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Sensitivity study of SFP experiment with MELCOR 1.8.6 YV SFP

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- Experiment
- Nodalization
- Comparison with experimental results
- Calculated long term behaviour
- Summary

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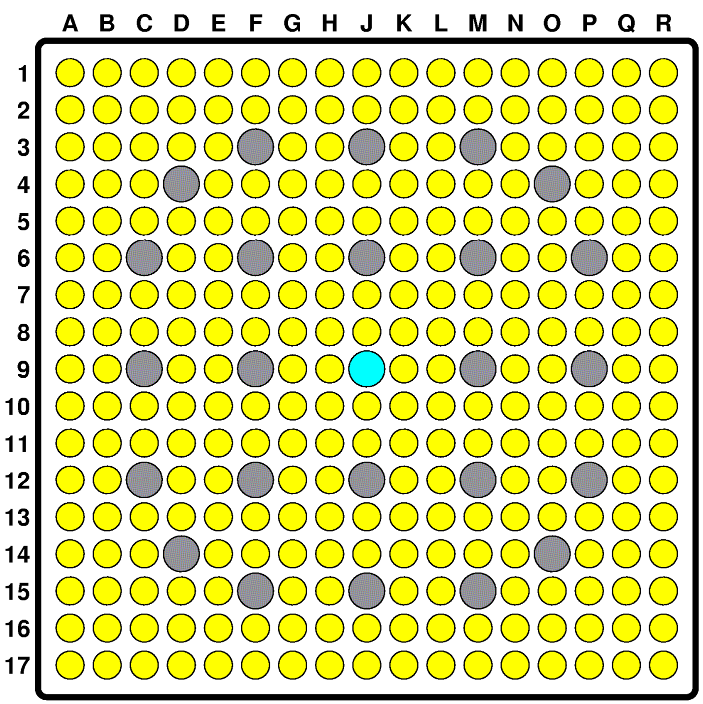
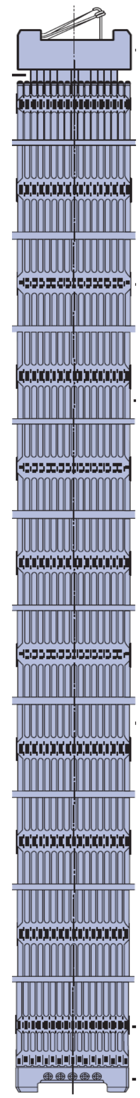
Experiment

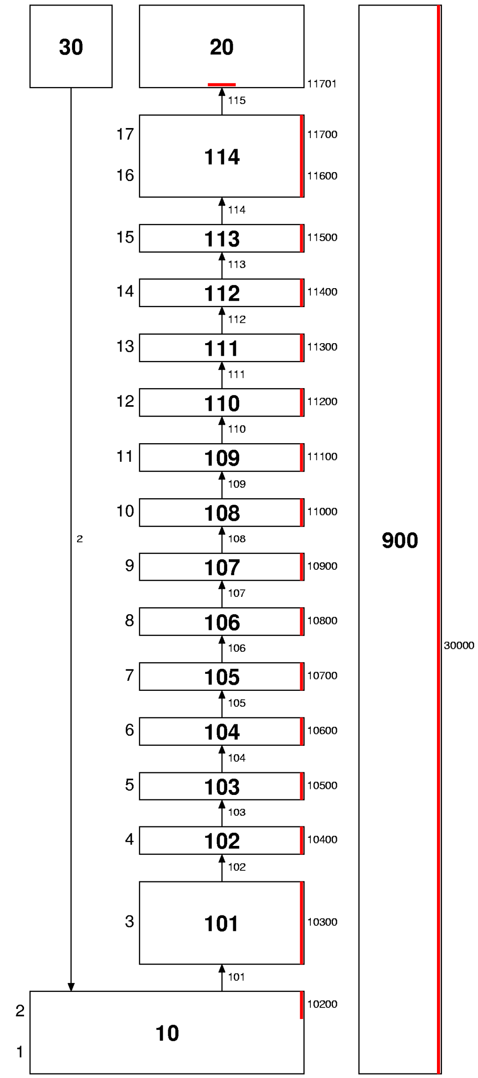
- Conducted at SANDIA National Laboratories
- 17 x 17 rods standard PWR fuel element
- Standard fuel pool storage cell
- Dry conditions
- Natural air convection
- Thermal behavior examined in pre tests

Nodalization I

Spent fuel rack with heater rods, guide tubes and 1 instrumentation tube

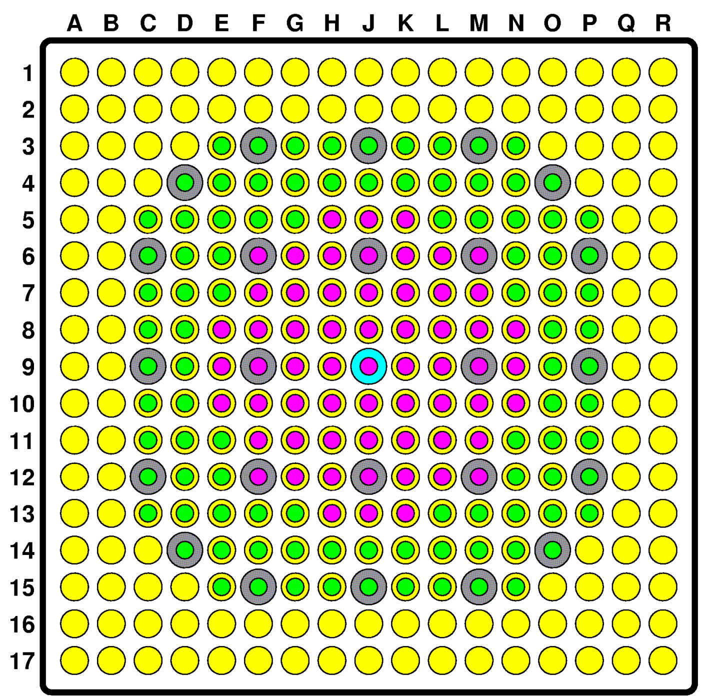


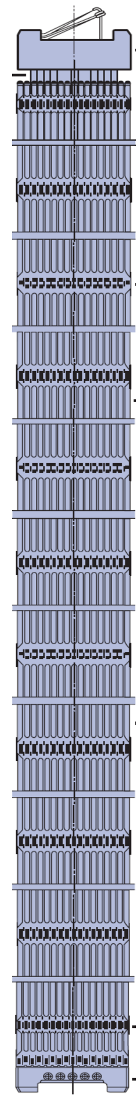


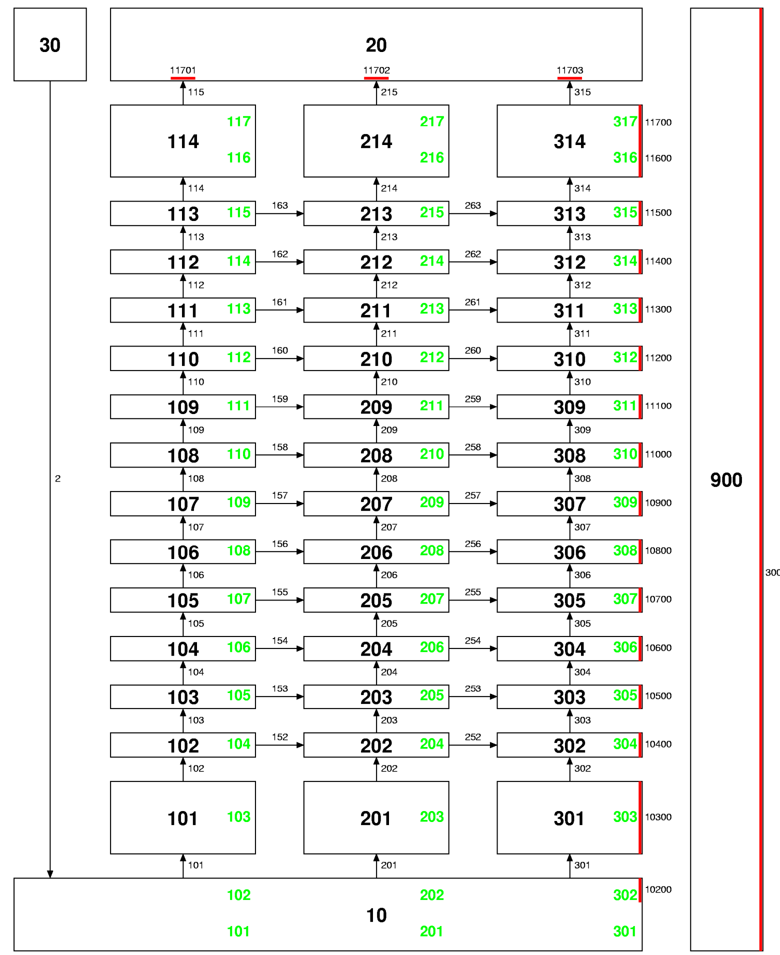


Nodalization II

Spent fuel rack with heater rods, guide tubes and 1 instrumentation tube







Boundary Conditions

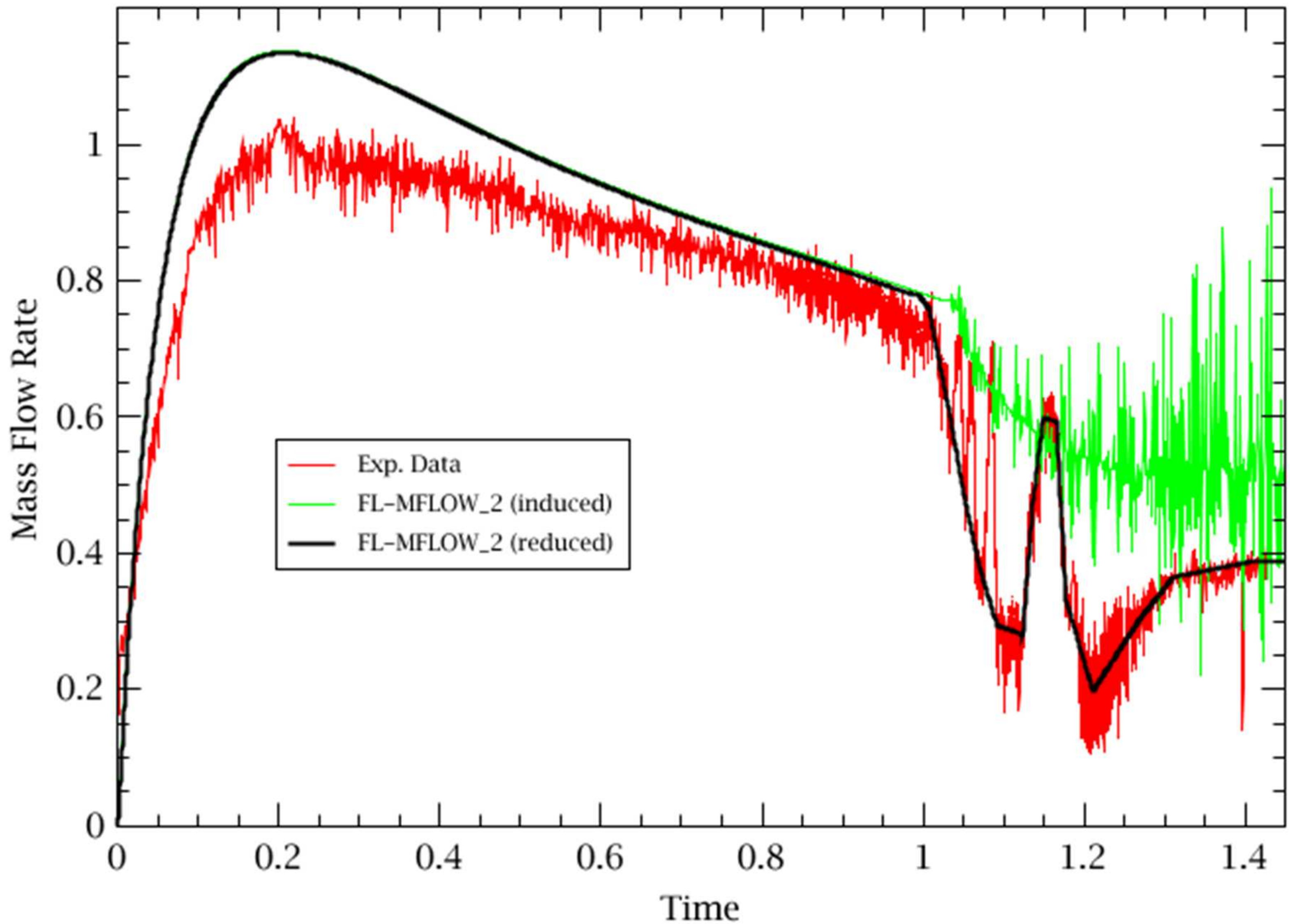
The induced flow rate using the thermal hydraulic boundary conditions (Σk and S_{lam}) was calculated to be higher than the measured at maximum by 12%. In the important time before reaching the ignition time the estimation of calculated and measured data was in better agreement.

The slope of the gas flow could not be properly reproduced by the calculation.

For the time after ignition relocation of broken oxide crusts or molten rack material influences the flow area and therefore the flow rate, so that for the final runs after this time a reduced mass flow was used (EDF file).

The power history showed several instabilities after first failure of heater rods for several minutes before it was switched off. It was modeled as constant power until failure conditions were reached.

Air Flow Rate



Air oxidation model

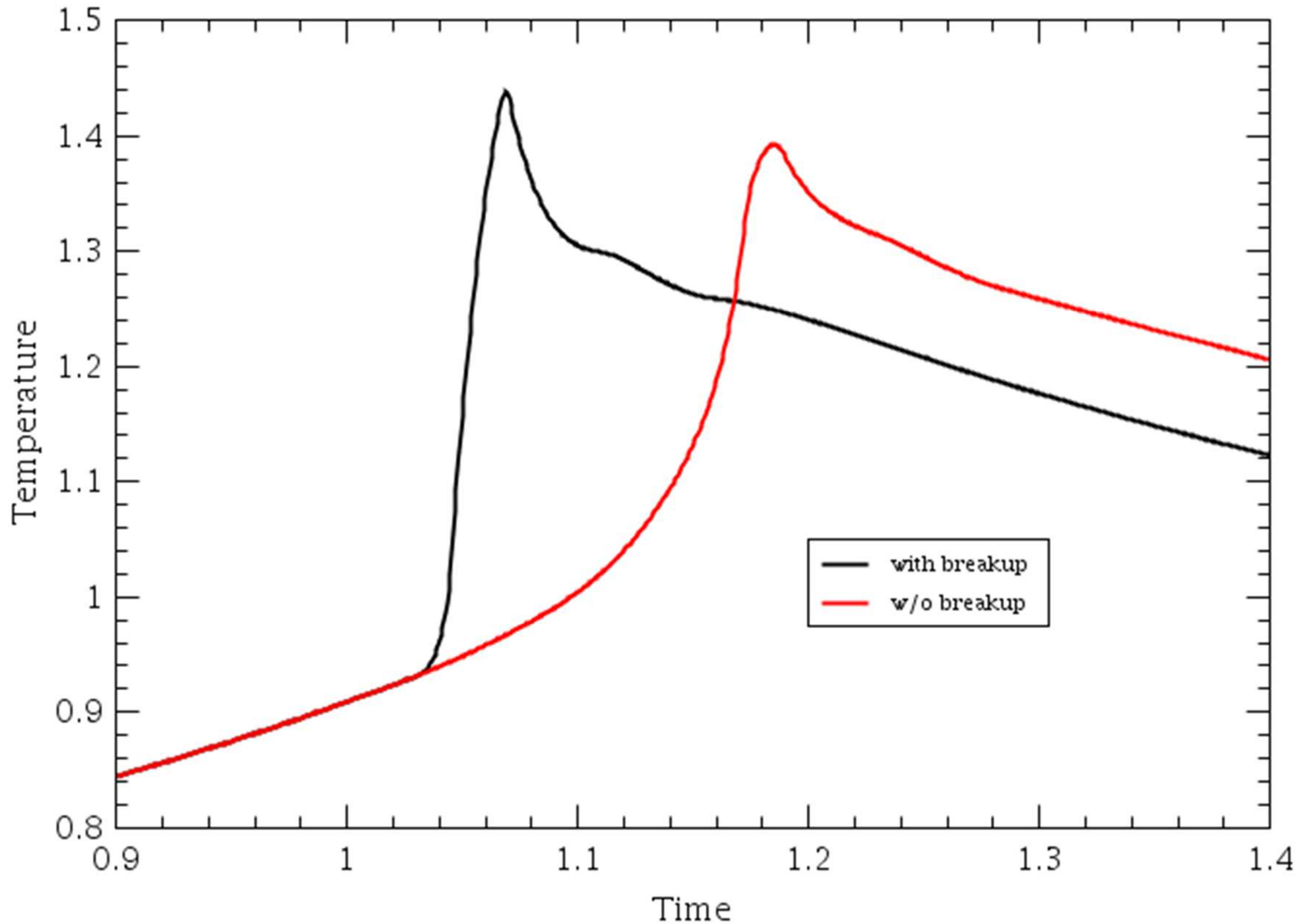
A simplified air oxidation model is coupled with a breakaway model in the MELCOR code produced for the SFP experimental programme.

Due to the production of high density zirconium nitrides cracks will form and fresh metal is offered to the oxidant (break away).
Separate effect test showed strong breakup of the oxidic crust under oxidation in pure air.

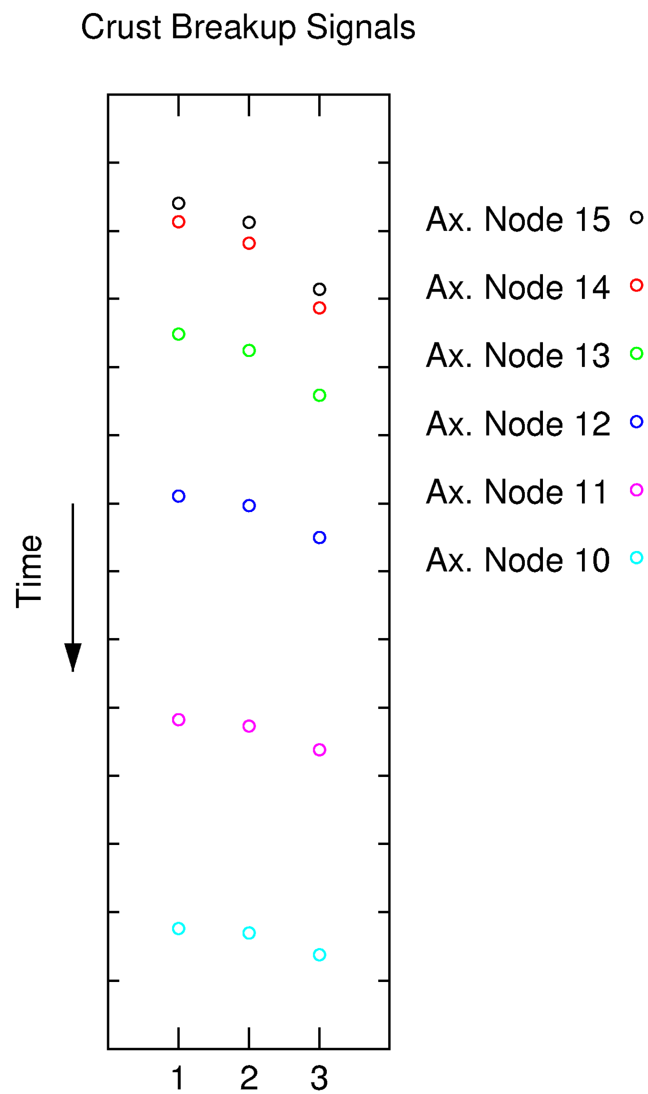
This leads to enhanced oxidation rates and therefore temperature excursion at the elevation of the breakup and following starvation of the oxidant.

Calculations showed clearly that the breakaway model is triggering the calculated ignition of the bundle.

Influence of breakaway model



Breakaway of Oxide crust



The crust breakup signals for the different radial nodes are the starting signals for the heatup leading to ignition of the zirconium fire. As can be seen, the ignition started in the upper region of the fuel element and then the zirconium fire propagates downward.

Breakaway model

SUBROUTINE OXBRK (TEMP, DT, SSLFR, TLEFT)	suppose temp = 1000 K (sslfr initially 0.0)
tr = -12.528*LOG10(TEMP) + 42.038	tr = 4.454 (< 20)
IF (TR .LT. 20.0) THEN	(tr = 0 if temp = 2267 K)
TR = 10.0**TR	tr = 28445 s
SSLFR = SSLFR + DT/TR	sslfr increment → 1.0 at t = 28445 s
ELSE	
TR = 10.0**20.0	never happens
END IF	
IF (SSLFR .LT. 1.0) THEN	
TLEFT = (1.0-SSLFR)*TR	some time left to breakaway
ELSE	
TLEFT = 0.0	no time left to breakaway
END IF	
.....	

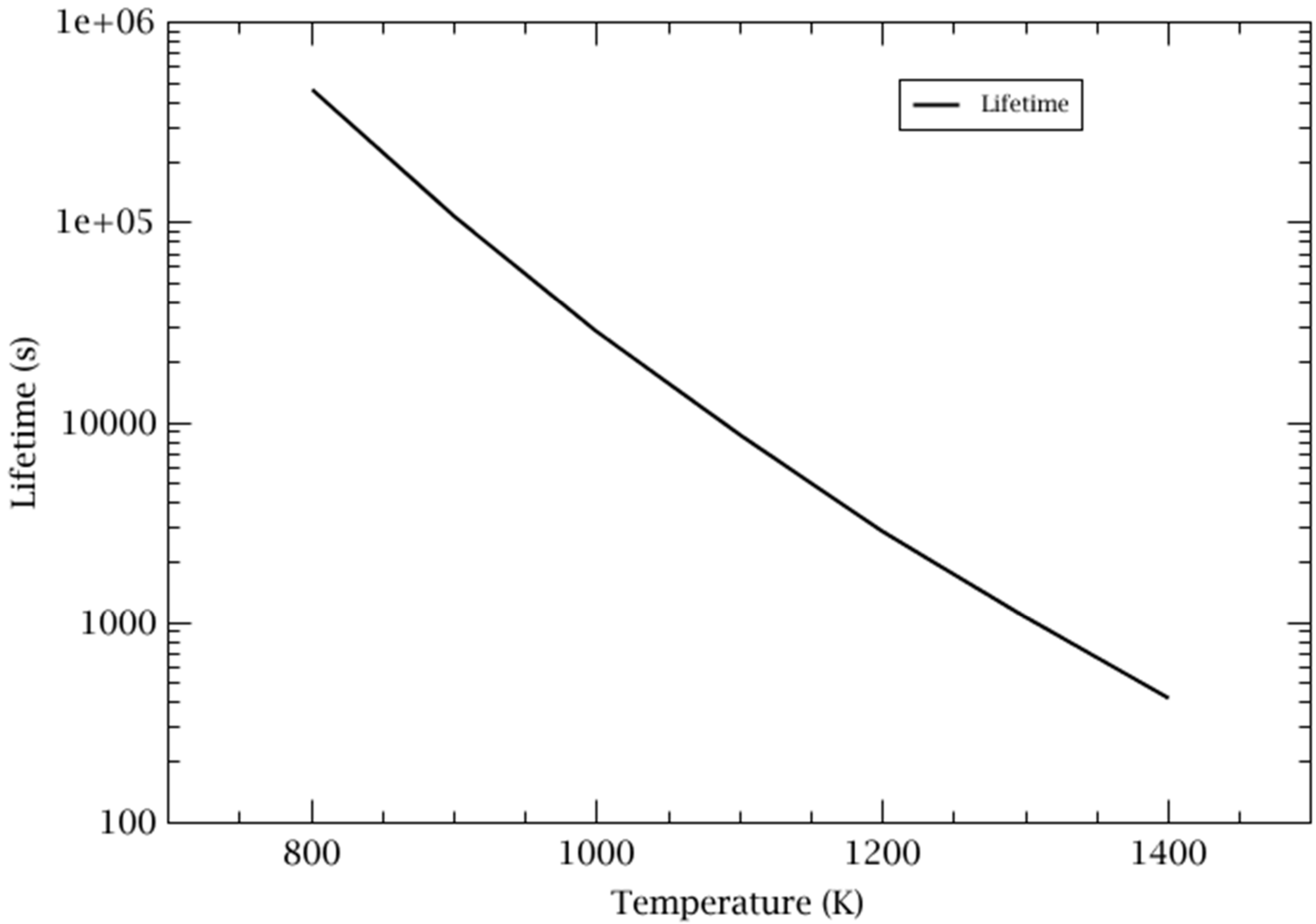
At constant temperature we can calculate lifetime from new

T =	800	900	1000	1100	1200	1300	1400
life(T) =	465682	106476	28445	8618	2897	1063	420

↑↑↑

We can see how the remaining life is used up quickly as T increases much above 1000

Lifetime dependency



A physical basis for the lifetime model?

SC1017 parameters (42.038, -12.528) determine lifetime = f(T)

- can be changed by input

They give the right time of ignition for SFP BWR and also OECD SFP-1

Does that means they are correct? Or that the cladding used in the two tests behave the same?

What is their physical significance?

Imagine changing the values slightly 42.038 → 41.5, say
then life(1000): 28445 s → 8241 s

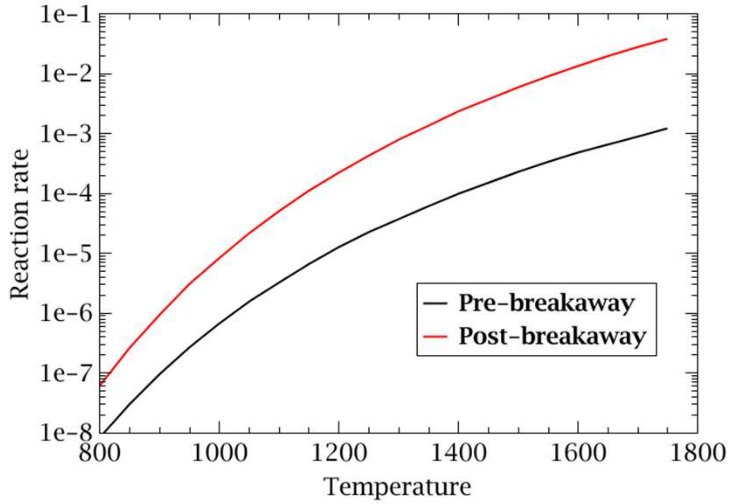
So life(T) is rather sensitive to the values

What else

- MELCOR default model is to apply model if oxygen is present
- breakaway is <u>no more likely</u> to occur in oxygen than steam
- it is the <u>nitrogen</u> that can trigger breakaway-type oxidation; <u>why no nitrogen dependence?</u>
- breakaway in <u>steam</u> is most likely at temperatures < 1300 K but not at higher temperatures
- it occurs earlier as the temperatures increase within that range

Pre- and post-breakaway kinetics in MELCOR

- Default values
- R = A * exp(-B/T) (kg-Zr^2 / m^{-4} s^{-1})
- Pre-breakaway (changed from previous versions)
- - A = 26.7 B = 17490.0 R = 1.25e-05 at 1200 K
- Post-breakaway
- - A = 2970.0 B = 19680.0 R = 2.24e-04 at 1200 K
- R increases by a factor of ca. 18



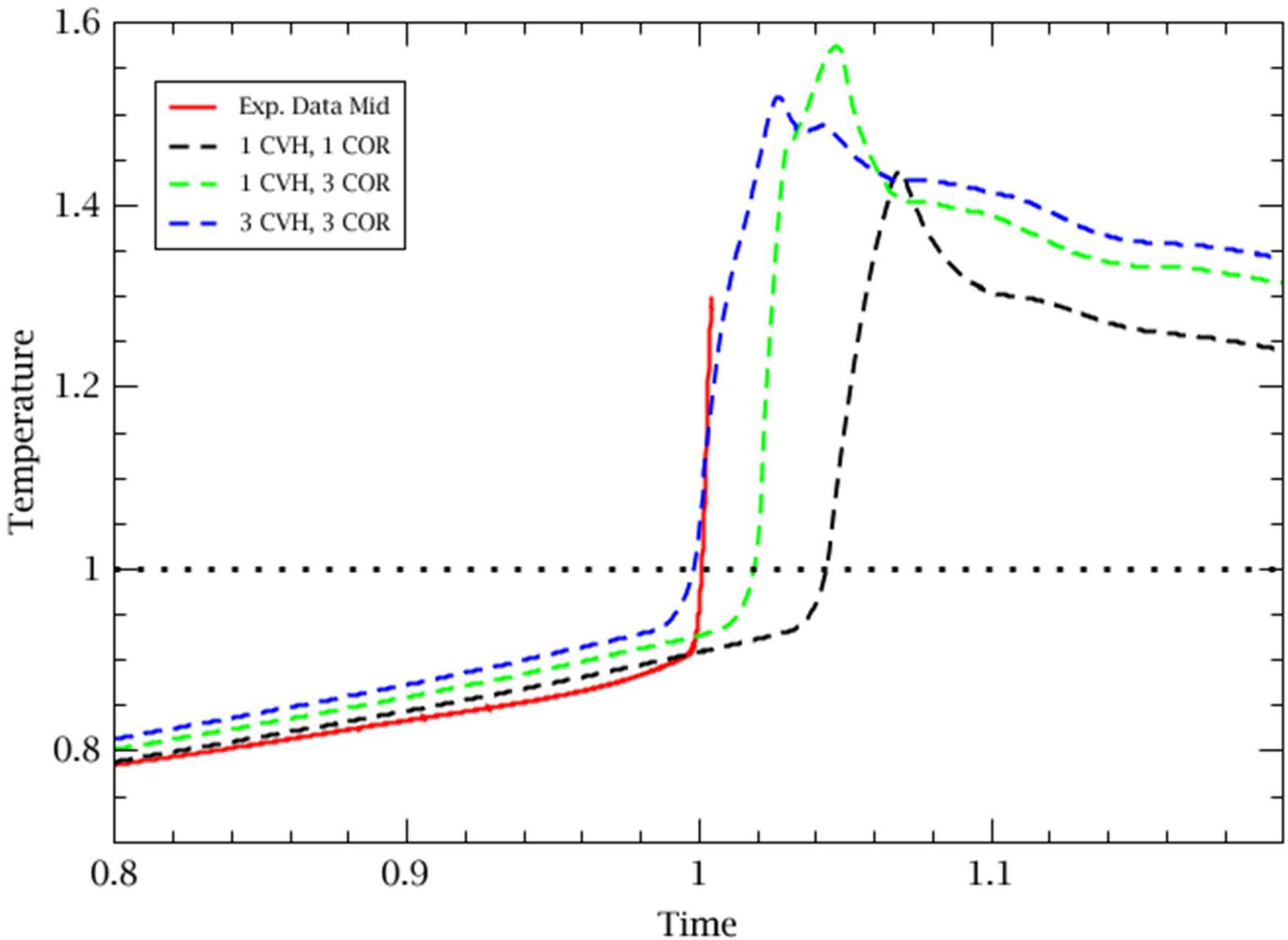
Influence of the geometrical modeling

3 different calculations were executed under the same thermal hydraulic boundary conditions

- In each axial zone only 1 radial core node and 1 control volume
- In each axial zone 3 radial core nodes but with a common control volume
- In each axial zone 3 core nodes and separate control volumes for each core node with cross flow modeled

The results showed different onset of breakaway and therefore different ignition times. This was expected because of higher temperatures in the center and lower temperatures in the outer region. The data are normalized on ignition conditions.

Modeling Sensitivity



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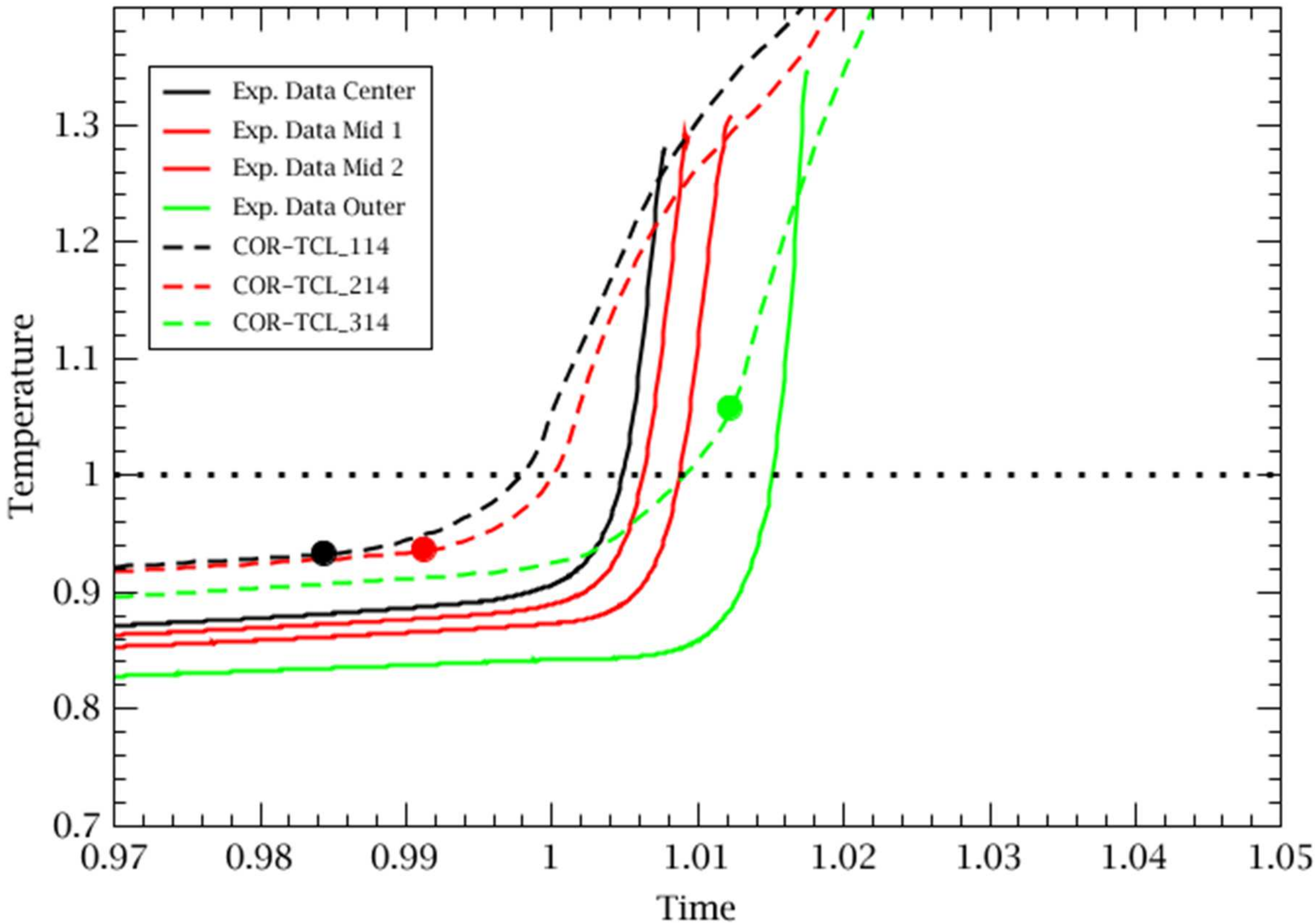
Radial Zirconium Fire Propagation

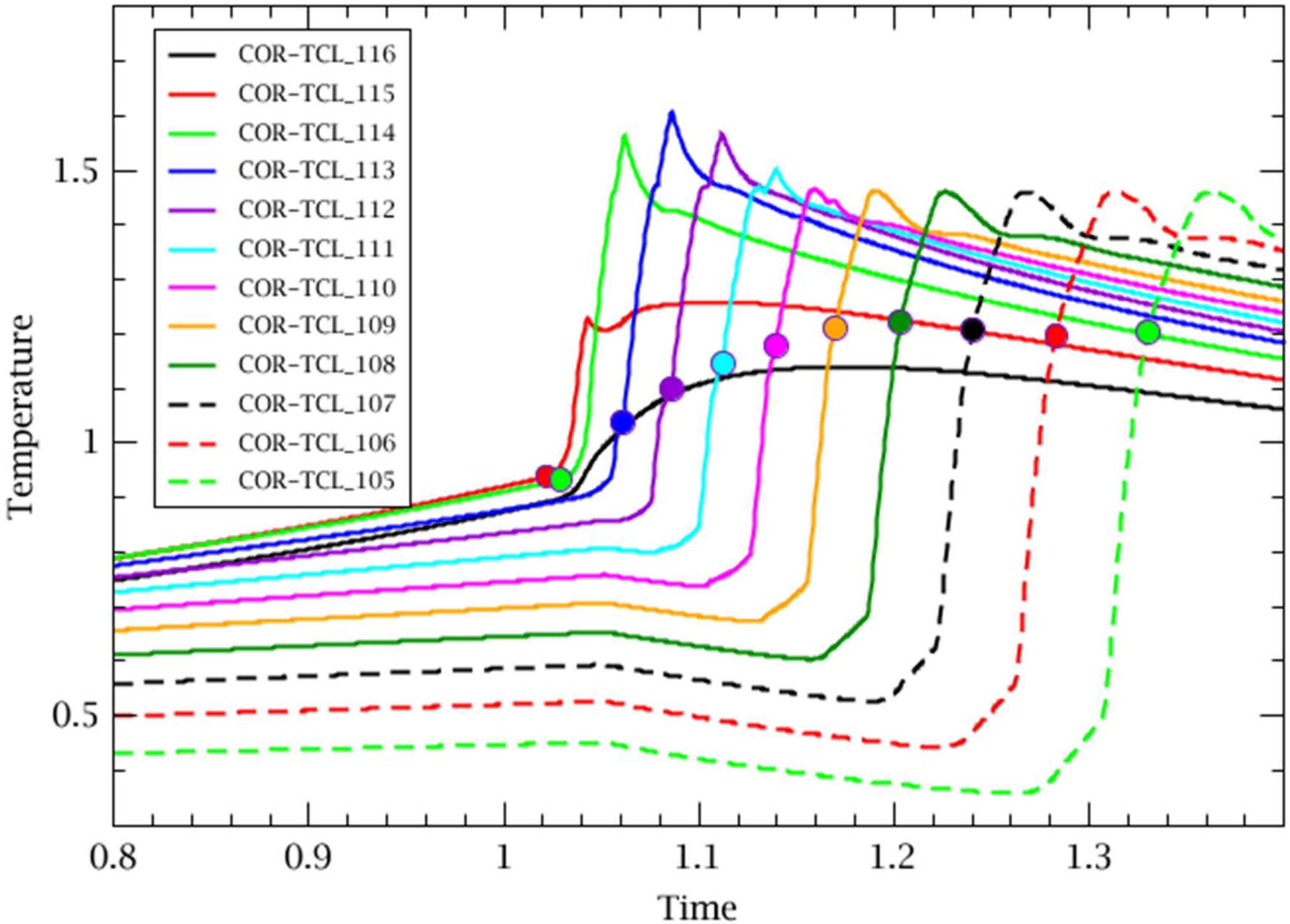
At several elevations of the fuel bundle temperature profiles were measured at different rods. From this data a radial temperature distribution could be deduced. Comparison of the calculated data of the 3 radial nodes showed a surprisingly good estimation with the experimental data. The “plane“ of the measured data is slightly below the “plane“ of the calculated data and therefore a shift is observed due to the slowly downward propagation of the zirconium fire.

The dots in the plot marks the points, where the breakaway was calculated. This shows that the radial “fire propagation“ is mostly controlled by radiation at least in the calculation.

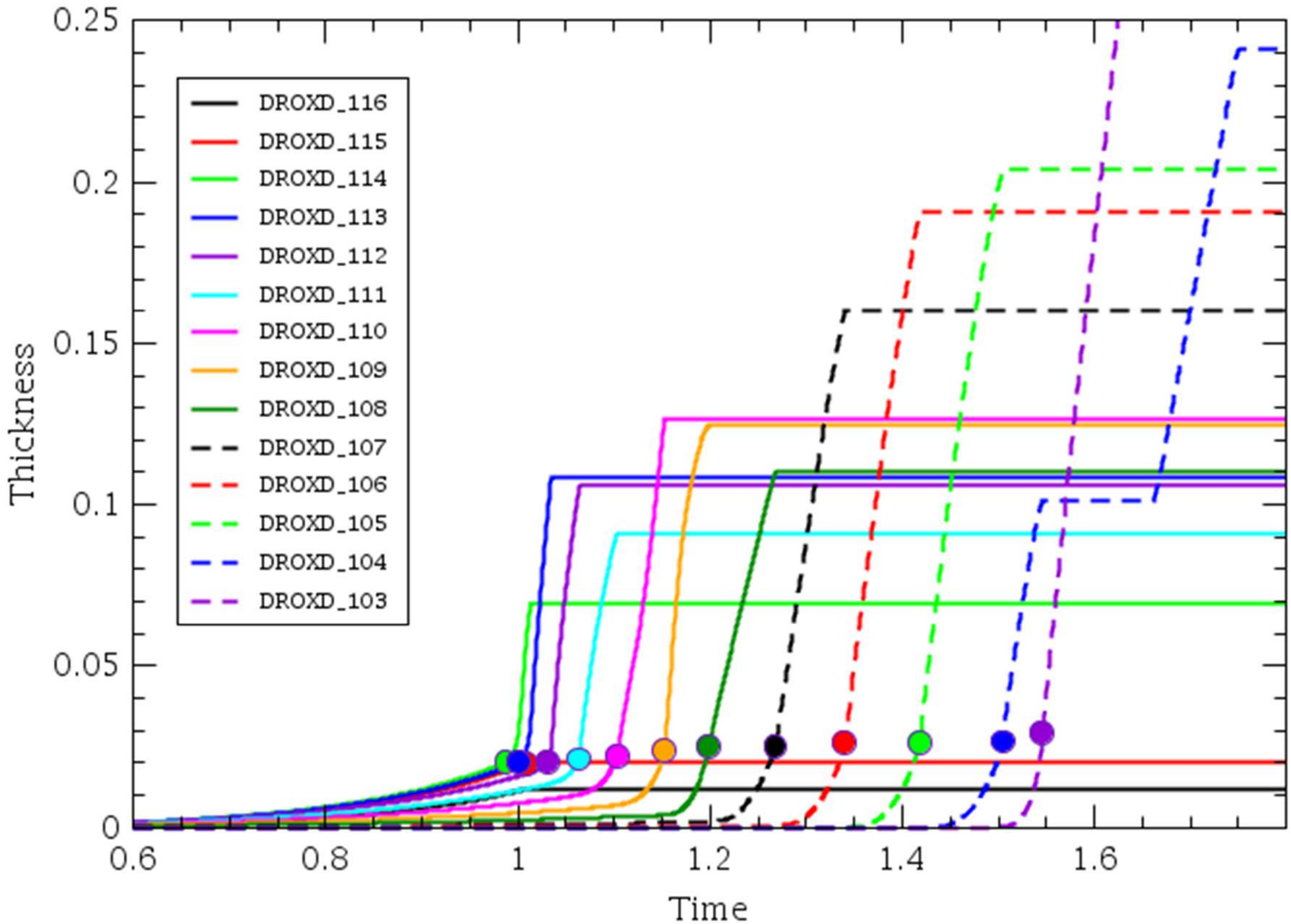
Radial zirconium fire propagation (3 CVH, 3 COR)



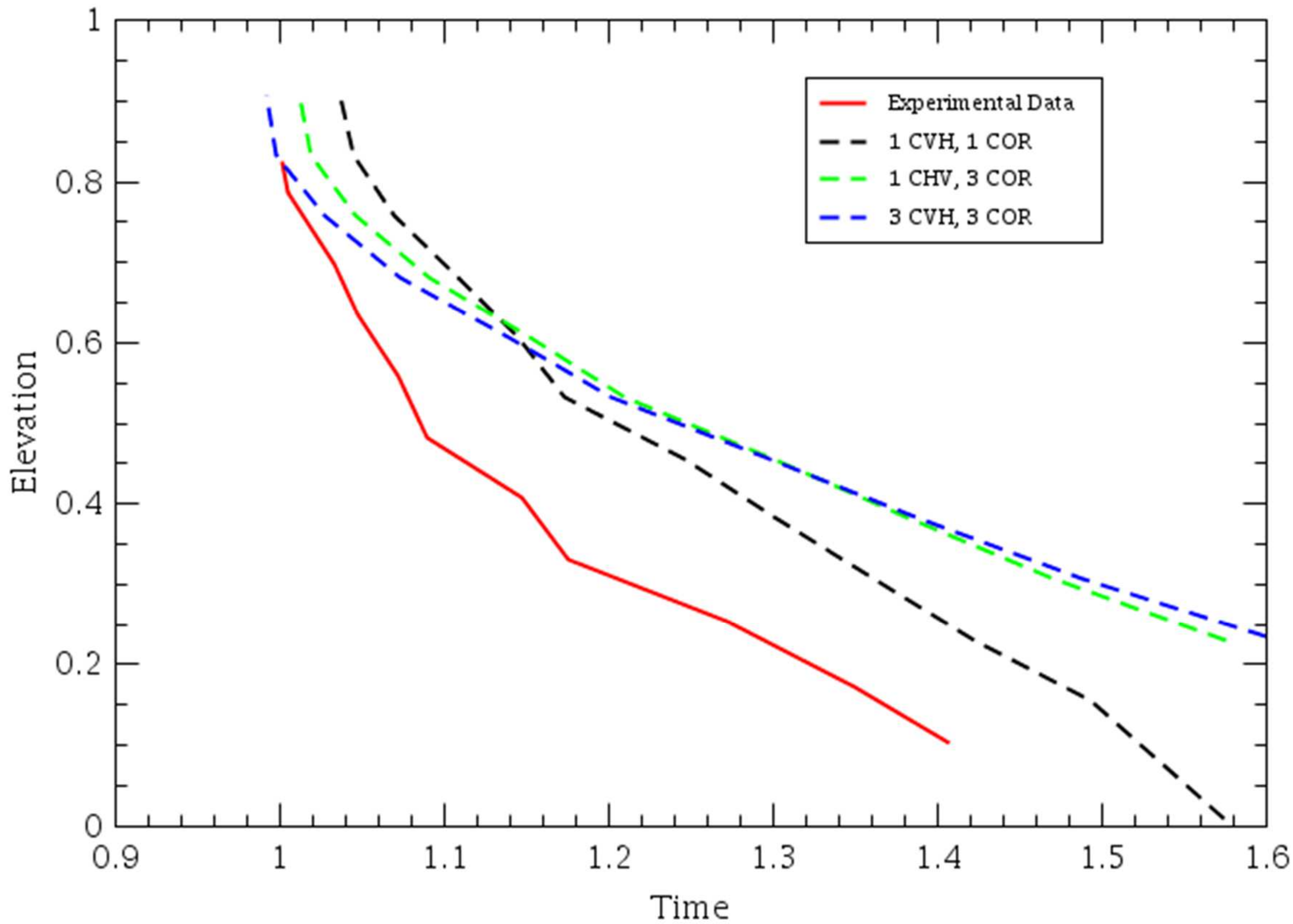
Axial temperature distribution (1 CVH, 1 COR)



Oxide layer thickness (1 CVH, 1 COR)



Downward propagation of the zirconium fire I



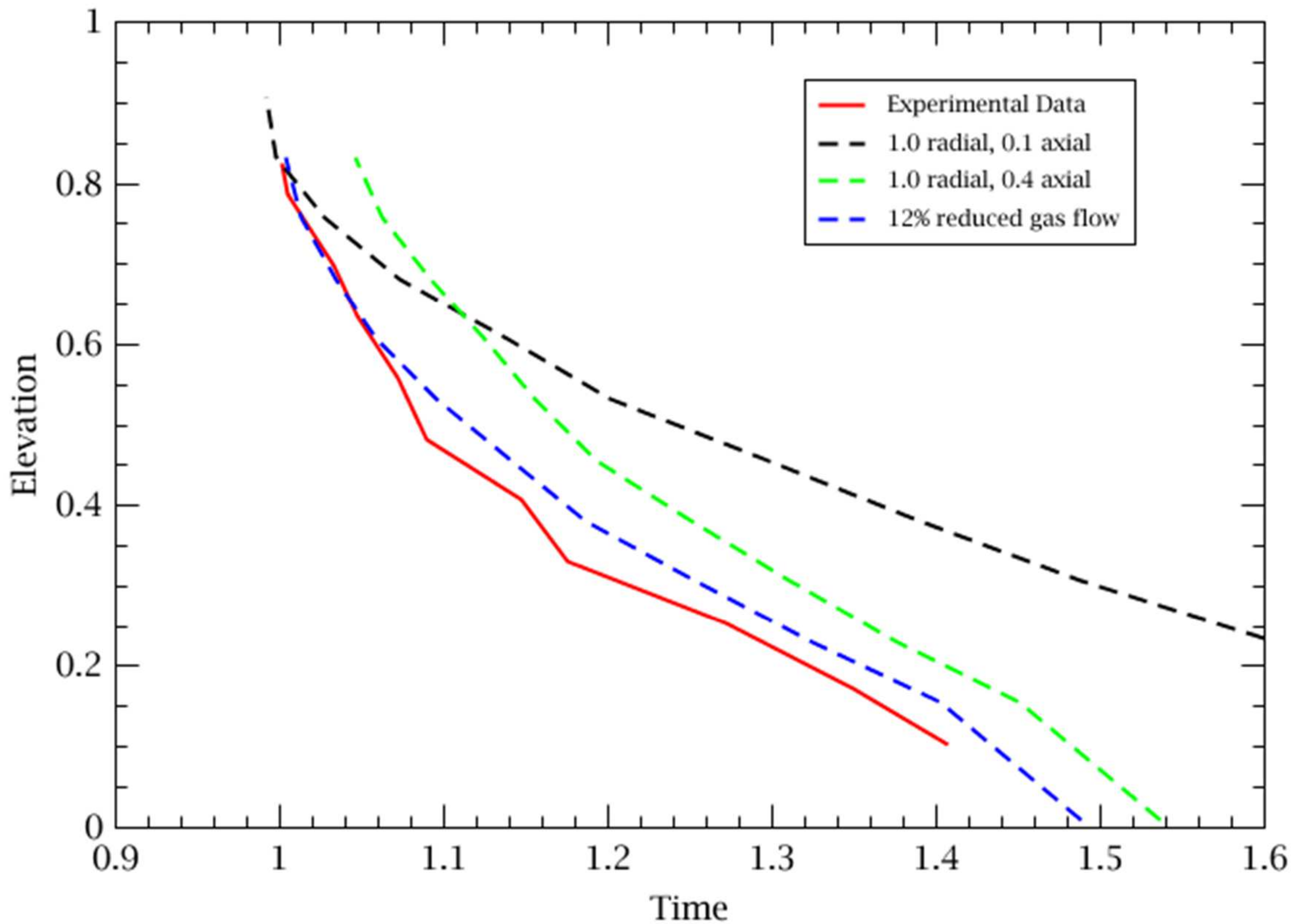
Axial Zirconium Fire Propagation I

The downward propagation velocity of the zirconium fire is very closely reproduced by the MELCOR calculation for the simplest geometrical model with only 1 core node and 1 control volume for each axial zone. But the time of ignition was much better calculated for the more detailed modeling.

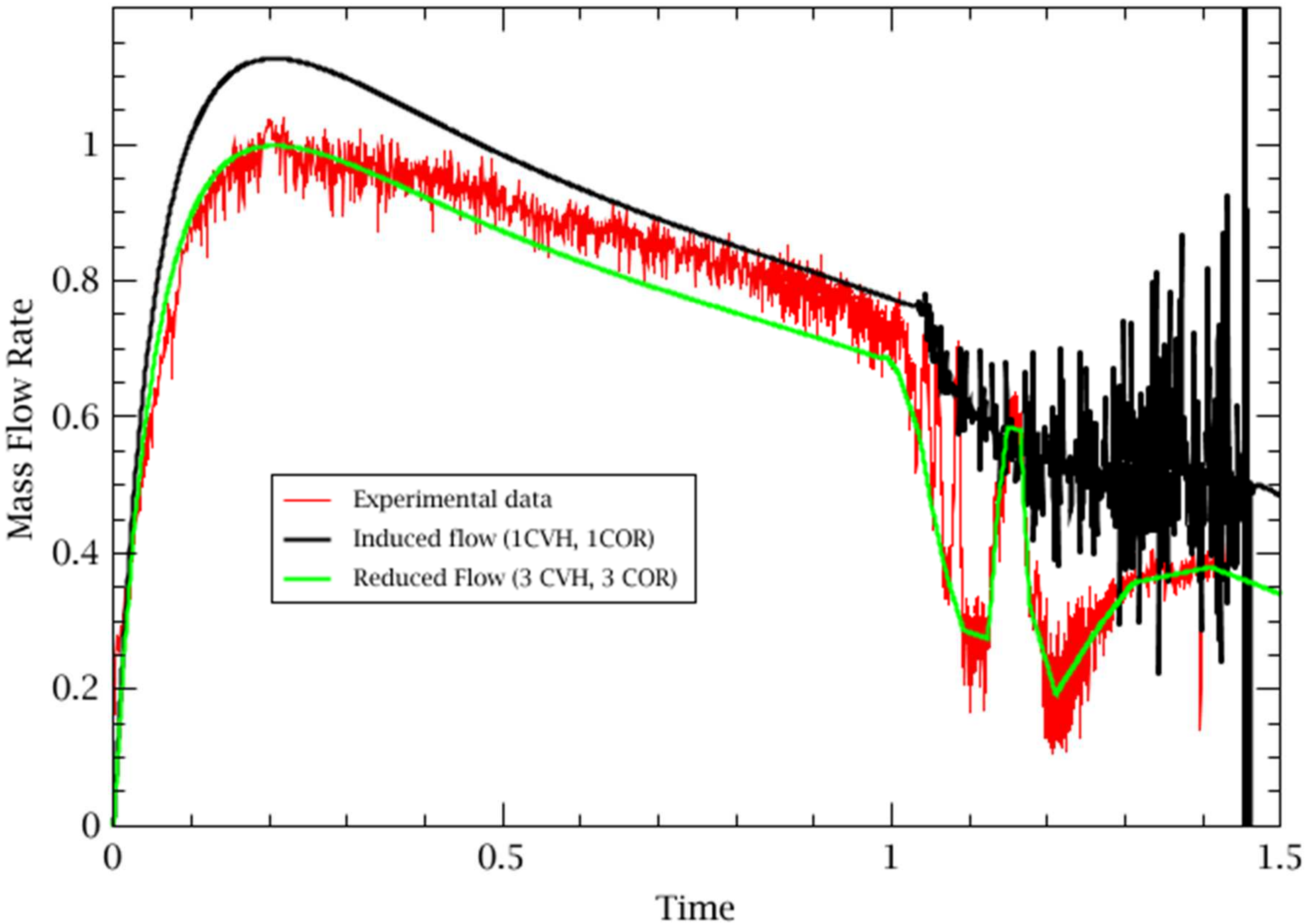
The axial temperature development clearly shows, that only heat radiation can be the driving force for the downward propagation of the zirconium fire. The breakaway signal is shown as circle for the different axial nodes.

The change in geometrical modeling had a strong influence on the velocity of the downward propagation of the fire front.

Downward propagation of the zirconium fire II



Reduced air flow



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Axial Zirconium Fire Propagation II

In the MELCOR input radial and axial heat exchange coefficients can be defined (COR00003). The preset values are 0.25 for both parameters.
In the input deck from SANDIA they were changed to 1.0 for the radial direction and to 0.1 for the axial direction.

Does the energy transfer calculated due to radiation has a modeling limitation in the MELCOR code?

The axial heat exchange is only to the direct axial partner and not to the neighbored axial partners below or above. Therefore the geometrical modeling of the bundle may influence the heat radiation and therefore the zirconium fire propagation.

Long term behavior I

After the downward propagation of the zirconium fire reached the lower end of the fuel bundle the experimental team lost almost all of the instrumentation. The data aquisition then was stopped.

The burning of the non oxidized zirconium went on until almost all of the metal was oxidized. Post test examinations showed, that almost no metal was left unoxidized after cool down of the facility.

After the downward propagation of the fire the rack material was calculated to change its state from “intact“ to “debris“. MELCOR is not able to oxidise debris material and therefore the available oxygen is completely used up for the zirconium oxidation.

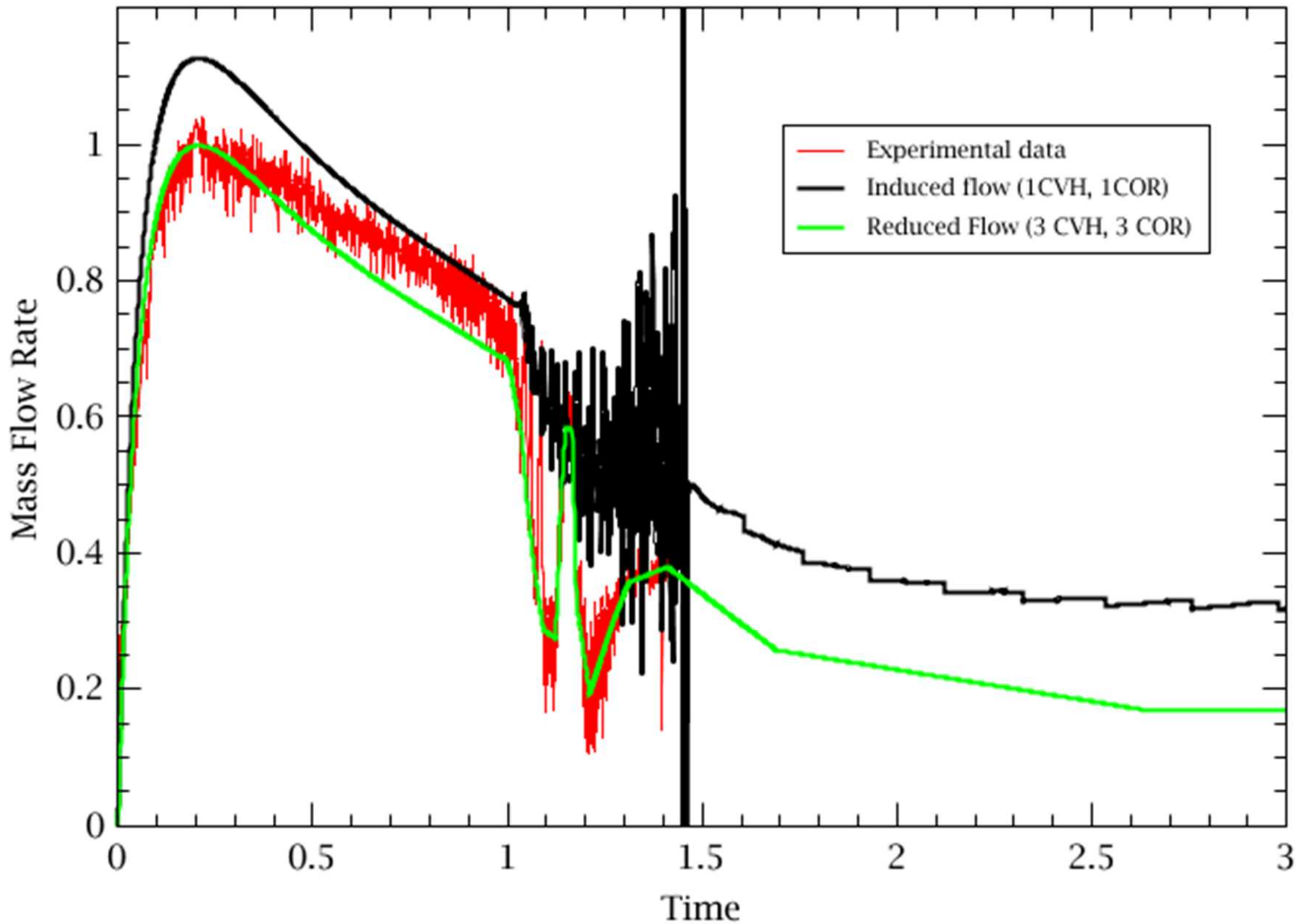
Long term behavior II

From the total masses of zirconium and steel it was calculated in case of complete oxidation, that about 43% of the oxygen would be used for the oxidation of steel and 57% for the oxidation of zirconium.

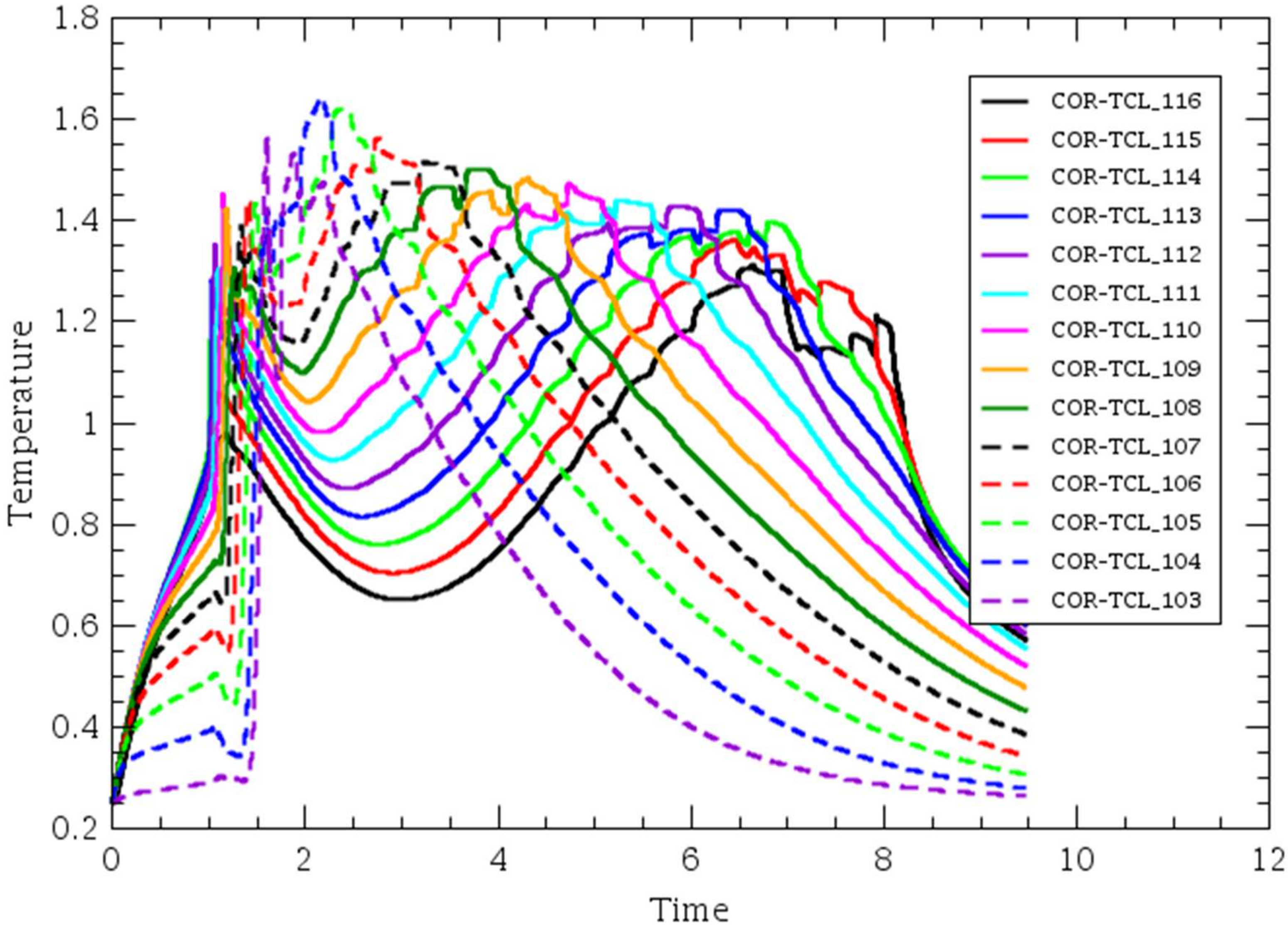
To correct for the limitation of MELCOR the air flow for the calculation of the long term behavior of the fuel bundle was reduced by about 50% to estimate the upward fire propagation until complete oxidation of the fuel bundle material.

As base for the air flow an induced flow calculation was used.

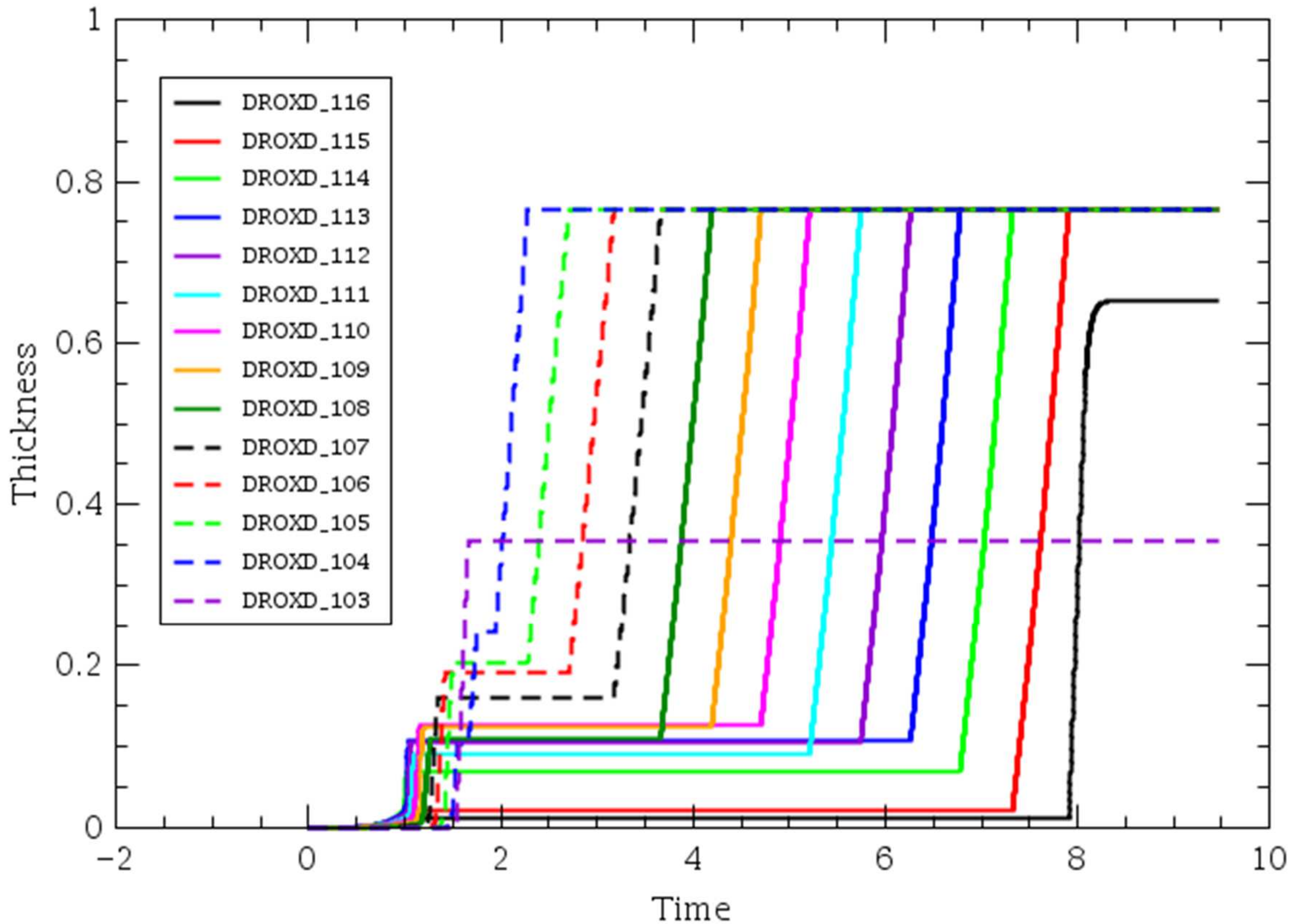
Reduced Air Flow



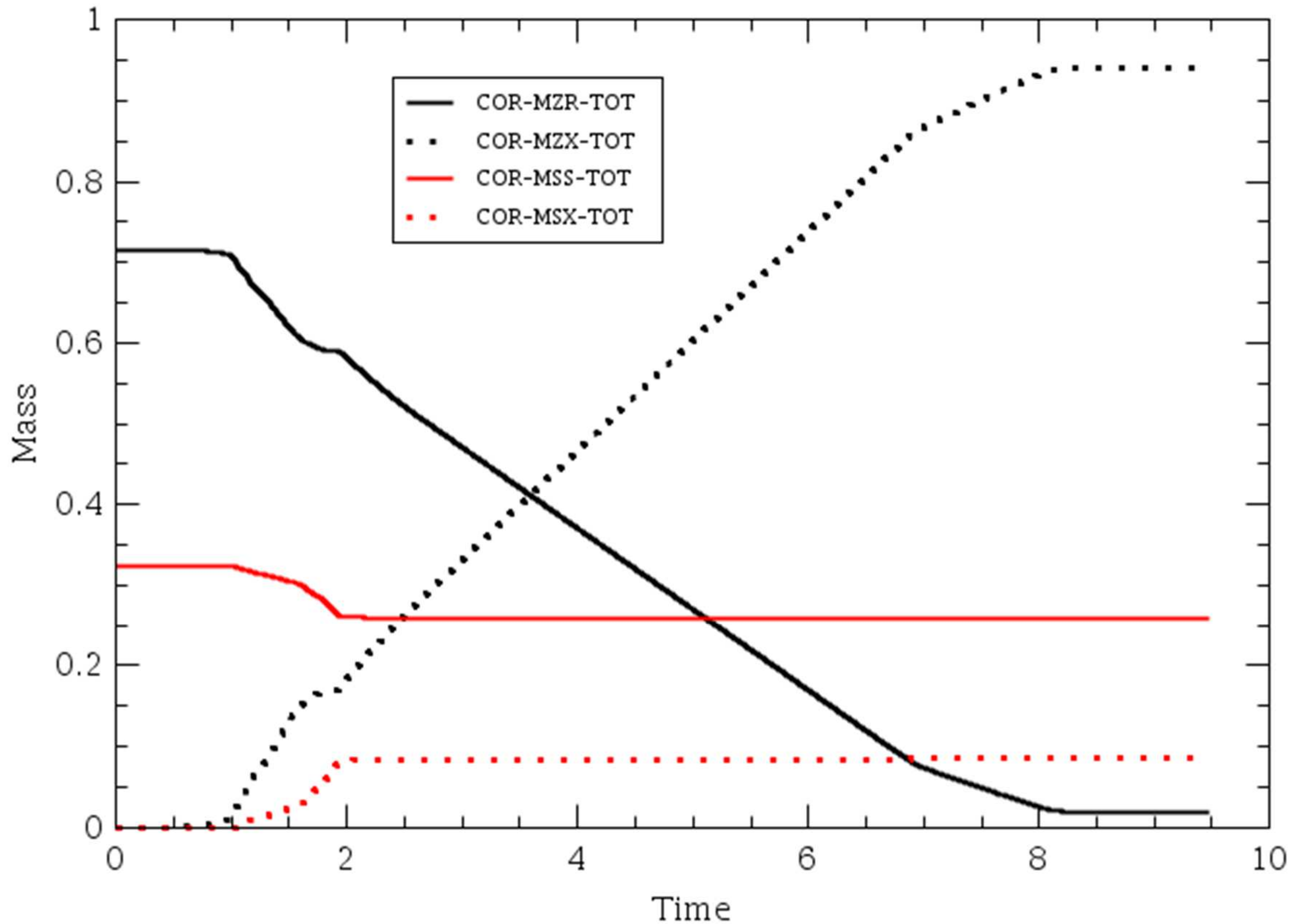
Axial Temperature Development



Cladding Oxide Thickness



Metallic and Oxidic Mass Evolution



Summary

Important outcome of the sensitivity study are the following points:

- Breakaway was the triggering event for the ignition but radiation was the driving force for the propagation
- The breakaway model seems to be fitted to the SFP experiment and may not be suitable for other experiments with different heatup rates, temperature histories or materials
- The radiative exchange coefficients are very important for calculations if radiation is the dominant heat transfer mode
- The nodalisation of the core components shows a strong effect on the downward propagation of the zirconium fire (Maybe the radiation model has to be re-examined)

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Thank you for your attention