Numerical and Experimental Research of In-Vessel Retention of Corium Melt for VVER Reactors

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Computational and Experimental Works in support of IVR for VVER-type reactors

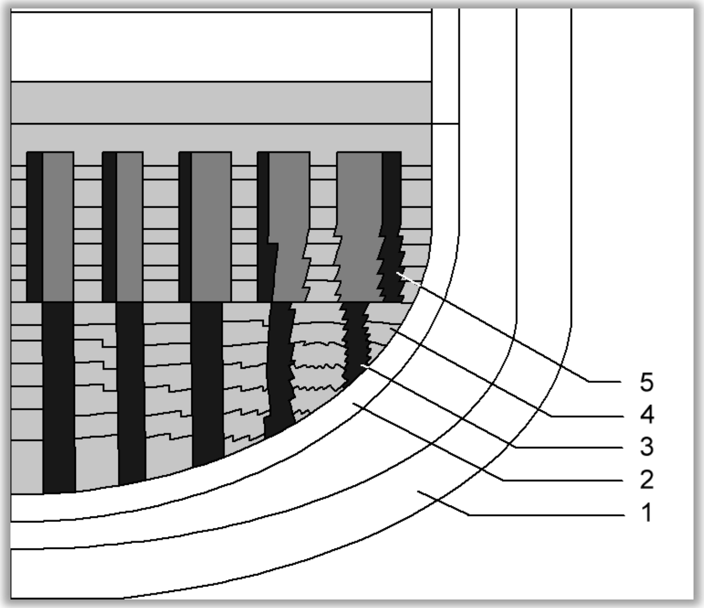
project implementation period – 2013 – 2015 years
Participants – JSC “ATOMPROEKT”, Saint-Petersburg State Institute of Technology (Technical University) (St. Petersburg), Alexandrov Research Institute of Technology (Sosnoviy Bor), OKB “GIDROPRESS”, Nuclear Safety Institute ‘IBRAE’ RAS (Moscow) , RFNC-VNIIEF (Sarov)

Main objectives:

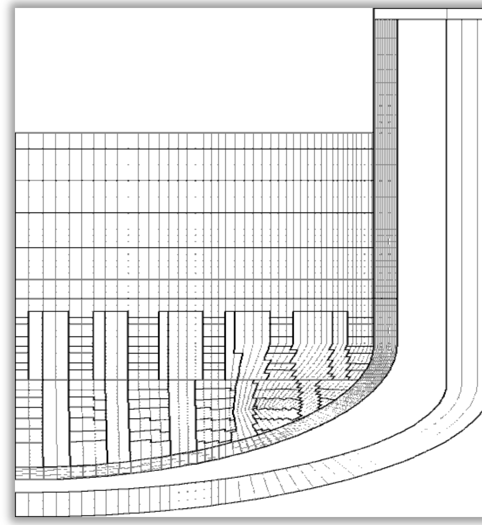
- improvement in existing SA codes for modeling of melt retention inside the reactor vessel
- execution of computational analysis for IVR of VVER-type reactors; as a representative scenario, double-end break of main pipeline (Drep 850) accompanied ECCS failure was chosen.
- definition of limit power for IVR
- definition of additional technical solutions for IVR of high-power NPP
- development of preliminary NPP design for IVR conception

SA code SOCRAT for IVR modeling

- RATEG — best-estimate code , which can be used for calculate of thermal and hydraulic processes in primary and secondary circuit
  - Two-fluid 1D thermal-hydraulic flow
  - 1D and 2D heat conductivity
- SVECHA — realistic simulation of core degradation phenomena
  - hydrogen generation
  - flowing materials models
- HEFEST— realistic simulation of core debris behavior in the reactor bottom chamber
  - Vessel-corium interaction
  - Vessel deformations and failure



Partition of internal space filled with relocating core materials:
1 – reactor pressure vessel, 2 – core barrel wall, 3 – steel supports, 4 – modeled melt layers, 5 – fuel assemblies' support tubes filled in the first place.

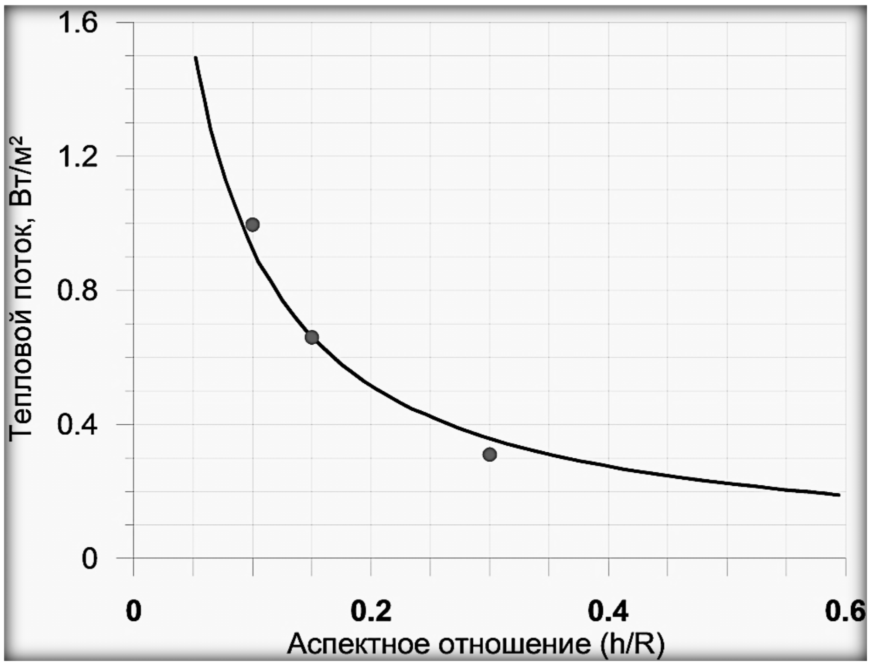


Finite element-based division of the lower plenum chamber

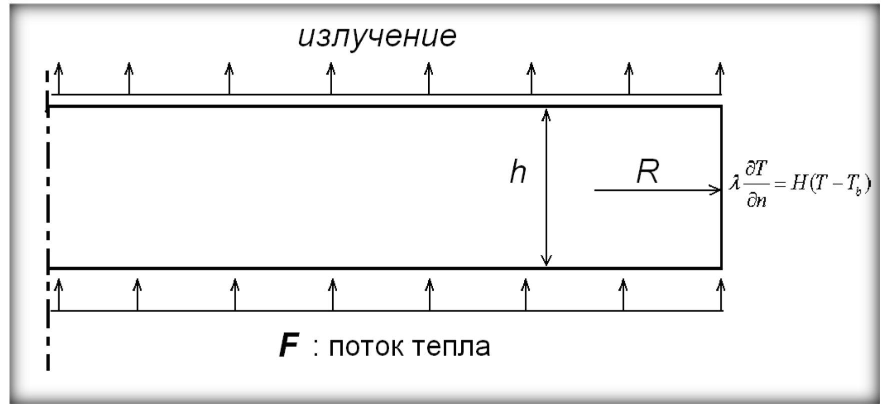
SA code verification for IVR modeling

Heat flux focusing effect in the molten metal layer. A comparison with the Theofanous' data

T. G. Theofanous, et al, "Critical Heat Flux Through Curved, Downwards Facing, Thick Wall," Proceedings of the OECD/CSNI/NEA Workshop on Large Molten Pool Heat Transfer, Grenoble, France, March 9-11, 1994



The dependence of heat flux on the ratio of the layer height to its radius



Kutateladze correlation:

$$Nu_{lat} = 0.13\ Ra^{1/3}$$

for heat transfer in the radial direction

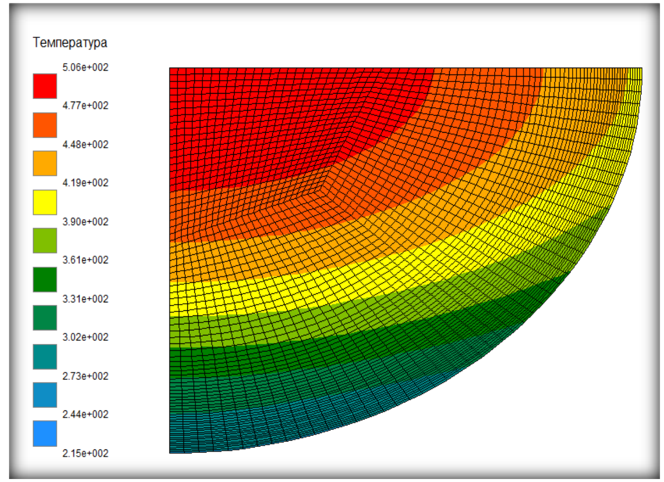
$$Nu_{up} = 0.0076\ Ra^{1/3}$$

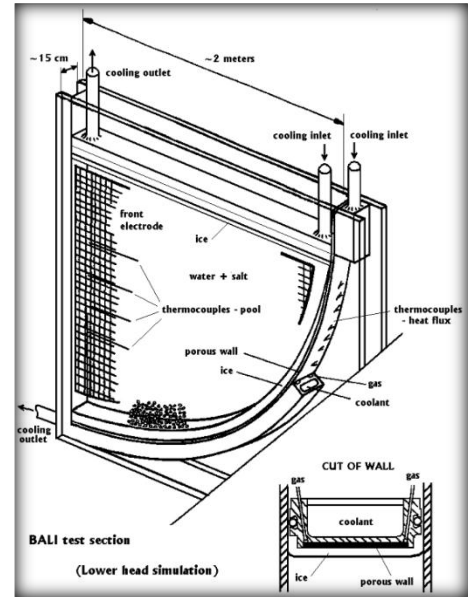
for heat transfer in the axial direction

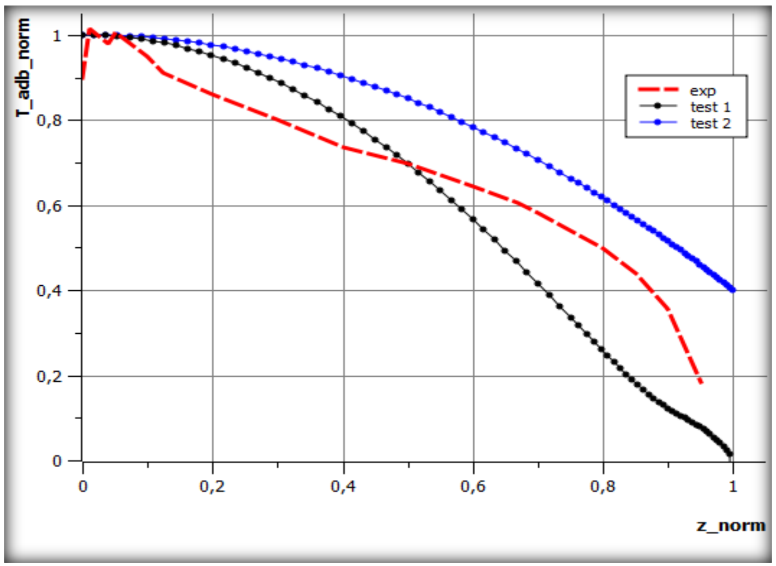
$$Ra = \Delta T\ g\ \beta\ R^3 / (\kappa\ \nu)$$

SA code verification for IVR modeling

Heat transfer in the melt oxide layer. Comparison with the results of BALI experiments







The dependence of heat flux on the ratio of the layer height to its radius

Mini-ACOPO correlation:

$$\mathrm{Nu}_{lat} = 0.13\ \mathrm{Ra}^{1/3}$$

for heat transfer in the lateral direction

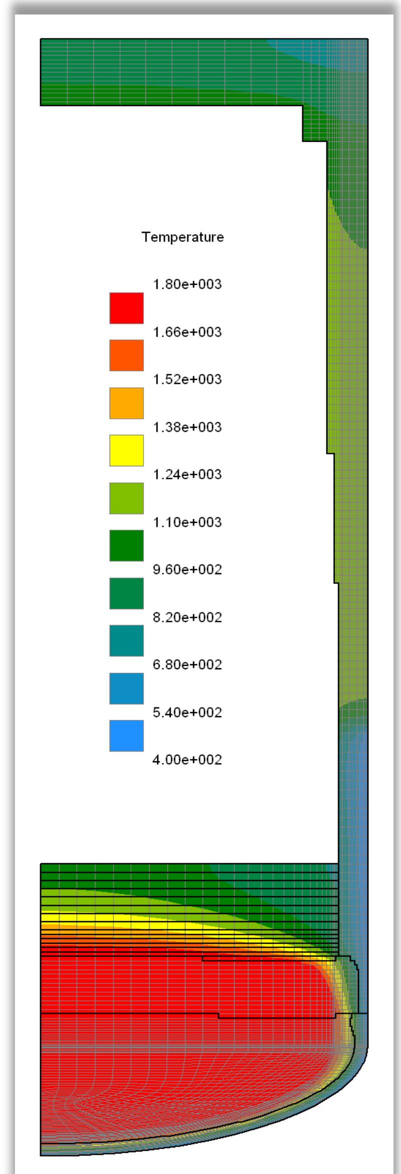
$$\mathrm{Nu}_{up} = 0.345\ \mathrm{Ra}'^{0.233}\mathrm{Ra}^{1/3}$$

for heat transfer to the upper metal layer

$$\mathrm{Ra}' = Q\ g\ \beta\ R^5 / (\lambda\ \kappa\ \nu)$$

Main results of first stage of R&D project (2013)

- existing SA codes SOCRAT and HEFEST were adapted for IVR modeling
- computational schemes for IVR modeling was developed and preliminary IVR analysis was carried out
- the necessity of limiting the initial heat capacity of reactor to 2400 MW level was confirmed (if no special technical solutions are applied)
- minimum level of coolant in the reactor cavity required for reliable reactor vessel cooling was defined
- the necessity of considering "MASCA" effect was confirmed



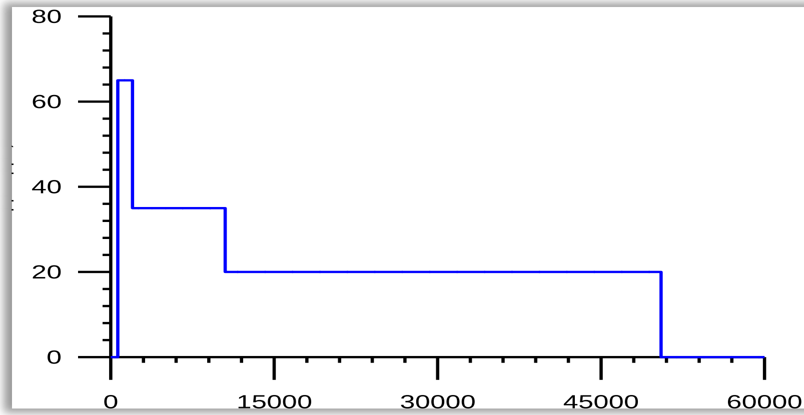
Computational analysis of IVR possibility for high-power (3200 MW) VVER-type reactors

Technical solution for IVR possibility – the temporary water supply to the reactor core

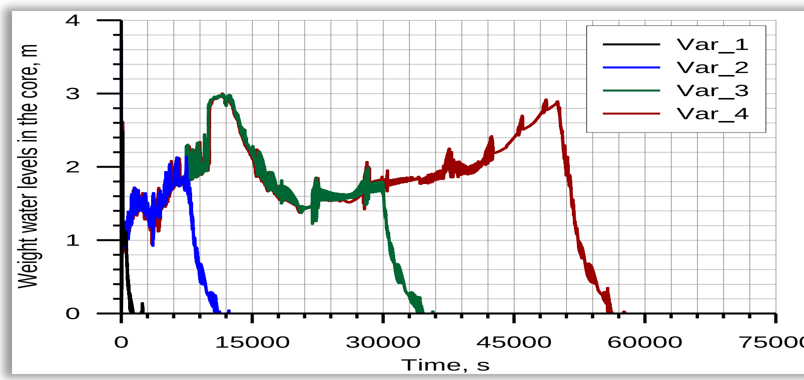
Objective – to decrease of residual heat power at the core dry-out start time

Variants of the water supply for calculations

№	Time interval of water supplying beginning – end (s)	Total value of additional water injection, m3
Var_1	0	0
Var_2	150 -7 200	290
Var_3	150 - 29 900	785
Var_4	150 - 50 000	1190

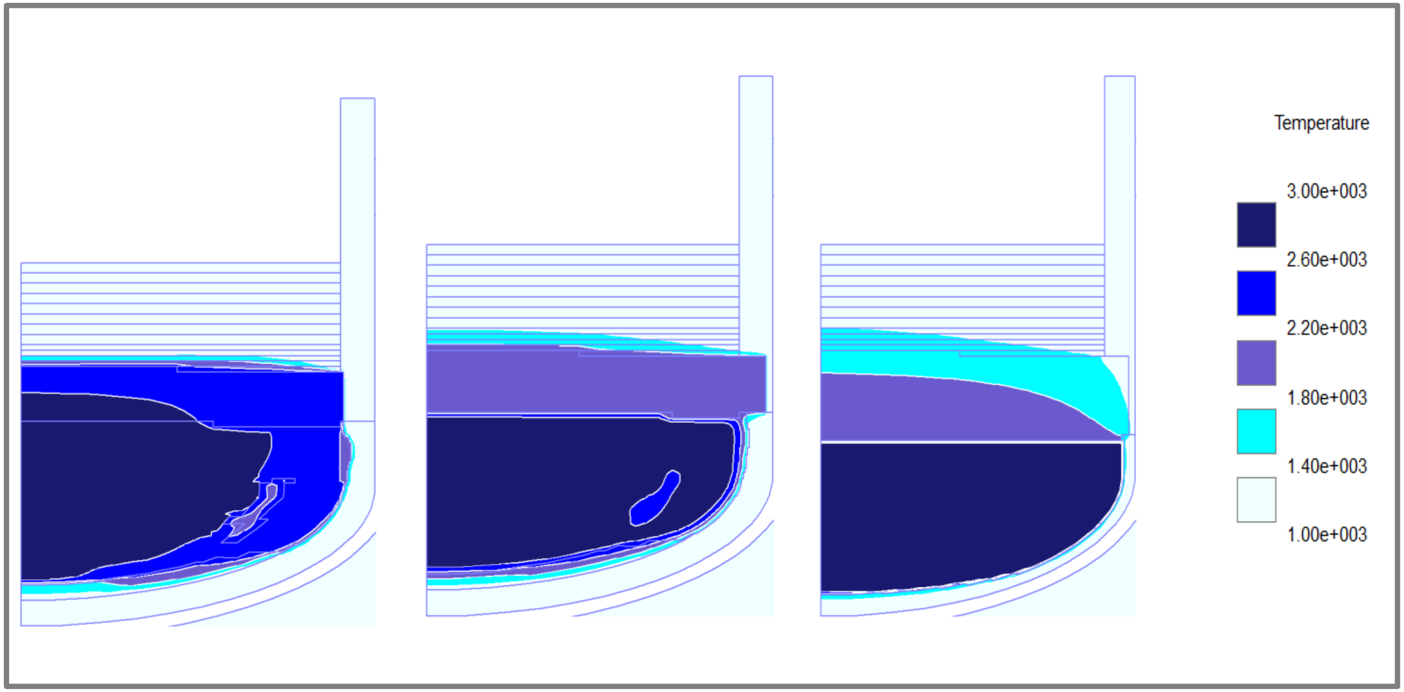


The additional water injection flow rate (kg/s) to the internal volume of the reactor vs. time (s)



Time dependence of the water level height in the core

Results of IVR modeling for high-power (3200 MW) VVER-type reactor

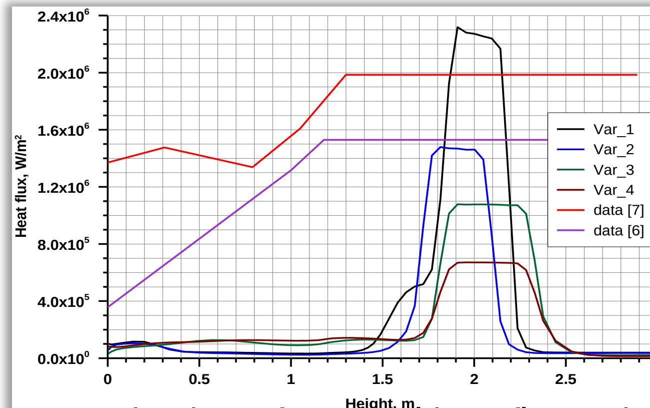


Distribution of temperature after melt pool formation at the bottom of the reactor vessel

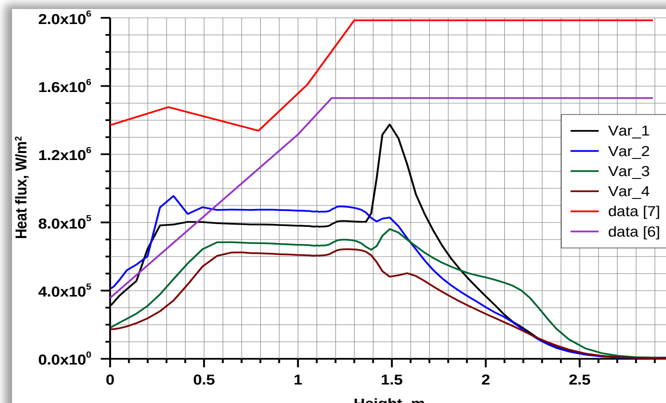
Calculation data for different variants of water supply

Parameter	Variants of calculations			
	Var_1	Var_2	Var_3	**Var_4**
time for complete drainage of the core, sec	1 480	11 400	35 120	**56 230**
The capacity of residual heat at the moment of core drying, MW	61,52	31,69	25,67	**19,36**
Time when core melt begins to enter the lower mixing chamber, , sec	2 900	12 630	33 170	**58 090**
The degree of zirconium oxidation, %	24	47	50	**44**
Maximal heat flux on the cylindrical part of the reactor vessel wall: to reaching the value, sec value , MW/m2	5 940 2,32	15 856 1,48	41 277 1,08	**64 839 0,67**
Maximal heat flux on the elliptical part of the reactor vessel wall: to reaching the value, sec value , MW/m2	**10 126 0,85**	**29 103 0,96**	**56 448 0,69**	**78 242 0,622**

Distribution of heat flux on the wall of the reactor vessel when it reaches the maximum value



the time of maximal heat flux at the elliptical bottom of reactor



the time of maximal heat flux at lower cylindrical part of the reactor vessel wall

Experimental studies in support of IVR possibility

Alexandrov Scientific Research Institute of Technology (Sosnovy Bor, Russia):

- Definition of core melt properties in the presence of temperature gradients (APL1 - APL3)
- Investigation of the possibility of oxide crust formation in the metal melt when it contacts with the reactor vessel wall (AP1-AP7)

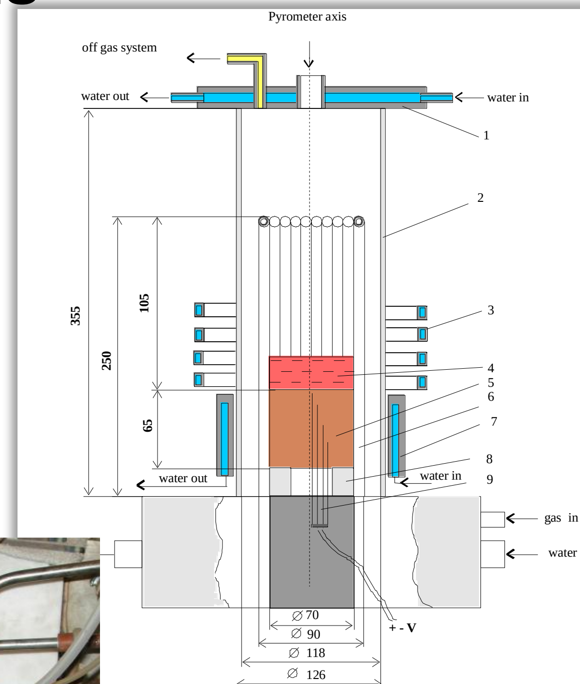
Definition of the liquidus temperature of complex mixtures for IVR conditions

Specification of experiments APL1-APL3:

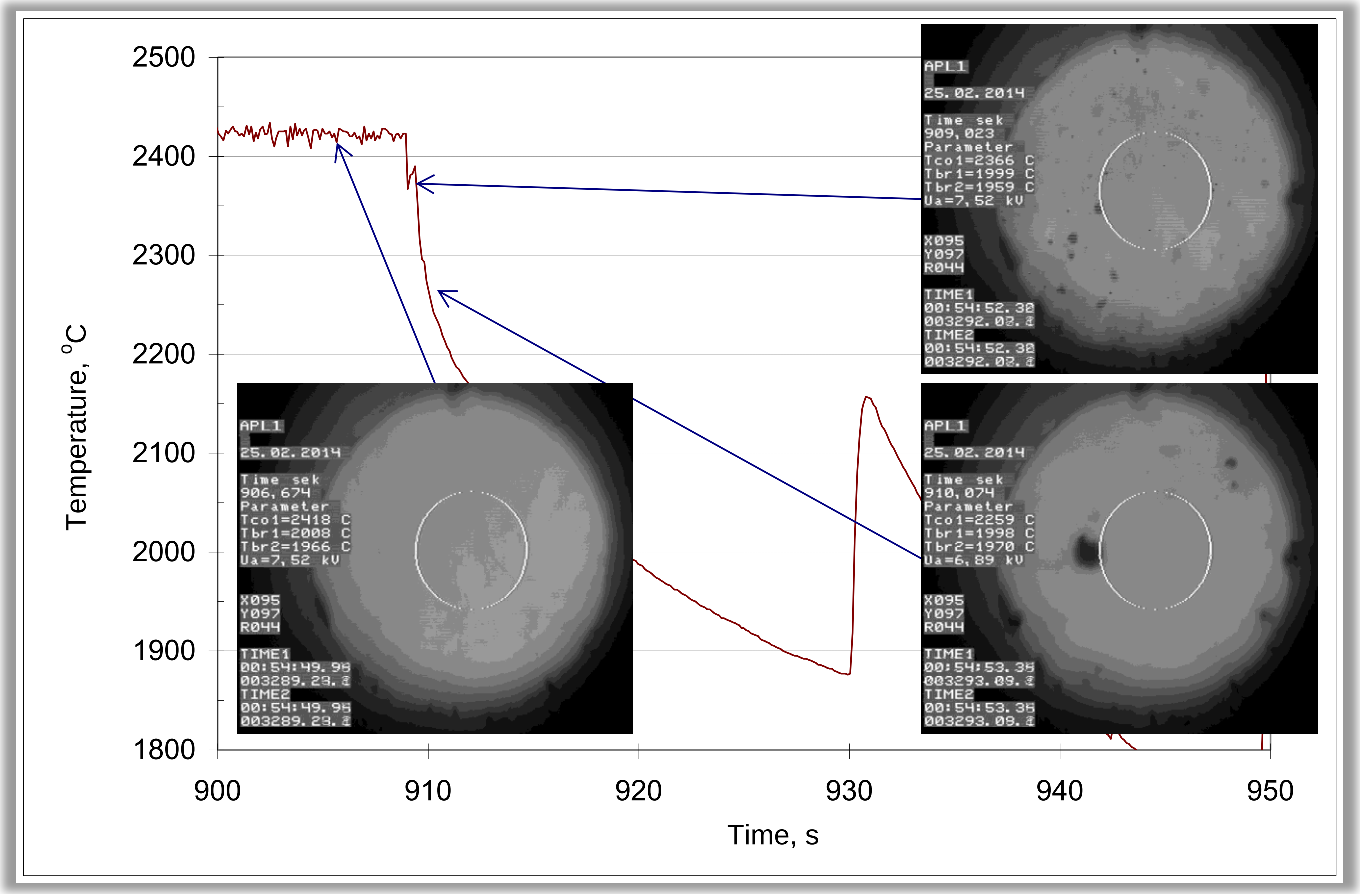
- atomic ratio U / Zr = 1,06;
- the atmosphere above the melt - dry high purity argon;
- water-cooled multisection bottom calorimeter was applied

components	APL1		APL2		APL3	
	Mass.%	mass, g	Mass.%	mass, g	Mass.%	mass, g
UO_2	74.1	1037.82	48.2	963.60	49.4	839.46
ZrO_2	8.6	120.68	5.6	112.00	18.3	310.42
Zr	17.3	241.50	11.2	224.20	2.2	37.06
Without steel	100.0	1400.00	65.0	1299.80	69.8	1186.94
Stainless steel 12X18H10T	-	-	35.0	700.00	30.2	513.06
Full mass	-	-	100.0	2000.00	100.0	1700.00

1- Water-cooled cover
2 - quartz tube
3 - inductor;
4 - melt
5 - specimen
6 - section of the crucible
7 - water-cooled screen;
8 - thermal insulation ring
9 - Thermocouple



Liquidus temperature behavior in the experiment APL1 (fragment of pyrometric and visually-thermal measurements during melt cooling)



Investigation of the possibility of appearance of oxide crusts in the metal melt. Goals of AP1-AP7 experiments

Experiment	AP1	AP2	AP3	AP4-AP5	AP6	AP7
UO_2, mass %	69,16	53,37	–	48,18	49,38	66,72
ZrO_2, mass %	8,40	6,21	–	5,60	18,26	7,76
U, mass %	–	–	38,82	-	-	
Zr, mass %	13,20	1,42	13,57	11,21	2,18	15,53
steel 12X18H10T, mass %	9,25	28,00	47,62	35,00	30,18	10,00
Ratio of steel mass to total mass (M_{st}/M_{Σ})	0,09	0,28	0,48	0,35	0,30	
Degrees of oxidation	C-32	C-27	–	C-27	C-86	C-27
Atomic ratio U/Zr	1,20	1,06	1,09	1,06	1,06	1,06

AP1 - investigation of interaction of two-fluid metal-oxide melt with vessel steel specimen for the its bottom location

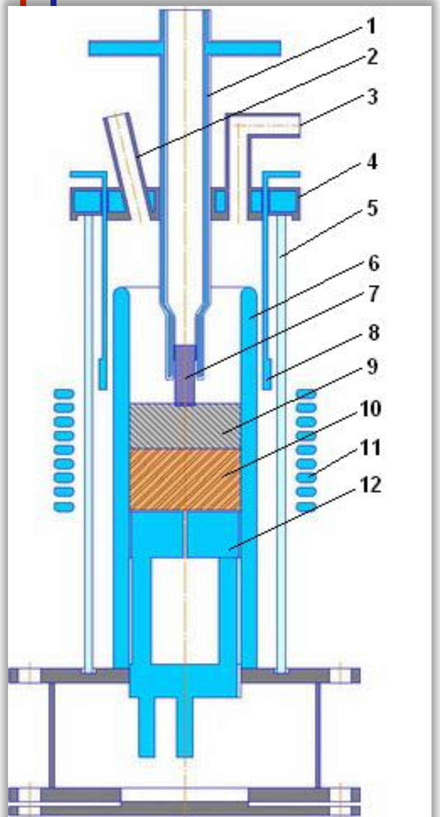
AP2, AP4, AP5, AP6, – – investigations of interaction between two-fluid metal-oxide melt and vessel steel specimen immersed from the top

AP3 - investigation of interaction between molten metal, consisting of steel, zirconium and uranium, and vessel steel specimen

AP7 – investigation of the interaction between two-fluid metal-oxide melt and water-cooled steel specimen located below with a surface initially covered by oxide crust

Scheme of the experimental facility

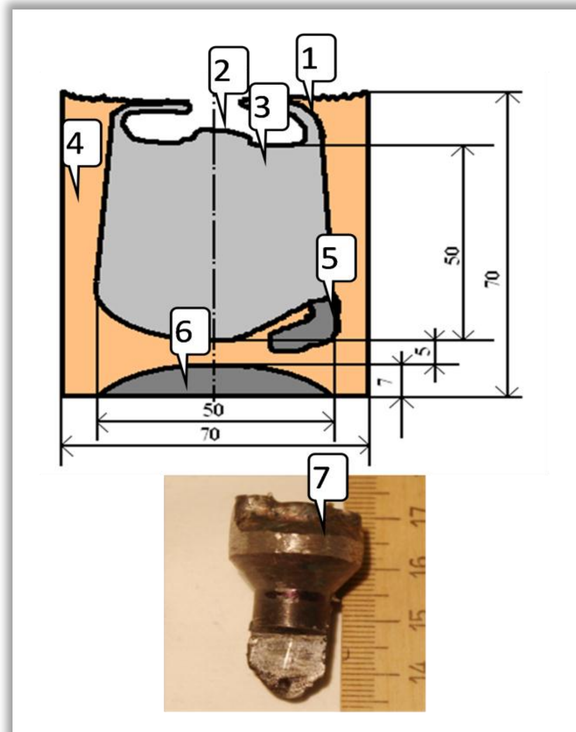
AP5 experimental results



1 - sliding shaft for vessel steel specimen
2 - registration port, 3 - tube drainage of gases and aerosols, 4 - cover of the furnace, 5 - quartz shell, 6 - section of the crucible, 7 - vessel steel specimen, 8 - screen 9 - molten metal layer, 10 - layer of oxide melt, 11 - inducer, 12 - bottom of the partitioned crucible

mass balance of the AP5 experiment (degrees of oxidation – C27)

region	U, %	Zr, %	Fe, %	O, %	Cr, Ni, Mn and et al.
3	25	14	41,5	3	16,5
4	63,4	19,7	2,7	12,4	1,8
5	36,3	13,1	35,2	0,2	15,2
6	27	14,7	35,6	4,7	18



Scheme of metal fragments location in the oxide-metal ingot and axial cross-section of specimen from AP5 experiment
1 - metal edge, 2- shrinkage cavity, 3 - metal fragment, 4 – oxide fragment, 5 - metal bridge, 6 - metal lens, 7 - specimen after the experiment

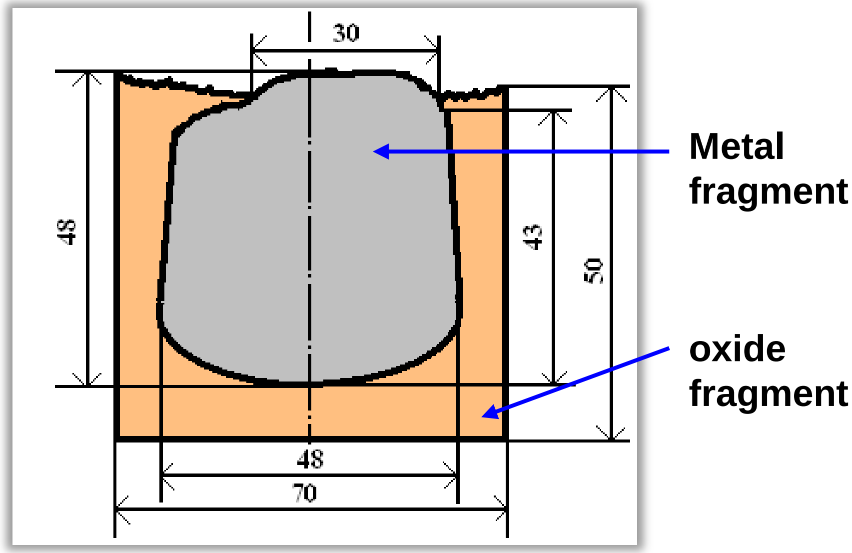
AP6 experimental results

mass balance of the AP6 experiment
(degrees of oxidation – C87)

region	U, %	Zr, %	Fe, %	O, %	Cr, Ni, Mn and et al.
metal	2,2	2,1	68,8	2,9	24
oxide	63,5	22,7	0,4	13	0.4

GEMENI2 +NICLEAR estimation of AP6 experiment mass balance

Element	Mass %
U	8,40
Zr	3,90
Fe	65,24
Cr	12,57
Ni	8,82
Si	0,62
Ratio of steel mass to total mass	31,13



Scheme of metal fragments location in the oxide-metal ingot from AP6 experiment

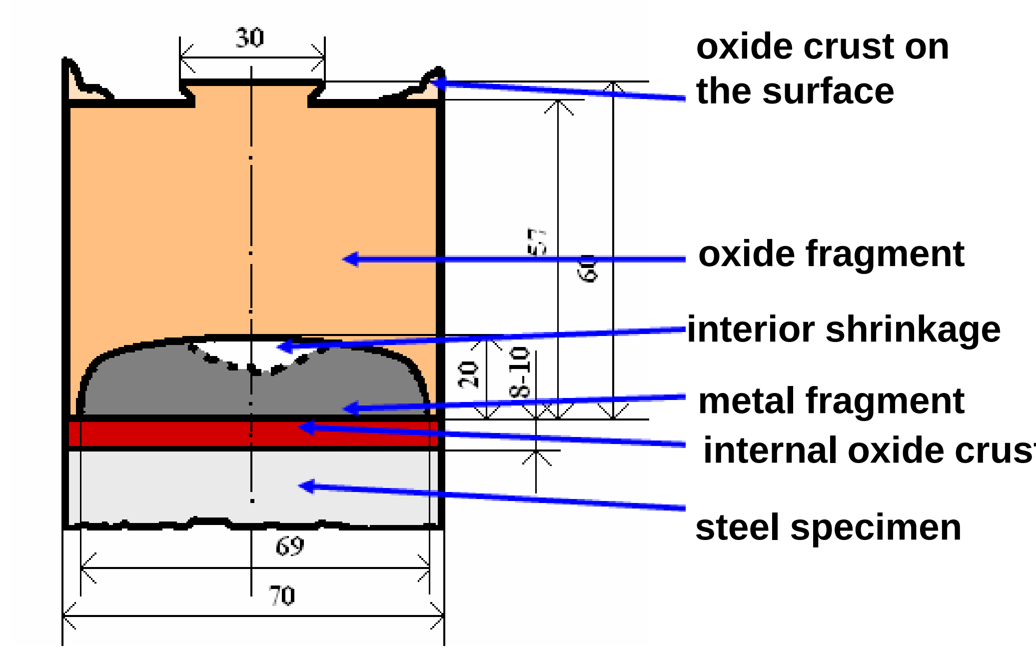
AP7 experimental results

mass balance of the AP7 experiment
(degrees of oxidation – C27)

region	U, %	Zr, %	Fe, %	O, %	Cr, Ni, Mn and et al.
metal	38,9	24,5	25,8	0,1	10,7
oxide	61	24	1,3	12,5	1,2

ingot

steel specimen



Scheme of metal-oxide ingot on the surface of steel specimen from AP7 experiment

Main results of AP1-AP7 experiments

- Experimental study of interaction between metal-oxide melt and a cooled reactor steel wall confirmed the possibility of multiple layers formation
- Extraction of U, Zr and O into metal melt was detected
- Experiment showed, that the oxide crust is not formed on the boundary between metal melt and reactor vessel wall
- The initial existing oxide crust, which was formed on the cooling surface in oxide melt, retains its integrity at contact with molten metal

The experimental data will be used to improve accuracy of melt pool behavior modeling for IVR

Conclusions

- Retention for VVER-1200 type reactor can only be guaranteed in the case of using specific technical solutions which reduce the peak heat flux at the wall. It can be achieved by using the additional core cooling at the initial stage of the accident

- Using of special deflector allows to reduce the water storage volume needed for external cooling of the reactor vessel. However, it's necessary, that experimental data regarding of deflector efficiency for VVER-type reactor sharp bottom, will be obtained

- **Common remark**. All full-scale conditions experiments were carried out at the small-scale experimental facilities. Scale factor is important for melt behavior modeling at the IVR. For reliable confirmation of IVR possibility the large-scale experiments are required.

Thank you !

Acknowledgments

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