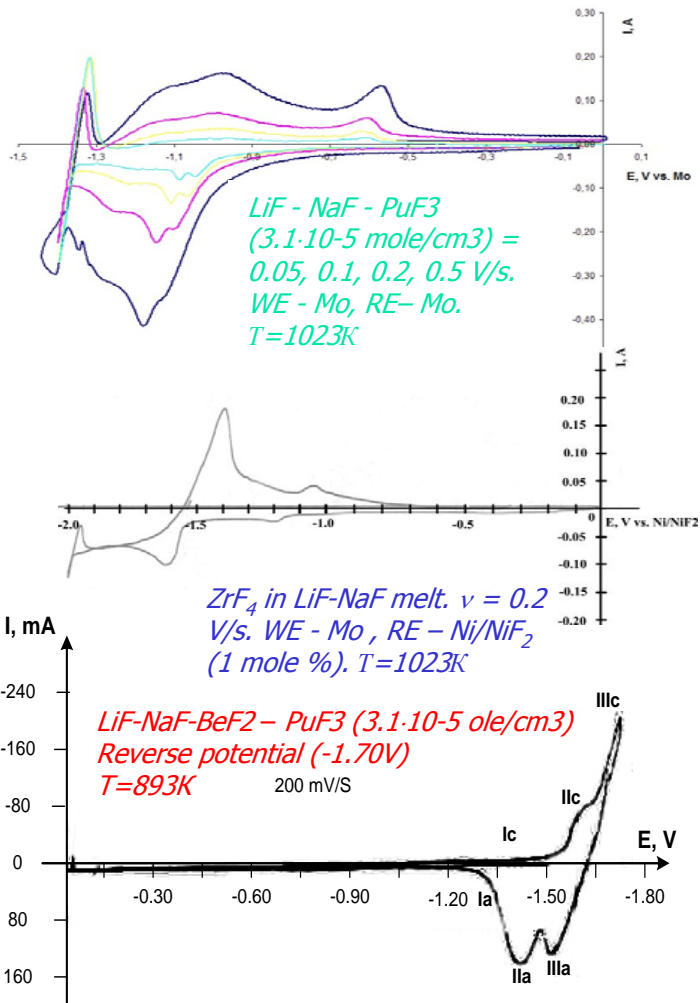




Fuel salt clean up: Phase 2

- Investigation of the influence of metal solvent nature on An/Ln separation in case of liquid Bi and Sb. Measurements of RE's and Pu distribution in system (liquid metal-Li) – (Na,Li,Be/F)
- Studies on electrochemical properties (conditional standard electrode potentials, ion behavior, activity coefficients etc.) of Pu and RE's and their trifluorides in molten Li,Na/F and Na,Li,Be/F systems
- Determination of PuF_3 free energy of formation on the base of standard potential measurements solid-state galvanic in cells
- Development of Ni-NiF₂ reference electrode based on boron nitride container for electrochemical studies in Na,Li,Be/F

Electrochemical study



Equilibrium potentials of the Pu^{3+}/Pu , Zr^{n+}/Zr , Be^{2+}/Be , Na^+/Na couples in 60LiF-40NaF and 15LiF-58NaF-27BeF₂ (mole%) melts were determined:

$$E_{\text{Zr}^{2+}/\text{Zr}} \approx -1.55 \pm 0.02 \text{V (Li, Na/F; 1023K)}$$

$$E_{\text{Pu}^{3+}/\text{Pu}} = E_{\text{Na}^+/\text{Na}} + 0.30 \text{V} \approx -1.63 \pm 0.02 \text{V (Li, Na/F; 1023K)}$$

$$E_{\text{Ln}^{3+}/\text{Ln}} < E_{\text{Na}^+/\text{Na}} = -1.93 \pm 0.01 \text{V (Li, Na/F; 1023K)}$$

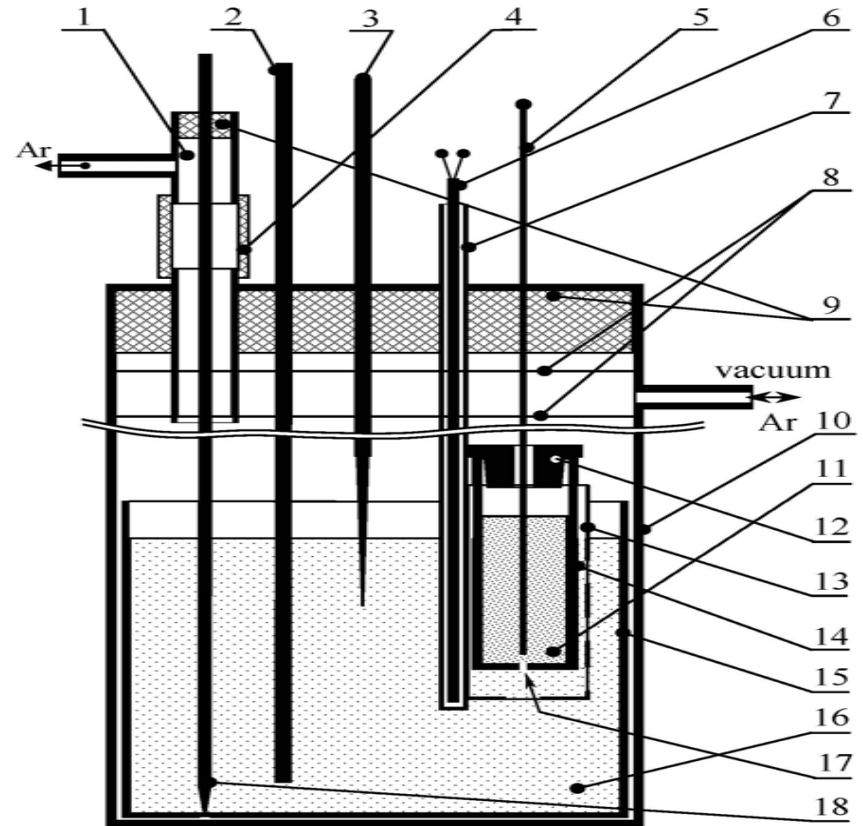
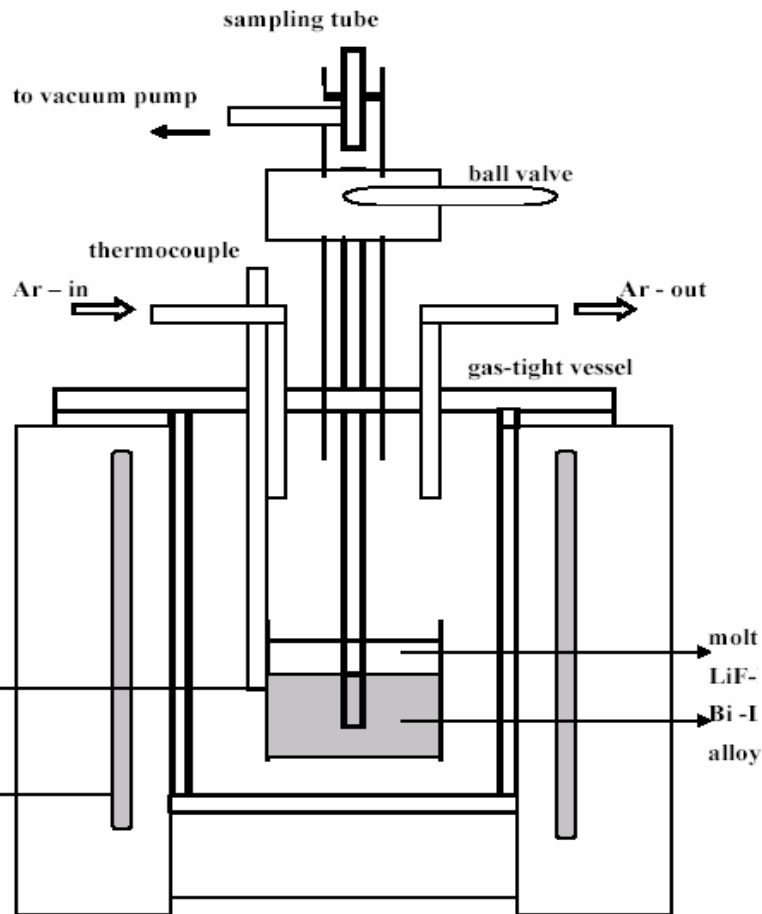
$$E_{\text{Zr}^{2+}/\text{Zr}} = -1.50 \pm 0.02 \text{V (Li, Na, Be/F; 873K)}$$

$$E_{\text{Pu}^{3+}/\text{Pu}} = E_{\text{Na}^+/\text{Na}} + 0.15 \text{V} \approx -1.75 \pm 0.05 \text{V (Li, Na, Be/F; 893K)}$$

$$E_{\text{Be}^{2+}/\text{Be}} = (-1.90 \pm 0.01 \text{V}) \text{ (Li, Na, Be/F; 893K)}$$

Assumption was made concerning alloying of Pu with Be, Na and Ni in process of Pu ions electrochemical reduction in system

Fuel salt clean up



2 – glassy-carbon auxiliary electrode; 3 – glassy-carbon working electrode; 5 – nickel reference electrode; 11 – melt in reference electrode; 14 – graphite crucible with pyrolytic boron nitride coat; 15 – nickel crucible; 16 – test melt;



ISTC#1606 Training Activity

“Training in modern experimental and analytical methods for study of actinide-containing molten salts properties”

- *The objective of the training is to gain experience and practical skills in the novel experimental methods for MSR technology study and development, which will be applied to the Work plan of the Project 1606 Phase 2*

Session 1: CEA-Cadarache, France, 2006, March, 06-10

Session 2 : VNIITF, Snezhinsk, Russia, 2006, November



Program of Session 1

day	type	schedule	topics	providers
day 1	lecture	3 hours	MSR general features, status of MSR in FP6 and Gen IV	CEA (C. Renault)
	training	3 hours	MOST database	CEA (C. Eichenbaum)
day 2	lecture	3 hours	MSR different concepts	EDF (D. Lecarpentier)
	training	3 hours	Pre-design of MSR concepts (COPERNIC)	CEA (C. Thevenot)
day 3	lecture	3 hours	MSR reactor physics	EDF (D. Lecarpentier), CEA (O. Koberl)
	training	3 hours	Analysis of temperature feedback coefficients (sensitivity analysis with APOLLO2)	CEA (O. Koberl), EDF (D. Lecarpentier)
day 4	lecture	3 hours	Physico-chemical properties of molten salts : modeling and databases	JRC-ITU (R. Konings), EDF (E. Walle), CEA (O. Gastaldi)
	training	3 hours	ITU database (www.f-elements.net), database on Labview	JRC-ITU (R. Konings), EDF (E. Walle), CEA (N. Simon)
day 5	lecture	3 hours	Materials in molten salt environment (corrosion, control of salt,...)	CEA (C. Cabet), CNRS (S. Sanchez)
	training	3 hours	Formation of the potential/acidity diagram of a metal in a molten salt; description of corrosion/passivity domains	CEA (C. Cabet), CNRS (S. Sanchez)



Program of Session 2

day	type	schedule	topics	lecturers
day 1	lecture	3 hours	MSR thermal-hydraulics and fuel cycles considerations	EDF (D. Lecarpentier)
	training	3 hours	Pre-design of MSR concepts (COPERNIC)	FZK (M. Schikorr), CEA (C. Renault)
day 2	lecture	3 hours	MSR safety aspects	CEA (C. Renault), FZK (M. Schikorr)
	training	3 hours	Pre-design of MSR concepts (COPERNIC)	FZK (M. Schikorr), CEA (C. Renault)
day 3	lecture	3 hours	Fuel salt clean-up (techniques, flow-sheets)	CEA (O. Gastaldi, H. Boussier), EDF (E. Walle)
	training	3 hours	Simulation of MSR reprocessing unit	CEA (N. Simon, O. Gastaldi), EDF (E. Walle)
day 4	seminar	3 hours	ISTC-1606 developments	ISTC#1606 team
	visit	3 hours	MS experimental facilities	ISTC#1606 team



Papers prepared within 2005-2006

MS7

- Electrochemical study of zirconium, lanthanides and TRU in fluoride melts by *R. Zakirov, V. Ignatiev, A. Panov, A. Toropov, V. Afonichkin, Paper 114*
- Physical properties of Na,Li,Be/F MOSART fuel salt by *V. Ignatiev, Y. Golovатов, A. Merzlyakov, A. Panov, V. Subbotin, Paper 082*
- Alloys compatibility with fuel and coolant salts by *V. Ignatiev, A. Surenkov, V. Fedulov, V. Afonichkin, A. Bovet, V. Subbotin, A. Toropov, Paper 080*

NURETH 11

- Measurement of transport properties for molten Na,Li,Be/F mixtures by *A. Merzlyakov and V. Ignatiev, Paper 083*

ICENES'05

- Characteristics of Molten Salt Advanced Reactor Transmuter systems by *V. Ignatiev, O. Feynberg, V. Smirnov, A. Tataurov, G. Vanukova, R. Zakirov*



Papers prepared within 2005-2006

GLOBAL 2005

- Integrated Study of Molten Na, Li, Be/F Salts for LWR Waste Burning in Accelerator Driven and Critical Systems, *Ignatiev V., O. Feynberg, A. Merzlyakov, A. Surenkov, A. Tataurov, G. Vanukova, Raul Zakiro¹, V. Subbotin, A. Toropov, A. Panov², V. Afonichkin, V. Khokhlov³, Paper 027.*

ICAPP' 06

- Experience with Alloys Compatibility with Fuel and Coolant Salts and their Application to Molten Salt Actinide Recycler & Transmuter, *Ignatiev V., A. Surenkov, I. Gnidoj, V. Fedulov, V. Afonichkin, A. Bovet, V. Subbotin, A. Toropov, Paper 6002*

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