A.P. Alexandrov Research
Institute of Technology (Russia)

ISTC
МНТЦ

Progress Report on the ISTC project #3592 "Investigation of Corium Melt Interaction with NPP Reactor Vessel Steel" (METCOR-P)

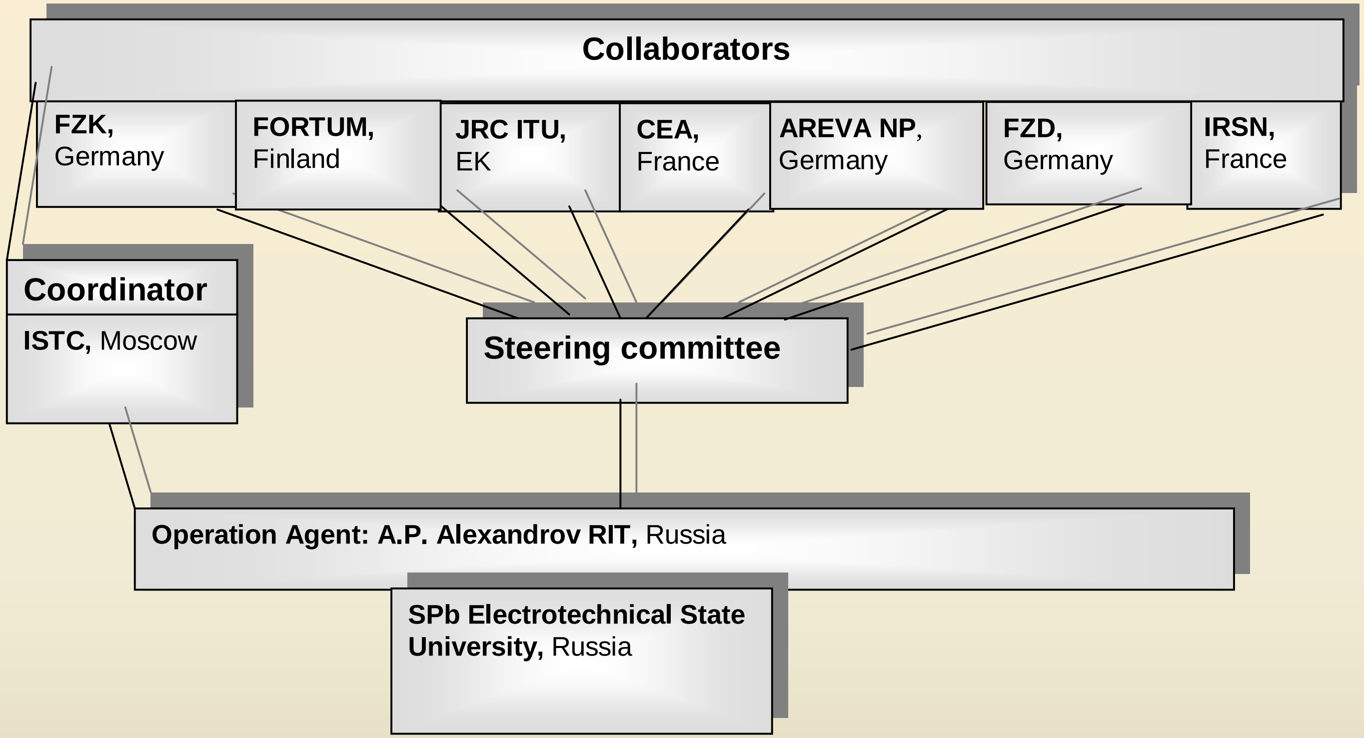
Presented by S. Bechta

15th CEG-SAM meeting
March 10-12, 2009, Villigen

Contents

General information

Project participants and coordination



Project duration	36 months
Financial party	EU
Budget	543,877.58 USD
Project status	Started in April 2007

Objectives of METCOR-P project

Qualification and quantification of physicochemical phenomena of corium melt interaction with reactor vessel steel with a focus on:

- Interaction characteristics at the vertically positioned interface
- Peculiarities of interaction with European vessel steel
- Corium melt oxidation transients

Experimental matrix for METCOR-P project

#	Item	Experimental conditions			Notes
		Composition	Surface temperature, ºC	Atmo-sphere	
1	Interaction at vertically positioned interface	UO_2+ZrO_2 C100	1400 (Steel)	Ar	Reference-test *
		UO_2+ZrO_2+Zr C30			MCP1: MC6 conditions
		Fe-U-Zr-Cr-Ni-O			Metallic phase of the melt enriched with U and Zr
2	Interaction at molten corium oxidation transients	UO_2+ZrO_2+Zr C30 with vessel steel specimen		Ar steam	10-hour exposure in Ar until the interaction stabilizes. Replacement of Ar with steam after it
		UO_2+ZrO_2+Zr C30 without vessel steel specimen	2500 (Melt)		The oxidic melt is in contact with a calorimeter
		Fe-U-Zr-Cr-Ni-O without vessel steel specimen			Molten metal enriched with U and Zr is in contact with a calorimeter
3	Interaction of molten corium with european vessel steel	UO_2+ZrO_2+Zr C30	1400 (Steel)	Ar	Reactor steel will be provided by collaborators
		UO_{2+x}+ZrO_2	1300 (Steel)	Steam	

***) In accordance with a decision of the 1st project meeting, it is replaced by MCP-2 test with UO_{2+x}– ZrO_2 corium in air and horizontally positioned interface**

METCOR-P experimental part status

Interaction characteristics at the vertically positioned interface:

- MCP-1 test with the vertical orientation of specimen surface have not shown any significant difference with MC6 test results in respect to the final corrosion depth and IZ composition
- At present the ultrasonic technique is adjusted to measure corrosion kinetics of vertically positioned steel specimen

METCOR-P experimental part status (2)

Peculiarities of interaction with European vessel steel:

- The tests are under preparation
- AREVA has shipped European vessel steel specimens; their delivery is delayed due to customs formalities
- A three-party agreement between AREVA, ISTC and NITI has been prepared. Specimens are sending to the ISTC

Corium melt oxidation transients:

- One test (MCP-3) and its analyzes have been made
- Results interpretation is in progress

VVER vessel steel corrosion at its interaction with oxidized corium melt in the oxidizing atmosphere

Objective

- Development of model and correlations describing METCOR experimental data
- Reactor application of the results to the IVR conditions

Experimental Data

Test	Corium	Atmosphere	Point #	Specimen Surface Temperature, °C	Heat Flux, MW/m^2	Corrosion Rate, mm/h
MC1	UO_{2+X}-ZrO_2-FeO_y	Air	1	950	0.90	0.1
MC2			1	900	0.39	0.014
			2	990	0.44	0.068
			3	1050	0.47	0.076
			4	720	0.30	0.003
MC10	UO_{2+X}-ZrO_2	Steam	1	1035	0.95	0.55
			2	1185	1.05	1.07
			3	1235	1.1	2.07
MC11	UO_{2+X}-ZrO_2-FeO_y		1	950	0.99	0.17
			2	1050	1.16	0.25
			3	1130	1.23	2.8
			4	1200	1.29	7.8
MC12		Air	1	1000	0.92	0.10
			2	1035	0.95	0.31
			3	1075	0.98	0.51
			4	1135	1.04	3.25
		Steam	5	1065	1.00	0.46
			6	1125	1.09	2.78
MCP-2	UO_{2+X}-ZrO_2	Air	1	870	0.74	0.085
			2	950	0.81	0.13
			3	1080	0.92	0.7
			4	1165	1.00	1.77
			5	1210	1.04	2.38
			6	1230	1.06	3.46
			7	1325	1.15	4.25
			8	1350	1.17	4.75
			9	1370	1.19	5.8

Qualitative experimental results

- Oxidation follows the linear law
- Corrosion rate is sensitive to the following factors: temperature on the specimen surface, corium – steel heat flux and corium composition
- Intensified corrosion at higher temperatures (above 1050°C on the steel specimen surface) for corium with a high content of iron oxides
- Corrosion rate is not sensitive to the replacement of air with steam

Correlations

- For UO_{2+X}-ZrO_2 corium:

$$\frac{W\cdot(2723-T_S)}{q}=4.98\exp\left(-\frac{1.1\cdot10^5}{RT_S}\right)$$

Solid-phase diffusion

Diffusion at corium crust liquefaction

- For UO_{2+X}-ZrO_2-FeO_y corium:

$$\frac{W\cdot(1613-T_S)}{q}=0.1\exp\left(-\frac{0.91\cdot10^5}{RT_S}\right)+3.4\cdot10^{14}\exp\left(-\frac{4.99\cdot10^5}{RT_S}\right)$$

where W – corrosion rate, m/s

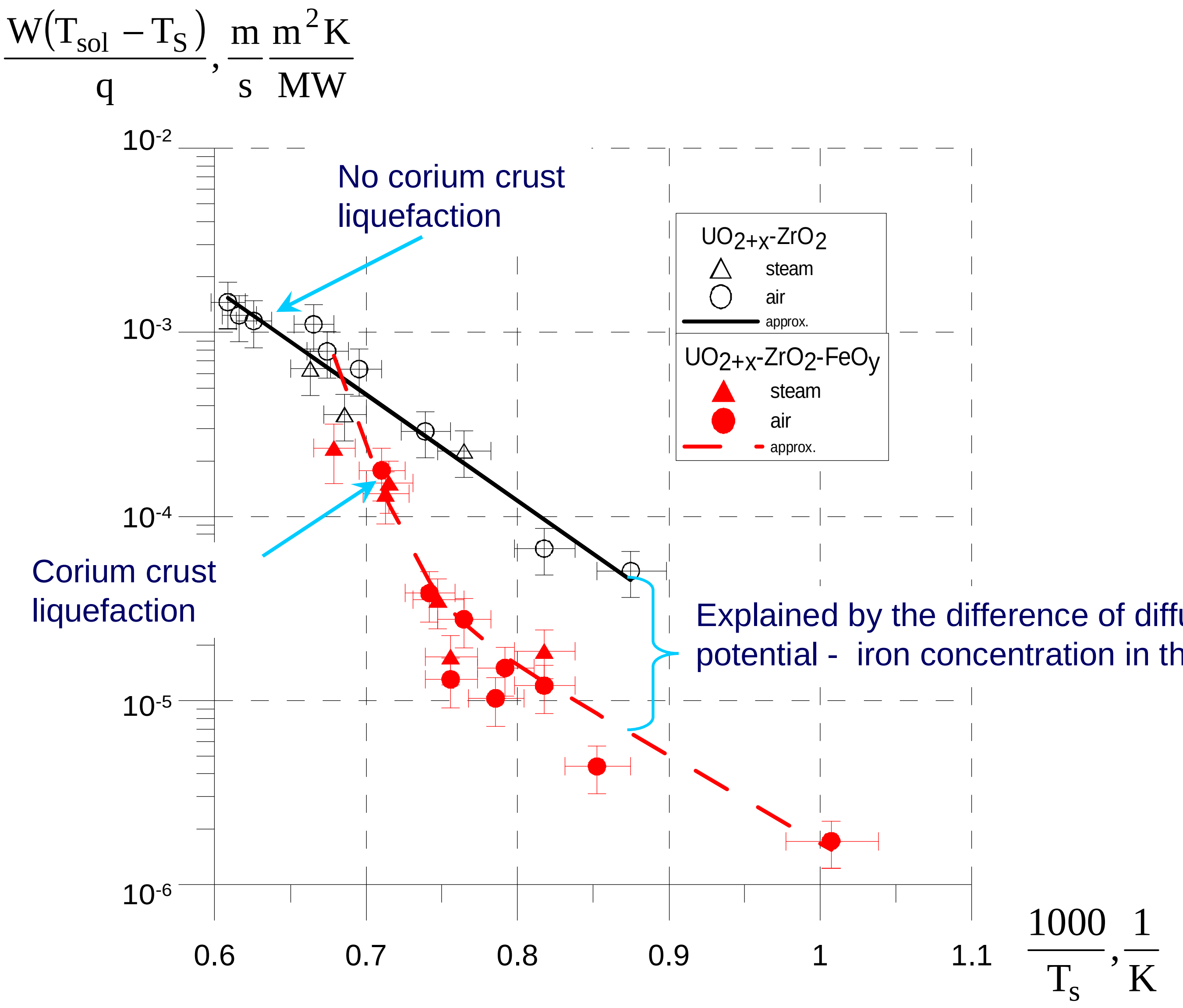
q – heat flux, MW/m^2

T_S – temperature of the steel surface, K

T_{sol} – solidus temperature, K

(2723 K – the 1st case and 1613 K – the 2nd case)

Generalization of Experimental Data



Conclusion remarks to the 4th Part

ü Corrosion phenomena are determined by the diffusion of Fe^{2+} ions through the surface corium crust

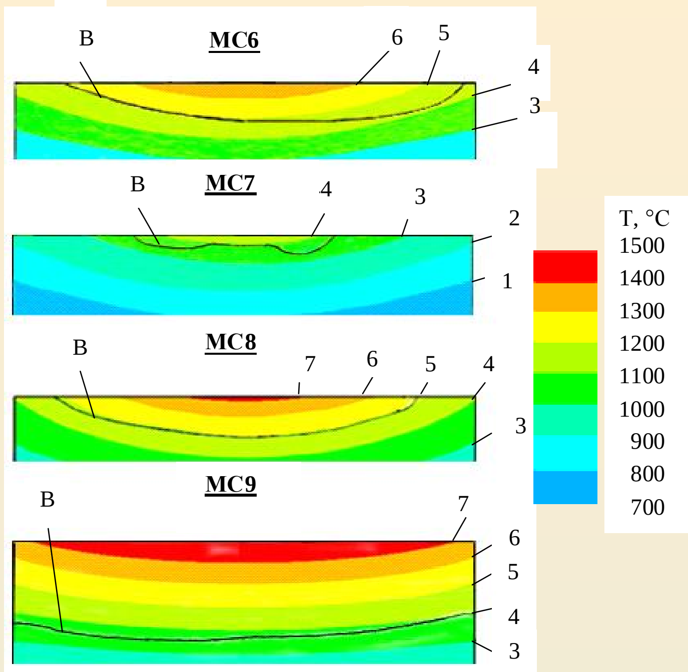
ü Corrosion rate of vessel steel interacting with fully oxidized corium follows the Arhenius law

ü Intensified corrosion at higher temperatures (above 1050°C on the steel specimen surface) for corium with a high content of iron oxides is caused by liquid-phase percolation channels formed in the corium crust

ü Semi-empirical correlations have been used for IVR analyses of VVER

VVER vessel steel corrosion at its interaction with suboxidized corium melt

Objectives



- Ø **Develop a model for determining temperature of corrosion front final position (T_B)**
- Ø **Get experimental data about influence of thermogradient conditions on U, Zr and Fe partitioning between oxidic and metallic melts**

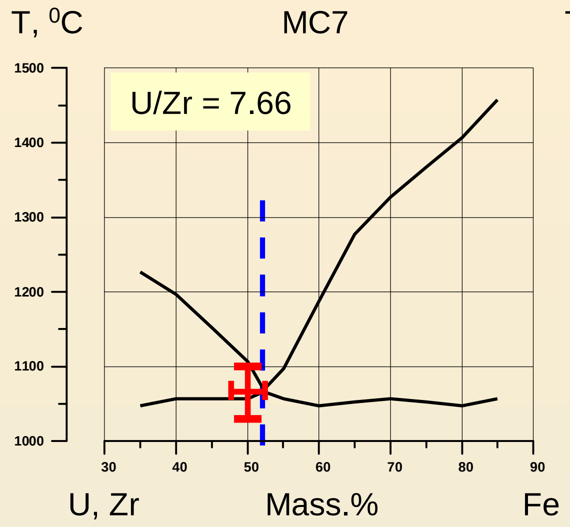
Results of Tests with Suboxidized Corium

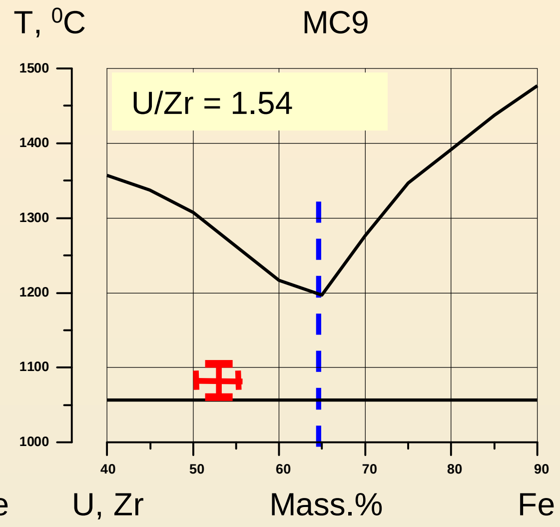
Test	Corium oxidation index, C_n	Temperature of corrosion front final position, T_B ,°C	Mass fraction of interacted steel of specimen, %	IZ composition*, mass%			Composition of metallic body, mass%		
				U	Zr	Fe	U	Zr	Fe
MC6	C-30	1120…1200	3.4	25.6	5.4	64.4	55.0	25.0	15.0
MC7	C-30	1030…1100	0.4	44.0	2.2	50.0	Metallic body was not found		
MC8	C-70	1200	2.9	22.0	6.1	68.2			
MC9**	C-30	1060…1100	9.2	33.3	8.3	53.0	–	–	–
MCP-1	C-17	1000…1090	7.1	44.0	14.0	40.0	57.0	24.0	18.0

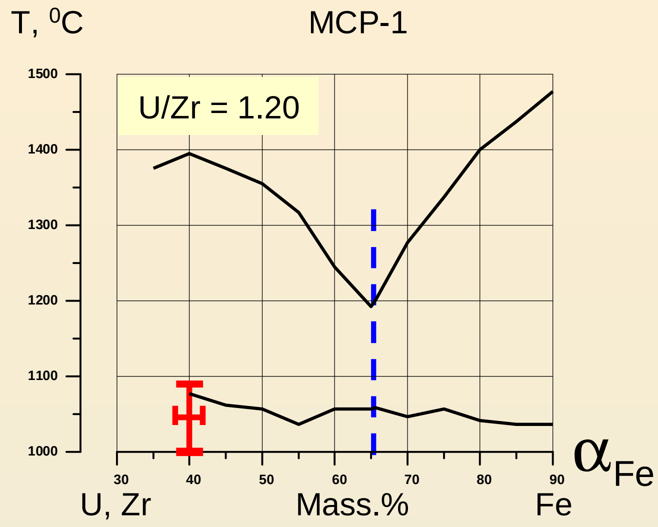
* – oxygen content on the IZ is not given in the table (from 0.2 to 0.5 mass%)

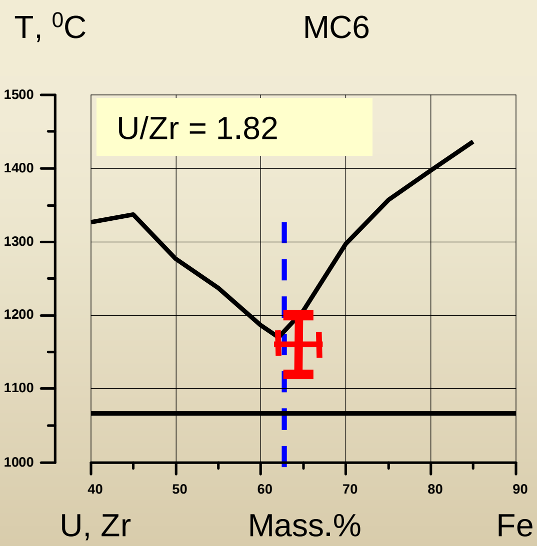
** – a considerable part of iron transferred to the melt volatilized during the pool exposition

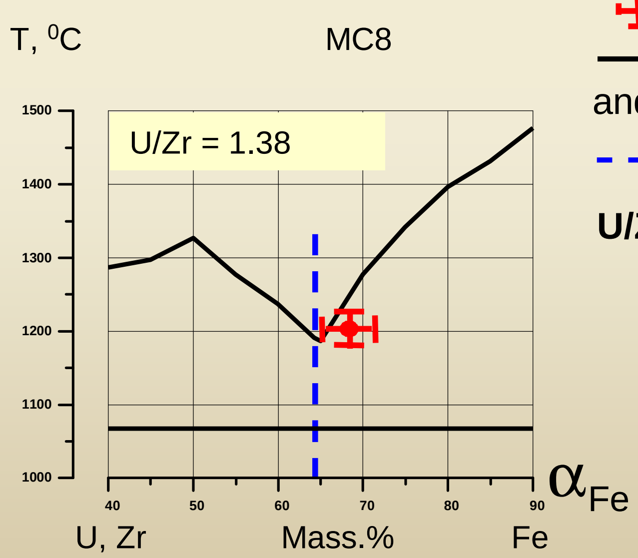
Temperature of corrosion front final position in comparison with simplified phase diagram











experiment

calculation of solidus (eutectic) and liquidus temperature by NUCLEA

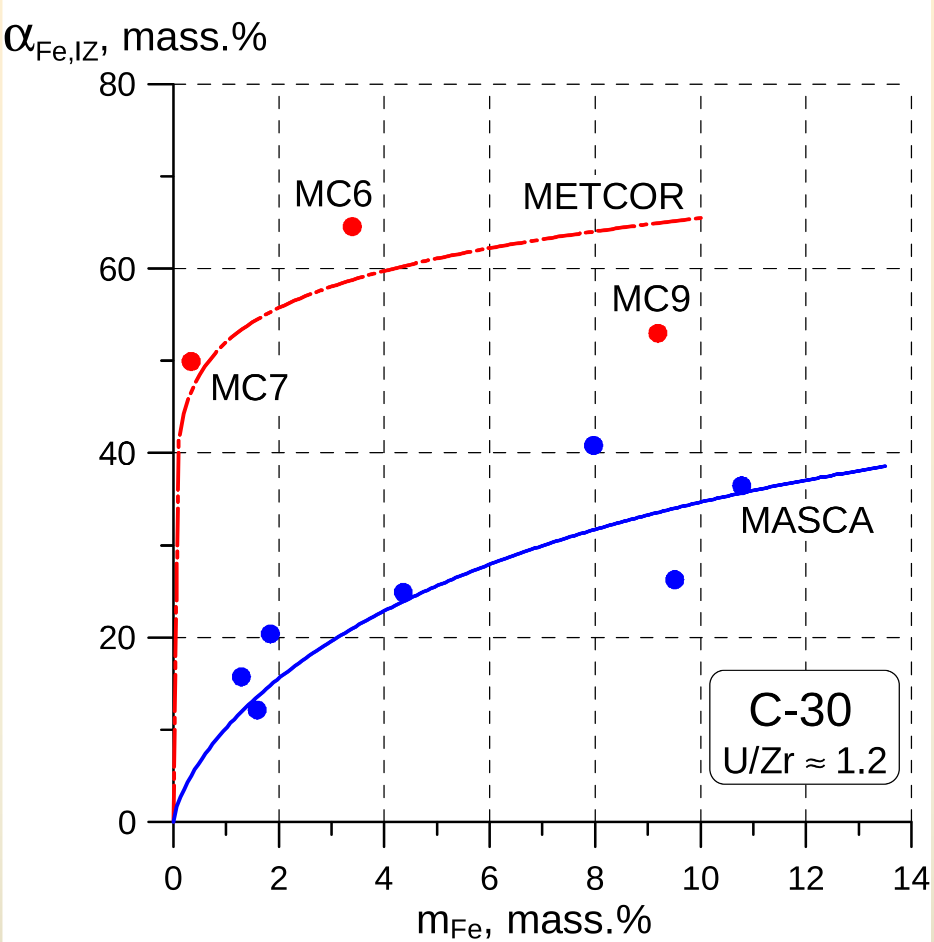
binary eutectic point ($\alpha_{Fe,eut}$)

U/Zr ratio in IZ !

Hypothesis

$$T_B = \begin{cases} T_{eut}, & \alpha_{Fe} < \alpha_{Fe,eut} \\ T_{liq}, & \alpha_{Fe} > \alpha_{Fe,eut} \end{cases}$$

Influence of thermal gradient on U, Zr and Fe partitioning



In MASCA tests:

$$\left(T_{ox} - T_{met}\right) \approx 0$$

In METCOR tests:

$$\left(T_{ox} - T_{met}\right) \approx$$
$$\approx \left(T_{ox} - T_{met}\right)_{IVR} = 1200...1350\,K$$

ü In comparison with MASCA Fe concentration in the metallic phase is considerably higher, i.e. U and Zr extraction considerably decreases

Conclusion remarks to the 5th Part

- Thermal gradient conditions are found to have considerable influence on the partitioning of components between oxidic and metallic phases. This factor is to be taken into account in determining the molten pool configuration. Quantitative characteristics and model development require a dedicated experimental study

- Specified final temperature on the corrosion front (T_B) is not likely to have relevance for IVR of VVERs, as shown in*, corrosion is not dangerous for the vessel integrity. But vessel steel corrosion contributes to the molten pool composition and configuration

- Model for T_B evaluation is under development. It will be discussed with collaborators at the 3rd METCOR-P meeting

* – *S.V. Bechta, V.S. Granovsky, V.B. Khabensky, E.V. Krushinov, S.A. Vitol, V.F. Strizhov, D. Bottomley, M. Fischer, P. Piluso, A. Miassoedov, W. Tromm, E. Altstadt, H. G. Willschutz, F. Fichot, O. Kymalainen* **"VVER Steel Corrosion During In-Vessel Retention of Corium Melt"** Proc. of the 3rd European Review Meeting on Severe Accident Research (ERMSAR 2008), Nesseber, Bulgaria, September 23-25, 2008, Paper 2.7

Publications of 2008

- *S.V. Bechta, V.S. Granovsky, V.B. Khabensky, E.V. Krushinov, S.A. Vitol, A.A. Sulatsky, V.V. Gusarov, V.I. Almiashev, D.B. Lopukh, D. Bottomley, M. Fischer, P. Piluso, A. Miassoedov, W. Tromm, E. Altstadt, F. Fichot, O. Kymalainen* **"Interaction between Molten Corium UO_{2+X} - ZrO_2- FeO_y and VVER Vessel Steel"**, Proceedings of ICAPP '08, Anaheim, CA USA, June 8-12, 2008, Paper 8052

- *S.V. Bechta, V.S. Granovsky, V.B. Khabensky, V.V. Gusarov, V.I. Almiashev, L.P. Mezentseva, E.V. Krushinov, S.Yu. Kotova, R.A. Kosarevsky, M. Barrachin, D. Bottomley, F. Fichot, M. Fischer* **"Corium Phase Equilibria based on MASCA, METCOR and CORPHAD Results"**, Nuclear Engineering and Design 238 (2008), pp. 2761-2771

Publications of 2008 (2)

- *S.V. Bechta, V.S. Granovsky, V.B. Khabensky, E.V. Krushinov, S.A. Vitol, V.F. Strizhov, D. Bottomley, M. Fischer, P. Piluso, A. Miassoedov, W. Tromm, E. Altstadt, H. G. Willschutz, F. Fichot, O. Kymalainen* **"VVER Steel Corrosion During In-Vessel Retention of Corium Melt"**, Proc. of the 3rd European Review Meeting on Severe Accident Research (ERMSAR 2008), Nesseber, Bulgaria, September 23-25, 2008, Paper 2.7

- *S.V. Bechta, V.S. Granovsky, V.B. Khabensky, E.V. Krushinov, S.A. Vitol, A.A. Sulatsky, V.V. Gusarov, V.I. Almiashev, D.B. Lopukh, D. Bottomley, M. Fischer, P. Piluso, A. Miassoedov, W. Tromm, E. Altstadt, F. Fichot, O. Kymalainen* **"VVER Vessel Steel Corrosion at Interaction with Molten Corium in Oxidizing Atmosphere" ",** Nuclear Engineering and Design (in Press, Corrected Proof, http://dx.doi.org/10.1016/j.nucengdes.2008.12.009)

Publications of 2008 (3)

- *S.V. Bechta, V.S. Granovsky, V.B. Khabensky, E.V. Krushinov, S.A. Vitol, A.A. Sulatsky, V.V. Gusarov, V.I. Almiashev, D.B. Lopukh, D. Bottomley, M. Fischer, P. Piluso, A. Miassoedov, W. Tromm, E. Altstadt, F. Fichot, O. Kymalainen* **"Interaction between Molten Corium UO_{2+X} - ZrO_2 – FeO_y and VVER Vessel Steel"**, Nuclear Technology (Accepted for Publication)

Organizational issue

- In August 2007 ROSATOM Export Control required export license for METCOR-P project and a partner to be responsible for the project result confidentiality

- The situation was discussed at the 13th and 14th CEG-SAMs

- In August 2008 JRC-ITU confirmed their ability to be the project partner

- In November 2008 NITI initiated the 2nd expertise of ROSATOM Export Control

Organizational issue (2)

Ø In February 2009 ROSATOM Export Control approved METCOR-P Work Plan but required a confirmation to be provided to NITI that:

- The project results will NOT be used for military purposes
- IAEA INFCIRC/254/Rev.6/Part 1 procedure will be applied in Germany for re-export control
- Nuclear and special materials, facilities and equipment (developed with use of the project results) will be under IAEA control and will have IAEA-recommended physical protection during all operation time in Germany (or under German jurisdiction)

Conclusions

- Ø Essential results of completed METCOR and METCOR-P tests have been summarized and published

- ØThere is a delay of project experimental part due to the Export control problem

- Ø The Export control problem of project realization is practically solved now

- Ø If the METCOR-P Work Plan is not fulfilled within the predetermined timeframe; OA will ask for project prolongation without requesting additional funding

- Ø The next METCOR-P project meeting will be held in St Petersburg, May 25, 2009