

Investigation of corium melt interaction with NPP reactor vessel steel (METCOR-P)

Progress report 01/01/09 -31/03/09

STEAM OXIDATION EFFECT ON ZONE OF INTERACTION OF C-32 CORIUM WITH VESSEL STEEL

EXPERIMENT MCP-3

Project title	Investigation of Coriu NPP Reactor Vessel S 3592	m Melt Interaction with teel (METCOR-P) No.
Contracting organization	ISTC	1
File code	RMP-03	
Project location	Alexandrov Research of the RF Agency for NITI, Sosnovy Bor, 1 Russia	Institute of Technology Atomic Energy. 88540 Leningrad Region,
Project manager	Name Signature	V.B. Khabensky

Date

March, 2009

AUTHORS

Dr.(Eng.), Prof.	V. B. Khabensky
Dr.(Eng.)	S. V. Bechta
Ph.D.	V. S. Granovsky
Ph.D.	A. A. Sulatsky
	S. A. Vitol
	E. V. Krushinov
Ph.D.	S. Yu. Kotova
Acadomician	
Academician	V. V. Gusarov
Ph.D.	I. V. Kulagin
Ph.D.	D. B. Lopukh
	V. I. Almjashev
	V. G. Bliznyuk
	V. R. Bulygin
	E. K. Kalyago
	N. E. Kamensky
	A. V. Lysenko
	A. P. Martynov
	A. P. Martynov V. V. Martynov
	A. P. MartynovV. V. MartynovE. V. Shevchenko
	A. P. MartynovV. V. MartynovE. V. ShevchenkoA. A. Chertkov

ABSTRACT

A description and results of MCP-3 experiment carried out within the ISTC METCOR-P project # 3592 are presented.

The experimental studies cover the oxidation phenomena taking place in the steam atmosphere above the interaction zone. It was formed on the surface of VVER vessel steel after the contact with C-30 corium taking place in the argon atmosphere before steam supply.

CONTENTS

INTRODUCTION 6

1	DE	CRIPTION OF EXPERIMENT	7
	1.1	Experimental setup schematics	7
	1.2	Materials	9
	1.3	Experimental procedure	
	1.4	Ultrasonic measurements of steel corrosion	
2	PO	STTEST ANALYSIS	
	2.1	Specimen temperature conditions	17
	2.2	Physicochemical analysis	
3	DIS	SCUSSION OF RESULTS	
С	ONCL	USIONS 51	
R	EFER	ENCES 52	

INTRODUCTION

The ISTC METCOR Project has determined qualitative and quantitative characteristics of the interaction between suboxidized molten corium and cooled surface of VVER vessl steel. Experimental data on the corrosion depth and kinetics have been summarized; the mechanics of corrosion has been explained. Like in the studies carried out within the OECD MASCA program it was found that the interaction is accompanied by the partitioning of corium and steel components, after which an interaction zone (IZ) is formed on the steel specimen surface. Similar to MASCA case with metallic melt, the IZ consists of U, Zr, Fe and a small quantity of O. At this, other conditions being equal, concentrations of U, Zr and O in the METCOR IZ are considerably smaller than in MASCA, which is explained by the METCOR thermogradient conditions. The steel itself undergoes corrosion during its dissolution in the IZ liquid phase. These METCOR findings are discussed in $[1\div3]$.

Of special interest for the in-vessel retention (IVR) studies is the change of initially inert above-melt atmosphere by steam (a case with suboxidized corium). It is assumed that such change of atmosphere results in the oxidation of the system, which was formed at the melt-specimen interaction in the METCOR experiments. The system also includes a metallic part – the IZ, similar to the one observed in MASCA tests [4].

Experiment MCP-3 was performed for determining qualitative and quantitative phenomena of IZ oxidation in the given conditions. The experiment was conducted in accordance with the METCOR-P Work plan as a continuation of MC6 [5], in which the IZ was formed as a result of interaction between C-30 corium and steel specimen, the maximum temperature on the interface of which was 1400°C, i.e. in MCP-3 the neutral atmosphere was replaced with steam after the MC6 procedure was repeated.

Sections below present MCP-3 procedure, data and their analysis.

1 DECRIPTION OF EXPERIMENT

1.1 Experimental setup schematics

The experiment was conducted on the Rasplav-3 tests facility. The furnace schematics are given in Fig. 1.2. Top and bottom calorimeters and ultrasonic sensor were used to determine heat fluxes from the melt into the specimen and cooling of the interaction zone.



1 – gas and aerosol vent; 2 – gas supply pipe; 3 – water-cooled pyrometer shaft; 4 – water-cooled cover; 5 – quartz tube; 6 – water-cooled electromagnetic screen; 7 – crucible section; 8 – inductor; 9 – melt; 10 – acoustic defect; 11 – molten ZrO₂ (fianite); 12 – vessel steel specimen; 13 – K-type thermocouples; 14 – top calorimeter; 15 – bottom calorimeter; 16 – ultra-sonic sensor





Fig. 1.2 – Vessel steel specimen

Table 1.1 shows the positioning of thermocouple junctions (K-type), which were embedded into the specimen. Thermocouples located within a 10-mm radius from the specimen

axis were embedded into 1.5 mm-diameter holes, those located 29 mm from the axis were embedded into the 1.5 mm-wide grooves.

#	α° (azimuth angle)	r, mm (distance between the specimen axis and hot junction)	h, mm (distance between the top edge and hot junction)
TC01	180	10	1
TC02	90	10	2
TC03	135	10	3
TC04	45	10	4
TC05	270	10	6
TC06	0	10	8
TC07	225	10	20
TC08	180	29	1
TC09	90	29	2
TC10	45	29	4
TC11	225	29	8
TC12	315	29	20
TC13		7.5	104

Table 1.1 – Location of thermocouple junctions

To exclude the electromagnetic heating of specimen the lower sections of the crucible top zone were welded together to serve as an electromagnetic screen. The specimen was positioned in the crucible so that its top was 1 mm lower than the top of welded sections. The gap between the specimen and crucible sections was filled with ZrO_2 powder and molten ZrO_2 granules (11). Water-cooled movable screen (6) was used for additional specimen screening from electromagnetic heating and for controlling the thickness of molten pool bottom crust. The melt surface was monitored through the water-cooled pyrometer shaft blown with argon (3).

Acoustic defect (10) was made in the specimen to measure the vessel steel corrosion rate. Same ultra-sonic sensor (14) as in MC6 was used. Differently from MC6 the acoustic defect was farther from the specimen top because of the estimated interaction zone depth. The furnace was sealed with water-cooled cover (4), which had quartz tube (5).

Fig. 1.3 shows the system of steam and gas supply and gas-aerosol sampling.



1 –Ar,N tanks; 2 – water regulator-meter; 3 – evaporator; 4 – steam supply into the furnace; 5 – steam condenser; 6 – condensate collector; 7 – condensate drop collector; 8 – ejector; 9 – large-area filter; 10 – silica-gel dryer; 11 – Petrianov filters; 12 – O and H electrochemical sensors; 13 – vacuum receiver; 14 – large-area filter, startup line; 15 – strain sensor; 16 – hydrolock.

Fig. 1.3 – Gas-aerosol system

The system operated in the following way. Startup heating, charge melting and first part of the experiment were performed in argon supplied from the tank to the furnace. Hydrolock (16) provided the excess argon pressure in the furnace. After studies in the argon atmosphere steam was supplied through steam pipe (4) from evaporator (3). Steam flow rate was measured by water regulator-meter (2). To exclude steam condensation the steam pipe was heated up to 120-150°C. Steam-gas mixture went from the furnace to steam condenser (5). The condensate flew into tank (6). Strain sensor (15) was used for on-line measurement of condensate weight. Ejector (8) collected non-condensable gases from the condenser, nitrogen was used as the carrier-gas (1). After that gas went to filter (9) and silica-gel drier (10). The gas composition, in particular, H and O concentration in it, were measured by electrochemical sensors (12) after additional cleaning by filter (11).

1.2 Materials

The following materials were used in the test: vessel steel 15Kh2NMFA–A, uranium dioxide, zirconium oxide, metallic zirconium, argon, steam. All materials were analyzed for the content of the basic component. Along with that, the O to U ratio was measured in UO_2 powder by the gravimetric method; it was 2.0. Table 1.2 shows the composition of charge and steel introduced into the melt in MCP-3.

Table 1.2 –MCP-3 cl	harge composition
---------------------	-------------------

Components	Content of main substance, mass.%	Admixtures, mass. %	Source
UO2 powder, dispersivity <200 μm	UO ₂ >99.0	Fe<0.03; As<0.0003; CuO<0.01; phosphates<0.002; chlorides<0.003.	Certificate data, thermogravimetry
ZrO ₂ powder, dispersivity <100 μm	(ZrO ₂ +HfO ₂) >99.3	$\begin{array}{c} Al_2O_3{<}0.03; Fe_2O_3{<}0.05;\\ CaO{<}0.03; MgO{<}0.02; SiO_2{<}0.2;\\ TiO_2{<}0.1; P_2O_5{<}0.15;\\ (Na_2O{+}K_2O){<}0.02. \end{array}$	Certificate data
Zr metallic rods H6-1	Zr >99.0	Nb<1.0	XRF data
Steel 15Kh2NMFA–A	Fe>95.1	Si-0.25; P<0.02; Ni-1.0; Mn-0.49; Cr-2.24; Cu-0.07; Mo-0.7; V-0.1; Co<0.03; As<0.003.	XRF data

The charge was placed into the crucible in the argon atmosphere following a special technology tested in previous experiments. 150 g of corium C-29.8 (76.7 %UO₂; 7.0 % ZrO₂; 16.3 %Zr, here and hereafter mass.%) was put on the top of steel specimen. The corium dispersivity was not more than 50 μ m. Corium C-29.8 had been synthesized in the argon atmosphere in Pr1-MCP-1. On top of it the following charge was placed: UO₂, ZrO₂ and metallic zirconium having the C-32 composition (76.00 %UO₂; 9.33 % ZrO₂; 14.67 %Zr).

Table 1.3 gives the composition and mass of components placed into the crucible before melting.

Function	Component	Fraction, µm	Mass, g	Percent
Crust simulant	Corium C-29.8 (76.7%UO ₂ ; 7.0% ZrO ₂ ; 16.3%Zr)	< 50	150	8.2
	UO_2	< 500	1271.7	69.8
	ZrO ₂	< 50	150.6	8.3
Main charge	Metallic zirconium, Zr	Rods 3 mm in diameter and 15 mm high	250.0	13.7
	1822.3	100.0		

 Table 1.3 – Charge composition and mass of components

The required fractions of uranium dioxide and corium were produced by crushing tablets from fuel elements and C-29.8 corium ingot from Pr1-MCP-1 in the argon atmosphere.

1.3 Experimental procedure

Fig. 1.4÷1.10 shows the measurements of main parameters excluding specimen corrosion depth.

The furnace was flushed with argon during 10 minutes (flow rate 10 l/min). It was followed with startup heating to produce molten pool. To prevent the uncontrollable specimen heating its top was lowered by 35 mm (Z_c) versus the lower edge of inductor, and the top edge of screen was positioned 25 mm (Z_e) below the bottom edge of the inductor. Temperature of the specimen top was controlled by thermocouple measurements. At seconds 700 and 800 the crucible was lowered into the inductor for 7 and 8 mm respectively.

At 850 s temperature on the molten pool surface was approx. 2300°C. To raise the temperature on the specimen top at 1300, 1870 and 2170 s power release into the melt was increased. From 2680 till 5100 s the crucible and screen were moved versus the inductor; temperature on the specimen top was stabilized (at $Z_c = 20 \text{ mm}$, $Z_e = 27 \text{ mm}$). At 5300 s in accordance with thermocouple measurements temperature on the specimen top reached approx, 1400°C (Fig. 1.4). After this in conditions close to MC6, in the temperature stabilization regime the specimen was ablated for 10 hours until its corrosion stopped (like in MC6). Differently from MC6 the crust did not form on the molten pool surface. Temperature on the surface of molten pool during the interaction zone formation was approx. 2400°C (Fig. 1.4). After 10 hours of ablation regime and interaction zone formation the molten pool was prepared for the oxidation by steam. For that during seconds 38300 - 42000 temperature on the interface was lowered and a thick crust was formed on the specimen top by moving screen and crucible ($Z_c = 53 \text{ mm}$, $Z_e = 38$ mm) and reducing power deposition in the melt. After crust formation (between the interaction zone and the melt) at 42500 s steam was supplied into the furnace (flow rate approx. 400 g/h, temperature 140÷150°C (Fig. 1.9)). At that time the melt surface had a crust, which did not disappear at the interaction temperature approx. 500°C. Therefore, the molten pool was oxidized through the crust. At 44300 s the crust broke off from the molten pool surface. Its parts got into the steam condenser (5) via silicon pipes. At that moment HF heating was shortly disconnected, which resulted in the temperature drop in the interaction zone. The IZ temperature was increased by stepping up power and moving screen and crucible versus the inductor ($Z_c = 38$ mm, $Z_e = 33$ mm); it was stabilized at 600÷700°C level. Up to 45300 s no condensate was found in collector (7), and small amount in collector (6, Fig. 1.3), which probably means that practically all steam was absorbed by the melt. The pyrometer shaft was periodically flown with nitrogen to observe the molten pool surface, at this the steam supply was stopped. At 46500 s steam-gas line between the furnace and inductor was checked and replaced (5, Fig. 1.3). By 47400 s the volume of liberated hydrogen (Fig. 1.10) reduced to 1% vol., which indicated the end of oxidation of the main volume of molten pool. After this the IZ was heated to melt the crust above it by moving crucible and screen versus inductor ($Z_c = 21 \text{ mm}$, $Z_e = 30 \text{ mm}$) and increasing power deposition in the melt by 49039 s (Fig. 1.8). Judging by the heat flux into the specimen calorimeter (Fig. 1.7, 1.8) heat flux into the molten pool bottom grew up to 1.5 kW, and the IZ oxidation started. Indications of hydrogen sensor grew and thermocouples started to break down. At 49257 s power deposition was reduced, temperature was maintained on the 1400°C level (like in TC-06). At 49990 s the surface crust broke off from the melt surface again, and a part of condensate spilled from the collector (6, Fig. 1.3). At 50490 s signal from the acoustic defect disappeared (was not indicated by the US sensor). After that the steam supply was stopped, the furnace was flushed with nitrogen and at 50960 s the HF heating was disconnected.



Fig. 1.4 – Pyrometer and thermocouple readings; anode voltage dynamics



Fig. 1.5 – Fragment of thermocouple readings and anode voltage dynamics



Fig. 1.6 – Dynamics of anode current and voltage, inductor voltage and current on the mesh of oscillating tube



Fig. 1.7 – Dynamics of heat and electromagnetic fluxes into the crucible and heat flux into the top calorimeter



Fig. 1.8 –Dynamics of heat and electromagnetic fluxes into the crucible and heat flux into the top calorimeter, fragment.



Fig. 1.9 – Readings of thermocouples, steam pressure and flow rate gage Gpv1







1.4 Ultrasonic measurements of steel corrosion

The methodology of ultrasonic sounding previously tried in METCOR experiments was applied for measuring interaction front position versus time. The specimen was probed by the pulse-periodic signal having varied reference frequencies. . Between pulses the ultrasonic transducer is automatically switched to receiving echo signal. Distance between the reflecting surfaces (from the specimen top and acoustic defect):

 $D = 0.5c\Delta t$.

(1.1)

where c - speed of sound in the specimen;

 Δt – time interval between the sent and reflected echo signals.

Dependence of the speed of sound from temperature was determined in the regimes of specimen heat up and cool down in absence of its corrosion.

Fig. 1.11 shows the image of echo signals on the monitor, which looks like two groups of sinusoidal signals. Left group corresponds to the signal from defect, and right - from the specimen top. Main frequency of oscillations - own resonance frequency of ultrasonic transducer. Spectral composition of the groups is different due to the different shape of reflecting surfaces.

To determine the time interval one half-wave was chosen in each group on condition of their coherence. Two characteristic points were fixed on each of the waves: one – at crossing the 'zero' line; and second – at the amplitude maximum. After that the time delay between the corresponding points or any couples of points was changed. Knowing the speed of sound at the measured temperatures the distance from defect to the specimen top was calculated; it kept reducing versus time due to steel corrosion. Calculations were made by computer processing of online data. Error of the measured interaction front position was 0.01 mm.

In experimental measurements with suboxidized corium is a necessity to separate signals reflected from the following surfaces: the IZ boundary and specimen (bottom boundary); and IZ



1 – echo signal reflected from defect; 2 – echo signal reflected from the specimen top; «max» – position of cophasal half-waves maximums; «0» – positions of zero points of cophasal half-waves

Fig. 1.11 – Echogram of the specimen in interaction with molten corium

Fig. 1.12 shows the measured data. Before the IZ oxidation completion and steel specimen oxidation start it was not possible to determine the position of bottom boundary (stage E) correctly using the interferogram.

Section 3 gives a detailed analysis of the measurement data.



Fig. 1.12 – Ultrasonic measurements of specimen corrosion depth

As evident from Fig. 1.12, by the onset of IZ oxidation the corrosion depth was 7.6 mm, the estimated error is $\pm 17\%$, and the maximum corrosion depth by the end of the test was approx. 9.4 mm.

2 POSTTEST ANALYSIS

2.1 Specimen temperature conditions

Similar to the posttest analysis of all METCOR tests calculations of the specimen temperature conditions were made for determining the temperature field in it during a stationary 10-hour regime. The calculations were made using the finite-element program, in which the equation of stationary heat conductivity in the axi-symmetrical formulation was solved. The boundary conditions were as follows: temperature on the internal surface of the top calorimeter, which, in accordance with estimates, was approx. 100°C, temperature on the internal surface of the bottom calorimeter (20°C) and temperature on the external surface of the periphery layer of heat insulation, which was assumed to be equal to the average temperature of cooling water. Heat conductivity of steel 15Kh2NMFA-A, the specimen material, was taken from the data provided by the ISTC METCOR, Phase 1 [6]. The average heat flux into the specimen top and heat conductivity of periphery heat insulation layer were varied for the best convergence of numerical and experimental temperatures in the specimen in the locations of thermocouple junctions. At this the distribution of heat flux along the radius of the specimen top was assumed to be the same as in MC6.

Results of calculations are given in Fig. 2.1, 2.2. Fig. 2.1 shows experimental and calculated temperatures 10 and 29 mm from the specimen axis. Their comparison shows satisfactory convergence of calculations and experimental data. Fig. 2.2 shows calculated temperature distribution across the axial section of the specimen; maximum temperature on the specimen top was, like in MC6, approximately 1400°C. At this the heat flux from the melt (in the USS sighting spot) was 1.2, and in MC6 – 1.3 MW/m².



Fig. 2.1 – Experimental and calculated vertical temperature distribution in the specimen

Fig. 2.2 shows the position of corrosion front by the end of 10-hour exposition in the stationary regime (final position of the IZ boundary) in the USS sighting spot. Maximum specimen ablation depth was 7.6 mm, which is 1.4 mm more than in MC6. Temperature on this boundary is approximately 1160°C. In MC6 the corresponding value was 1120÷1200°C, i.e. the result is close to MC6.



Fig. 2.2 – Temperature field in the specimen

2.2 Physicochemical analysis

2.2.1 Ingot macro- and micro-structure

When the MCP-3 furnace was disassembled it was found that crucible sections were covered with a layer of aerosols (Fig. 2.3). When the corium ingot and steel specimen were extracted from the crucible, the oxidic ingot was partially destructed. Oxidic ingot and steel specimen were included into the epoxy resin and used for template preparation (Fig. 2.4).



Fig. 2.3 – Ingot surface and aerosol depositions on the crucible sections

Fig. 2.5 shows the photograph of the axial section of the steel specimen top and a profilogram of corroded steel surface. It is seen that the maximum corrosion depth (on the specimen axis) was approximately 9.9...10.0 mm, which is close to the value determined by ultrasonic measurements (see Section 1.4). Profile of the surface is close to axisymmetrical.



Fig. 2.4 – Oxidic ingot adjacent to the steel specimen



1 – boundary of undamaged specimen, 2 – specimen boundary after the experiment, 3 – boundary of decarbonated zone of steel, 4 – boundary of the temperature influence on the macro- and microstructure (727°C isotherm)

Fig. 2.5 – Longitudinal specimen section and profilogram

Fig. 2.6 shows a template of the longitudinal section of corium ingot and the top part of the steel specimen with locations of steel microstructure studies.



1 - profile of the specimen top after the experiment; 2 - decarbonized steel boundary;3 - zone of melt temperature influence on the steel macro- and microstructure.

Fig. 2.6 – Macrostructure of the longitudinal section of corium ingot and top part of the steel specimen

The template was prepared and polished following the standard methodology.

For revealing the microstructure a prepared microsection was etched, and the quality was controlled using metallographic microscopes. Etchants for pearlite and austenitic steels were used, their combined application revealed macro- and microstructure of the zone of high-temperature impact of corium melt on steel and steel microstructure.

The surface of polished sections was photographed using digital camera NIKON on the metallographic microscope METALLUX with the 200, 400 and 900 magnification factor.

Fig. 2.7 shows images of steel microstructure in the locations mentioned in Fig. 2.6.

In the near-surface layers of the specimen top, the profile of which is shown in Fig. 2.6 (above line 2), a ferrite structure with a minimum content of carbon was formed (Fig.2.7a,b). This zone goes to the depth of 11,5 - 11,7 mm in the central part of the specimen; it is likely to have been formed by melting. The specimen macro- and microstructure below line 2 underwent changes caused by the carbon and chrome redistribution and grain roughening. In this zone (Fig.2.7c) a 'new' ferrite-pearlite structure was formed. Such structure can result from the cooling of steel heated above the critical point As₃ (from austenite condition), from the redistribution of carbon and relatively high cooling rate. Different pearlite modifications can be produced, i.e. sorbite, troostite or martensite (even with such small amount of carbon). The resulting acerous pearlite enhances steel strength and hardness, but it results in lower impact resistance and relative lengthening. The region with structural changes has the depth up to 32 mm from the initial position of the top surface (Fig. 2.7 c, d). Attention should be paid to the pores formed in the near-surface layers (Fig. 2.7a); they probably appeared during melting followed by crystallization of these layers.



Fig. 2.7 – Steel microstructure at the specimen top in locations a – d, shown in Fig.2.6.

2.2.2 Material balance of the experiment

To make the MCP-3 material balance initial components of the charge and molten products were weighed with an accuracy up to 0.1 g. The molten products were subjected to the physicochemical analysis, its data were included into the material balance.

Put into the m	elt, g	Collected after experiment, g				
Corium C-29.8 (<50 μm)	150.00	Aerosols from F3 filters	8.08			
UO ₂	1271.70	Aerosols from F2 filters	2.13			
ZrO ₂	150.60	Aerosols from quartz tube (Fig. 1.1, pos. 5)	55.28			
Zr metal.	250.00	Aerosols from steam and condensate collector (Fig. 1.3, pos. 6)	11.06			
ZrO_2 coating ²⁾	84.20	Aerosols from crucible sections (Fig. 1.1, pos. 7)	18.32			
		Crust above the melt	464.20			
		Probe sample	3.52			
		Ejections	119.01			
		Spillages ¹⁾	41.52			
		ZrO_2 coating ²)	68.72			
Σ	1906.50	$\Sigma^{3)}$	_			

Table.	2.1	MCP-3	material	balance

¹⁾ – powders (unused charge, spillages, aerosols); ²⁾ – ZrO_2 coating was put on the crucible sections to reduce steam condensation;

 $^{3)}$ – ingot mass was not determined, because it was destructed at disassembling, its parts were collected to produce an average sample for physicochemical analysis; and a part adjacent to the steel specimen was included into the resin with steel specimen; after that an axial cut was made for SEM/EDX analysis and pfofilogram construction.

As mentioned in section 1.2, C-29.8 corium was used as a crust (m = 150 g); it had a composition synthesized in Pr1-MCP-1; results of its analysis are given in Table 2.2.

Method								
	XRF Chemical analysis							
Composition, mass. %								
U	67.6	U	68.0					
Zr	21.5	Zr	21.5					
Admixtures and O ¹⁾	10.9	Admixtures and O ¹⁾	10.5					

 Table 2.2 – Physicochemical analysis of an average sample of Pr1-MCP-1 ingot

¹⁾ – admixtures and oxygen from the residue

Volumetric method [7, 8] was applied to determine the content of free zirconium in the average sample. It was 16.3 mass.%, which corresponds to C-29.8 corium..

2.2.3 XTF of witness specimen and molten products

The elemental analysis of witness specimen and molten products was made by X-ray fluorescence (XRF) analysis with spectrometers SPARK-1M and SPECTROSCAN MAX-GV [9].

A 40mm-diameter disk was cut on a lathe from the witness specimen and analyzed by XRF.

Table 2.3. shows the XRF data of the vessel steel witness specimen in comparison with the steel specifications.

Specif. and		Content of chemical elements, mass. %										
method of	С	Si	Mn	Cr	Ni	Mo	V	Р	S	Cu	Co	As
analysis												
Specif. 108- 765-78	0.13- 0.18	0.17- 0.37	0.30- 0.60	1.8- 2.3	1.0- 1.5	0.5- 0.7	0.10- 0.12	< 0.02	< 0.02	< 0.3	<0.03	<0.003
XRF	—	0.25	0.49	2.24	1.00	0.70	0.10	< 0.02	—	0.07	< 0.03	< 0.003

Table 2.3 – XRF data of the 15Kh2NMFA-A steel witness specimen

The XRF data prove the compliance of steel used in the experiments to 'Specifications TU 108-765-78'.

After the test the oxidic ingot, above-melt crust, ejected melt, sample from the probe, spillages and aerosols were separately crushed to the particle size $< 200 \ \mu m$ (excluding aerosols), and the average sample were prepared by quartering. The average samples were subjected to additional crushing to have the particle size $< 50 \ \mu m$, after which they were analyzed.

Table 2.4. shows the XRF data of molten products.

Table 2.4 – XRF data of molten products

Studied meterial		Content	, mass.%		Масс а	Mass, g			
Studied material	U	Zr	Zr Fe		wiass, g	U	Zr	Fe	0
Aerosols from F3 filter	60.1	3.3	26.6	9.92	8.08	4.86	0.27	2.15	0.80
Aerosols from F2 filter	37.1	1.4	55.6	9.9	2.13	0.79	0.03	1.18	0.13
Aerosols from quartz tube (Fig. 1.1,	61.5	127	12.4	59	55.28	33.99	7.03	6.86	7.40
pos. 5)	01.5	12.7	12.7	5.7	55.20	55.77	7.05	0.00	7.40
Aerosols from the steam condensate	59 7	21.4	1.8	13.4	11.06	6.61	2 36	0.19	1 90
collector (Fig. 1.3, pos. 6)	57.1	21.1	1.0	15.1	11.00	0.01	2.50	0.17	1.90
Aerosols from crucible sections	60.7	12.6	12.3	171	18 32	11 13	2 30	2 25	2 64
(Fig. 1.1, pos. 7)	00.7	12.0	12.5	17.1	10.52	11.15	2.50	2.25	2.04
Ingot	57.3	19.9	7.8	14.4	—	_	-0	—	—
Crust above the melt	62.0	18.7	4.1	15.0	464.20	288.00	86.90	19.11	70.20
Probe sample	62.9	21.2	0.0	15.1	3.52	2.22	0.75	0.0	0.56
Ejections	60.3	20.1	4.4	15.9	119.01	71.79	23.97	5.20	18.06
Spillages	59.7	16.8	9.2	15.2	41.52	24.77	6.99	3.83	5.93
ZrO ₂ coating ^{**}	Not detect.	74.0	Not det	26.0	68.72	_	50.85	_	17.87

*) – oxygen taken from the residue; **) – in the analysis of the coating Zr / O ratio was taken as ZrO₂.

Error in determining the content of U, Zr and Fe by XRF did not exceed 5 rel.%.

2.2.4 Chemical analysis of molten products

Samples for chemical analysis were prepared in a way similar to XRF (see Section 2.2.3). The samples were analyzed for the content of U, Fe and Zr ions. For this a previously tested method [10] was used: the crushed 0.1 g portion of corium was dissolved in a mixture of concentrated orthophosphoric and sulfuric acids (1:2) in the argon flow. Further on the content of Fe⁺² and Fe⁺³ was determined by photocolorimetry with orthophenantroline, and U+4, U+6 – with arsenazo III [11-13].

To determine Zr+4 an aliqot of $0.1\div0.5$ g was molten with (3.0 ± 0.5) g of potassium pyrosulphate at (900 ± 25) °C to produce transparent fusion cake, which later was dissolved by heating in 200÷250 ml of 1M melt of sulfuric acid; after that Zr was determined as Zr4+ by photocolorimetry with xylenol orange. The method of determining total zirconium is based on the formation of colored complex compound of zirconium (IV) with xylenol orange in the sulfuric acid solution with a molar concentration of equivalent $0.3\div0.4$ mol/dm3 [14÷16]. Zirconium determination is not complicated by the presence of large amounts of Mo, W, U, Zn and Ti, and by admixtures of Fe (up to 50 µg), Pb, Ni, Cu, Th and Ta (>100 µg) [15, 16].

Methodology for determining U+4, U+6 is applied to identify coequalities of uranium in corium samples [17, 18]. Sensitivity $-0.04 \mu g/ml$. The method is based on using colored compounds of tetravalent uranium with arsenazo III reagent in the 4 N HCl environment. For uranium reduction granulated zinc is used in the presence of ascorbic acid. When interacting with arsenazo III the tetravalent uranium forms a green complex. If the reagent is in excess, a mixed basically violet coloring is observed. Spectrophotometric determination gives the best results at 2÷5-fold molar excess of the reagent. The coloring appears almost instantly and it is stable for, at least, two hours. The method enables to determine the content of tetravalent uranium is evaluated from the difference between uranium (IV) content and total uranium.

The methodology for Fe+2, Fe+3 determination evaluates the content of iron oxides in uranium-bearing corium without uranium separation [11]. The range of measured iron concentrations is $0.5 \div 2.0 \text{ mg/dm}^3$. The total relative error of the method does not exceed $\pm 3 \%$ on condition that measured optical densities are within $0.2 \div 0.6$. The method is based on the reaction between orthophenanethroline (1.10-phenanthroline) with ions of ferrous iron to produce a complex compound having an orange-red coloring. The intensity of coloring is in proportion to the concentration of iron. Due to a high stability of the complex compound (generation constant is $9.8 \cdot 1021$) the optical density does not depend on pH within $2 \div 9$. The coloring has high dynamics at pH= $3.0 \div 3.5$ in presence of orthophenanethroline in excess; and it is stable during several weeks. In more acidic solutions the coloring intensifies slower and it is less saturated. Direct evaluation of iron is possible at its mass concentration from 0.5 to 2.0 mg/dm^3 [19, 20]. The method enables to determine the content of ferrous iron separately and total iron in the solution. The amount of ferric iron is evaluated from the difference between iron (II) and total iron [19, 20].

Error in determining U content by photocolorimetry was below 5 rel.%, and for Zr and Fe – not more than 3 rel.%.

Table 2.5 gives the data of chemical analysis of molten products and elemental mass balance. Comparison with XRF data (Table 2.4) shows good convergence of both methods.

Studied material			Con	tent, mas	ss.%			Mass a	Mass. g			
Studied material	U^{+4}	U ⁺⁶	Zr ⁺⁴	Fe ⁰	Fe ⁺²	Fe ⁺³	0*	wiass, g	U	Zr	Fe	0
Aerosols from F3 filter	50.66	10.09	3.43.	8.52	11.65	1.58	14.07	8.08	4.91	0.28	1.76	1.14
Aerosols from F2 filter	31.64	6.95	1.39	21.17	23.35	1.87	13.63	2.13	0.82	0.03	0.99	0.29
Aerosols from quartz tube	40.0	0.2	16.0	Not	78	12	16.8	55.28	32.21	8 83	1 05	0.28
(Fig. 1.1, pos. 5)	49.0	9.2	10.0	det	7.0	1.2	10.8	55.20	52.21	0.05	4.95	9.20
Aerosols from the steam				Not								
condensate collector (Fig. 1.2,	33.0	22.4	22.4	det	2.4	1.7	18.2	11.06	6.12	2.48	0.45	2.01
pos. 6)												
Aerosols from crucible sections	40 5	34.0	2.4	Not	44	3.0	157	18 32	13 65	0 44	1 35	2.87
(Fig. 1.1, pos. 7)	10.5	51.0	2.1	det	1.1	5.0	10.7	10.52	15.05	0.11	1.55	2.07
Ingot	51.2	5.1	19.9	1.4	4.3	1.4	16.7	_	_	_	_	—
Crust above the melt	57.6	3.2	19.0	Not det	4.0	0.0	16.2	464.20	281.82	88.07	18.49	75.81
Probe sample	59.7	0.0	23.1	Not det	0.8	0.0	16.4	3.52	2.10	0.81	0.03	0.58
Ejections	56.4	0.0	21.8	Not det	3.3	1.6	16.9	119.01	67.16	25.92	5.86	20.07
Spillages	56.8	5.4	17.1	Not det	3.5	1.0	16.2	41.52	25.85	7.10	1.86	6.71
ZrO ₂ coating ^{**}	Not det	Not det	74.0	Not det	Not det	Not det	26.0	68.72	_	50.87	_	17.85

 Table 2.5 – Results of chemical analysis of molten products and elemental mass balance

*) – oxygen taken from the residue; **) – in the analysis of the coating Zr / O ratio was taken as ZrO₂.

.

Five templates were made for SEM/EDX analysis. Four of them represented different parts of corium ingot, and the fifth included corium and a part of vessel steel surface.

Fig. 2.8-2.10 and Table. 2.6-2.8 show the microstructure and EDX data of the first three corium ingot templates. It can be said that the observed structure repeats microstructural peculiarities of the oxidic part of experiments in steam ([21], II2, Fig. 1.33).

Analysis of the total composition of templates has some divergence, in mol% it is: $37.2\pm1.6 \text{ U}$, $31.8\pm1.1 \text{ Zr}$, $29.7\pm1.4 \text{ Fe}$. This result agrees very well with the XRF data (Table 2.4). The analysis of microstructure identified three phases: the one based on solid solution from the side of UO₂ (Table. 2.6, point P1), solid solution from the side of ZrO₂ (Table. 2.6, point P2) and a phase based on Fe(Cr,Ni)O_y, in which uranium and zirconium oxides do not dissolve (Table. 2.6, point P3, Table. 2.7 and 2.8, point P1). The chemical analysis (Table. 2.5) enables to make a conclusion that in these conditions iron oxide is close to the Fe₃O₄ stoichiometry. In accordance with ultrasonic measurements at the final stage of experiment after the established interaction zone got oxidized the oxidation of vessel steel was in progress and continued into the melting stage, after which the experiment was terminated. The specimen melting is confirmed by metallic droplets found in corium, which had no time to get oxidized. Fig. 2.11-2.13 and Table. 2.9-2.11 show microstructure and EDX data of the polished section of the fourth template with a rounded metallic inclusion. Analysis of the metallic inclusion proves that uranium and zirconium do not dissolve in the metallic phase, if the melt is fully oxidized (Fig.2.12 Table. 2.10, location SQ1).

Fig. 2.14 shows a template with corium – steel interaction boundary with marked locations chosen for studies.

No traces of interaction zone similar to those of MC6 were found. It means that it dissolved in the melt completely during oxidation in the steam atmosphere

The best preserved structure of steel-melt interface was in region 3-1 (Fig. 2.17). Dark Fe₂O₃ inclusions are the result of oxidation during the preparation of samples (droplets of water remained in the crack between steel and oxidic part); they have no relation to the experiment itself. A layer between steel and corium crust, which was likely to form after the oxidation of metal-oxidic interaction zone, has a characteristic thickness of 10-100 μ m; it consists of ~30 (closer to periphery) – ~70 (in the central part) vol. % of FeO (Fig. 2.15, region 1-1-1-1, points P5-6). Other phases of this layer – two UO₂-based solid solutions (Fig. 2.15, region 1-1-1-1, point P2) and ZrO₂ -based (Fig. 2.15, region 1-1-1-1, point P3), there is also a γ -(Fe,Ni), FeO-based phase, also as droplets. There also exist small zones with a structure similar to eutectics (Fig. 2.15, region 1-1-1-1). At melting the crust in this region probably stayed solid; and oxidation of the liquid specimen steel continued under it. The crust was likely to be broken in some locations, and corium melt was in direct contact with molten metal of the specimen (Fig. 2.18 region 6).

The melt composition crystallized completely near crust and a distance from it in mol.% is 36.1 ± 1.2 U, 31.9 ± 0.2 Zr, 29.3 ± 2.3 Fe (Table. 2.13 region 2-3, S(Q2) and Table. 2.15 region 8, S(Q1)), which coincides with the data on melt samples with an accuracy up to 1 mol.% and testifies to a high homogeneity of the whole molten pool in this experiment.



Fig. 2.8 – Microphotograph of template #1 fragment

	#	U	Zr	Fe	Cr	Ni	Mn	~0	Phase
	mass.%	53.3	17.4	9.1				20.2	
SQ1	mol.%	12.2	10.4	8.8		-		68.7	-
	mol.% MeO _x	38.8	33.0	28.2					
	mass.%	54.1	17.0	8.2			0.3	20.3	
SQ2	mol.%	12.4	10.2	8.0	-	-		69.2	-
	mol.% MeO _x	40.1	32.9	26.0			0.9		
P1	mass.%	60.5	15.2	4.3	0.3			19.7	
	mol.%	14.7	9.6	4.5	0.3 -		-	70.9	U(Zr,Fe)O ₂
	mol.% MeO _x	50.5	33.0	15.4	1.1				
	mass.%	35.9	36.5	3.8				23.8	
P2	mol.%	7.2	19.0	3.2		-		70.6	$Zr(U,Fe)O_2$
	mol.% MeO _x	24.4	64.7	10.9					
P3	mass.%			86.0		5.2		8.8	
	mol.%	-		70.8	-	4.1	-	25.2	FeO
	mol.% MeO _x			94.6		5.5			

Table 2.6 –EDX data of sample #1



Fig. 2.9 – Microphotograph of template #2 fragment

Table	27	-EDX	data	٥f	samnle #	2
1 ant	4 •1	$-\mathbf{D}\mathbf{D}\mathbf{A}$	uata	UI	sample π	-

	#	U	Zr	Fe	Cr	Si	~0	Phase
	mass.%	50.8	16.9	10.4	0.4	0.2	21.4	
SQ1	mol.%	11.0	9.6	9.6	0.4	0.3	69.1	-
	mol.% MeO _x	35.7	30.9	31.0	1.4	1.0		
	mass.%			65.8	2.1		32.1	
P1	mol.%			36.5	1.3	-	62.2	FeO
	mol.% MeO _x			96.7	3.4			



Fig. 2.10 – Microphotograph of template #3 fragment

		#	U	Zr	Fe	Cr	~0	Phase
		mass.%	52.3	17.0	9.9	0.5	20.3	
SQ1	mol.%	11.8	10.0	9.5	0.5	68.2	-	
		mol.% MeO _x	37.1	31.5	29.9	1.5		
P1		mass.%			66.6	1.8	31.5	
		mol.%	-		37.3	1.1	61.6	FeO
1	mol.% MeO _x			97.1	2.9			

Table 2.8 – EDX data of sample #3



1 (SQ1)

1-1 (SQ2)

Fig. 2.11 – Microphotograph of template #4, region 1

Table	2.9	-EDX	data	for	region	#1
			-		.0	

	#	U	Zr	Fe	Cr	Si	~0	Phase
	mass.%	32.5	11.6	9.3	0.5	0.3	45.7	
SQ1	mol.%	4.1	3.8	5.1	0.3	0.4	86.3	-
	mol.% MeO _x	30.2	28.1	36.9	2.1	2.7		
	mass.%	51.2	18.3	12.2	0.5		17.8	
SQ2	mol.%	12.2	11.4	12.4	0.5	-	63.4	-
	mol.% MeO _x	33.5	31.2	33.9	1.5			
	mass.%	72.7	5.7	4.3	0.0	0.2	17.1	
P1	mol.%	20.1	4.1	5.1	0.0	0.4	70.2	U(Zr,Fe)O ₂
	mol.% MeO _x	67.6	13.9	17.2	0.0	1.3		
	mass.%	36.3	37.8	4.6	0.3		21.0	
P2	mol.%	7.8	21.1	4.2	0.3	-	66.7	$Zr(U,Fe)O_2$
	mol.% MeO _x	23.3	63.4	12.6	0.8			
P3	mass.%			63.0	1.9	0.2	35.0	
	mol.%	-	-	33.6	1.1	0.2	65.2	FeO
	mol.% MeO _x			96.4	3.1	0.5		



2-1 (SQ2)

Fig. 2.12 – Microphotograph of template #4 fragment, region 2

abic	E .IV LDA uat		SIVII "						
	#	U	Zr	Fe	Cr	Ni	Si	~0	Phase
SO	mass.%			95.1		4.9			
SQI	mol.%	-		95.3	-	4.7	-		-
	mass.%	42.9	16.9	19.8	0.7		0.3	19.4	
SQ2	2 mol.%	9.2	9.5	18.1	0.7	-	0.5	62.0	-
	mol.% MeO _x	24.2	24.9	47.7	1.8		1.3		

Table 2.10 – EDX data of region #2



3 (SQ1)

Fig. 2.13 – Microphotograph of template #4, region 3

 Table 2.11 – EDX data of sample #3

	#	U	Żr	Fe	Cr	Ni	Si	~0	Phase
	mass.%	53.2	19.2	10.5	0.4		0.3	16.6	
SQ1	mol.%	13.3	12.5	11.2	0.4	-	0.6	62.0	-
	mol.% MeO _x	35.0	33.0	29.4	1.1		1.6		

Table 2.12 – EDX data of region 1

	#	U	Zr	Fe	Cr	Ni	Si	~0	Phase	
	mass.%	59.7	18.2	5.8			0.2	16.2		
SQ1	mol.%	16.0	12.7	6.6	-		0.4	64.3	-	
	mol.% MeO _x	44.8	35.6	18.5			1.1			
D1	mass.%			97.0	1.1	1.5			staal	
11	mol.%	-		96.6	1.2	1.5	•		SIEEI	
	mass.%	72.8	5.3	2.4				19.6		
P2	mol.%	18.8	3.6	2.6		-		75.1	$(U,Zr)O_2$	
	mol.% MeO _x	75.3	14.3	10.4						
	mass.%	18.5	21.9	40.2	1.5			17.9		
P3	mol.%	3.6	11.0	32.9	1.3	-	-		$Zr(U)O_2$	
	mol.% MeO _x	7.3	22.6	67.4	2.7					
D/	mass.%	-		88.1		11.9			v (Eo Ni)	
14	mol.%			88.6	-	11.4	•		γ-(re,m)	
	mass.%			70.8	0.4	2.6	0.2	25.9		
P5	mol.%	-		43.0	0.3	1.5	0.3	54.9		
	mol.% MeO _x			95.5	0.6	3.4 0.6			FaO	
P6	mass.%	2.6	4.1	65.9	2.0			25.4	reo	
	mol.%	0.4	1.6	41.2	1.3	-	_			
	mol.% MeO _x	0.9	3.5	92.6	3.0					



Fig.2.14 –MCP-3 polished section with locations of SEM/EDX studies



Fig. 2.15 – Microphotograph of region 1



Fig. 2.16 – Microphotograph of region 2

Table	2.13 -	-EDX	data	of	region	2
				~-		_

	#	U	Zr	Fe	Cr	Ni	Mn	Mg	~0	Phase
	mass.%	57.2	18.0	7.4					17.5	
SQ1	mol.%	14.5	11.9	7.9		-	-		65.8	-
_	mol.% MeO _x	42.2	34.6	23.2						
	mass.%	54.7	18.9	11.3	0.5		0.3		14.3	
SQ2	mol.%	14.8	13.4	13.0	0.6	-	0.3	-	57.9	-
_	mol.% MeO _x	35.2	31.8	30.9	1.3		0.8			
	mass.%	54.6	18.2	12.2	0.6				14.4	
SQ3	mol.%	14.7	12.8	14.1	0.7		-		57.7	-
	mol.% MeO _x	34.8	30.3	33.3	1.7					
D1	mass.%			97.4		2.2		0.4		
11	mol.%	_		97.1	-	2.1	-	0.9	-	staal
DJ	mass.%			98.1		1.9				SICCI
1 4	mol.%	-		98.2	-	1.9		-		
	mass.%	76.1	6.4	1.8					15.7	
P3	mol.%	22.8	5.0	2.3		-	-		69.9	$(U,Zr)O_2$
	mol.% MeO _x	75.8	16.6	7.7						
P4	mass.%	30.9	39.6	9.2					20.3	
	mol.%	6.5	21.7	8.2		-	-		63.6	$Zr(U)O_2$
	mol.% MeO _x	17.8	59.6	22.6						



Fig. 2.17 – Microphotograph of region 3

Table	2.14 -	-EDX	data	of	region	3
I GOIC	- • + •		unun	••	region	•

	#	Fe	Cr	Ni	Si	Mn	~0	Phase
D1	mass.%	95.2	2.3	1.5	0.4	0.6		
11	mol.%	94.7	2.5	1.5	0.8	0.6	-	staal
D)	mass.%	97.8	0.4	1.8			steer	
14	mol.%	97.9	0.4	1.7		-		
	mass.%	60.2	0.3	1.3			38.3	
P3	mol.%	30.8	0.2	0.6	-		68.4	
_	mol.% MeO _x	97.6	0.5	2.0				mist
	mass.%	40.6		0.7	0.4		58.4	Tust
P4	mol.%	16.5	-	0.3	0.3	-	82.9	
	mol.% MeO _x	96.8		1.5	1.7			





Fig. 2.18 – Microphotograph of regions 4, 5 and 6



Fig. 2.19 – Microphotograph of regions 7 and 8

|--|

	#	U	Zr	Fe	Cr	Si	~0	Phase
	mass.%	48.4	16.1	8.5	0.6	0.2	26.2	
SQ1	mol.%	9.3	8.1	7.0	0.5	0.3	74.8	-
	mol.% MeO _x	36.9	32.1	27.7	2.1	1.3		

3 DISCUSSION OF RESULTS

Experimental results are discussed in stage-wise succession. Table 3.1 denotes and describes the stages. Oxidant (steam) was supplied into the furnace and possible oxidation of the melt and/or IZ material and specimen took place at stages C, D and E. In terms of experimental objectives of most interest is stage E and, to a certain degree, stages A and C.

Stage	Time interval, s	Description
Α	038300	Molten pool is produced and interaction zone is formed
В	3830042500	Vessel steel temperature is reduced and crust thickness on the IZ surface increases
С	4250044300	Molten pool oxidation
D	4430049200	Increase of vessel steel temperature, reduction of crust thickness on the IZ surface
E	49200 [*] 50960	Oxidation of IZ and specimen

 Table 3.1 – Experimental stages

*) –stage E is assumed to start when an intensive hydrogen liberation is registered

Such division of experiment into stages corresponds to the description of experimental procedure (section 1.3); it is well illustrated by Fig. $1.4\div1.10$.

First let's consider data of ultrasonic measurements. At stage A an interaction zone was formed, which was typical of the interaction between suboxidized corium melt and vessel steel. This process is well-studied (main results and conclusion are given in [2]). A long incubation period is typical for such conditions; noticeable ablation is not yet registered. As follows from Fig. 1.12, the incubation period lasted approx. 10000 s, which is by approx.6000 s shorter than in similar MC6 [5].

Fig. 1.12 also shows a calculated curve of steel ablation (corrosion) in the inert atmosphere (stage A) in accordance with methodology proposed in [2], which in the coordinates of the given plot has the following formulation:

$$\frac{dh}{dt} = -0.46 \cdot 10^{-4} \sqrt{T_{int}(t) - T_{B}}, \text{ mm/s},$$
(3.1)

where t > 15800 s (for experimental conditions MCP-3), $[T_{int}(t)] = [T_B] = C$, $T_{int}(t)$ – temperature on the boundary between the specimen and IZ at time t, T_B – final temperature on the boundary between the specimen and IZ. For MCP-3 conditions T_B is 1160°C (in MC6 – 1180°C). Time curve $T_{int}(t)$ was plotted in accordance with measured ultrasonic data (see section 1.4) and results of calculated specimen temperature conditions (see section 2.1). It is evident that calculated results have a good convergence with experimental data – difference between calculated and experimental value of maximum ablation depth in the end of stage A does not exceed 2 %. In the absolute value it is 7.4 (±0.1) mm. In the above-mentioned similar MC6 test the ablation depth was smaller – 6.2 mm, i.e. the difference is not more than 20 % and it is likely to be explained by the difference of specimen temperature conditions in the compared tests.

After ablation stopped in the inert atmosphere the specimen and IZ temperatures substantially decreased, and for a long period (stages B, C and D) the IZ was kept in a 'conserved' condition. Stage E started with the oxidation of metals contained in the IZ. It is seen in Fig. 1.12 that these processes started a bit earlier than the time of stage E beginning given in Table. 3.1 (49200 s). Their real time of start is close to the increase in power deposition in the melt (49039 s). A thinning of the IZ is confirmed by thermocouples, breakdowns of which correlate well with the

progression of the IZ front (position of its bottom boundary did not change). It is worth to remind here that the position of the top boundary registered by the USS is not realistic due to a considerable reduction of the speed of sound in the mushy IZ.

Approximately at 49800 s the top and bottom IZ boundaries merge (at corrosion depth approx. 7.4 mm), and later (approx, from 50000 till 50750s) steel corrosion takes place during its oxidation.

Approximately at 50800s an abrupt increase (by 0.93 mm) of registered corrosion depth was registered - from 9.4 to 10.4 mm (in the absolute value), which was identified as specimen melting start. This assumption is confirmed by the fact that immediately after power disconnection, at 50960 s a reverse abrupt reduction of registered corrosion depth took place - to the level before the abrupt depth increase, at which the ultrasonic parameters of the material were restored. The natural explanation to it is the molten steel freezing (see section 2.2.1).

Therefore, in accordance with ultrasonic measurements, the final corrosion depth was approx. 9.4 mm (absolute value), which is close to the results of visual posttest measurements of the specimen axial section (see Section 2.2.1): absolute corrosion depth in the specimen center \approx 9.6 mm at maximum depth 9.95 \approx 10.0 mm (see Fig. 2.4). That is, we can say that the final corrosion depth is $h_{IZ}^{(fin)} \approx$ 9.5 mm (±1 %).

Let us consider the on-line gas analysis given in Fig. 1.10 and 3.1. Main generation of hydrogen takes place at stages C and E. Three sharp peaks of hydrogen content on curve 2 at stage D, and one at stage E correspond to the furnace flushing with nitrogen. It was accompanied by the replacement of hydrogen present in the zones of stagnation, which resulted in its higher content in the flue gases. Along with that, a sharp drop of hydrogen content was observed at stage C, which is explained by a temporary increase of carrier gas flow rate from 540 to 700 l/h at \approx 43000 s. If we exclude these drops and rises on curve 2, we see that after power disconnection at stage D hydrogen decreased exponentially (curve 3) in the flue gases, which is typical of a delay explained by the capacity of the furnace and gas lines. For the same reason the growth of hydrogen content at stages C and E has a similar pattern of asymptotic stabilization at a certain level, which is very well seen at stage C. Taking into account everything above-said we can conclude that the oxidation of melt components and respective generation of hydrogen takes place only at stages C and E.

An important issue is the heat from redox reactions. In the given experimental conditions an indicator of such reactions is the above-discussed hydrogen release. But, due to a high volatility of hydrogen and related uncontrolled losses in the furnace components and gas lines it is not possible to determine the melt and steel oxidation rate using direct gas measurements. It is also impossible to determine oxidation kinetics from the balance of steam supplied into the furnace and collected condensate, because it was not possible to make a precise evaluation of non-reacting steam due to its losses by absorption in the porous materials of the furnace and in the ingot; also due to the losses by condensate ejections from collectors.

As shown by MASCA and EVAN studies [21, 22], the oxidation of molten corium has the regime, which is controlled (limited) by the availability of the oxidant at the interaction surface. At this the oxidation rate does not depend on the content of reducing agents in the melt, but only on the oxidant supply conditions (flow rate of the carrier gas, oxidant concentration in the gas, pattern of hydrodynamics inside the furnace, etc.). That is, the reaction rate is practically constant until nearly complete depletion of reducing agent. If we assume that this regime of oxidation is typical of the experimental conditions, we can evaluate power released from the oxidation of melt components, IZ and steel.



1 – flow rate of carrier-gas (N₂). 2, 3 – hydrogen content in flue gases : 2 – registered, 3 – furnace blowing taken into account

Fig. 3.1 – Carrier gas flow rate and hydrogen content in furnace gases

Let us assume that the oxidation rate of melt, IZ and steel is in proportion to the hydrogen release at a certain stage; and in terms of integral value the amount of absorbed oxygen is determined by the availability of reducing agents in the system at the corresponding stage. As mentioned above, the presence of hydrogen at stage D is explained by a delay related to the capacity of the furnace and gas lines. So we can assert that no oxidation was in progress at this stage.

For a correct evaluation of heat deposition from the redox reactions it is necessary to know the melt mass and composition before stage C and IZ composition before stage E. Mass of the melt is determined by the following parameters: furnace charge (Table. 1.3), losses by spillages and crust formation, aerosol release (Table. 2.4 and 2.5). Along with that, during stage B a part of zirconium and uranium from the melt migrated to the IZ, and some iron from the IZ went into the melt.

First let's determine the amount of uranium and zirconium, which went to the IZ from the melt at stages A and B. In the course of this experiment the IZ, which formed at its early stages, later was completely destructed, so its composition can be evaluated only using the previously provided data on the IZ composition in the inert atmosphere. As said above, first stage of this experiment was similar to MC6 [5]. In accordance with its data the MCP-3 IZ composition is assumed to be as follows: U – 27.7, Zr – 5.2, Fe – 67.1 mass.%. The following should be mentioned: first, Cr, Ni and other doping admixtures present in steel were added to iron; second, oxygen present in IZ was neglected. After that the IZ composition was renormalized by 100 %. The error in determining concentrations of components taking into account the procedure of renormalization is about 9 rel.%, i.e. we have the following composition IZ: U – 28, Zr – 5, Fe – 67 mass.% (\pm 9 rel.%).

The IZ density (ρ_{IZ}) can be determined by the following formula taken from [21]:

$$\rho_{\rm IZ} = \frac{1}{\left[\left(\frac{a_{\rm U}}{\rho_{\rm U}} \right)^{6/5} + \left(\frac{a_{\rm Zr}}{\rho_{\rm Zr}} \right)^{6/5} + \left(\frac{a_{\rm Fe}}{\rho_{\rm Fe}} \right)^{6/5} \right]^{5/6}}$$
(3.2)

where a_U , $a_{Zr} \ \mu \ a_{Fe}$ – atomic fractions of uranium, zirconium, iron, respectively. The assumed densities of uranium, zirconium, iron are: $\rho_U = 19.04$, $\rho_{Zr} = 6.45$ and $\rho_{Fe} = 7.85$ g/cm³, respectively. Taking into account the IZ composition its density is $\rho_{IZ} = 8.60$ g/cm³. An error of this formula, the atomic fractions of uranium, zirconium, iron are known, is approx. 5÷6%. Taking into account the above-mentioned error in the determined concentration (fractions) of components, the error calculated by method [23] grows to $\sqrt{(6\%)^2 + (9\%)^2} \approx 11\%$.

The total volume of corroded part of the steel specimen $(V^{(fin)})$ can be evaluated from profilogram (Fig. 2.4): it is between 23 - 27 cm³, i.e. $V_{IZ}^{(fin)} \approx 25$ cm³ (±8%). Knowing this volume and the final position of the bottom corrosion boundary after the experiment, we can evaluate the IZ volume before the start of stage E, if we assume the proportionality of volume to a certain corrosion depth at a certain moment of time. Then the IZ volume $(V_{IZ}^{(E)})$ before the beginning of stage E is:

$$V_{IZ}^{(E)} = \frac{h_{IZ}^{(E)}}{h_{IZ}^{(fin)}} \cdot V^{(fin)} = \frac{7.4 \text{ mm} (\pm 17 \%)}{9.5 \text{ mm} (\pm 1 \%)} \cdot 25 \text{ cm}^3 (\pm 8 \%) = 17 \text{ cm}^3 (\pm 19 \%) \quad (3.3)$$

In (3.3) the total error of IZ volume evaluation was calculated using a conventional formula for an error in indirect measurements [23]:

$$\left(\frac{\Delta V_{IZ}^{(E)}}{V_{IZ}^{(E)}}\right) = \sqrt{\left(\frac{\Delta h_{IZ}^{(E)}}{h_{IZ}^{(E)}}\right)^2 + \left(\frac{\Delta V^{(\text{fin})}}{V^{(\text{fin})}}\right)^2 + \left(\frac{\Delta h_{IZ}^{(\text{fin})}}{h_{IZ}^{(\text{fin})}}\right)^2} = \sqrt{\left(17\%\right)^2 + \left(8\%\right)^2 + \left(1\%\right)^2} \approx 19\%$$

$$(3.4)$$

Used symbols need explanation. Δx in (3.4) and subsequent formulas of this section stands for the absolute error in determining x value expressed in physical units applied for measuring a given physical value. Term $\left(\frac{\Delta x}{x}\right)$ stands for the relative error in determining value x, expressed in percent. Therefore, if a formula used for calculating a relative value has a ratio of the

expressed in percent. Therefore, if a formula used for calculating a relative value has a ratio of the absolute error and any physical value, and the denominator has an average value of this term, it means that this fraction has been multiplied by 100 %.

If the IZ density and its volume are known, the IZ mass can be determined, which equals $m_{IZ} = 150 \text{ g} (\pm 22 \text{ \%})$. Error in determining the IZ mass was calculated by the formula, which was derived following methodology [23]:

$$\left(\frac{\Delta m_{IZ}}{m_{IZ}}\right) = \sqrt{\left(\frac{\Delta \rho_{IZ}}{\rho_{IZ}}\right)^2 + \left(\frac{\Delta V_{IZ}^{(E)}}{V_{IZ}^{(E)}}\right)^2} = \sqrt{\left(11\%\right)^2 + \left(19\%\right)^2} \approx 22\%$$
(3.5)

For the composition assumed above we get the following IZ content: U - 42, Zr - 8 and Fe - 100 g. The error in mass determination is 22 %.

Before interaction $V_{IZ}^{(E)}$ contained $m_{IZ}^{(0)} = 17 \text{ cm}^3 \cdot 7.85 \text{ g/cm}^3 = 130 \text{ g} (\pm 19\%)$ of iron (error in determining the iron density was taken as zero). In this way, at the early stage of experiment (stages A and B) the volume of iron transferred from the specimen into the melt was $m_{Fe} = m_{IZ}^{(0)} - m_{Fe,IZ} = 130 - 100 = 30 \text{ g}$. The error in determining this value is rather high:

$$\left(\frac{\Delta m_{Fe}}{m_{Fe}}\right) = \sqrt{\left(\frac{m_{IZ}^{(0)}}{m_{Fe}} \cdot \frac{\Delta m_{IZ}^{(0)}}{m_{IZ}^{(0)}}\right)^2 + \left(\frac{m_{Fe,IZ}}{m_{Fe}} \cdot \frac{\Delta m_{Fe,IZ}}{m_{Fe,IZ}}\right)^2} = \sqrt{\left(\frac{130}{30} \cdot 19\%\right)^2 + \left(\frac{100}{30} \cdot 22\%\right)^2} \approx 100\%$$
(3.6)

This high error in the volume of iron, which was transferred into the melt from the IZ at stages A and B is explained by the presence of factors with magnitude grater than unity in both radicand terms: ratio between the minuend and difference and ratio between the subtrahend and difference.

After calculating the volume of iron migrated into the melt at stages A and B, we can calculate other values, which determine the melt mass and composition. The furnace charge is given in Table. 1.3 and Table. 3.2. Absolute error in determining the charge volume is ± 0.01 g, in relative expression it is not more than $6 \cdot 10^{-3}$ %. We neglect the contribution of this error into the total error, i.e. assume that the charge value is quite accurate.

Let's evaluate the melt composition before stage C, mass losses taken into account (crusts, spillages, aerosols, partitioning between the melt and IZ). Table. 2.5 gives the data of determined composition of molten products and their masses. As mentioned in section 2.2, it was not possible to determine the ingot mass, and it complicates the evaluation of melt mass and composition, and, respectively increases the total error. Let's assume that before stage C the melt included both the ingot material (line 6 in Table.2.5) and sample of the probe (line 8, Table.2.5), taken after stage C, and ejections (line 8 in Table.2.5), which also happened after stage C. All other molten products were not included onto the melt composition. The resulting formulas used for the calculation of masses of uranium and zirconium dioxide, free zirconium and 'cations' Fe^0 , Fe^{+2} , Fe^{+3} (under a 'cation' we understand the iron, which **oxidizes at stage C** to a respective condition) are as follows:

$$m_{UO_2} = m_{UO_2}^{(0)} - \frac{M_{UO_2}}{M_U} \sum_i m_i C_{U,i} - \frac{M_{UO_2}}{M_U} m_{U,IZ}$$
(3.7)

$$m_{ZrO_2} = m_{ZrO_2}^{(0)} - \frac{C_n^{(0)}}{100} \cdot \frac{M_{ZrO_2}}{M_{Zr}} \sum_i m_i C_{Zr,i} + \frac{M_{ZrO_2}}{M_U} m_{U,IZ}$$
(3.8)

$$m_{Zr} = m_{Zr}^{(0)} - \left(1 - \frac{C_n^{(0)}}{100}\right) \cdot \sum_i m_i C_{Zr,i} - m_{Zr,IZ} - \frac{M_{Zr}}{M_U} m_{U,IZ}$$
(3.9)

$$\mathbf{m}_{\mathsf{Fe}^0} = \frac{\mathbf{C}_{\mathsf{Fe}^0,\mathsf{ingot}}}{\mathbf{C}_{\mathsf{Fe}^0,\mathsf{ingot}} + \mathbf{C}_{\mathsf{Fe}^{+2},\mathsf{ingot}} + \mathbf{C}_{\mathsf{Fe}^{+3},\mathsf{ingot}}} \cdot \mathbf{m}_{\mathsf{Fe}}$$
(3.10)

$$\mathbf{m}_{\mathsf{F}\mathsf{e}^{+2}} = \frac{\mathbf{C}_{\mathsf{F}\mathsf{e}^{+2},\mathsf{ingot}}}{\mathbf{C}_{\mathsf{F}\mathsf{e}^{0},\mathsf{ingot}} + \mathbf{C}_{\mathsf{F}\mathsf{e}^{+2},\mathsf{ingot}} + \mathbf{C}_{\mathsf{F}\mathsf{e}^{+3},\mathsf{ingot}}} \cdot \mathbf{m}_{\mathsf{F}\mathsf{e}}$$
(3.11)

$$\mathbf{m}_{\mathsf{Fe}^{+3}} = \frac{\mathbf{C}_{\mathsf{Fe}^{+3},\mathsf{ingot}}}{\mathbf{C}_{\mathsf{Fe}^{0},\mathsf{ingot}} + \mathbf{C}_{\mathsf{Fe}^{+2},\mathsf{ingot}} + \mathbf{C}_{\mathsf{Fe}^{+3},\mathsf{ingot}}} \cdot \mathbf{m}_{\mathsf{Fe}}$$
(3.12)

where $m_{UO_2}^{(0)}$, $m_{ZrO_2}^{(0)}$, $m_{Zr}^{(0)}$ – a component in the furnace charge, M_U , M_{UO_2} , M_{Zr} , M_{ZrO_2} – molecular masses of uranium, UO₂, zirconium and ZrO₂, respectively, $m_{U,IZ}$, $m_{Zr,IZ}$ – mass of uranium and zirconium displaced from the melt into the IZ, m_{Fe} – mass of iron transferred from the IZ into the melt (calculated above), m_i – mass of corresponding molten product, $C_n^{(0)}$ – initial oxidation index

of the melt, $C_{U,i}$ – concentration of all uranium cations in the i-th molten product, $C_{Zr,i}$ – zirconium concentration in the i-th molten product, $C_{Fe^{0},ingot}$, $C_{Fe^{+2},ingot}$, $C_{Fe^{+3},ingot}$ – concentrations of corresponding iron cation in the ingot (line 6 in Table. 2.5). Concentrations are given as fractions of one. The summing up is done for all molten products not included into the melt by the beginning of stage C. They are as follows: all types of aerosols (lines 1÷5, Table. 2.5), crust (line 7, Table. 2.5) and spillages (line 10, Table. 2.5). It was assumed that all aerosols were generated at the preceding stages, which took main time of the experiment.

Comment on (3.7)÷(3.12). First summands in (3.7)÷(3.9) are charges of certain components in the furnace, second summands – losses, note that in (3.8) and (3.9) the initial distribution of Zr atoms between its oxide and free Zr was taken into account (factors $C_n^{(0)}$ and $(1-C_n^{(0)})$, respectively). Third summands in (3.7) and (3.9) are related to the partial transfer of U and Zr into the IZ. Third summand in (3.8) and the fourth one in (3.9) stand for the following: when uranium gets into the IZ from the melt the oxygen bound to this uranium as dioxide stays in the melt and gets bound to free Zr, by this the amount of ZrO₂ increases and free Zr reduces. In (3.10)÷(3.12) it is assumed that the amounts of iron 'cautions' in the melt are correlated in the same way as in the ingot.

Let's determine the calculation errors UO_2 , ZrO_2 , zirconium and iron 'cations' in the melt. In accordance with [23] these errors are as follows:

$$\begin{pmatrix} \Delta \mathbf{m}_{UO_2} \\ \overline{\mathbf{m}_{UO_2}} \end{pmatrix} = \begin{pmatrix} \mathbf{M}_{UO_2} \\ \overline{\mathbf{M}_U} \end{pmatrix} \cdot \sqrt{\sum_i \left(\frac{\mathbf{m}_i \mathbf{C}_{U,i}}{\mathbf{m}_{UO_2}} \right)^2 \cdot \left[\left(\frac{\Delta \mathbf{m}_i}{\mathbf{m}_i} \right)^2 + \left(\frac{\Delta \mathbf{C}_{U,i}}{\mathbf{C}_{U,i}} \right)^2 \right] + \left(\frac{\mathbf{m}_{U,IZ}}{\mathbf{m}_{UO_2}} \cdot \frac{\Delta \mathbf{m}_{U,IZ}}{\mathbf{m}_{U,IZ}} \right)^2 }$$
(3.13)
$$\begin{pmatrix} \frac{\Delta \mathbf{m}_{ZrO_2}}{\mathbf{m}_{ZrO_2}} \\ = \sqrt{\left(\frac{\mathbf{M}_{ZrO_2}}{\mathbf{M}_{Zr}} \cdot \frac{\mathbf{C}_n^{(0)}}{100} \right)^2 \cdot \sum_i \left(\frac{\mathbf{m}_i \mathbf{C}_{Zr,i}}{\mathbf{m}_{ZrO_2}} \right)^2 \cdot \left[\left(\frac{\Delta \mathbf{m}_i}{\mathbf{m}_i} \right)^2 + \left(\frac{\Delta \mathbf{C}_{Zr,i}}{\mathbf{C}_{Zr,i}} \right)^2 \right] + \left(\frac{\mathbf{M}_{ZrO_2}}{\mathbf{M}_U} \cdot \frac{\mathbf{m}_{U,IZ}}{\mathbf{m}_{ZrO_2}} \cdot \frac{\Delta \mathbf{m}_{U,IZ}}{\mathbf{m}_{U,IZ}} \right)^2 } \right)^2$$
(3.14)
$$\begin{pmatrix} \left(\frac{\Delta \mathbf{m}_{Zr}}{\mathbf{m}_{Zr}} \right) = \sqrt{\left(1 - \frac{\mathbf{C}_n^{(0)}}{100} \right)^2 \sum_i \left(\frac{\mathbf{m}_i \mathbf{C}_{Zr,i}}{\mathbf{m}_{Zr}} \right)^2 \left[\left(\frac{\Delta \mathbf{m}_i}{\mathbf{m}_i} \right)^2 + \left(\frac{\Delta \mathbf{C}_{Zr,i}}{\mathbf{C}_{Zr,i}} \right)^2 \right] + \left(\frac{\mathbf{m}_{Zr,IZ}}{\mathbf{m}_{Zr}} \cdot \frac{\Delta \mathbf{m}_{U,IZ}}{\mathbf{m}_{ZrO_2}} \cdot \frac{\Delta \mathbf{m}_{U,IZ}}{\mathbf{m}_{U,IZ}} \right)^2 } \right)^2$$
(3.15)
$$\begin{pmatrix} \left(\frac{\Delta \mathbf{m}_{Zr}}{\mathbf{m}_{Zr}} \right) = \sqrt{\left(1 - \frac{\mathbf{C}_n^{(0)}}{\mathbf{m}_{Zr}} \right)^2 \left[\left(\frac{\Delta \mathbf{m}_i}{\mathbf{m}_i} \right)^2 + \left(\frac{\Delta \mathbf{C}_{Zr,i}}{\mathbf{m}_{Zr,i}} \right)^2 \right] + \left(\frac{\mathbf{m}_{Zr,IZ}}{\mathbf{m}_{Zr}} \cdot \frac{\Delta \mathbf{m}_{U,IZ}}{\mathbf{m}_{Zr,IZ}} \right)^2 + \left(\frac{\mathbf{M}_{U}}{\mathbf{m}_{U}} \cdot \frac{\mathbf{m}_{U,IZ}}{\mathbf{m}_{Zr}} \cdot \frac{\Delta \mathbf{m}_{U,IZ}}{\mathbf{m}_{U,IZ}} \right)^2 } \right)^2$$
(3.16)
$$\begin{pmatrix} \left(\Delta \mathbf{m}_{Fe^0} \right) = \sqrt{\left(\frac{\Delta \mathbf{C}_{Fe^0,i}}{\mathbf{m}_{Ee}^{-1}} \right)^2 + \left(\frac{\Delta \mathbf{m}_{Fe}}{\mathbf{m}_{Ee}} \right)^2 } \right)^2$$

$$\left(\frac{\Delta m_{Fe^{+2}}}{m_{Fe^{+2}}}\right) = \sqrt{\left(\frac{\Delta C_{Fe^{+2},i}}{C_{Fe^{+2},i}}\right)^2 + \left(\frac{\Delta m_{Fe}}{m_{Fe}}\right)^2}$$
(3.17)

$$\left(\frac{\Delta m_{Fe^{+3}}}{m_{Fe^{+3}}}\right) = \sqrt{\left(\frac{\Delta C_{Fe^{+3},i}}{C_{Fe^{+3},i}}\right)^2 + \left(\frac{\Delta m_{Fe}}{m_{Fe}}\right)^2}$$
(3.18)

Table 3.2 gives the masses of components in the melt before stage C, which are calculated using (3.7)÷(3.12) and errors are calculated using (3.13)÷(3.18). It also shows the changes in

oxidation index (C_n) and uranium-zirconium ratio in comparison with the charge. The charge composition is given taking into account both the main charge and crust simulant (Table. 1.3). Errors in determining oxidation index and U/Zr ratio were not calculated.

It is evident from the table that a partial transfer of uranium into the IZ together with Zr (without oxygen present in the respective amount of UO_2) resulted in a certain increase of the melt oxidation index, and U/Zr ratio decreased.

Р	arameter	Charge	Before stage C
	m _{UO2}	1386.6	924 (±2 %)
Mass, g	m _{ZrO2}	161.1	139 (±4 %)
	m _{Zr}	274.5	176 (±3 %)
	m _{Fe⁰}	0	6 (±100 %)
	m _{Fe⁺²}	0	18 (±100 %)
	m _{Fe⁺³}	0	6 (±100 %)
Oxidat	tion index (C _n)	30.3	37 (± 3 rel.%)
U/Zr ratio		1.19	1.12 (±3 %)

 Table 3.2 – Melt composition and parameters

Using data of Table. 3.2 we can evaluate the mass of molten corium before stage C:

$$m_{melt} = m_{UO_2} + m_{ZrO_2} + m_{Zr} + m_{Fe}$$
(3.19)

The error in determining the melt mass is calculated in the following way:

$$\left(\frac{\Delta m_{\text{melt}}}{m_{\text{melt}}}\right) = \sqrt{\left(\frac{m_{\text{UO}_2}}{m_{\text{melt}}} \cdot \frac{\Delta m_{\text{UO}_2}}{m_{\text{UO}_2}}\right)^2 + \left(\frac{m_{\text{ZrO}_2}}{m_{\text{melt}}} \cdot \frac{\Delta m_{\text{ZrO}_2}}{m_{\text{ZrO}_2}}\right)^2 + \left(\frac{m_{\text{Zr}}}{m_{\text{melt}}} \cdot \frac{\Delta m_{\text{Zr}}}{m_{\text{Zr}}}\right)^2 + \left(\frac{m_{\text{Fe}}}{m_{\text{melt}}} \cdot \frac{\Delta m_{\text{Fe}}}{m_{\text{Fe}}}\right)^2} (3.20)$$

Calculations using (3.19) and (3.20) give the melt masses before stage C: $m_{melt} = 1269 \text{ g} (\pm 3 \text{ \%}).$

Chemical analysis of molten products (Table. 2.5) has determined the presence of the following cations in the melt: U^{+4} , U^{+6} , Zr^{+4} , Fe^{0} , Fe^{+2} and Fe^{+3} . It means that at melt oxidation the following reactions with the corresponding thermal effects took place:

$Zr + 2H_2O = ZrO_2 + 2H_2 + 530 \text{ kJ/mol.}$	(3.21)
---	-------	---

$$UO_2 + H_2O = UO_3 + H_2 - 160 \text{ kJ/mol.}$$
 (3.22)

$$Fe + H_2O = FeO + H_2 - 30 \text{ kJ/mol.}$$
 (3.23)

$$2Fe + 3H_2O = Fe_2O_3 + 3H_2 - 120 \text{ kJ/mol.}$$
(3.24)

Of all reactions (3.21)÷(3.24) only the first one (3.21) is exothermal.

Let's assume that the reactions are heterogeneous, i.e. take place on the melt surface, so the heat of dissolved oxygen in the **suboxidized melt** is negligible. Note that the heat of oxygen dissolved in the melt of **metallic** uranium or zirconium is quite significant - about $60 \div 70$ % of the heat of oxidizing reaction with the corresponding element. And this process is exothermal [24].

Therefore, assuming that cation composition of the melt after stage C was the same as the cation composition of molten products, knowing the melt composition (Table. 3.2) and heat effects of reactions (3.21)÷(3.24), we can get the total power from the melt composition at stage C:

$$H^{(C)} = H_1^{(C)} + H_2^{(C)} + H_3^{(C)} + H_4^{(C)} = +949 \text{ kJ}$$
(3.25)

where
$$H_1^{(C)} = +530 \text{ kJ} / \text{mol} \cdot \left(\frac{m_{Zr}}{M_{Zr}}\right) = +1020 \text{ kJ} (\pm 3\%)$$
 (3.26)

$$H_{2}^{(C)} = -160 \text{ kJ} / \text{mol} \cdot \left(\frac{m_{UO_{2}} a_{U^{+6}, \text{ingot}}}{M_{UO_{2}}}\right) = -55 \text{ kJ} (\pm 5\%)$$
(3.27)

$$H_{3}^{(C)} = -30 \text{ kJ/mol} \cdot \left(\frac{m_{Fe^{+2}}}{M_{Fe}}\right) = -10 \text{ kJ} (\pm 100 \%)$$
(3.28)

$$H_4^{(C)} = -120 \text{ kJ} / \text{mol} \cdot \left(\frac{m_{Fe^{+3}}}{2M_{Fe}}\right) = -6 \text{ kJ} (\pm 100 \%)$$
(3.29)

– heat of reactions (3.21), (3.22), (3.23) and (3.24), respectively, $a_{U^{+6},ingot} = 0.10 (\pm 5\%)$ – atomic fraction of cation U^{+6} from all uranium atoms. Errors in determining atomic fractions correspond to the maximum errors given in section 2.2.4. M_{Zr} , M_{UO_2} , M_{Fe} – molecular masses of Zr, uranium and iron dioxides, respectively. Masses of Zr, UO₂ and Fe (m_{Zr} , m_{UO_2} , $m_{Fe^{+2}}$, $m_{Fe^{+3}}$) are given in the last column of Table. 3.2. As noted above, errors in evaluating $H_1^{(C)}$, $H_2^{(C)}$, $H_3^{(C)}$ and $H_4^{(C)}$ are calculated as follows [23]:

$$\left(\frac{\Delta H_1^{(C)}}{H_1^{(C)}}\right) = \left(\frac{\Delta m_{Zr}}{m_{Zr}}\right) = 3\%$$
(3.30)

$$\left(\frac{\Delta H_2^{(C)}}{H_2^{(C)}}\right) = \sqrt{\left(\frac{\Delta m_{UO_2}}{m_{UO_2}}\right)^2 + \left(\frac{\Delta a_{U^{+6},ingot}}{a_{U^{+6},ingot}}\right)^2} \approx \sqrt{\left(2\%\right)^2 + \left(5\%\right)^2} \approx 5\%$$
(3.31)

$$\left(\frac{\Delta H_3^{(C)}}{H_3^{(C)}}\right) = \left(\frac{\Delta m_{Fe^{+2}}}{m_{Fe^{+2}}}\right) = 100\%$$
(3.32)

$$\left(\frac{\Delta H_4^{(C)}}{H_4^{(C)}}\right) = \left(\frac{\Delta m_{Fe^{+3}}}{m_{Fe^{+3}}}\right) = 100\%$$
(3.33)

Relative calculation error of $H^{(C)}$ is:

$$\left(\frac{\Delta H^{(C)}}{H^{(C)}}\right) = \sqrt{\sum_{i=1}^{4} \left(\frac{H_{i}^{(C)}}{H^{(C)}} \frac{\Delta H_{i}^{(C)}}{H_{i}^{(C)}}\right)^{2}} = \sqrt{\left(\frac{1020}{949} \cdot 3\%\right)^{2} + \left(\frac{(-55)}{949} \cdot 5\%\right)^{2} + \left(\frac{(-10)}{949} \cdot 100\%\right)^{2} + \left(\frac{(-6)}{949} \cdot 100\%\right)^{2}} \approx 3\%$$

$$(3.34)$$

In this way, the total power release resulting from the melt oxidation at stage C is:

$$H^{(C)} \approx 950 \text{ kJ} (\pm 3\%)$$
 (3.35)

Then the average heat deposition from the heat of redox reaction at stage C is:

$$Q^{(C)} \approx \frac{H^{(C)}}{t_1^{(C)} - t_0^{(C)}} = \frac{950 \text{ kJ}}{44300 \text{ s} - 42500 \text{ s}} = 0.53 \text{ kW}$$
 (3.36)

where $t_0^{(C)}$, $t_1^{(C)}$ – time of stage C start and finish. To determine error $Q^{(C)}$ we should take into account error $H^{(C)}$ and errors in choosing $t_0^{(C)}$ and $t_1^{(C)}$. In accordance with the experimental procedure described in section 1.3 and gas measurement data (Fig. 1.10, 3.1) the absolute error in determining the start of stage C $t_0^{(C)}$ can be taken as ±50 s. The error in determining the completion of stage C $t_1^{(C)}$ is assumed to be larger (±100 s), in absence of any direct measurements and manipulation only the gas analysis data testify to the completion of melt oxidation. So, in accordance with methodology [23] the relative error in determining Q^(C) is:

$$\left(\frac{\Delta Q^{(C)}}{Q^{(C)}}\right) = \sqrt{\left(\frac{\Delta H^{(C)}}{H^{(C)}}\right)^2 + \left(\frac{\Delta t_0^{(C)}}{t_1^{(C)} - t_0^{(C)}}\right)^2 + \left(\frac{\Delta t_1^{(C)}}{t_1^{(C)} - t_0^{(C)}}\right)^2} = \sqrt{\left(3\%\right)^2 + \left(\frac{50 \text{ s} \cdot 100\%}{1800 \text{ s}}\right)^2 + \left(\frac{100 \text{ s} \cdot 100\%}{1800 \text{ s}}\right)^2} \approx 7\%$$
(3.37)

Therefore, the average heat deposition in the melt at stage C is:

$$Q^{(C)} = 0.53 \text{ kW} (\pm 7\%)$$
(3.38)

After that we determine the specific density of power release in the melt. For its calculation it is necessary to know the melt volume, which is not known – though the melt diameter is known, its depth was not measured in the experiment. The melt volume can be derived from its mass and density, which, in accordance with the model of ideal mixing, is calculated in the following way:

$$\rho_{\text{melt}} = \frac{\sum_{i}^{i} m_{i}}{\sum_{i} \left(\frac{m_{i}}{\rho_{i}(T)}\right)} = \frac{m_{\text{melt}}}{\sum_{i} \left(\frac{m_{i}}{\rho_{i}(T)}\right)},$$
(3.39)

Where: index i takes the following values: $i = UO_2$, ZrO_2 , Zr, Fe, $\rho_i(T)$ – density of the i-th melt component at temperature T. The corresponding temperature correlations have the formulation of [25÷27]:

$$\rho_{\rm UO_2}(T) = 11.58 - 0.0008987 \cdot T \tag{3.40}$$

$$\rho_{ZrO_2}(T) = 6.384 - 0.00023 \cdot T \tag{3.41}$$

$$\rho_{Zr}(T) = 6.84451 - 0.609898 \cdot 10^{-3} \cdot T + 2.05008 \cdot 10^{-7} \cdot T^{2} - 4.47829 \cdot 10^{-11} \cdot T^{3} + 3.26469 \cdot 10^{-15} \cdot T^{4}$$
(3.42)

$$\rho_{\rm Fe}(T) = 7.066 - 1.232 \cdot 10^{-3} \cdot (T - 1811.15 \, {\rm K}) \tag{3.43}$$

where $[\rho_i] = g/cm^3$, [T] = K. Melt temperature is close to 2400°C \approx 2673 K. Errors of (3.40) \div (3.43) at this temperature are unknown, but they are likely to be not smaller than the scattering of experimental data. E.g. for iron, a melt component, the properties of which are best-known, at the end of experimental range (2200 K) the scattering is $\pm 0.15 \text{ g/cm}^3$ [28]. This value is taken as the absolute error in determining densities. We get the following values for densities and their relative errors: $\rho_{UO_2} = 9.2 \text{ g/cm}^3 (\pm 2\%)$, $\rho_{ZrO_2} = 5.8 \text{ g/cm}^3 (\pm 3\%)$, $\rho_{Zr} = 6.0 \text{ g/cm}^3 (\pm 3\%)$.

In accordance with [23] the relative error of melt density is calculated in the following way:

$$\left(\frac{\Delta\rho_{\text{melt}}}{\rho_{\text{melt}}}\right) = \sqrt{\sum_{i} \left(\frac{m_{i}}{m_{\text{melt}}}\right)^{2} \left\{ \left[\left(1 - \frac{\rho}{\rho_{i}}\right) \cdot \frac{\Delta m_{i}}{m_{i}} \right]^{2} + \left(\frac{\rho}{\rho_{i}} \cdot \frac{\Delta\rho_{i}}{\rho_{i}}\right)^{2} \right\}}$$
(3.44)

$$\rho_{\text{melt}} = 8.0 \text{ g/cm}^3 (\pm 2\%). \tag{3.45}$$

Knowing the average heat power $Q^{(C)}$, melt mass m_{melt} and its density we can calculate the average specific heat deposition from redox reactions at stage C per a unit of melt volume:

$$q^{(C)} = \frac{Q^{(C)} \rho_{melt}}{m_{melt}}$$
(3.46)

The relative error in determining $q^{(C)}$ is calculated in accordance with [23]:

$$\left(\frac{\Delta q^{(C)}}{q^{(C)}}\right) = \sqrt{\left(\frac{\Delta Q^{(C)}}{Q^{(C)}}\right)^2 + \left(\frac{\Delta \rho_{melt}}{\rho_{melt}}\right)^2 + \left(\frac{\Delta m_{melt}}{m_{melt}}\right)^2}$$
(3.47)

The (3.46)÷(3.47) calculations give the following average densities of power deposition in the melt at stage C and corresponding relative error:

$$q^{(C)} = 3.3 \text{ W} / \text{cm}^3 = 3.3 \text{ MW} / \text{m}^3 (\pm 8\%)$$
 (3.48)

This value is considerably higher than the one for specific decay heat in the melt in the IVR conditions, which is about 1.6 MW/m^3 . The actual heat density distribution can be quite different from the unimodal distribution, therefore (3.48) gives only the average heat deposition value for the whole volume.

Let's determine heat release at the oxidation of IZ and vessel steel specimen (stage E). At this stage the oxygen from steam supplied to the melt penetrates it and gets to the specimen. By then the melt is fully oxidized, the heat of oxygen dissolution in its case is normally negligible. The reaction of steam decomposition into hydrogen and oxygen is endothermic, heat phenomena take place in the gas atmosphere and in the layer adjacent to the melt. At this stage of oxidation critical is the heat, which is released at the interface of steel (IZ) and melt, so the thermal effect of steam dissociation is not relevant.

Oxygen dissolved in the melt gets to the IZ because of the melt convection; there it interacts with its material and/or with steel. Let's list possible redox reactions taking place at such interaction:

$Zr + O_2 = ZrO_2 + 1090 \text{ kJ/mol}$	(3.49)
$U + O_2 = UO_2 + 1060 \text{ kJ/mol}$	(3.50)
$2U + 3O_2 = 2UO_3 + 2360 \text{ kJ/mol}$	(3.51)
$2Fe + O_2 = 2FeO + 500 \text{ kJ/mol}$	(3.52)
$4Fe + 3O_2 = 2Fe_2O_3 + 1440 \text{ kJ/mol}$	(3.53)

In this case all possible reactions are exothermic. Table. 3.3 shows the amount of reducing agents (Fe, U and Zr) in the IZ and in the part of steel specimen between the IZ and corrosion front before the beginning of stage E.

Dogion	Mass, g					
Region	Fe	U	Zr			
IZ	100 (±22 %)	42 (±22 %)	8 (±22 %)			
Specimen (between IZ and final position of the corrosion front)	70 (±42 %)	_	_			
Total	170 (±20 %)	42 (±22 %)	8 (±22 %)			

Table 3.3 – Reducing agents in the IZ and steel at stage E

Errors in determining masses of U and Zr in the IZ, as mentioned above, are equal to the error in determining the lower IZ boundary, i.e. ± 22 %. Error in determining the total iron is evaluated in a more complex way. Let the mass of iron in the undamaged specimen within the final position of the corrosion front be $m_{Fe}^{(0)} = \rho_{Fe} V^{(fin)} = 7.85 \text{ g/cm}^3 \cdot 25 \text{ cm}^3 \approx 200 \text{ g} (\pm 8\%)$, the error in determining this mass equals to the error in determining the volume of corroded part of the steel specimen during the experiment. $m_{Fe}^{(0)}$ can be conventionally divided into two summands:

$$m_{Fe}^{(0)} = m_{Fe,1}^{(0)} + m_{IZ}^{(0)}$$
(3.54)

where $m_{Fe,1}^{(0)}$ – iron mass between the final position of the corrosion front and lower IZ boundary before stage E, $m_{IZ}^{(0)}$ – mass of iron between the lower IZ boundary (before stage E) and top boundary of undamaged specimen. Second summand has been calculated above: 130 g (±19 %). Therefore, for calculating $m_{Fe,1}^{(0)}$ we have the following correlation:

$$m_{Fe,1}^{(0)} = m_{Fe}^{(0)} - m_{IZ}^{(0)} = 200 - 130 = 70 \text{ g}$$
(3.55)

and, consequently, for the relative error of this value:

$$\left(\frac{\Delta m_{Fe,1}^{(0)}}{m_{Fe,1}^{(0)}}\right) = \sqrt{\left(\frac{m_{Fe}^{(0)}}{m_{Fe,1}^{(0)}} \cdot \frac{\Delta m_{Fe}^{(0)}}{m_{Fe}^{(0)}}\right)^2 + \left(\frac{m_{IZ}^{(0)}}{m_{Fe,1}^{(0)}} \cdot \frac{\Delta m_{IZ}^{(0)}}{m_{IZ}^{(0)}}\right)^2}{m_{IZ}^{(0)}} = \sqrt{\left(\frac{200}{70} \cdot 8\%\right)^2 + \left(\frac{130}{70} \cdot 19\%\right)^2} \approx 42\%$$
(3.56)

In this way, (3.55) and (3.56) calculations give the following value for the mass of iron between the final position of corrosion front and lower IZ boundary before stage E:

$$\mathbf{m}_{\rm Fe,1}^{(0)} = 70 \, \mathrm{g} \left(\pm 42 \, \% \right) \tag{3.57}$$

As evident from (3.57), a large relative error results from the presence of factors with magnitude grater than unity in the both summands of the radicand.

Let's denote the mass of iron in the IZ and discussed part of the specimen before stage E as $m_{Fe}^{(E)}$:

$$m_{Fe}^{(E)} = m_{Fe}^{(0)} - m_{Fe} = 200 - 30 = 170 \text{ g}$$
 (3.58)

where m_{Fe} - above-calculated mass of iron displaced into the melt at stages A and C 30 g (±100 %) (Table. 3.2). It is followed by a formula for calculating the relative error in determining $m_{Fe}^{(E)}$:

$$\left(\frac{\Delta m_{Fe}^{(E)}}{m_{Fe}^{(E)}}\right) = \sqrt{\left(\frac{m_{Fe}^{(0)}}{m_{Fe}^{(E)}} \cdot \frac{\Delta m_{Fe}^{(0)}}{m_{Fe}^{(0)}}\right)^2 + \left(\frac{m_{Fe}}{m_{Fe}^{(E)}} \cdot \frac{\Delta m_{Fe}}{m_{Fe}}\right)^2} = \sqrt{\left(\frac{200}{170} \cdot 8\%\right)^2 + \left(\frac{30}{170} \cdot 100\%\right)^2} \approx 20\%$$
(3.59)

In this way, (3.58) and (3.59) calculations give the following iron mass in the IZ and considered part of specimen before stage E:

$$m_{\rm Fe}^{\rm (E)} = 170 \, {\rm g} \left(\pm 20 \,\%\right) \tag{3.60}$$

We should mention that $m_{Fe}^{(E)}$ was calculated not like the sum of $m_{Fe,1}^{(0)}$ and $m_{Fe,1Z}$, relative errors of which are quite high (> 20 %), but as a difference, the minuend of which having a rather small error of 8 %, is nearly seven times larger than the subtrahend. And the relative error $m_{Fe}^{(E)}$ evaluated in this way is rather small (and smaller than it would have been if calculated in the first way – as the sum mentioned above).

Knowing the distribution of atoms of reducing agents in the molten materials and assuming that it is equal to the distribution of oxygen consumption in the corresponding redox reactions at stage E (Table. 2.5), we can get the power effect for this stage:

$$H^{(E)} = H_1^{(E)} + H_2^{(E)} + H_3^{(E)} + H_4^{(E)} + H_5^{(E)} = 967 \text{ kJ}$$
(3.61)

where
$$H_1^{(E)} = +1090 \text{ kJ} / \text{mol} \cdot \left(\frac{m_{Zr}^{(E)}}{M_{Zr}}\right) = 96 \text{ kJ} (\pm 22 \%)$$
 (3.62)

$$H_{2}^{(E)} = +1060 \text{ kJ} / \text{mol} \cdot \left(\frac{m_{U}^{(E)} a_{U^{+4}}}{M_{U}}\right) = 170 \text{ kJ} (\pm 23 \%)$$
(3.63)

$$H_{3}^{(E)} = +2360 \text{ kJ/mol} \cdot \left(\frac{m_{U}^{(E)} a_{U^{+6}}}{2M_{U}}\right) = 21 \text{ kJ} (\pm 23\%)$$
(3.64)

$$H_4^{(E)} = +500 \text{ kJ} / \text{mol} \cdot \left(\frac{m_{\text{Fe}}^{(E)} a_{\text{Fe}^{+2}}}{2M_{\text{Fe}}}\right) = 460 \text{ kJ} (\pm 20 \%)$$
(3.65)

$$H_{5}^{(E)} = +1440 \text{ kJ/mol} \cdot \left(\frac{m_{Fe}^{(E)} a_{Fe^{+3}}}{4M_{Fe}}\right) = 220 \text{ kJ} (\pm 20 \%)$$
(3.66)

– heat released in reactions (3.51), (3.52), (3.53), (3.54) and (3.55), respectively. Errors in determining $H_1^{(E)}$, $H_2^{(E)}$, $H_3^{(E)}$, $H_4^{(E)}$ and $H_5^{(E)}$ are calculated in the following way:

$$\left(\frac{\Delta H_1^{(E)}}{H_1^{(E)}}\right) = \left(\frac{\Delta m_{Z_r}^{(E)}}{m_{Z_r}^{(E)}}\right) \approx 22\%$$
(3.67)

$$\left(\frac{\Delta H_2^{(E)}}{H_2^{(E)}}\right) = \sqrt{\left(\frac{\Delta m_U^{(E)}}{m_U^{(E)}}\right)^2 + \left(\frac{\Delta a_{U^{+4}}}{a_{U^{+4}}}\right)^2} \approx \sqrt{\left(22\%\right)^2 + \left(5\%\right)^2} \approx 23\%$$
(3.68)

$$\left(\frac{\Delta H_3^{(E)}}{H_3^{(E)}}\right) = \sqrt{\left(\frac{\Delta m_U^{(E)}}{m_U^{(E)}}\right)^2 + \left(\frac{\Delta a_{U^{+6}}}{a_{U^{+6}}}\right)^2} \approx \sqrt{\left(22\%\right)^2 + \left(5\%\right)^2} \approx 23\%$$
(3.69)

$$\left(\frac{\Delta H_4^{(E)}}{H_4^{(E)}}\right) = \sqrt{\left(\frac{\Delta m_{Fe}^{(E)}}{m_{Fe}^{(E)}}\right)^2 + \left(\frac{\Delta a_{Fe^{+2}}}{a_{Fe^{+2}}}\right)^2} \approx \sqrt{(20\%)^2 + (3\%)^2} \approx 20\%$$
(3.70)

$$\left(\frac{\Delta H_{5}^{(E)}}{H_{5}^{(E)}}\right) = \sqrt{\left(\frac{\Delta m_{Fe}^{(E)}}{m_{Fe}^{(E)}}\right)^{2} + \left(\frac{\Delta a_{Fe^{+3}}}{a_{Fe^{+3}}}\right)^{2}} \approx \sqrt{\left(20\%\right)^{2} + \left(3\%\right)^{2}} \approx 20\%$$
(3.71)

A relative $H^{(E)}$ calculation error is:

$$\left(\frac{\Delta H^{(E)}}{H^{(E)}}\right) = \sqrt{\sum_{i=1}^{5} \left(\frac{H_{i}^{(E)}}{H^{(E)}} \cdot \frac{\Delta H_{i}^{(E)}}{H_{i}^{(E)}}\right)^{2}} = \sqrt{\left(\frac{96}{967} \cdot 22\%\right)^{2} + \left(\frac{170^{2} + 21^{2}}{967^{2}}\right) \cdot \left(23\%\right)^{2} + \left(\frac{460^{2} + 220^{2}}{967^{2}}\right) \cdot \left(20\%\right)^{2}} \approx 12\%$$
(3.72)

It should be noted that the relative error in determining $H^{(E)}$ is smaller than relative errors of any of the five reactions. Mathematically it is explained by the presence of factors with magnitude lower than unity in each summand of the radicand (all reactions in the IZ and specimen taking place at stage E are exothermic, i.e. the total energetic effect from all reactions is higher than any partial energy effect). In this way, power release caused by the oxidation of IZ and/or steel at stage E is:

$$H^{(E)} \approx 970 \text{ kJ} (\pm 12 \%)$$
 (3.73)

The average heat release from redox reactions at stage E is:

$$Q^{(E)} \approx \frac{H^{(E)}}{t_1^{(E)} - t_0^{(E)}} = \frac{970 \text{ kJ}}{50960 \text{ s} - 49200 \text{ s}} = 0.55 \text{ kW} (\pm 14 \%),$$
(3.74)

where $t_0^{(E)}$, $t_1^{(E)}$ – time of stage E beginning and end. For determining error $Q^{(E)}$ we need to take into account both error $H^{(E)}$ and errors in choosing $t_0^{(E)}$ and $t_1^{(E)}$. The described experimental procedure (section 1.3), and gas measurements (Fig. 1.10, 3.1) enable to estimate the absolute error in determining these moments of stage E as ±100 s. Then, in accordance with methodology [23] the relative error in determining $Q^{(E)}$ is:

$$\left(\frac{\Delta Q^{(E)}}{Q^{(E)}}\right) = \sqrt{\left(\frac{\Delta H^{(E)}}{H^{(E)}}\right)^2 + \left(\frac{\Delta t_0^{(E)}}{t_1^{(E)} - t_0^{(E)}}\right)^2 + \left(\frac{\Delta t_1^{(E)}}{t_1^{(E)} - t_0^{(E)}}\right)^2} = \sqrt{\left(12\%\right)^2 + 2\cdot \left(\frac{100 \text{ s} \cdot 100\%}{1760 \text{ s}}\right)^2} \approx 14\%$$
(3.75)

Therefore, the average heat power in the melt at stage E is:

$$Q^{(E)} = 0.55 \text{ kW} (\pm 14 \%) \tag{3.76}$$

The recalculation for the surface area of the specimen having a 70 mm diameter gives the average heat flux on the surface:

$$q^{(E)} \approx 140 \text{ kW} / \text{m}^2 (\pm 14 \%)$$
 (3.78)

Let's compare the heat flux value of (3.78) with a characteristic value of heat flux on the external surface of the reactor lower head in the IVR conditions: $0.5 \div 1.0 \text{ MW/m}^2$. $q^{(E)}$ is about 14÷28 % of this value, which can be relevant for the IVR conditions.

Knowing heat fluxes from redox reactions and having the gas analysis data on hydrogen content in furnace gases, we can calculate hydrogen release. E.g. at gas measurements hydrogen losses took place due to its high volatility, so the calculations assumed that the actual content of

hydrogen at a random moment of time is in proportion (not equal, but larger) to the measured value. The coefficient of proportionality was adjusted in terms of stoichiometry from the inventory of reducing agents in the whole system (not only in the melt) for stages C and E. The incremental hydrogen release is shown in Fig. 3.2. It is seen that the curves have a stable inclination angle at the stabilized regimes of these experimental stages (at stage C in particular), which confirms our assumption about the constant oxidation rate and its independence on the content of reducing agents in the system (melt, IZ and/or steel).



CONCLUSIONS

The following has been established by the completed experiment, at which the neutral (argon) atmosphere was replaced with the oxidizing one (steam) above the suboxidized melt of prototypic corium:

- Oxidation rate of molten corium and interaction zone is controlled by the supply of oxidant to the melt surface. (In this case the IZ is formed on the steel specimen surface before the neutral atmosphere is replaced with steam, other conditions being equal).
- In the experimental conditions the specific volumetric power deposition caused by the redox reactions in the melt was approximately 3.3 MW/m³, which exceeds the specific decay heat in the melt for the IVR conditions.
- In the experimental conditions the heat flux into the specimen generated by the heat of redox reactions in the interaction zone was approximately 0.14 MW/m^2 , that is, commensurable with the heat flux from the melt into the vessel in the IVR conditions.

The provided data confirm that thermal effects taking place during the replacement of neutral atmosphere with the oxidizing one should be taken into account in the IVR analysis.

REFERENCES

- 1. S.V. Bechta, V.B. Khabensky, E.V. Krushinov et al. New Experimental Results on the Interaction of Molten Corium with Reactor Vessel Steel, Proc. of ICAPP'04, Pittsburgh, USA (2004).
- S.V. Bechta, V.B. Khabensky, E.V. Krushinov et al. Experimental Study of Interaction Between Suboxidized Corium and Reactor Vessel Steel, Proc. of ICAPP'06, Reno, USA (2006).
- S.V. Bechta, V.S. Granovsky, E.V. Krushinov et al. Corium Phase Equilibria based on MASCA, METCOR and CORPHAD Results, Nucl. Eng. Des. 238, p. 2761-2771 (2008).
- 4. V.G. Asmolov, S.V. Bechta, E.V. Krushinov et al., Molten Corium Stratification and Component Partitioning, MASCA 2 Seminar Cadarache, 11-12 October 2007, Cadarache, France (2007).
- 5. Investigation of corium melt interaction with NPP reactor vessel steel. Project # 833.2-2003. Annual technical report, 2004.
- 6. Investigation of corium melt interaction with NPP reactor vessel steel (METCOR). ISTC Project # 833-99. Final Technical Report (2001) (in Russian).
- 7. B.G. Eremina. Gas Analysis. M.: Mir, 1955. (in Russian).
- 8. L.E. Baksanova., V.I. Budnikov, V.A. Val'zifer. Gas-volumetric method for determining active aluminum in the polymer materials. Industrial laboratory, #7, V.66, 2000. (in Russian).
- 9. N.F. Losev. Quantitative X-Ray fluorescence analysis. M.: Nauka, 1969. (in Russian).
- 10. Investigation of corium melt interaction with NPP reactor vessel steel (METCOR 2). Final technical report . 2006 g. (in Russian).
- 11. V.K. Markov at al. Uranium. Methods of its determination. M.: Atomizdat, 1964. (in Russian).
- 12. D.I. Ryabchikov, M.M. Seniavin. Analytical chemistry of uranium. M.: A. Sc of the USSR. 1962. (in Russian).
- 13. V.F. Lukianov, S.B. Savin, I.V. Nikolskaya. Photometric determination of micro quantities of uranium with reagent arsenazo III. J of A,Ch., XV, issue.3. 1960. (in Russian).
- 14. GOST 12365-84. Alloyed and high-alloyed steels. Methods for determining zirconium. (in Russian).
- 15. S.V. Elinson, T.I. Nezhnova, Photometric determination of zirconium in niobium and other metals // Industrial laboratory, 1964. V. 30. #4, pp. 396-399. (in Russian).
- V.G. Goriushina, E.V. Romanova, T.AS. Archakova, Colorimetric methods for determining zirconium in melts // Industrial laboratory, 1961. V. 27. #7, pp. 795-797. (in Russian).
- 17. D.I. Ryabchikov, M.M. Seniavin. Analytical chemistry of uranium. M.: A. Sc of the USSR. 1962. (in Russian).
- V.F. Lukianov, S.B. Savin, I.V. Nikolskaya. Photometric determination of micro quantities of uranium with reagent arsenazo III. J of A,Ch., v. XV, issue.3. 1960. (in Russian).

- 19. OST 4011-72. Drinking water. Methods for measuring mass concentrations of total iron. (in Russian).
- 20. E. Sendel. Calorimetric methods for determining traces of metals. M., Mir,1964. (in Russian).
- 21. Main Results of the MASCA1 and 2 Projects// Integrated report, Project of OECD, November 2006, RRC "Kurchatov Institute".
- 22. Ex-vessel Source Term Analysis. Task 2. Final Report ISTC Project #3345 (EVAN), NITI, Sosnovy Bor, 2007.
- 23. O.N. Kassandrova, V.V. Lebedev. Processing of experimental results . M.: Nauka, 1970, 104 p. (in Russian)
- 24. Wang, W., Olander, D.R., 1993. J. Am. Ceram. Soc. 76, 1242.
- 25. B. Eppinger, G. Fieg, S. Schmidt-Stiefel, W. Tromm. IKET/FZK. Investigations of the metallic and oxidic in-vessel corium densities: GEMINI2 calculations.
- 26. TAPP, A Database of Thermochemical and Physical Properties, E S Microwave, 2234 Wade Court, Hamilton OH 45013 USA, 1994.
- 27. J.K. Kohorst, ed., "MATPRO-A Library of Materials Properties for LWR Accident Analysis", NUREG/CR-5273, EGG-2555, Vol.4, R3, February 1990.
- 28. A.A. Werman, A.M. Samarin. Properties of iron melts. Moskva: Nauka, 1969. (in Russian).