International Science and Technology Center

Progress Report on the Project # 2936

Modelling of Reactor Core Behaviour under Severe Accident Conditions. Melt Formation, Relocation and Evolution of Molten Pool

(Reactor Core Melting)

Presented by
M.S. Veshchunov (IBRAE)

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Forschungszentrum Dresden-Rossendorf (FZD)
Institute of Safety Research
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I S T C

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General Information

IBRAE

Leading Institution:	**IBRAE,** Moscow (Nuclear Safety Institute of Russian Academy of Sciences)
Duration: Commencement:	**3 years** **August 2004**
Total cost:	**$ 200 000**

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Non-CIS Collaborators

IBRAE

CEA	Commisariat à l'Energie Atomique	France Cadarache
FZK	Forschungszentrum Karlsruhe GmbH	Germany Karlsruhe
FZR	Forschungszentrum Rossendorf GmbH	Germany Rossendorf
IRSN	Institut de Radioprotection et de Sûreté Nucléaire	France Cadarache
ITU	European Commission Joint Research Centre Institut für Transurane	Germany Karlsruhe
KAERI	Korea Atomic Energy Research Institute	Korea Taejon

Organizational Structure and Managerial Responsibilities

Project Manager

Prof. M. Veshchunov

Laboratory for Condensed Matter Theory (IBRAE)

(Head: Prof. M. Veshchunov)

Tasks 1-5

Laboratory for Computational Heat and Hydrodynamics (IBRAE)

(Head: Dr. V. Chudanov)

Tasks 6-8

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Project Objectives

IBRAE

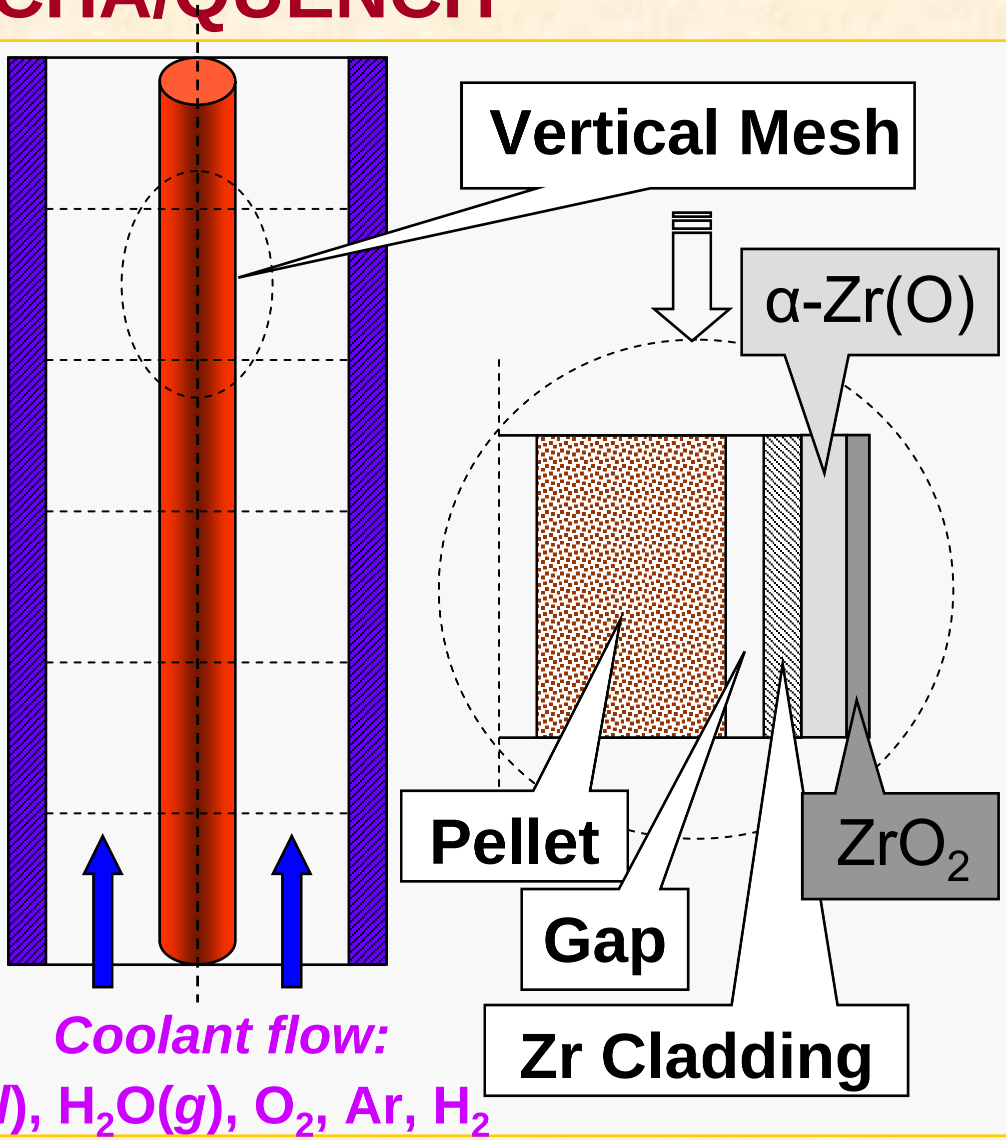
On the base of detailed analysis of available and new experimental data, to update, improve and verify models on reactor core molten materials behaviour at consecutive stages of a severe accident:

- from the early stage, when melt formation and progression during core degradation occur (**SVECHA/MELT** code),
- to the late stage, when the core is completely degraded and a molten pool is formed in lower head of the PRV (**CONV** code),

and to prepare them for benchmarking of simplified models and for implementation in the existing SA system codes

Single Rod Code SVECHA/QUENCH

- **SVECHA/QUENCH** code simulates fuel rod behaviour under severe accident conditions.
- Fuel rod is divided into a number of meshes along axial and radial directions.
- Mesh contains **UO_2** fuel pellet and the multilayered oxidized **Zr** cladding.

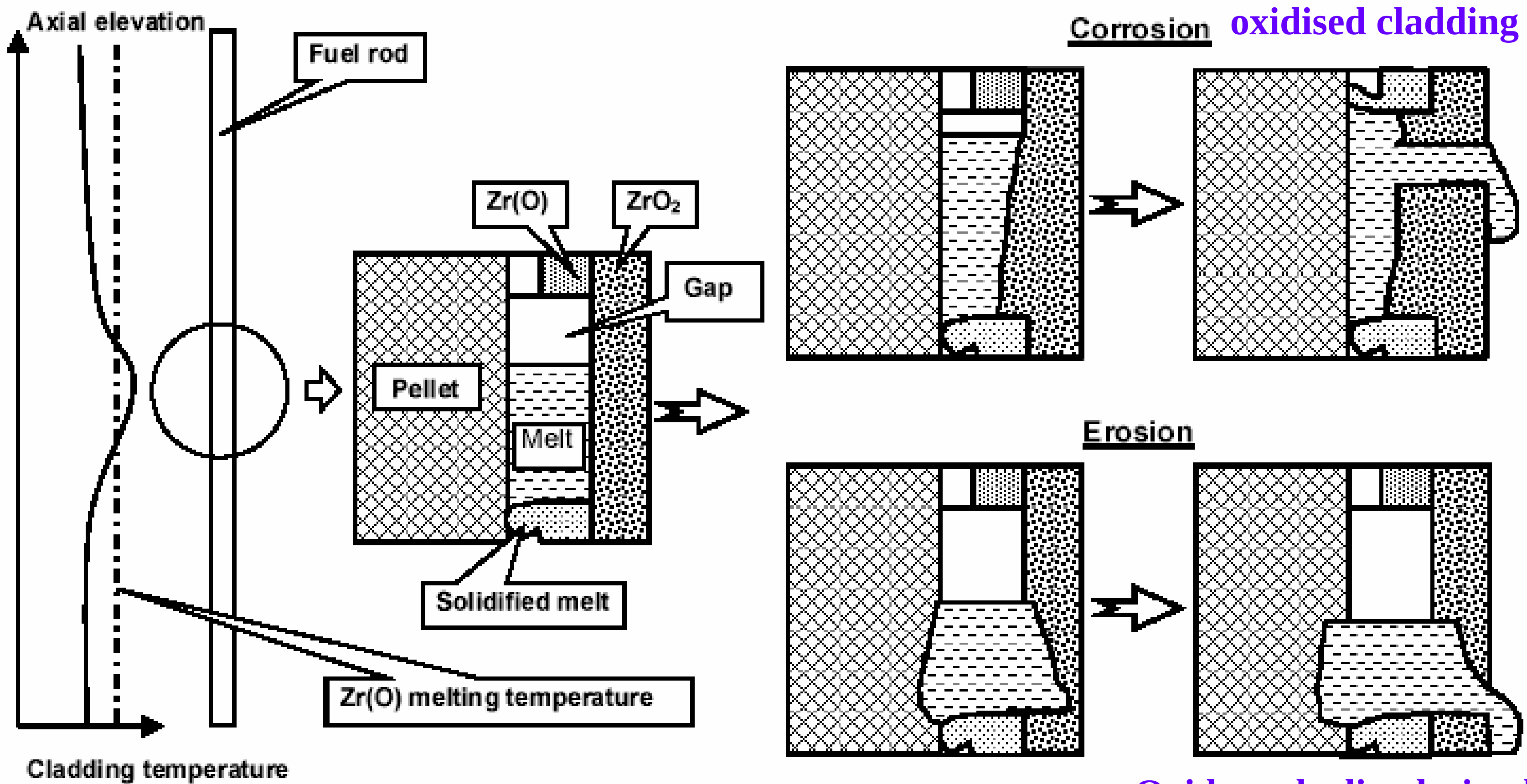


SVECHA/MELT Code Development

- **SVECHA/QUENCH structure optimization:** main driver program structure was simplified and optimized
- Development / improvement and implementation in the **SVECHA/MELT** code models for :
  - simultaneous dissolution of the fuel rod cladding oxide scale ZrO_2 and UO_2 pellet by molten Zr;
  - cladding breach formation;
  - release of U-Zr-O mixture from the cladding breach;
  - various regimes of melt slumping (droplets, rivulets, slug);
  - oxidation of relocating U-Zr-O melt.

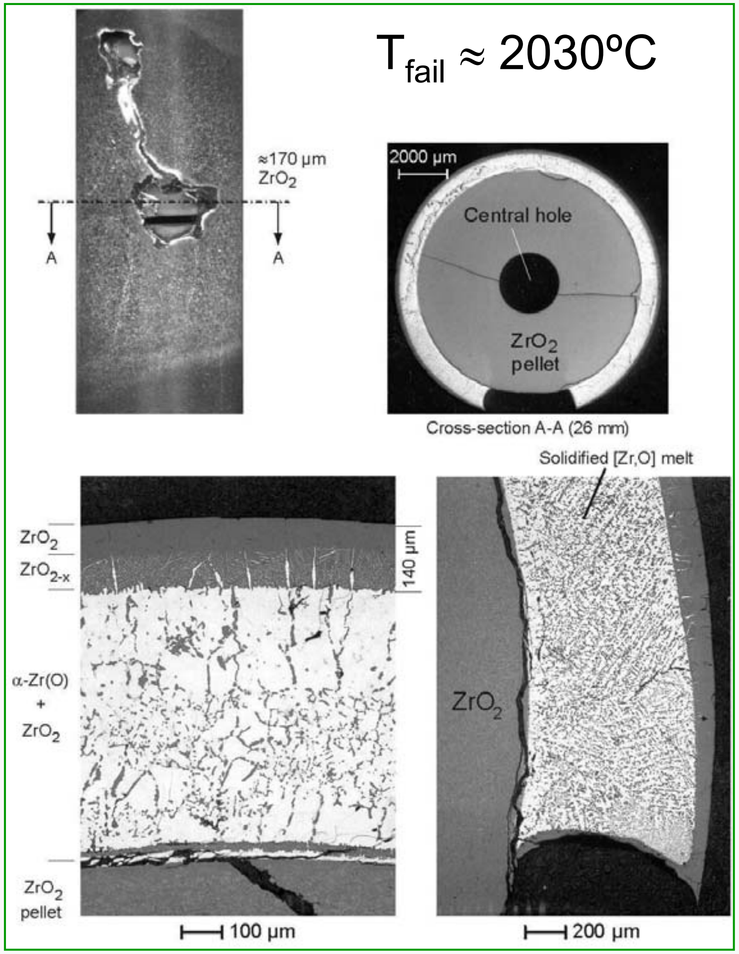
Failure Criteria of SVECHA Code

Gap vanishing owing to volumetric expansion of oxidised cladding

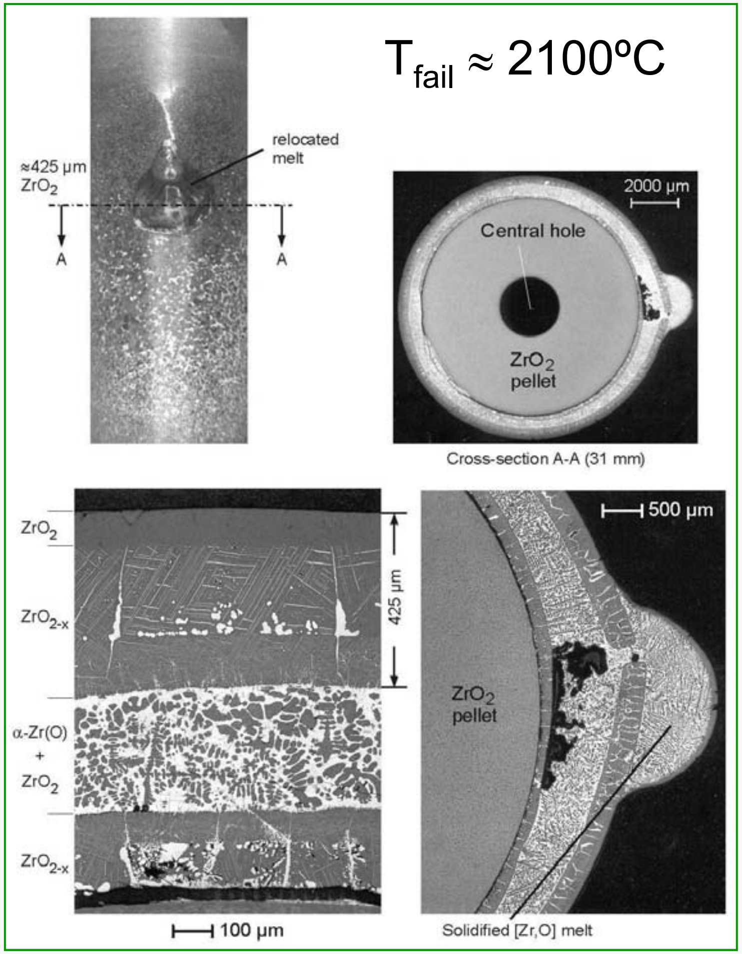


Oxide scale dissolution by metallic melt

Cladding Oxide Shell Failure in FZK Tests



High heat-up rate: 8 °C/s

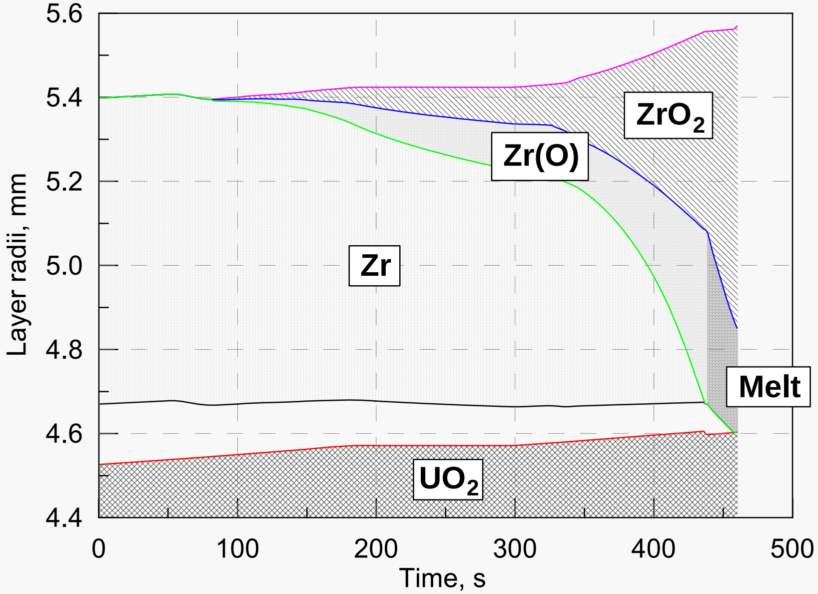


Low heat-up rate: 4 °C/s

Validation of SVECHA Failure Criteria against FZK tests

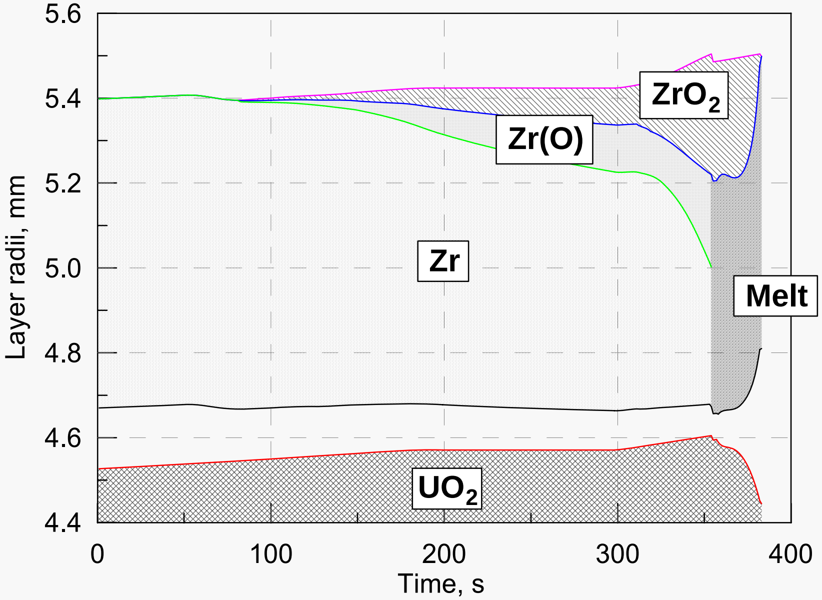
Evolution of oxidised cladding layers up to oxide shell failure

dT/dt = 4 K/c



«corrosion» mechanism
(volumetric expansion and gap vanishing)

dT/dt = 10 K/c



«erosion» mechanism
(dissolution of oxide shell)

Model for Release of U-Zr-O Mixture from the Cladding Breach

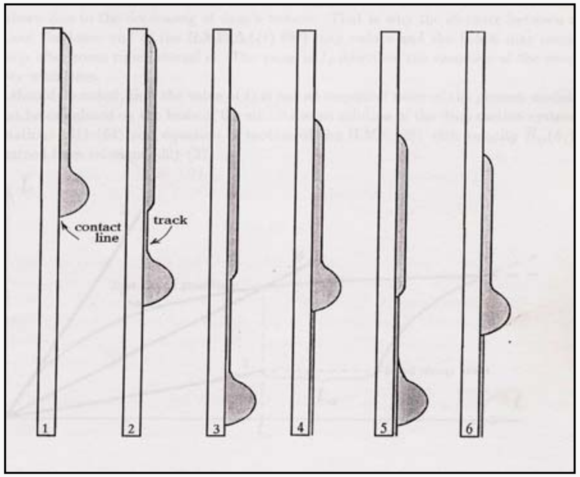
- Model key parameters
  - Initial dimensions of a liquid element appearing at the rod surface: volume V_{in} , width ω , thickness h
  - Capillary length: $a_c = \left(\frac{\sigma}{\rho g} \right)^{1/2}$
  - First critical volume: $V_{c1} \propto \left(\frac{\sigma}{\rho g} \right)^{3/2}$
  - Second critical volume: $V_{c2} \propto \left(\frac{\sigma}{\rho U^2} \right)^{3} \approx (3 \div 5) \cdot V_{c1}$
- Flow regimes

  depending on relation between *initial dimensions* of liquid element and *capillary length* and *critical volumes* :
  - no flow
  - separate drops formation
  - rivulet formation
  - mixed drop/rivulet flow

Candling Model

Physical mechanisms:

- ✓ capillary effects (contact angle hysteresis, contact line resistance to displacement, wetting of the fuel rod surface);
- ✓ viscous effects (viscous drag force, laminar/turbulent regimes);
- ✓ heat exchange influence (melting/solidification process, temperature dependence of viscosity, surface tension).

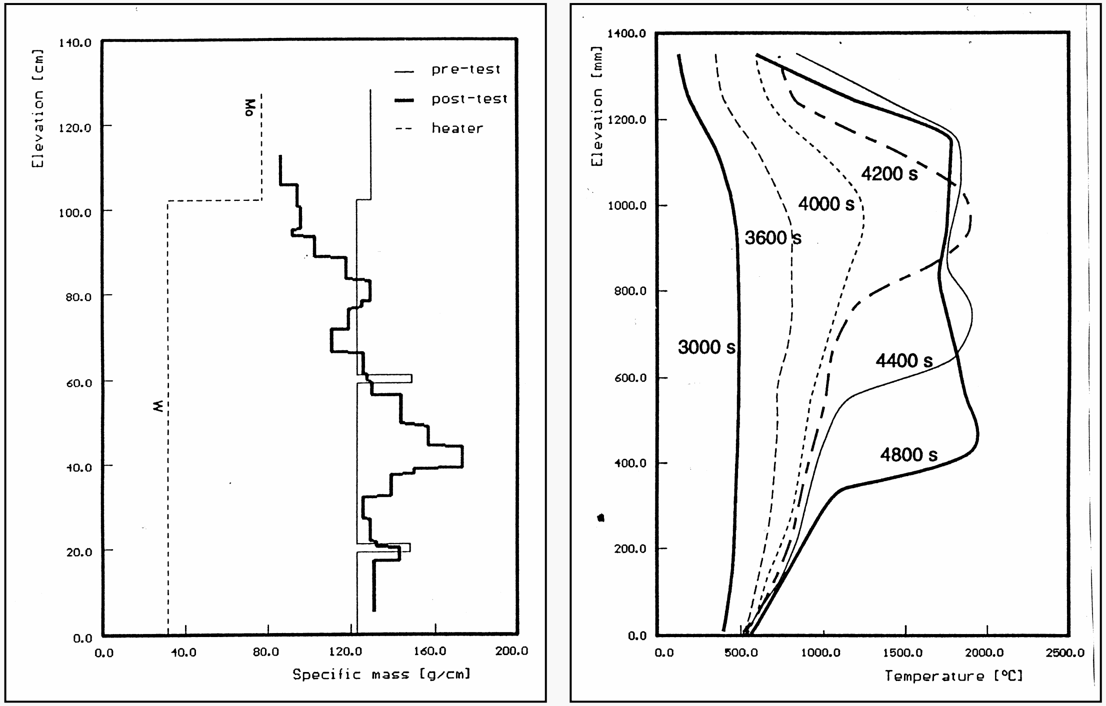


Relocation regimes:

- various types of downward flow (drops, rivulets of different length, films);
- transient processes (drop-rivulet transitions);
- non-stationary heat exchange of the liquid mixture with arbitrary temperature distribution along the fuel rod.

The model also describes the gap candling process - flowing down inside the gap formed by cylindrical structures (cladding/fuel pellet).

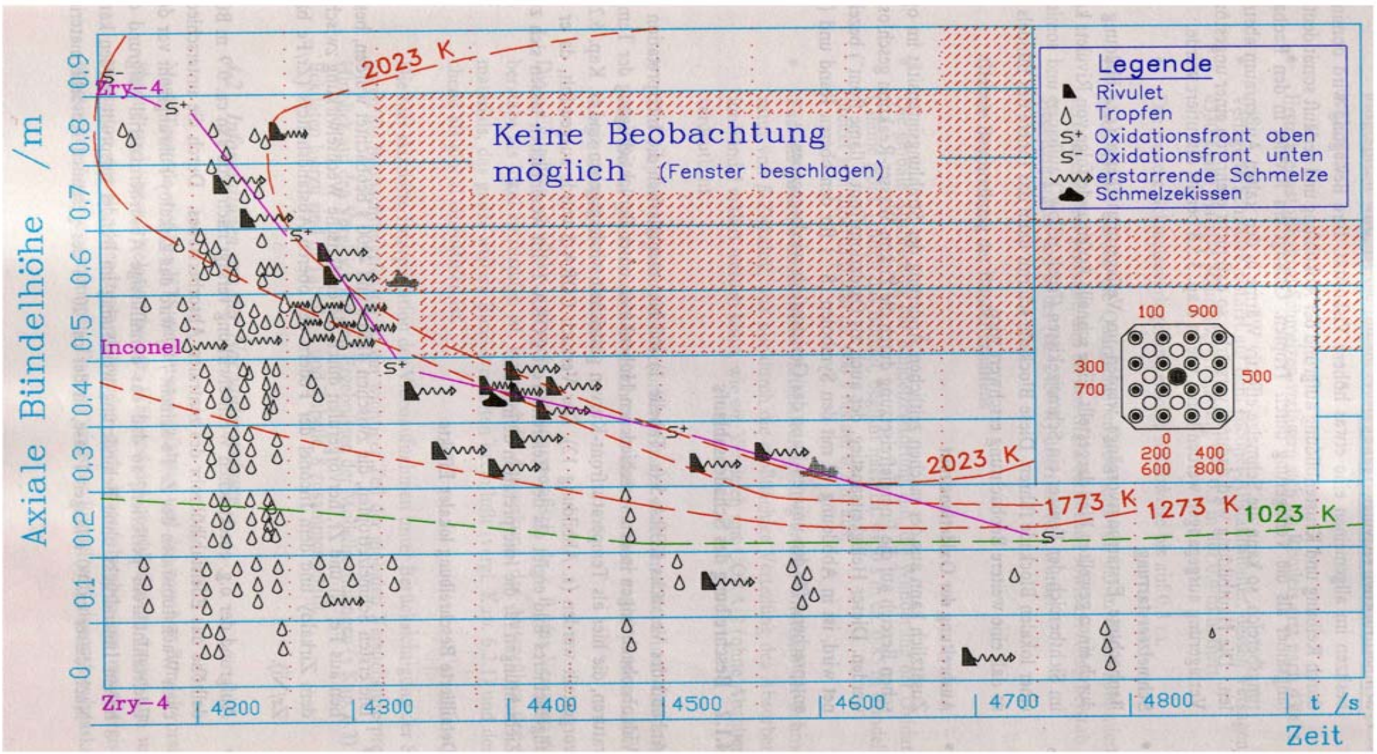
Slug Relocation Model



Axial mass distribution after the test and axial temperature distribution during the transient phase of the FZK bundle test CORA-W1 (from *S.Hagen, P.Hofmann, V.Noack, G.Schanz, G.Schumacher and L.Sepold*, Test Results of Experiment CORA W1, KfK 5212, 1994)

High and low temperature regions observed at t > 4200 *s* are separated by a rather pronounced temperature front. This front relocates downward with a characteristic velocity 1-2 *mm/s* which is extremely small in comparison with the velocities of rivulets and droplets (0.5 *m/s*).

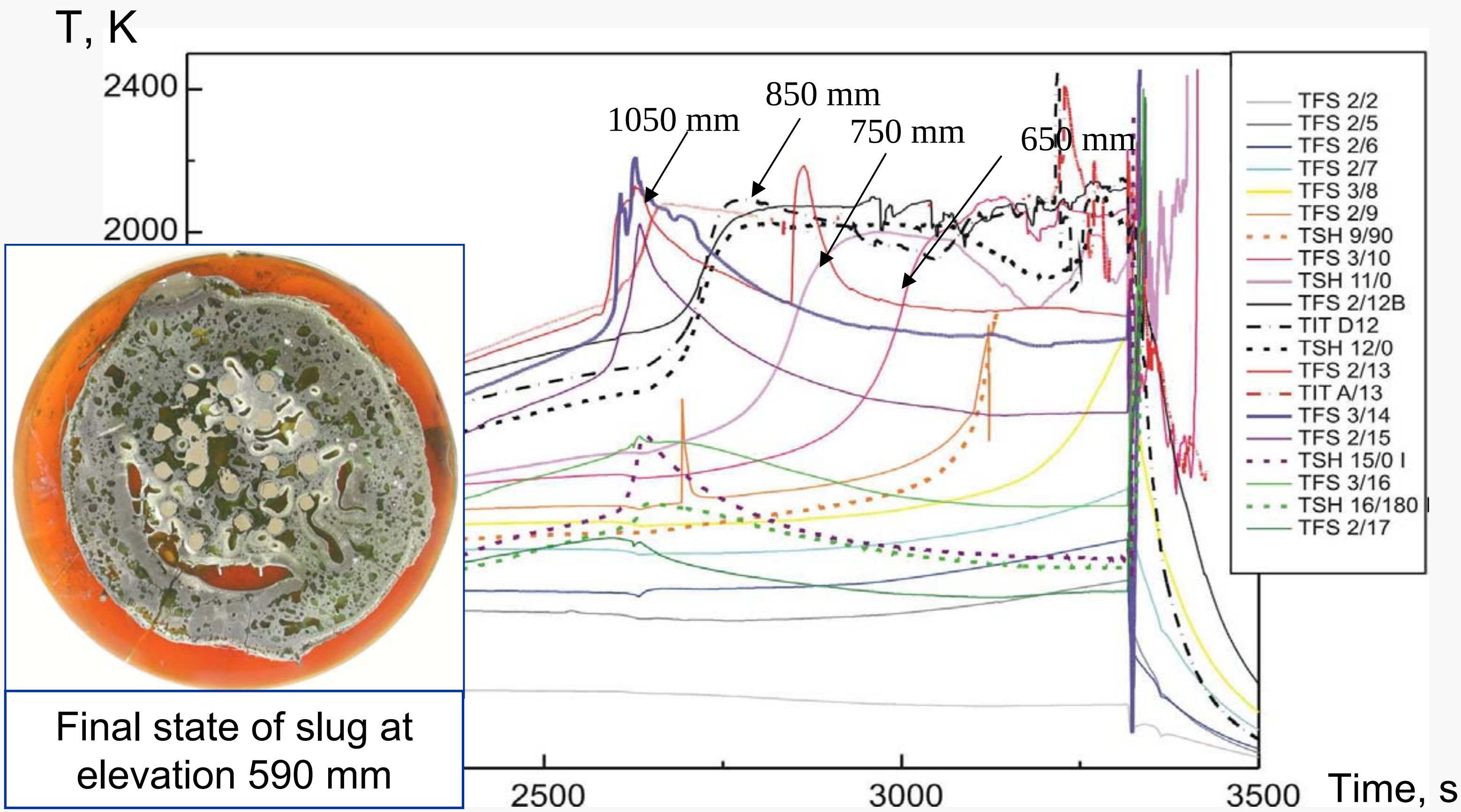
Progression of “flame” and “droplets/rivulets” fronts



Analysis of on-line video inspections in CORA-5 test

(W. Hering, FZK, thesis)

Progression of temperature front during melt relocation in Q-09 test



Final state of slug at elevation 590 mm

Temperature evolution at various elevations before quenching.

Estimated velocity of relocation front: ≈ 1mm/s

Main conclusions from tests observations

- Temperature front with T≈2000ºC in CORA tests relocated downward with a characteristic velocity $v_1 \sim$ 1-2 mm/s, which was extremely small in comparison with the characteristic velocities of metal rivulets and droplets ($v_2 \sim 0.5$ m/s)
- A similar melt progression ($v_1 \sim$1mm/s) apparently took place in QUENCH-09 test
- Oxidation front (or "flamefront") in CORA tests relocated coherently either with a "droplet/rivulets front" or with Zr melting isotherm, i.e. fairly associated with the melt progression front

Phenomenology of slug relocation

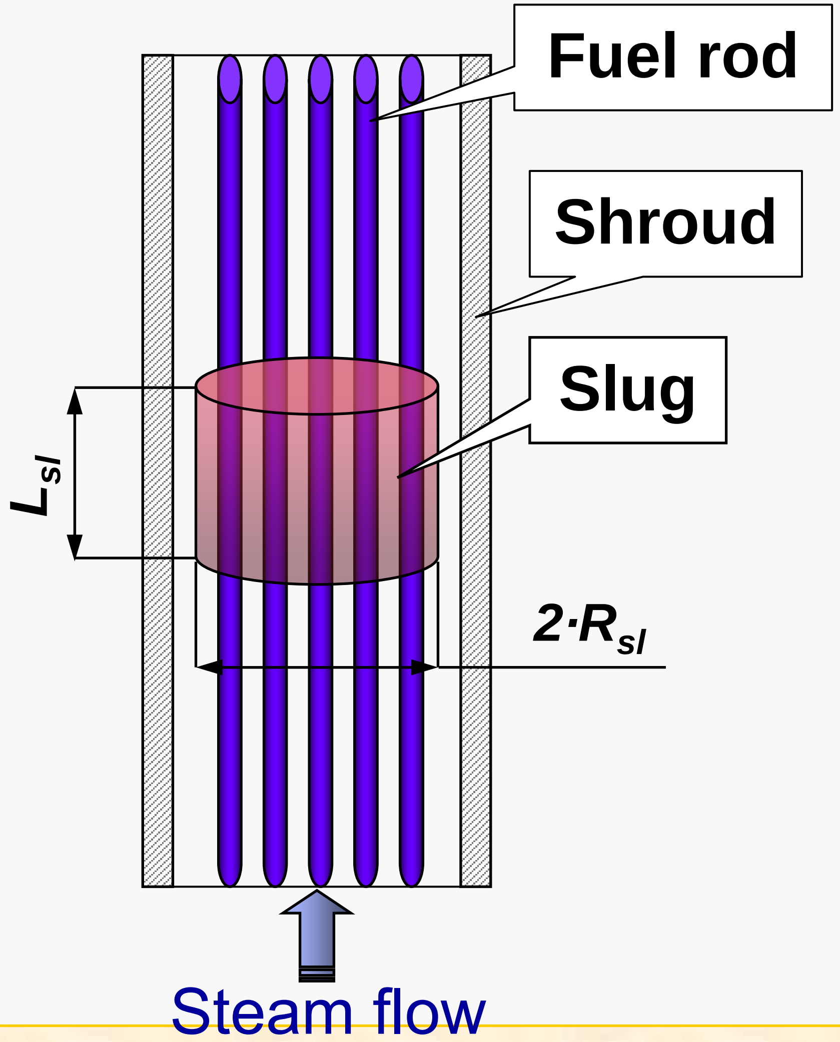
- ✓ During slow downward propagation of the slug, it accumulates fresh portions of melting cladding, extensively oxidizes and simultaneously dissolves UO_2 pellets and ZrO_2 scales of the claddings.

- ✓ Oxide crust formed at the progression front (due to steam interaction), has to prevent slug from further relocation. However, mechanical instability of thin oxide crust (supporting massive slug) results in its local breaching and rapid downward relocations of droplets and rivulets, their refreezing and accumulation at lower (and cooler) elevations, oxidation and formation of a new crust, until it fails again (at some critical thickness), and so on. This provides slow stepwise motion of the slug front and intensive oxidation of fresh relocated portions of melt at the front, represented in the new model (after time averaging) as continuous motion of slug front with the *critical oxide crust thickness* (as adjusting model parameter, estimated as ~100 μm).

- ✓ Heat flux matches at the slug front determine front relocation velocity (Stefan problem). For adequate solution of the heat exchange problem a model for molten pool (slug) oxidation/dissolution has been developed.

Slug model

- Melt blockage (pool) is modeled as a **cylindrical pool** with the vertical length - L_{sl} and radius - R_{sl} .
- Molten pool is in contact with ***N*** **fuel rods**.
- Slug consists of the **main (liquid) part** and a **crust** scale at lower surface



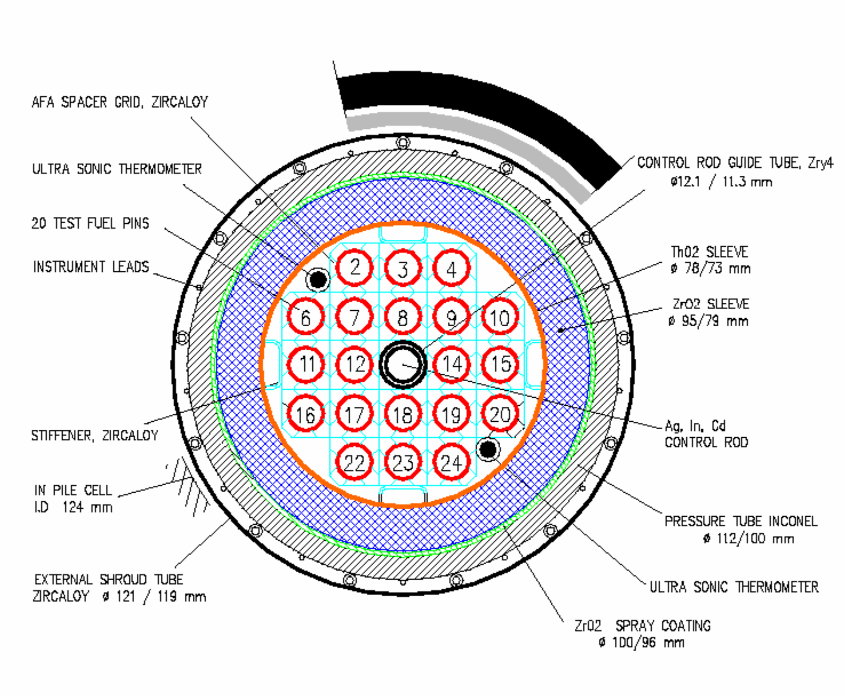
Slug module implementation in the SVECHA/MELT code

The main points of slug module:

- **Conditions of a melt blockage** formation control and first call initialization of a slug behaviour (when the total volume of the melt exceeds the critical minimal value for a blockage formation and the conditions for melt release are fulfilled).
- **Heat exchange** with surroundings (fuel rods, shroud, gas phase) are provided by the heat exchange and gas dynamics modules coupled with the slug module on a global time step.
- Interface with the **dissolution-oxidation** module at the local time step of calculations
- Local **time step** adjusting and iteration procedure **convergence** check-up
- The **melt properties** (enthalpy, density, specific heat capacity, thermal conductivity) are determined using MATPRO data base

Simulation of melt oxidation and fuel dissolution in molten pool (slug)

"Effective" fuel rod approach



Horizontal cross section of FPT1 test bundle

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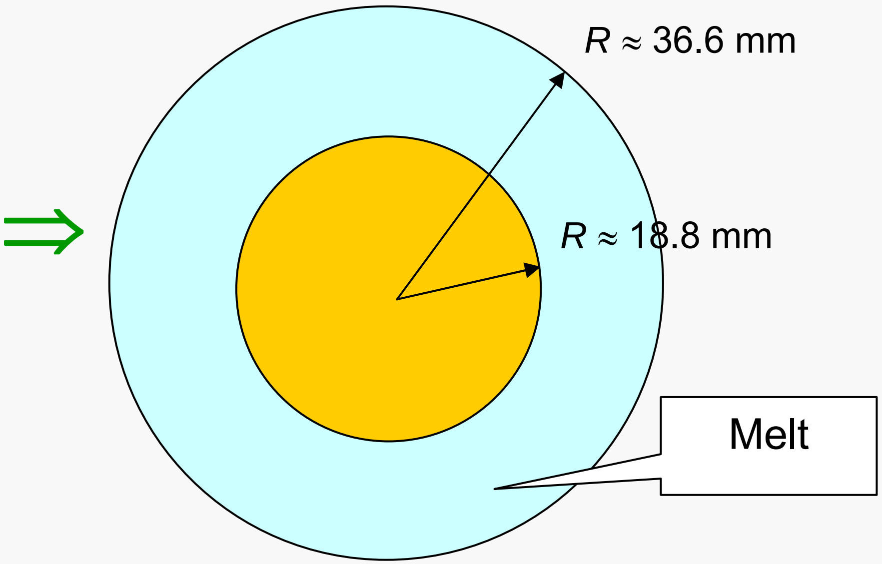
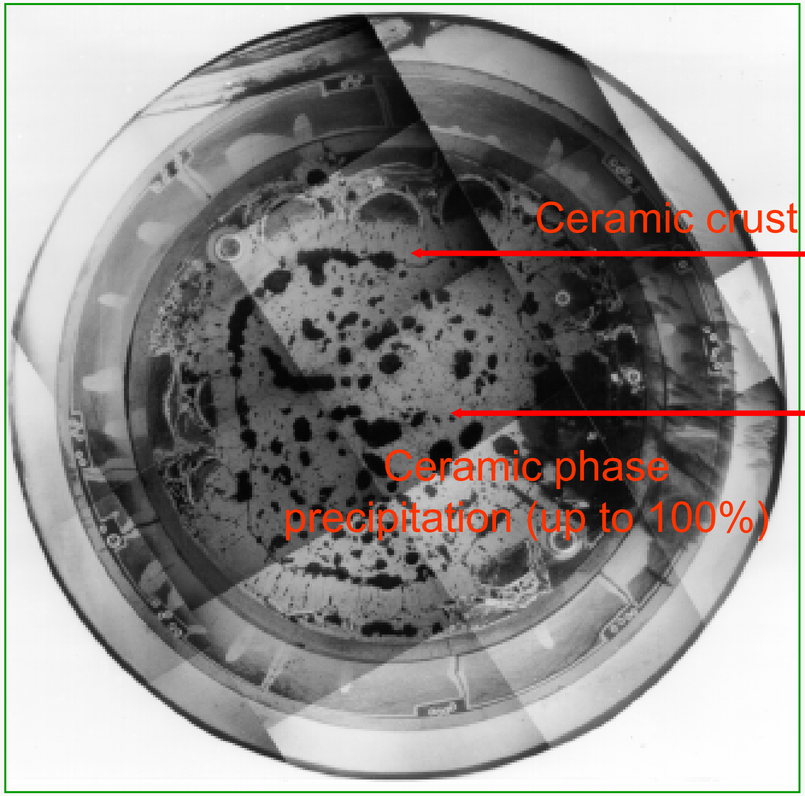


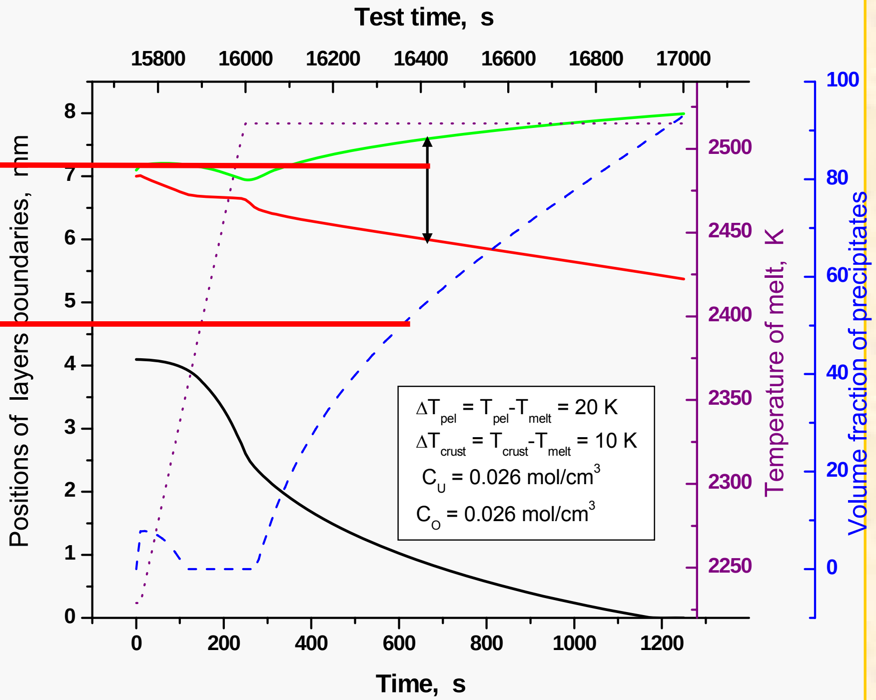
Horizontal cross section of MP with "effective" fuel rod

2-d Molten Pool Oxidation Model
(Mass Transfer)

Intensive dissolution of fuel rods and oxidation of molten pool up to complete conversion into ceramic phase



Post-test macrograph of $(U,Zr)O_2$ ceramic corium (molten pool)



Evolution of molten pool layers during transient

2-d Molten Pool Oxidation Model

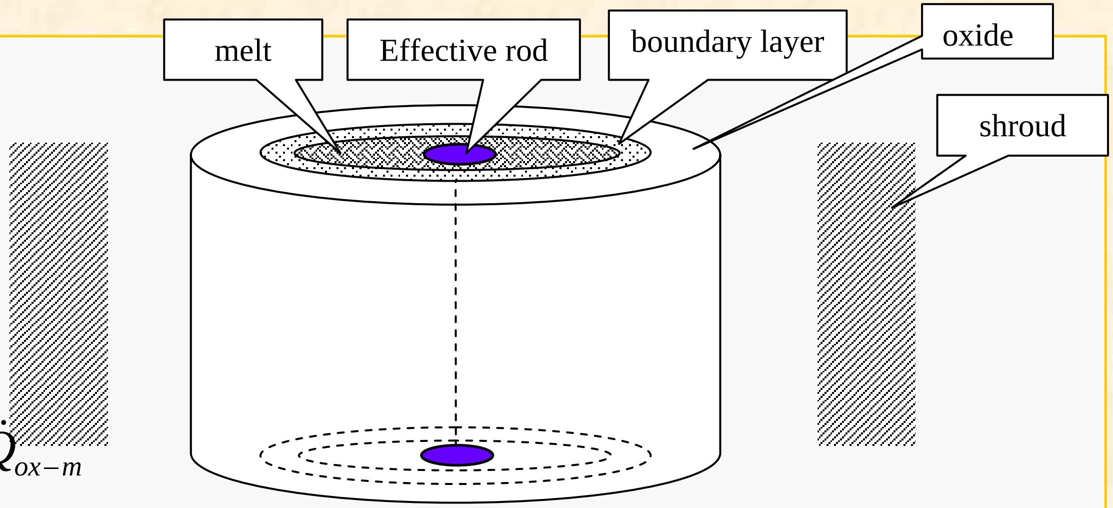
(Heat Transfer)

Heat flux matches:

(at 2 interfaces of oxide layer)

$$h\left(T_{ox}-T_s\right)-\frac{\lambda_{ox}\left(T_{\text{int}}-T_{ox}\right)}{\delta_{ox}}=\dot{Q}_{ox-g}$$

$$\frac{\lambda_{liq}\left(T_{\text{int}}-T_{mp}\right)}{2R_{mp}}Nu+\frac{\lambda_{ox}\left(T_{\text{int}}-T_{ox}\right)}{\delta_{ox}}=\dot{Q}_{ox-m}$$

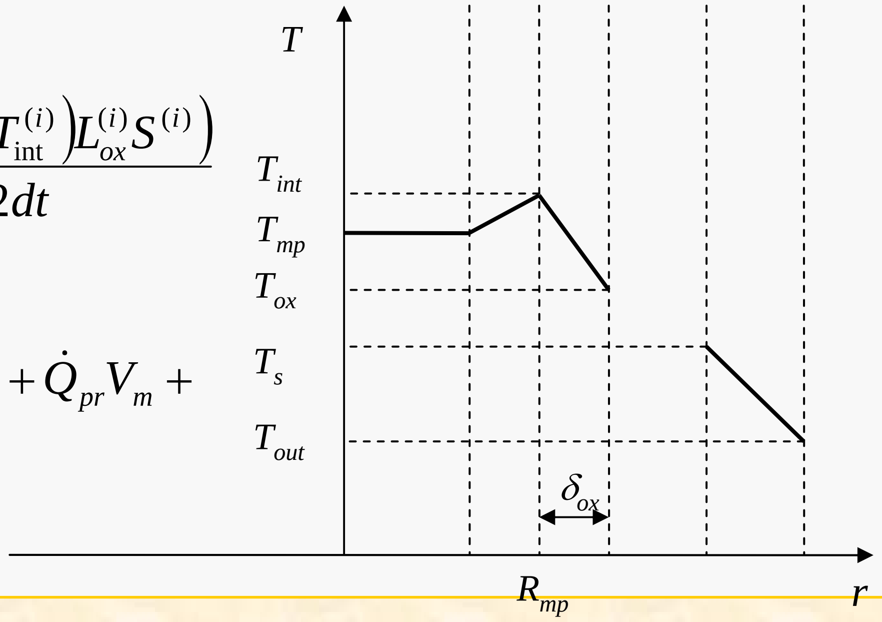


Heat balance:

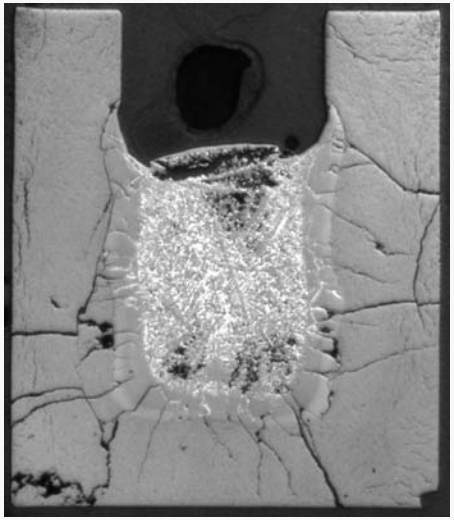
$$\rho_m C_m \frac{d\left(T_{mp}V_m\right)}{dt}+\rho_{ox}C_{ox}\sum_{i=r,up,low}\frac{d\left(\left(T_{ox}^{(i)}+T_{\text{int}}^{(i)}\right)L_{ox}^{(i)}S^{(i)}\right)}{2dt}$$

$$+\rho_{rod}C_{rod}\frac{d\left(T_{rod}V_{rod}\right)}{dt}=\dot{Q}_{fis}^{(m)}V_m+\dot{Q}_{fis}^{(ox)}V_{ox}+\dot{Q}_{pr}V_m+$$

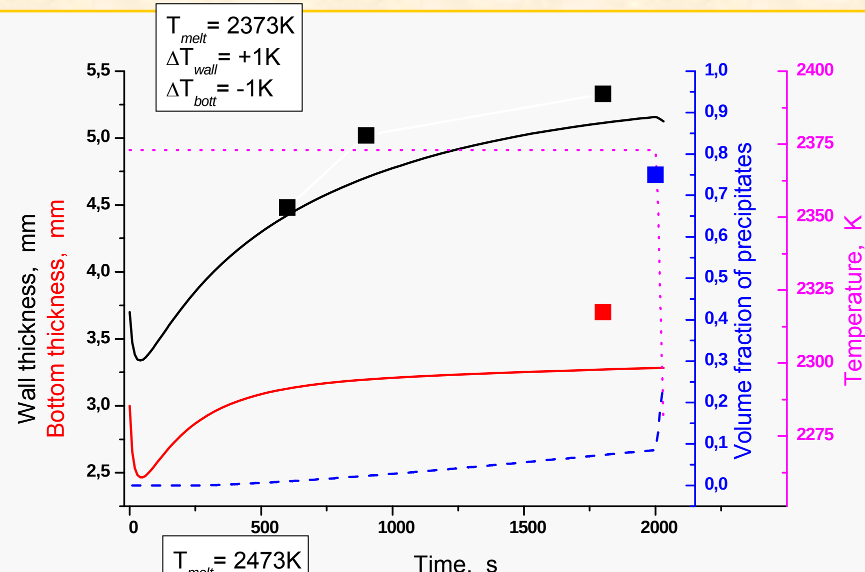
$$+\sum_{i=r,up,low}\dot{Q}_{ox}^{(i)}S^{(i)}-\sum_{i=r,up,low}h\left(T_{ox}^{(i)}-T_s^{(i)}\right),$$



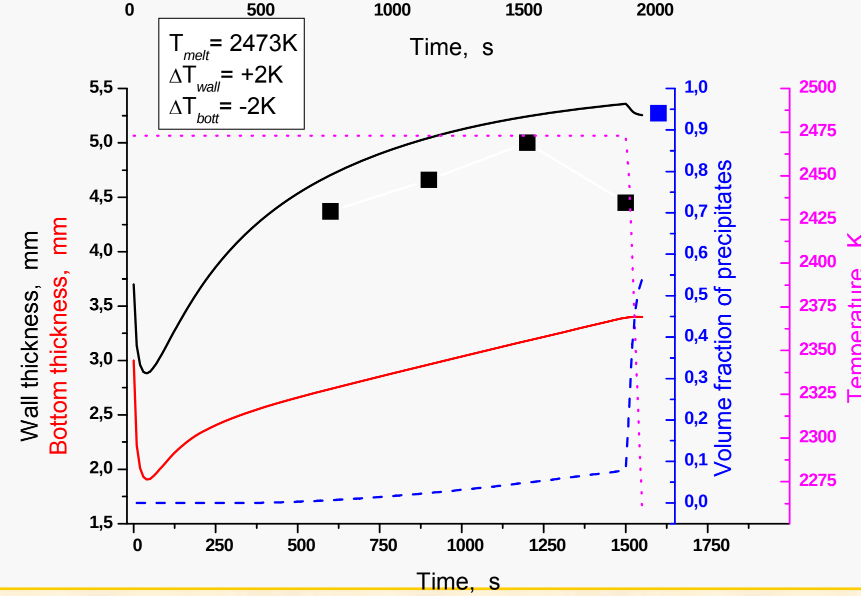
Validation of 2-d MP oxidation model against short-term FZK crucible tests



10 min.

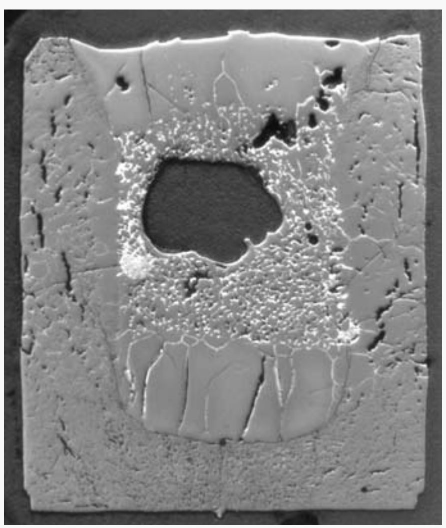


20 min.

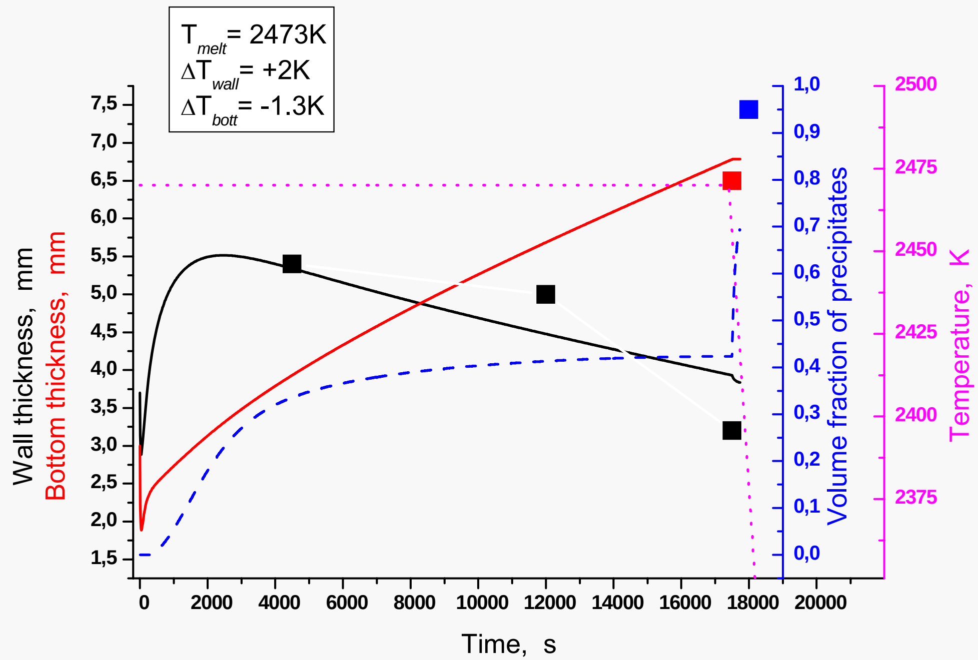


Validation of 2-d MP oxidation model against long-term FZK crucible tests

200 min.

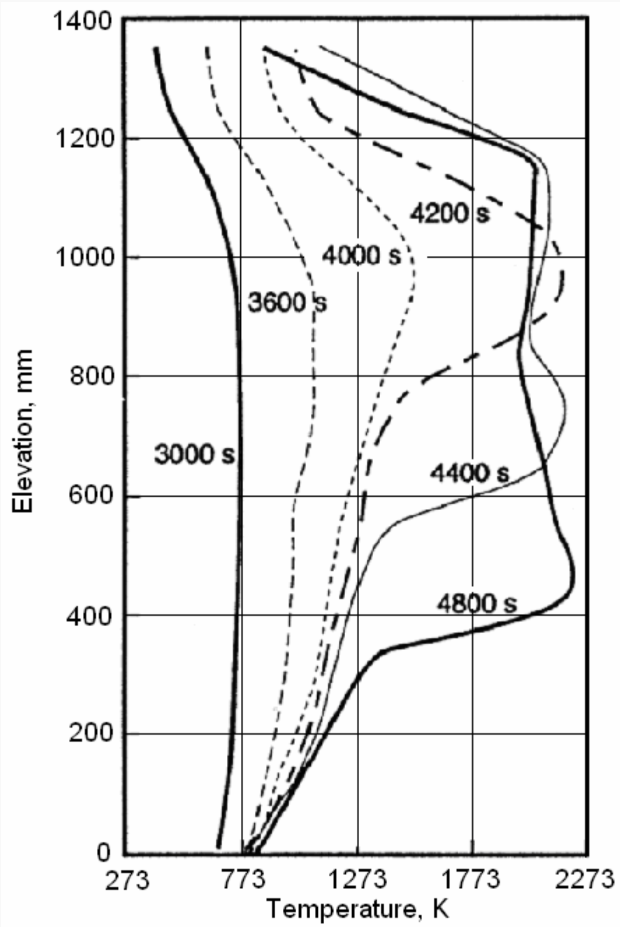


290 min.

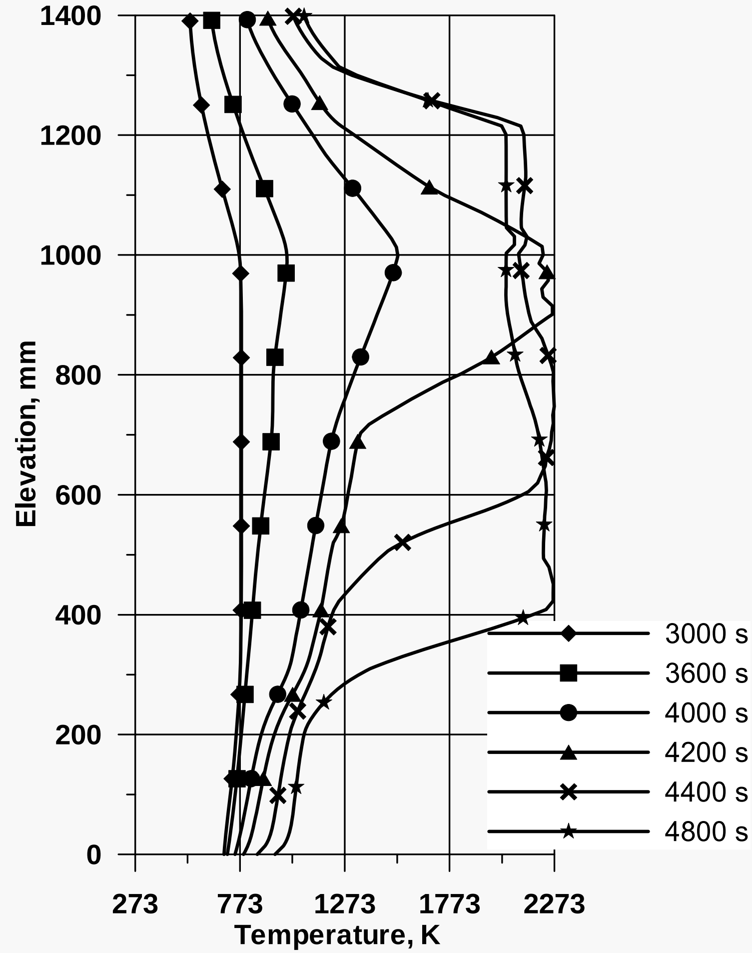


Conclusion: Oxide dissolution on “hot” lateral walls was accompanied with oxide growth on “cold” non-oxidized (!) free surface of melt (+ heavy precipitation in the melt)

Preliminary validation of the slug model against CORA-W1 test

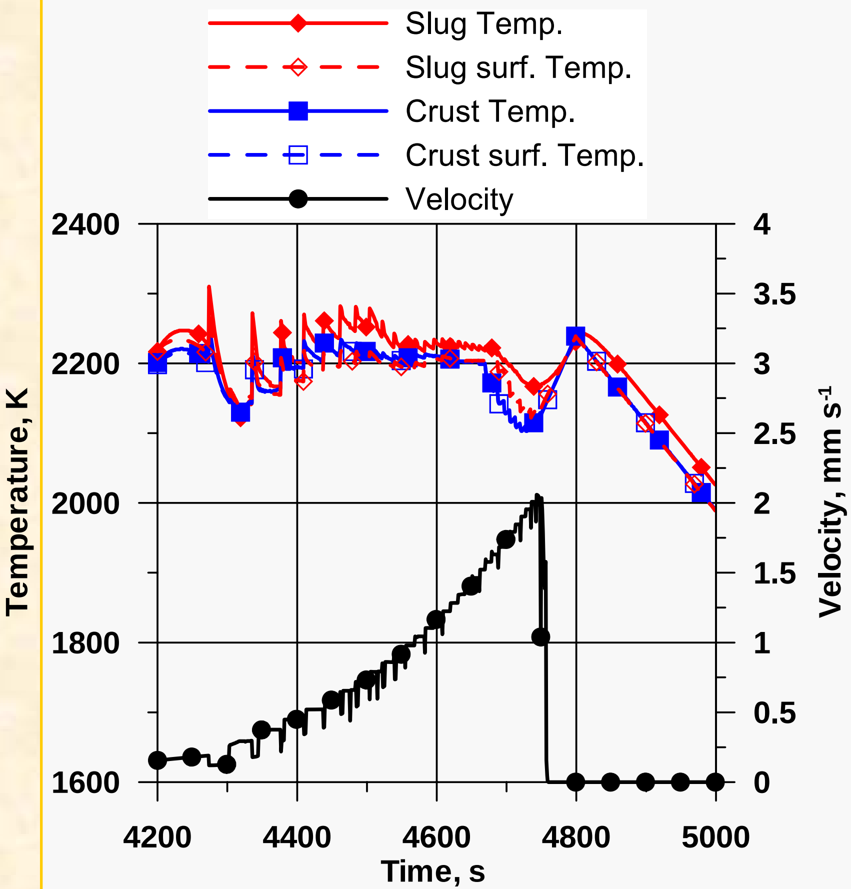


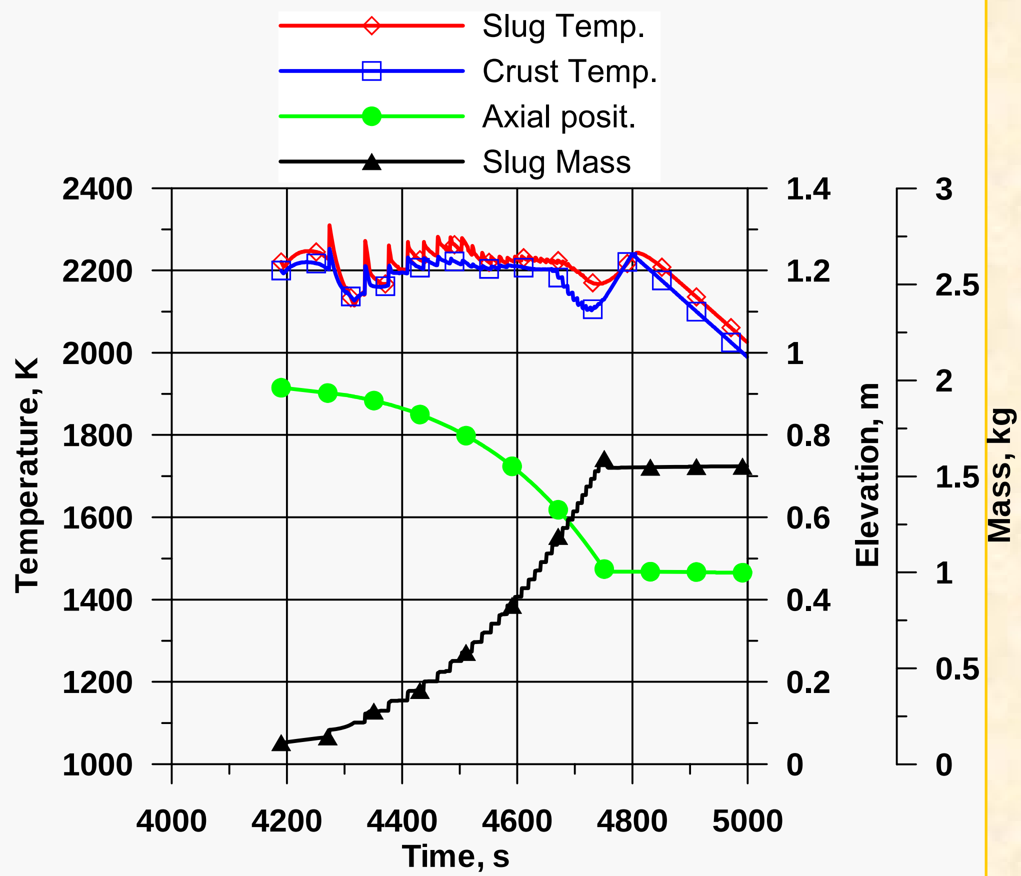
Measured evolution of temperature axial profile



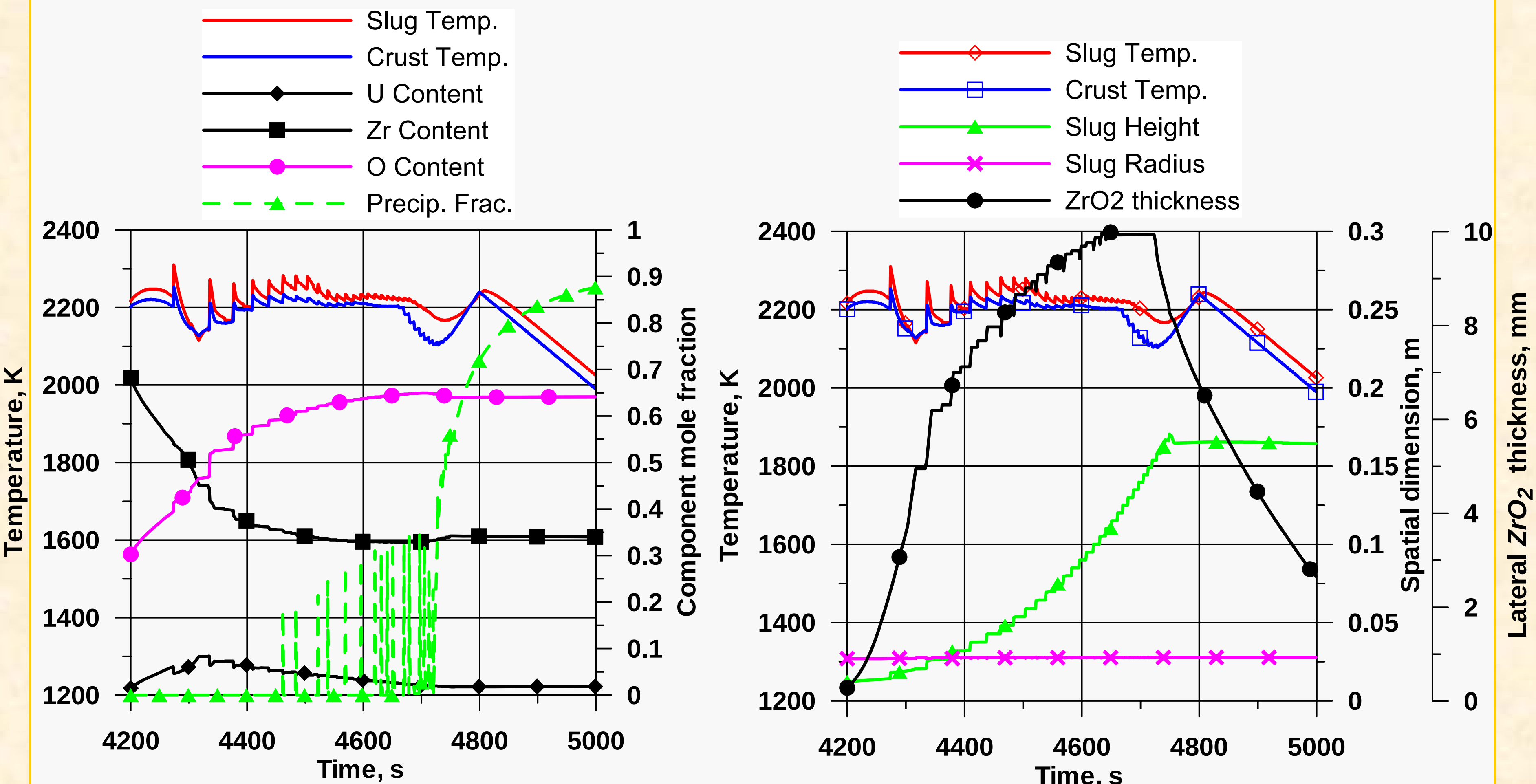
Fuel rod temperature vertical profile evolution ***emulated*** in calculations

Slug velocity and mass behaviour (simulation results)





Slug composition and geometry evolution (calculation results)



Final slug composition

Experimental measurements of material chemical composition at different locations at elevation 605 mm of the CORA-W2 test bundle

Element	Loc.1	Loc.2	Loc.3
O (at%)	66.7	65.1	66.3
Zr (at%)	25.4	27.3	25.3
U (at%)	7.1	7.6	8.4

Calculation results for final slug position at elevation 465 mm

Element	**Slug bulk**
O (at%)	63.0
Zr (at%)	34.0
U (at%)	3.0

Conclusions (slug model)

- Computer module simulating slug simultaneous relocation and oxidation was developed and implemented in the code SVECHA/MELT.
- The basic data relative to oxidation and dissolution (components mass flows) is provided by the melt oxidation / fuel dissolution module coupled with the slug relocation module on the local time step. The coupled module allows self-consistent calculation of the slug relocation velocity and thus gives the complete description of slug relocation and oxidation.
- Preliminary validation of the slug model was performed using experimental data of CORA-W1 and CORA-W2 tests. Calculations show the capabilities of the model to simulate main features of the massive blockage behaviour. The module is currently under extensive validation.

General Conclusions

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- In order to describe melt behaviour during initial stage of the SA, the following set of mechanistic models were revised and/or developed:
  - Model for simultaneous dissolution of UO_2 and ZrO_2 cladding shell by molten Zry;
  - Model for breach formation in oxidised cladding;
  - Model for release of U-Zr-O mixture from the cladding breach;
  - Candling model for melt slumping in the form of droplets and rivulets;
  - Model for oxidation of corium molten pool (MP);
  - Slug model for melt slumping in the form of massive MP.
- The models were thoroughly validated against available separate-effect tests and implemented in the single-rod code SVECHA/MELT (S/M).
- The S/M code was applied to interpretation of observations of melt behaviour in various bundle tests (CORA, QUENCH, PHEBUS FP) and used for further validation of the newly developed models.
- The work was carried out in tight connection with the SARNET Project and with substantial support of the European collaborators.