International Science and Technology Center

A.P. Alexandrov Research Institute of Technology

VVER steel corrosion during in-vessel retention of corium melt

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- Free-convection heat-exchange in the molten pool
- Vessel temperature condition
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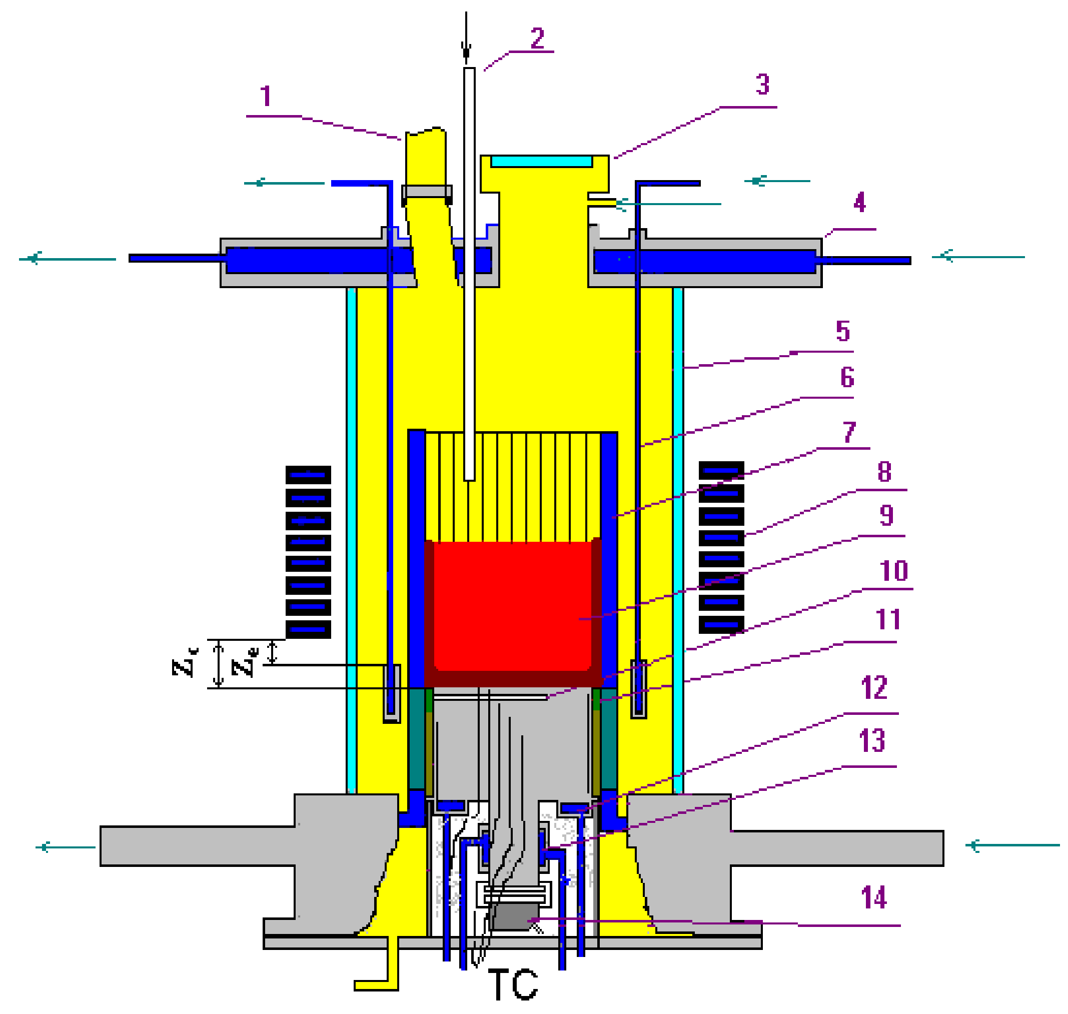
Objective

- **Estimate vessel steel corrosion influence on the vessel strength during the in-vessel melt retention**

RASPLAV-3 Furnace



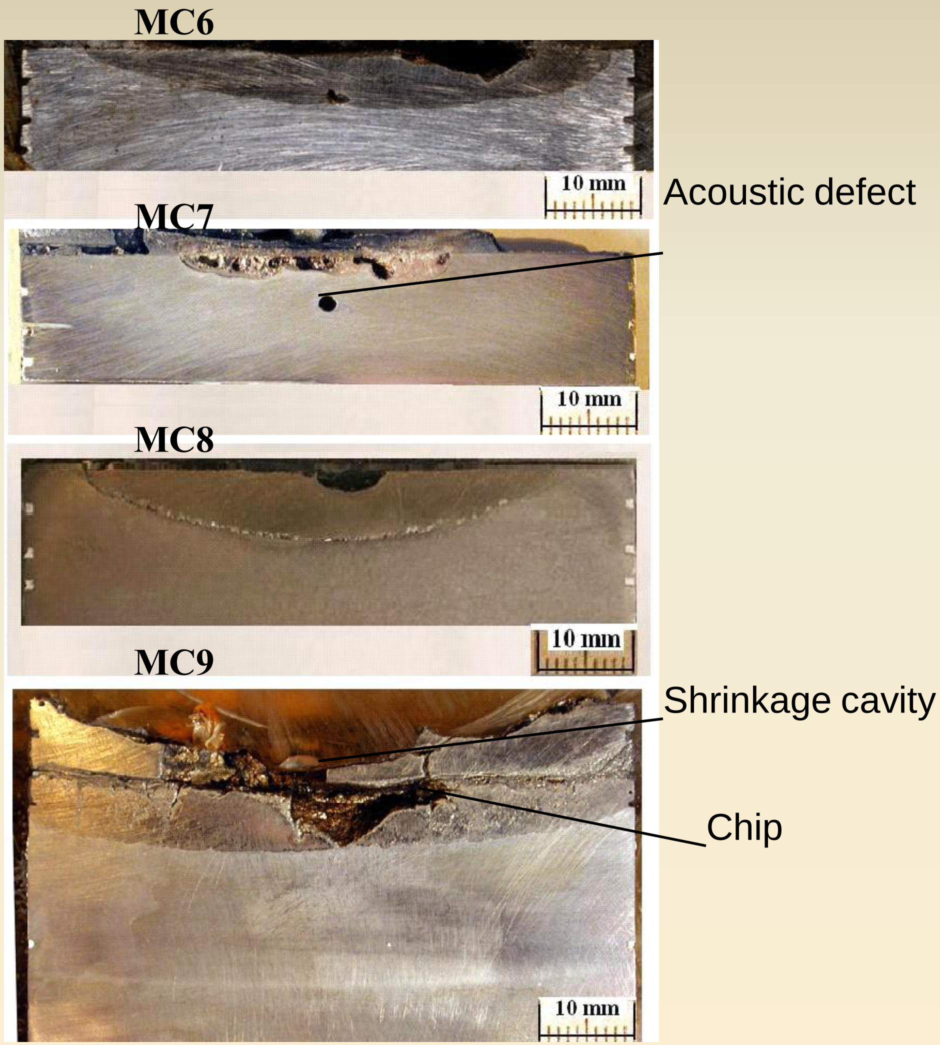
1 – steam vent from the furnace
2 – steam line
3 – lid –
4 – water-cooled cover
5 – quartz tube
6– water-cooled electromagnetic screen
7 – crucible sections
8 – inductor
9 – melt
10 – acoustic defect
11 – thermal insulation of the specimen
12 – top specimen calorimeter
13 – bottom specimen calorimeter
14 – US sensor

METCOR experimental matrix

Test	Corium composition	Atmosphere	Melt temperature, °C	Specimen surface temperature, °C	Heat flux, MW/m^2
MC1	$(U, Zr)O_{2+x}$- FeO_y	air	2700	950	0.9
MC2	$(U, Zr)O_{2+x}$- FeO_y	Air	2050…2350	720…1050	0.3…0.47
MC3	$(U, Zr)O_2$- FeO	nitrogen	2100…2150	920…1220	0.28…0.48
MC5	C-100; $(U, Zr)O_2$	argon	2600…2650	1075…1435	0.95…1.3
MC6	$(U, Zr)O_{2-x}$ (C-30)	argon	2400	1400*	1.23…1.31
MC7	$(U, Zr)O_{2-x}$ (C-30)	argon	2400	1150*	1.1
MC8	$(U, Zr)O_{2-x}$ (C-70)	argon	2450	1420*	1.35
MC9	C-30 and SS	argon	2450	1440*	1.1
MC10	$(U, Zr)O_{2+x}^{**}$	steam	2750…2800	1035…1235	0.95…1.1
MC11	$(U, Zr)O_{2+x}$- FeO_y	steam	1950…2100	950…1200	0.99…1.29
MC12	$(U, Zr)O_{2+x}$- FeO_y	air, steam	2000...2100	1000...1135	0.92...1.09

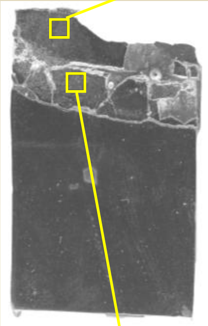
*** – initial temperature on the interaction interface;**
**** – initial composition.**

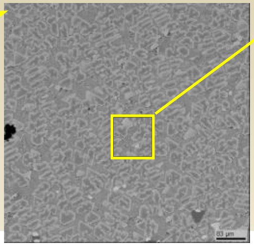
Interaction of vessel steel with suboxidized molten corium

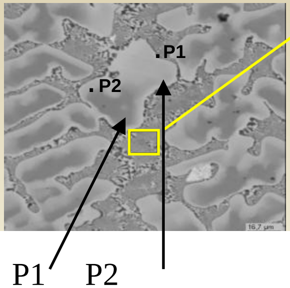


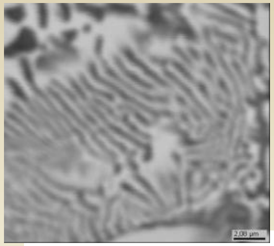
- **Formation of the interaction zone on the specimen surface**

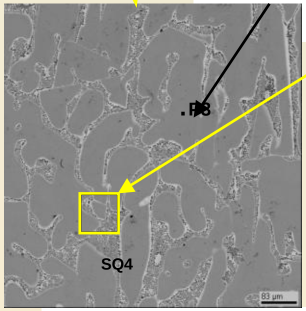
Interaction of vessel steel with suboxidized molten corium (2)









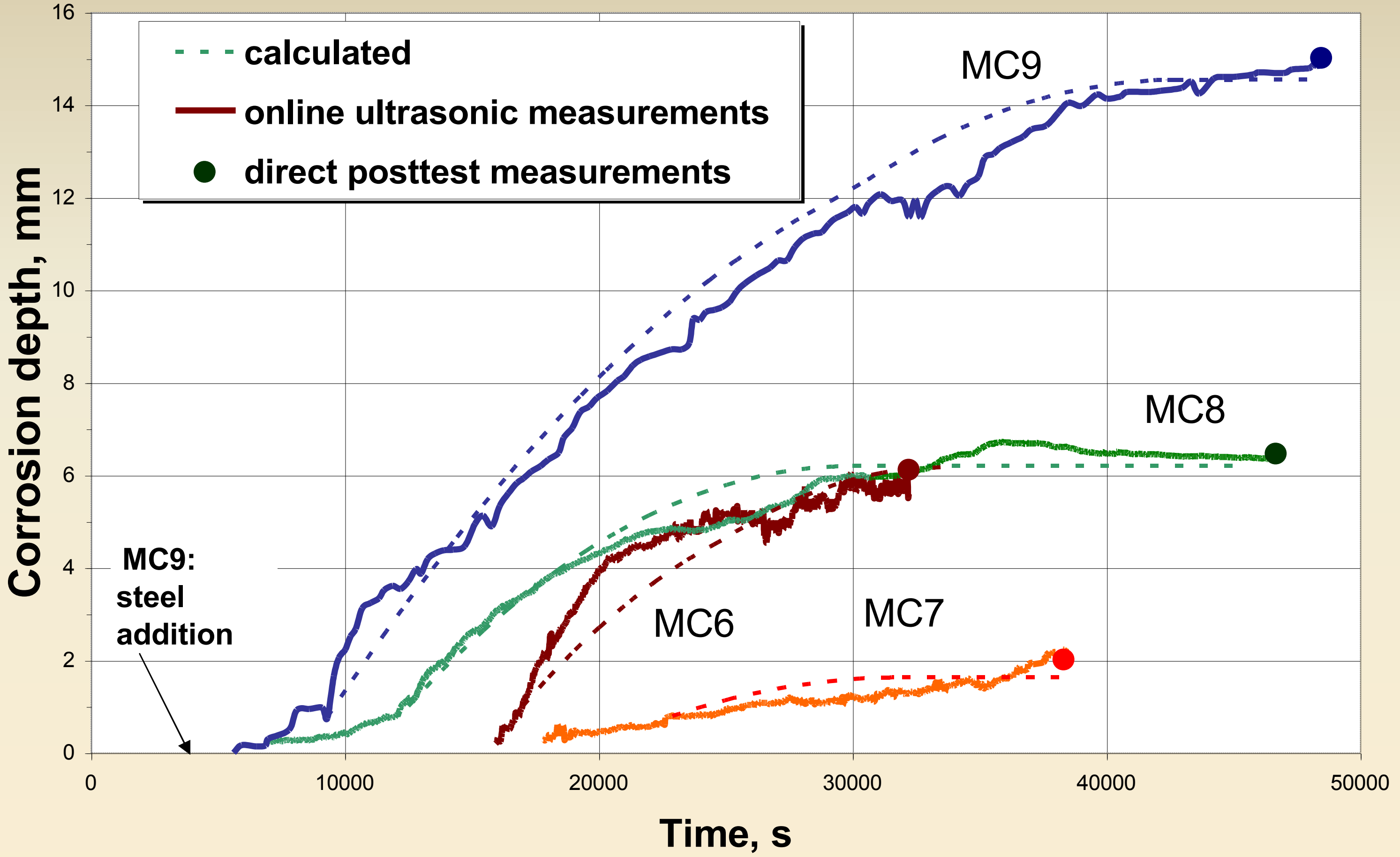


Composition Determined by EDX, mol %

№	U	Zr	Fe	Cr	Ni	Mn	~O	Note
SQ1		6.8	74.7	2.2	1.3	0.4	-	Average
SQ2	13.7	1.4	79.7	3.2	1.5	0.6	-	Eutectic
SQ3	7.9	10.2	69.0	1.3	1.4	-	10.2	Average
SQ4	10.7	1.2	79.8	3.2	1.1	0.5	3.5	Eutectic
P1	23.6	3.6	70.0	0.9	1.8	-	-	$U(Zr)Fe_3$
P2	7.4	16.4	73.1	1.3	1.4	0.5	-	$Zr(U)Fe_3$
P3	5.1	13.5	60.6	1.1	1.3	0.3	18.2	$Zr(U)Fe_3(O)$

- **In a general case the interaction zone is mushy**
- **Interaction zone composition: U-Zr-Fe(Cr, Ni…)-(O)**
- **IZ is formed by the repartitioning of components between molten corium and steel; difference from MASCA – thermal gradient conditions**

Interaction of vessel steel with suboxidized molten corium (3)



$$W = 0{,}46 \cdot 10^{-7} \sqrt{T_{int} - T_B}$$

$1440 \geq T_{int} \geq T_B$, $(U/Zr)_{at} \approx 1.2$, W – corrosion rate, m/s,

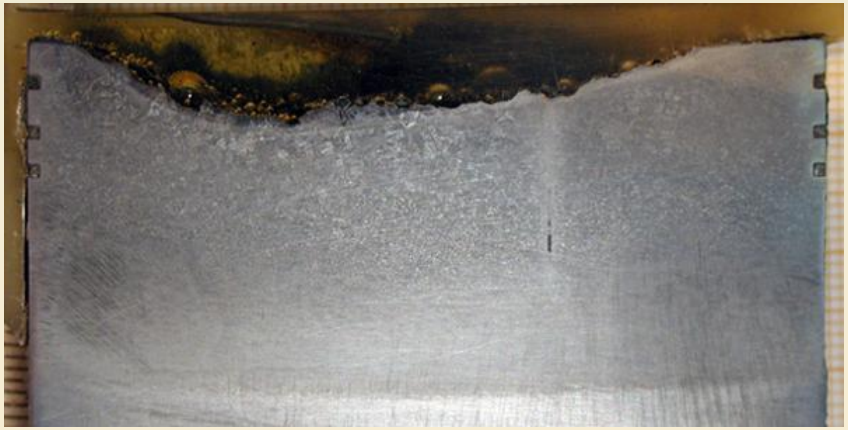
T_{int},T_B – current temperature on the interaction front and its final value, °C

Interaction of vessel steel with fully oxidized molten corium

Longitudinal section of the specimens

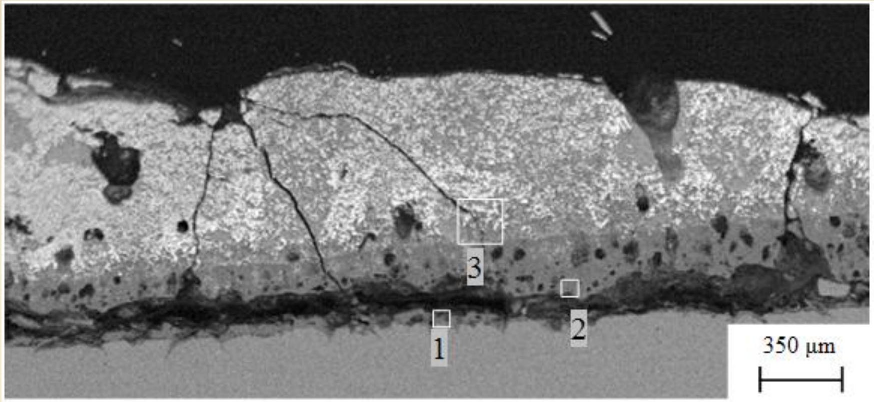
MC11

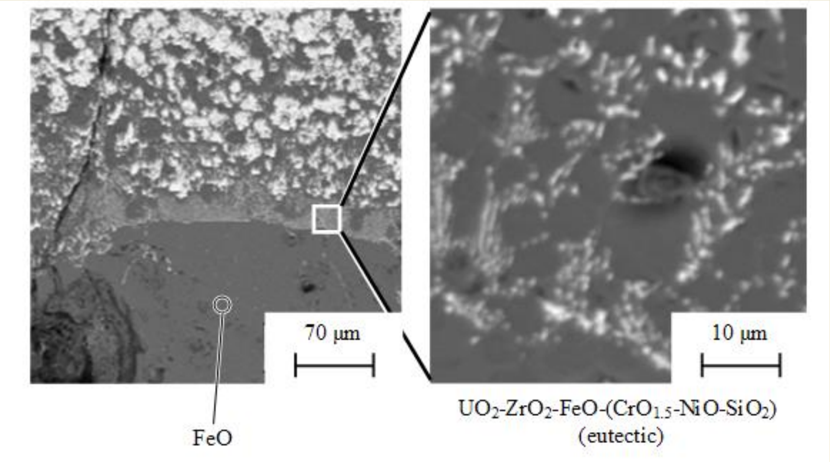
MC10

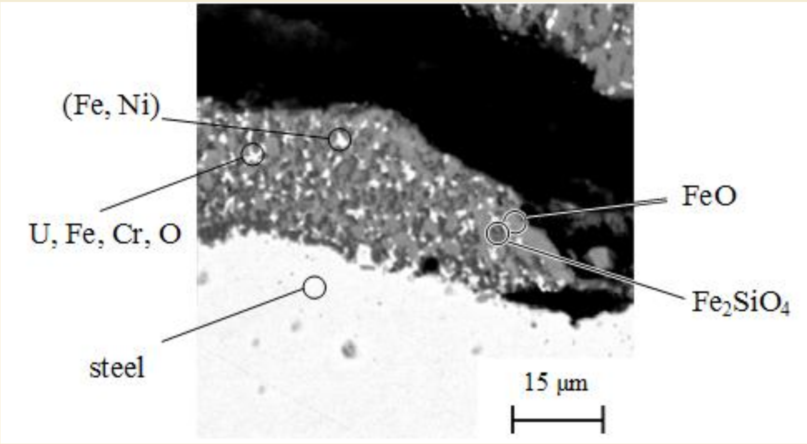


- Corrosion is caused by steel oxidation

Interaction of vessel steel with fully oxidized molten corium (2)

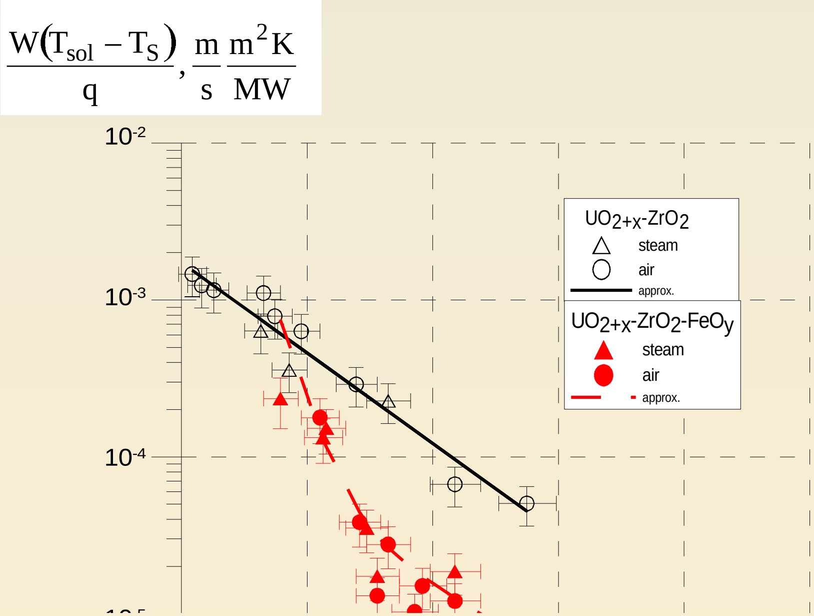






- For the UO_{2+x} – ZrO_2 – FeO_y corium - liquid phase in the corrosion layer at T > 1050°C
- Liquid phase is present in the whole corium crust

Interaction of vessel steel with fully oxidized molten corium (3)



For corium UO_{2+x}-ZrO_2

$$\frac{W(2723 - T_S)}{q} = 4.98\exp\cdot\left(-\frac{1.1\cdot 10^5}{RT_S}\right)$$

For corium UO_{2+x}-ZrO_2- FeO_y

$$\frac{W(1613 - T_S)}{q} = 0.1\exp\left(-\frac{0.91\cdot 10^5}{RT_S}\right) +$$

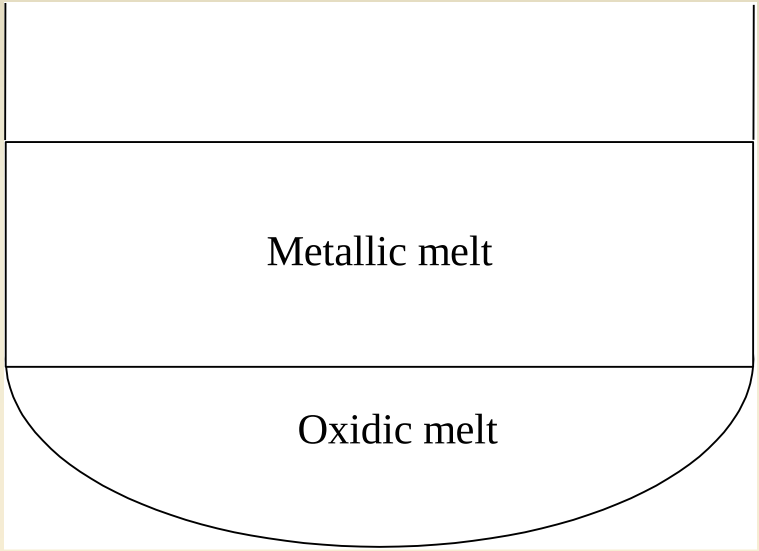
$$+3.4\cdot 10^{14}\exp\left(-\frac{4.99\cdot 10^5}{RT_S}\right)$$

W – m/s, q – MW/m^2, T – K

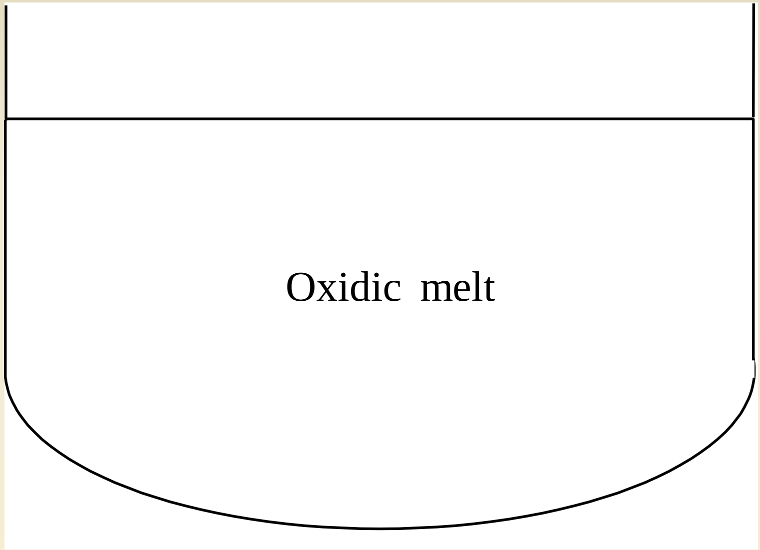
- **Corrosion intensification at T > 1050°C for fusible corium explained by the liquid-phase diffusion of Fe ions in the corium crust**

Molten pool configuration in the VVER-1000 lower head

Stratified pool



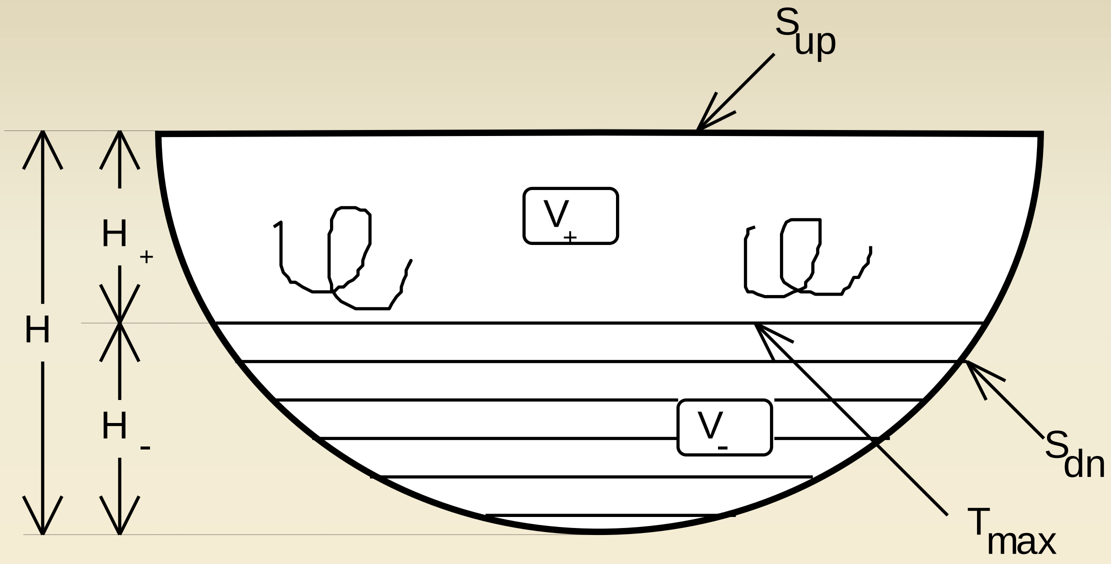
Homogeneous pool



- **Initial melt composition: UO_2 – 76 t, ZrO_2-11 t, Zr-14 t, SS-80 t, C_n=37%, m_{st}=0.45**
- **Stratified pool (MASCA): oxidic melt – C=82%, V=8.6m3**

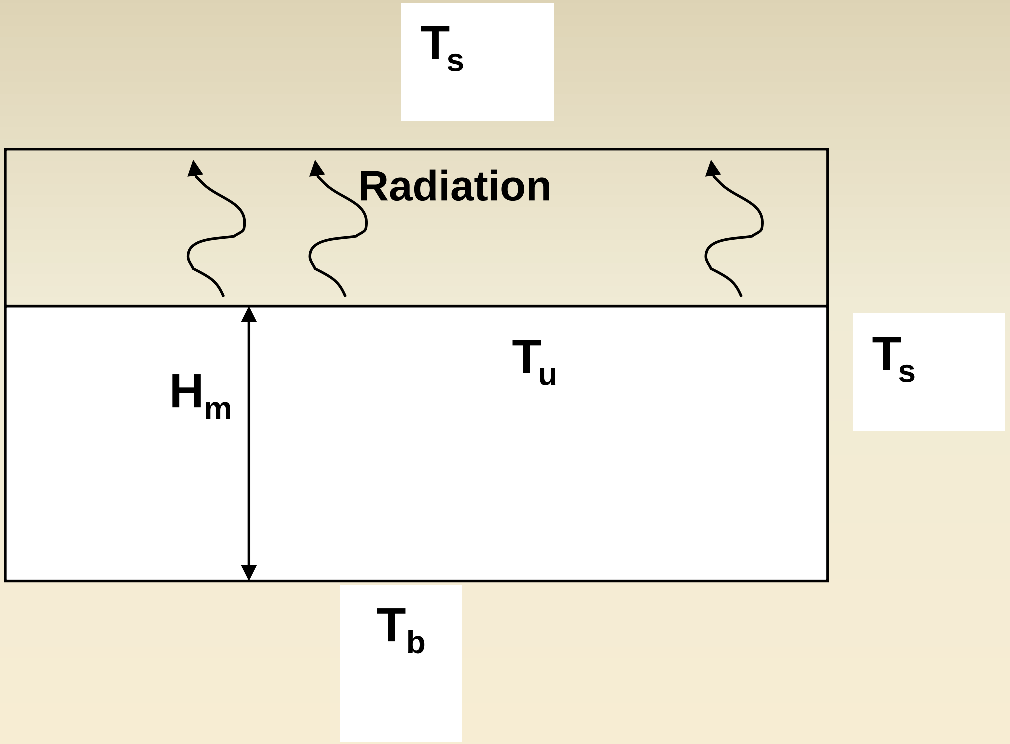
  metallic melt - U-Zr-Fe(Cr, Ni…)-(O), V=16m^3
- **Homogeneous pool: UO_{2+x} – ZrO_2 – FeO_y, V=37m^3**

Free convection in the heat-generating oxidic melt



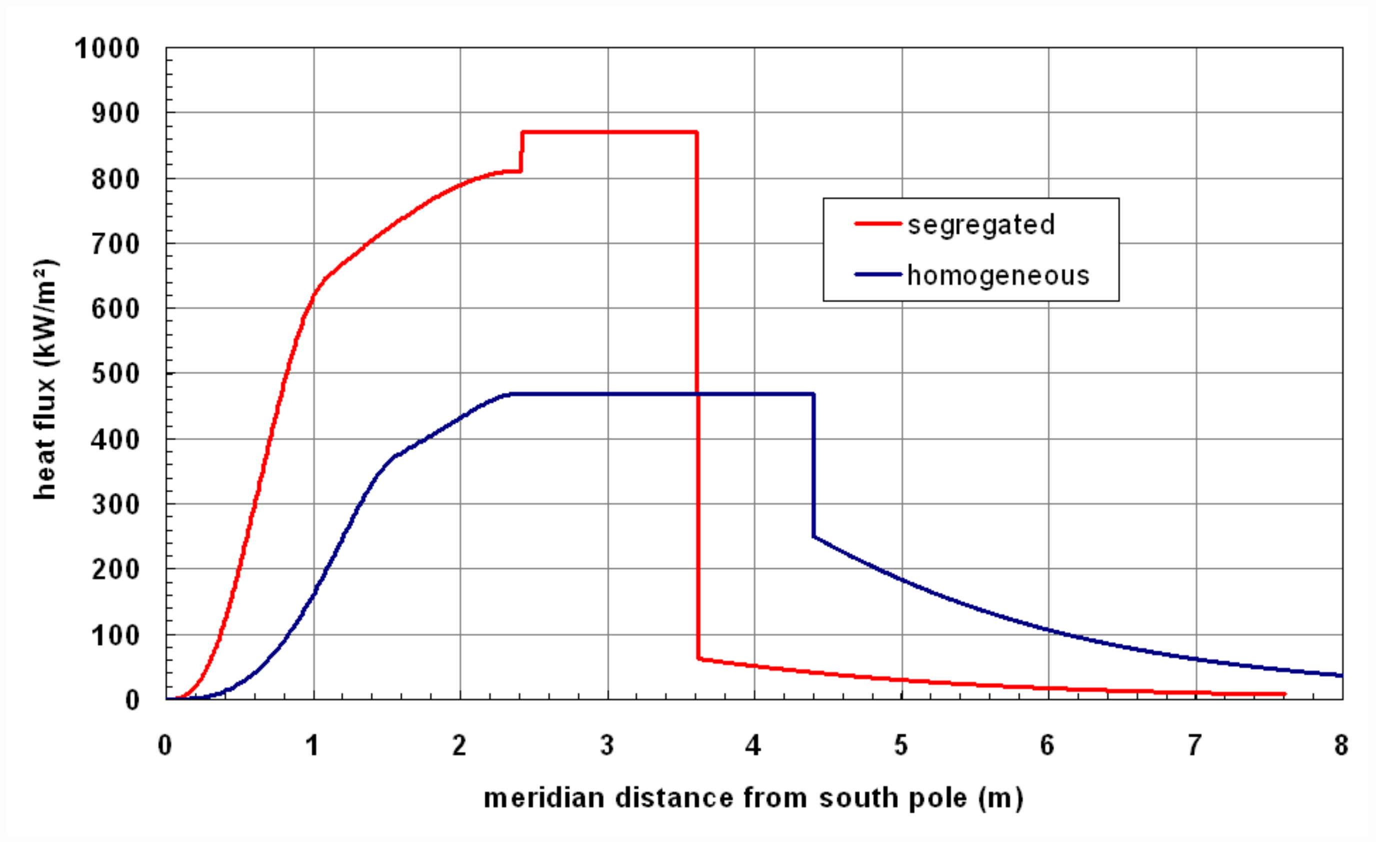
- Stationary model with lumped parameters, based on the maintained energy balance
- Temperature (density) stratification in the molten pool bottom with a vertical parabolic temperature profile; the pool top – uniform temperature
- Heat exchange with vessel bottom: correlation for turbulent boundary layer, the tilt angle taken into account
- Heat exchange in the pool top: the Kulacki – Emara convection

Free convection in the metallic melt



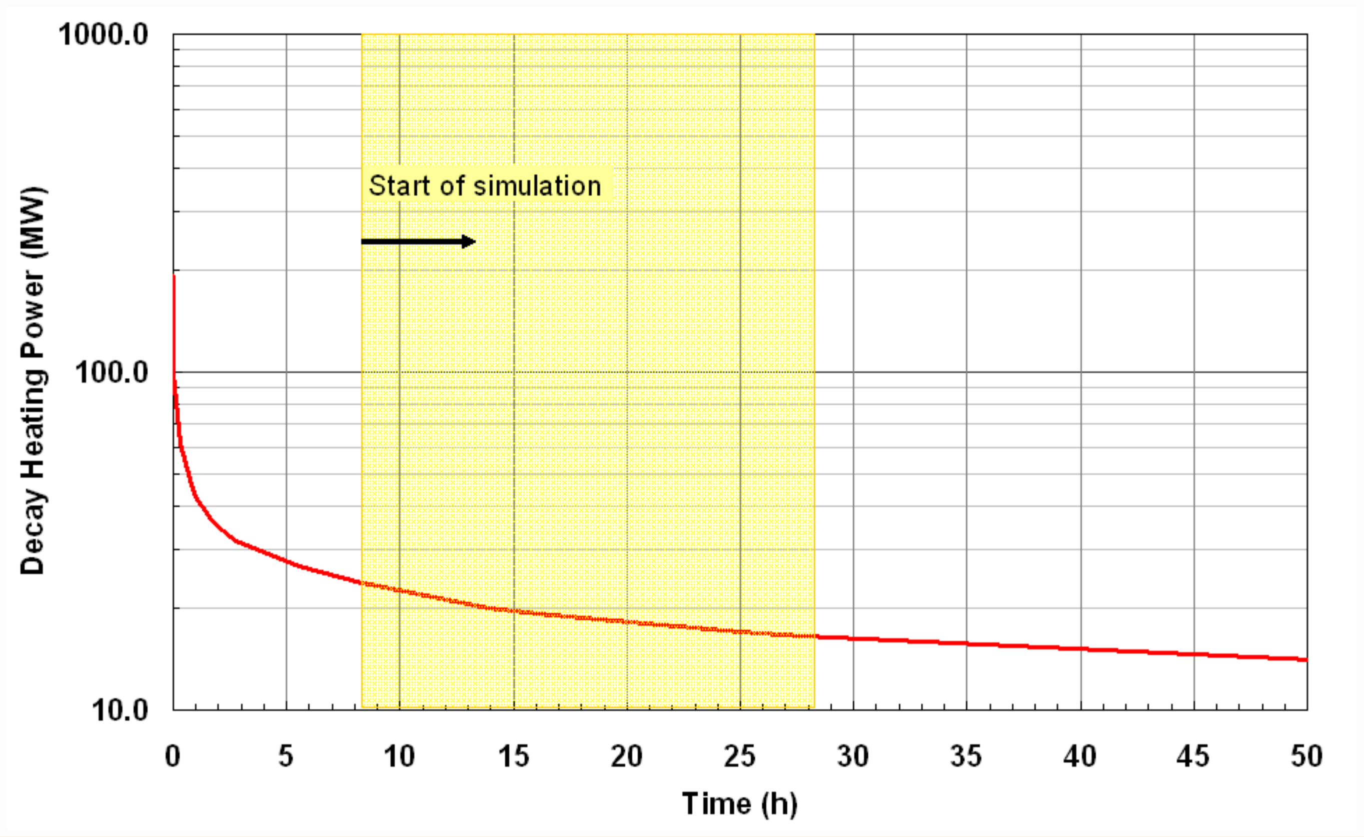
- Heat flux to the top surface: the Raleigh – Benard convection
- Heat flux to the vessel wall: correlation for turbulent boundary layer
- Temperature on the internal wall and surface subjected to the radiative heat flux – liquidus temperature of steel

Heat flux distribution on the internal vessel surface



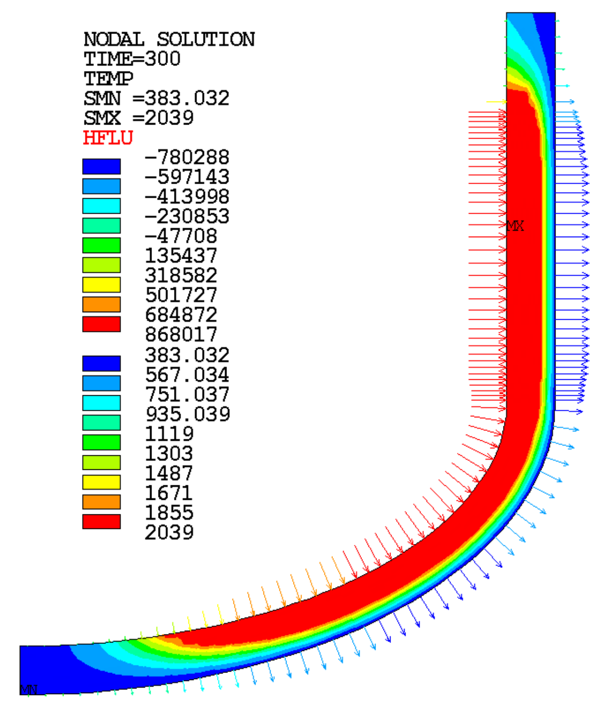
- **Completion of the melt formation: t=30000s, N=24MW**

Decay heat history

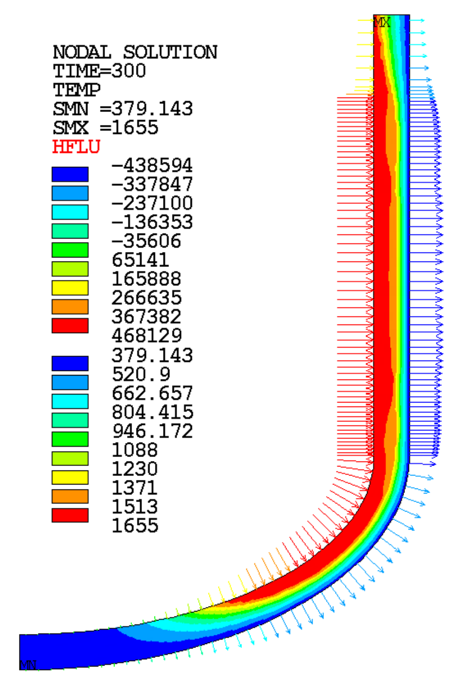


- **Heat flux to the vessel decreases in proportion with the reduced decay heat**

Temperatures and heat fluxes



segregated pool



homogeneous pool

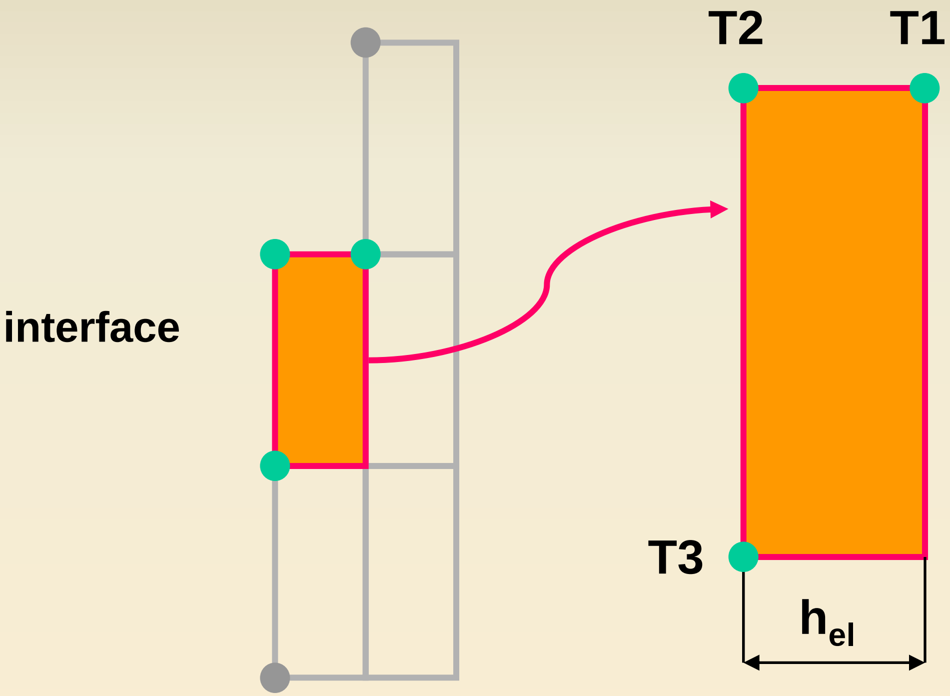
- **t=300s – quasi-stationary condition is reached**
- **Boundary conditions: temperature on the external vessel surface – 393K**

  heat flux to the internal surface – calculation
- **Part of the vessel wall having a temperature exceeding the steel liquidus is excluded from further calculations**

Analysis of four scenarios

- A: segregated pool without corrosion
- B: segregated pool with corrosion
- C: homogeneous pool without corrosion
- D: homogeneous pool with corrosion

Algorithm of ablation calculation



$$T_{int} = \frac{1}{N_i}\sum_{n=1}^{N_i} T_n \qquad N_i = \{2, 3, 4\}$$

$$\Delta D_{corr} = \frac{\dot{h}(T_{int})}{h_{el}} \cdot \Delta t$$

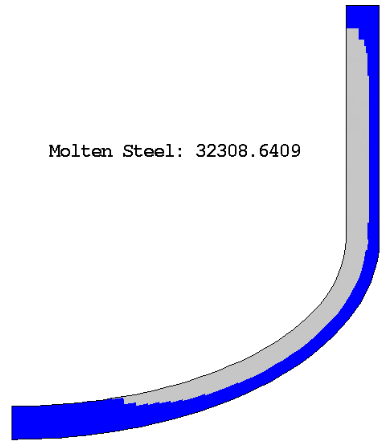
$$\dot{h}(T_{int}) = \frac{dh}{dt} = W$$

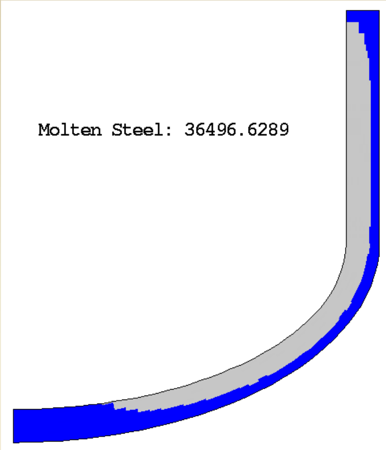
$$D_{corr}^{el}(t) = D_{corr}^{el}(t - \Delta t) + \Delta D_{corr}$$

Element killed if $D_{corr} \geq 1$

Final ablation

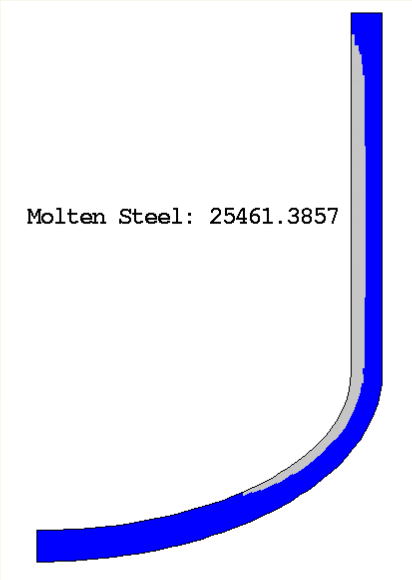
A

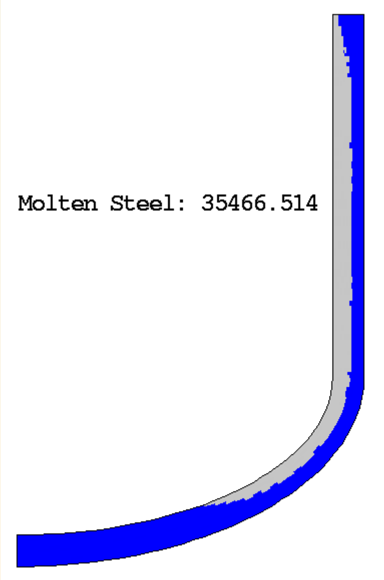




B

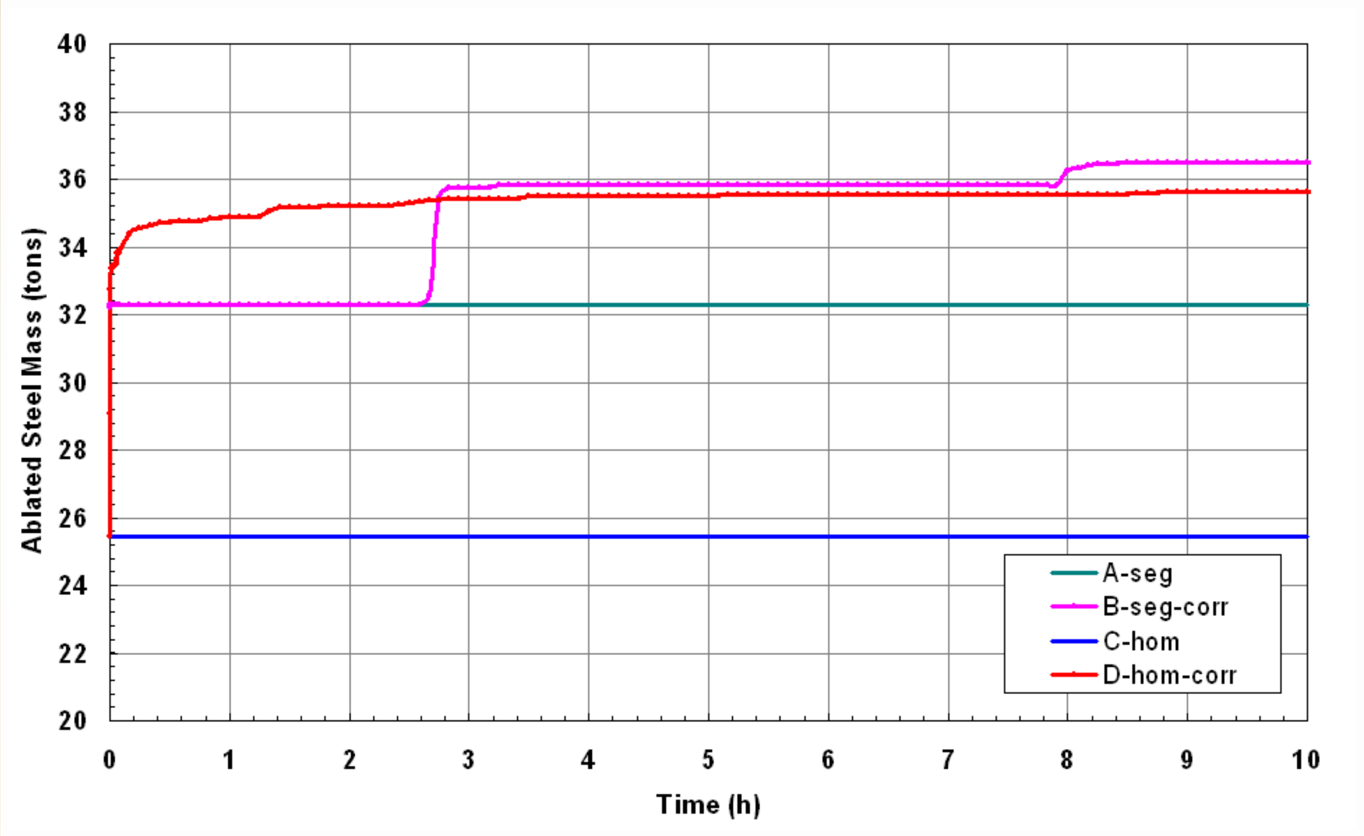
C





D

Ablation kinetics

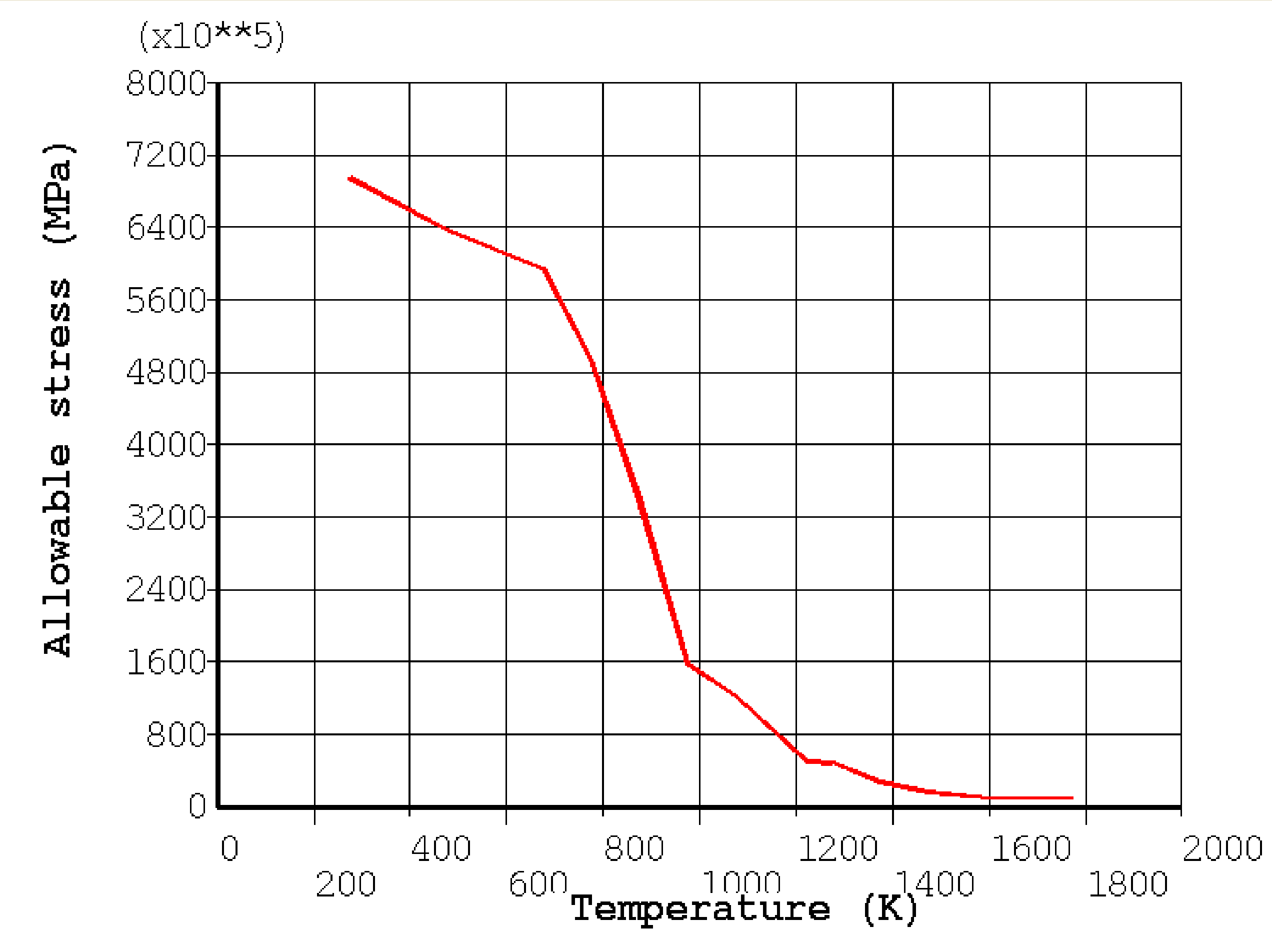


- "Leaps" are explained by the grid digitization
- Ablation practically stops at 1363K on the interaction interface
- Corrosion effect is larger for a homogeneous pool, and ablation depth is larger for the stratified pool

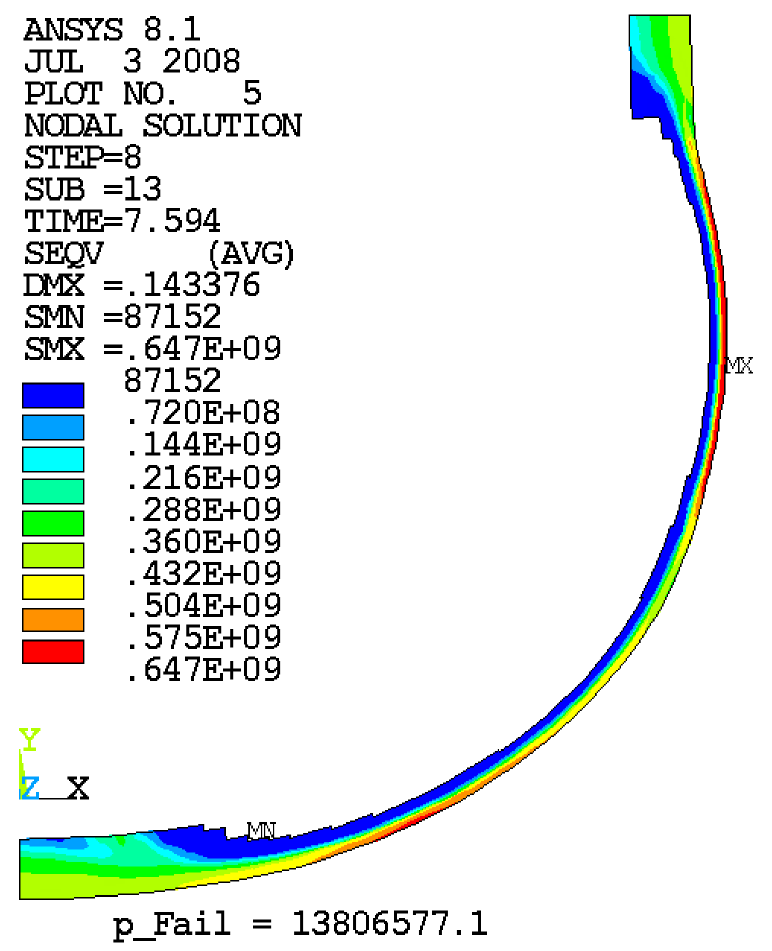
Strength calculation model

- 2D plasto-elastic formulation
- Vessel configuration – final condition (completed ablation)
- Temperature field at t=300s (conservative evaluation)
- Vessel and molten pool weight load
- Rise of internal pressure up to vessel failure
- Failure criterion – permissible stresses

Allowable stress

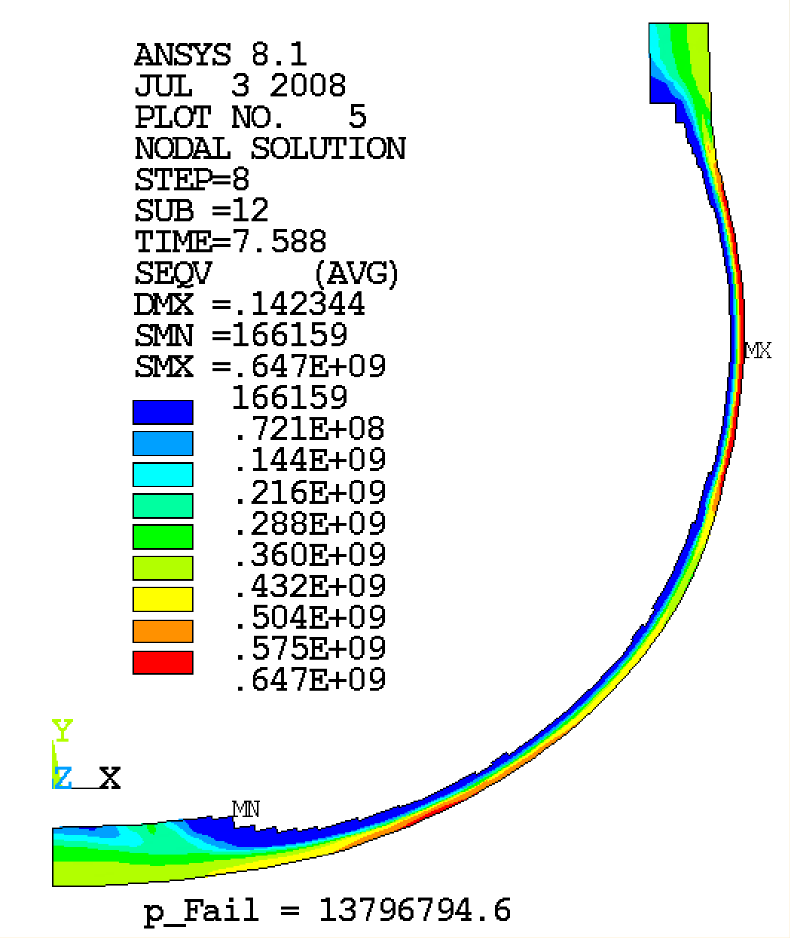


Stresses from the pressure causing failure (stratified pool)



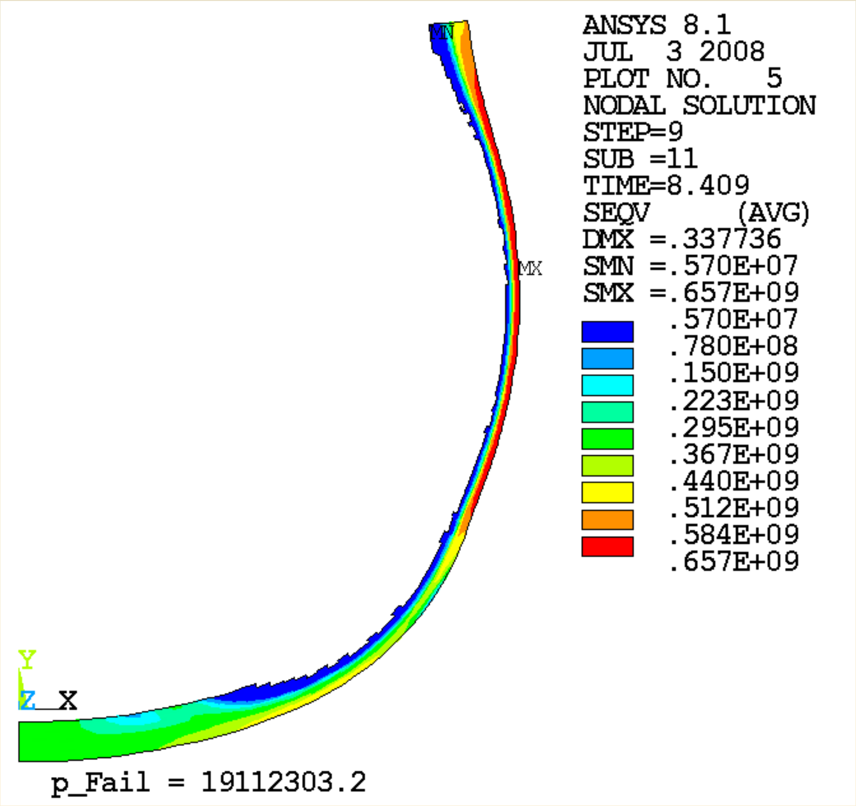
A

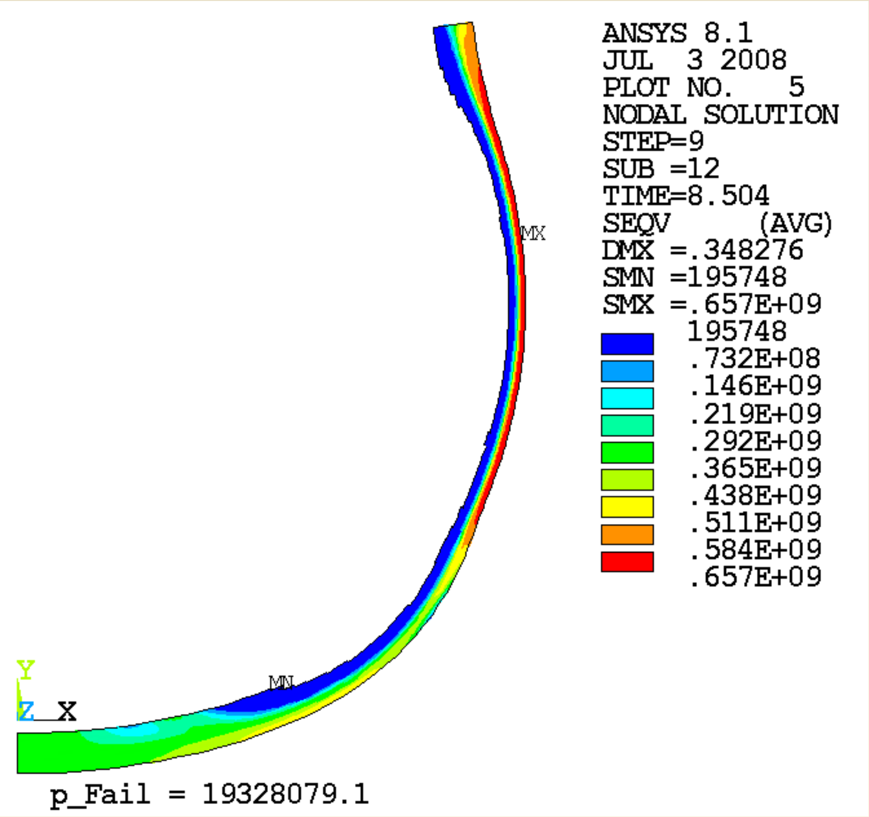
B



Stresses from the pressure causing failure (homogeneous pool)

D





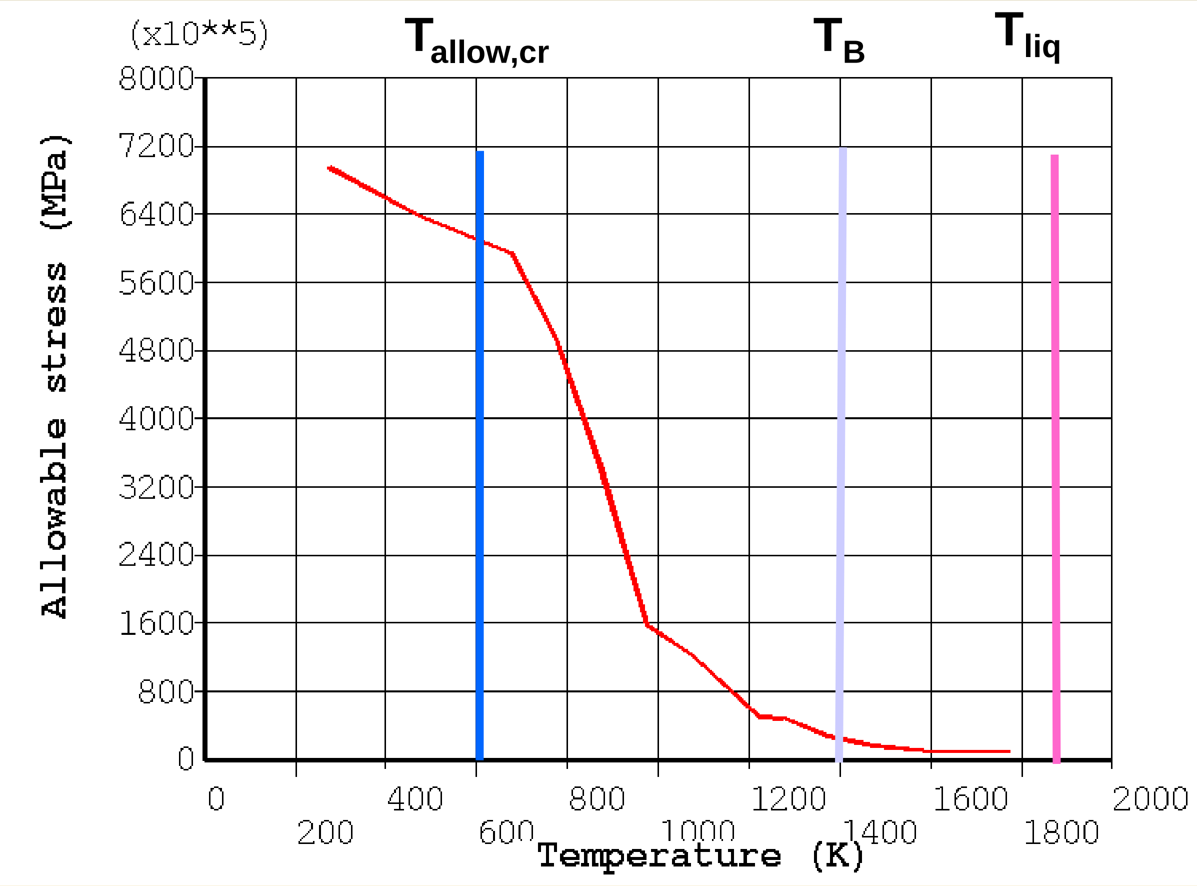
C

Main results of calculations

Scenario	A	B	C	D
Pool configuration	segregated	segregated	homogeneous	homogeneous
Corrosion	no	yes	no	yes
Ablated steel mass	32.3 t	36.5 t	25.5 t	35.5 t
Min. wall thickness	60 mm	50 mm	100 mm	70 mm
Pressure of failure	13.81 MPa	13.80 MPa	19.33 MPa	19.11 MPa

- **Insignificant influence of corrosion on the vessel strength**

Allowable stresses and characteristic temperatures



- **Corrosion results in the disappearance of “hot” steel layer having insignificant strength properties**

Conclusions

- Stratified and homogeneous pool configurations have been studied in the VVER-1000 IVR conditions
- Calculations of free convection in the molten pool have determined heat flux distribution on the internal vessel surface
- 2D calculations have determined temperature distribution in the vessel
- METCOR correlations have been used for determining vessel steel ablation kinetics and its maximum value; ablation effect has a stronger influence at the homogeneous pool configuration
- 2D calculations of the stress-and-strain vessel condition have determined the value of internal pressure, at which the vessel fails with and without corrosion
- Vessel steel corrosion has been found not to have any significant influence on the vessel strength, because the unaffected external ‘cold’ layer of steel takes all load
- The developed methodology can be applied for the analysis of other accident scenarios and reactor vessels.