SFP LOCA Analysis with MELCOR

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EU DuC=N

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Outline

- ☐ Introduction
    - ➢ NRG applications of MELCOR
- ☐ NUGENIA+ AIR-SFP
- ☐ Results of the Calculations
    - ➢ SFP Loss of Cooling Accident
    - ➢ SFP LOCA
- ☐ Modelling Issues
    - ➢ SFP reactor type
    - ➢ Zircaloy Oxidation
- ☐ Conclusions

Introduction

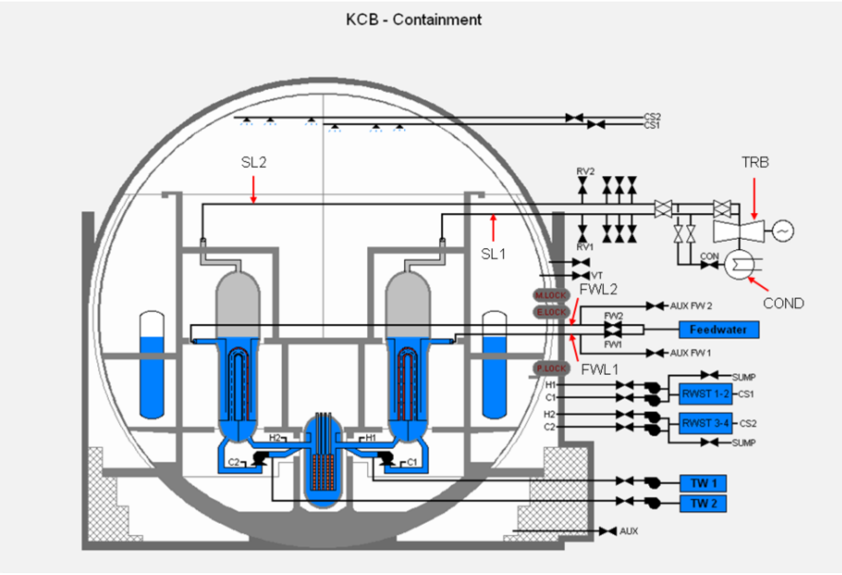
Uses of MELCOR @ NRG:

- ☐ **Post-Fukushima SFP analyses**
  - Spent Fuel Pool analyses in MELCOR (and other codes) in order to assess the coolability after a SFP LOCA scenario
- ☐ **Severe accident analysis for KERENA**
  - (Part of) PSA Level 2 analysis
  - Safety analyses for shutdown and power scenarios
- ☐ **HFR calculations for license renewal**
  - Severe accident analyses
  - PSA Level 2 analysis
- ☐ **Severe accident analyses for the KCB power plant**
  - Safety analysis calculations
- ☐ **KCB power plant desktop simulator**
  - Development of an interactive simulator of the Borssele NPP
  - Dutch regulator personnel training
- ☐ **GKN Dodewaard Power Plant**
  - PSA Level 2 analysis
  - Direct containment heating analysis (comparison of MELCOR vs CONTAIN)

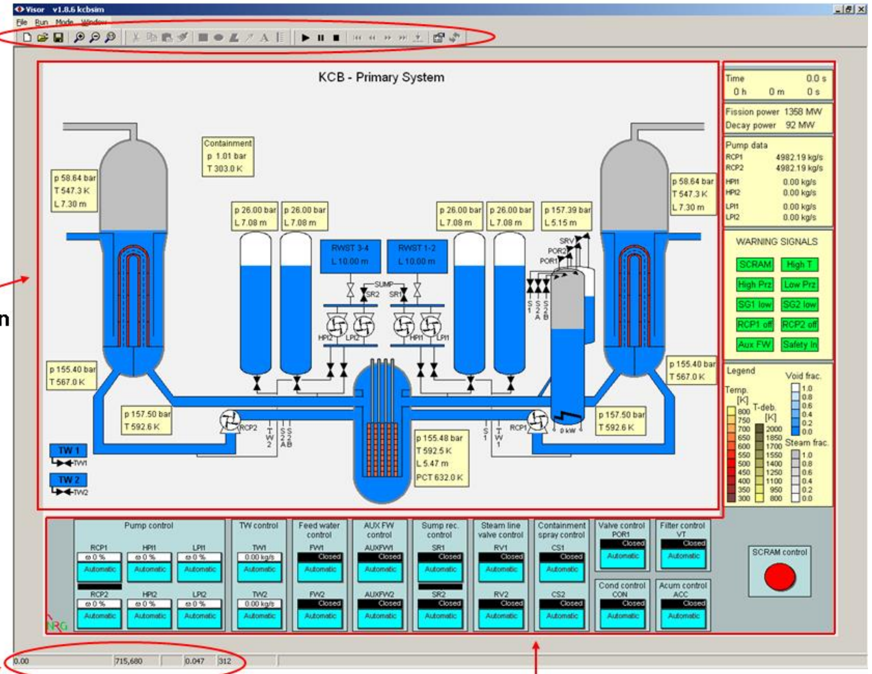
Introduction

Desktop simulator

- ☐ TH codes: MELCOR, RELAP, MAAP and SPECTRA (NRG code)
- ☐ Visor: NRG visualization software compatible with the most widespread TH and SA codes



Window control



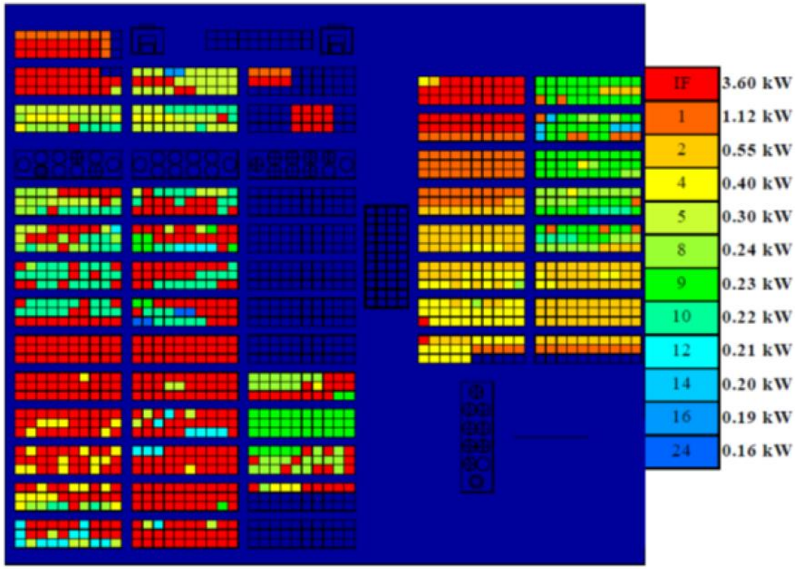
Plant mimic screen

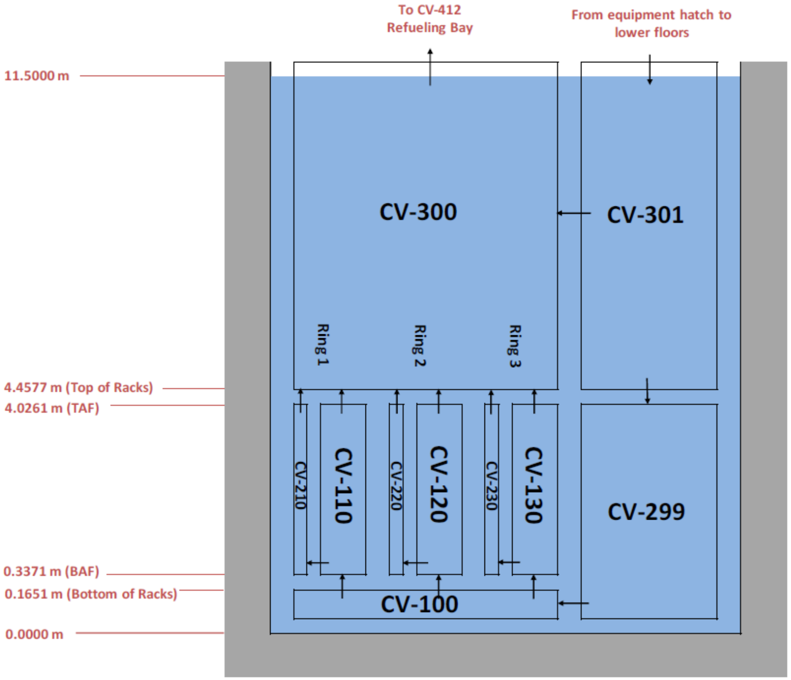
Window information

Plant control and display board

AIR-SFP: Description

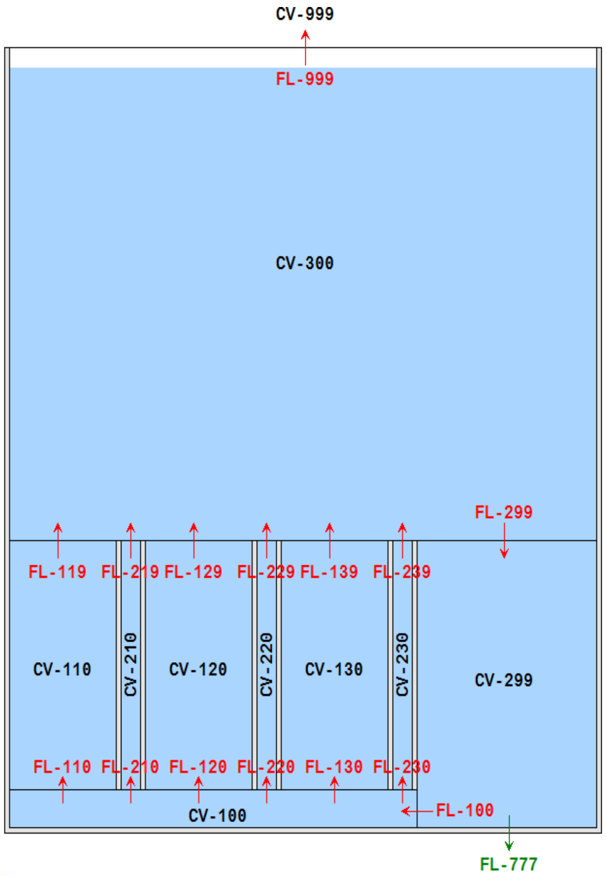
- ☐ **Analysis of severe accidents of SFP**
- ☐ **The SFP model is derived mainly from the Fukushima-Daiichi Unit 4 SFP**
- ☐ **Two scenarios are considered:**
  - ➢ SFP Loss of Cooling Accident
  - ➢ SFP LOCA

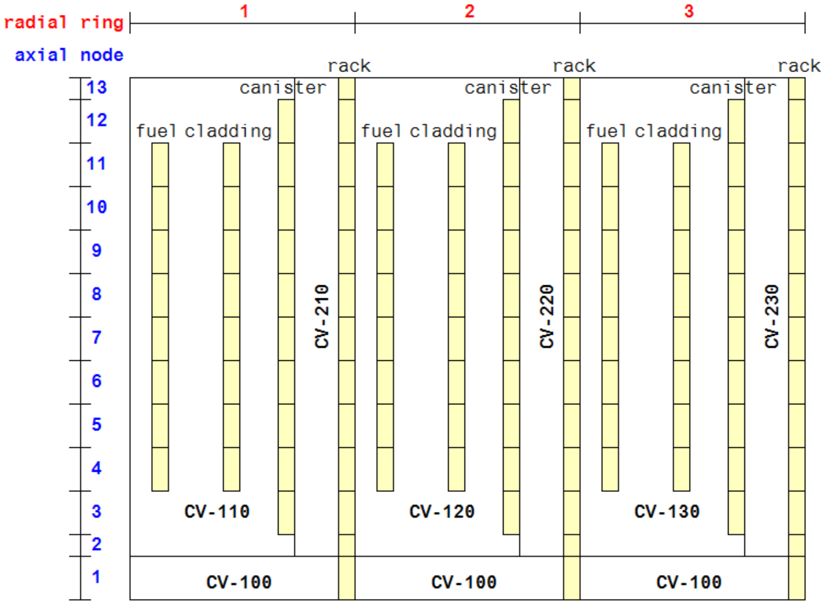




AIR-SFP: Model

- ☐ SFP: 1 fuel & 1 bypass channel per ring + downcomer and pool top
- ☐ CORE: 3 rings × 13 axial levels (8 for active fuel)
- ☐ One radioisotope inventory representative of the hottest FAs





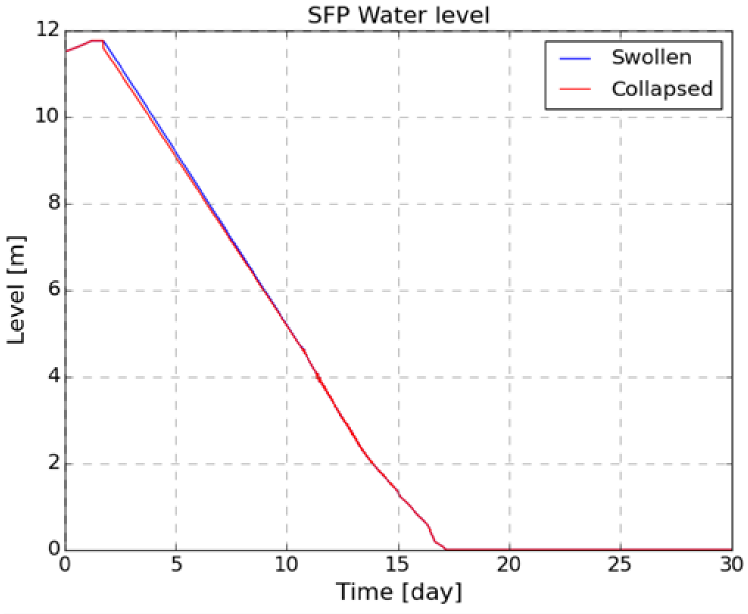
SFP Loss of Cooling

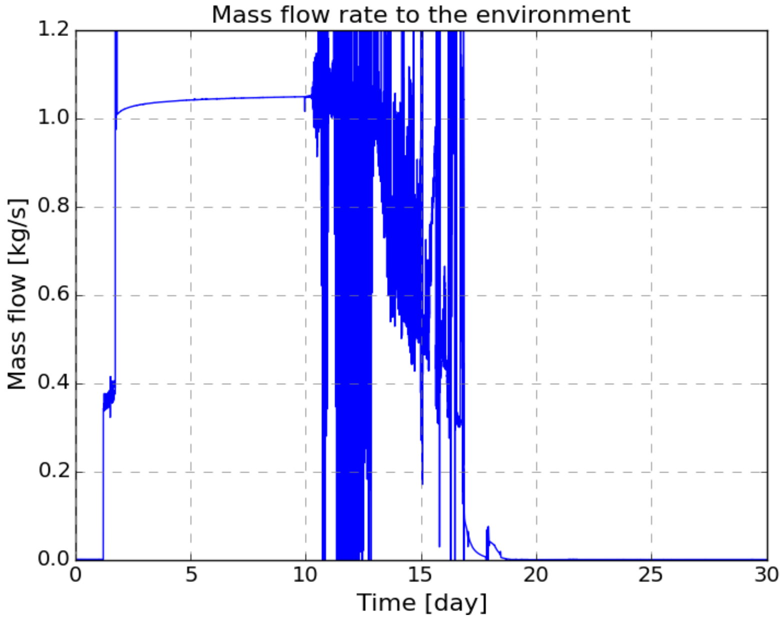
- ☐ **Sequence of events of the Scenario 1**
- ☐ **Rack base plate failure occurs in all three radial rings**
  - ➢ The fuel in the ring 3 does not produce power (fresh fuel)
  - ➢ Power is radiated from neighbor ring 2

Event	Time [s]	Time [days]	Remarks
Gap release in rod group 1	1,275,350	14.8	
Gap release in rod group 2	1,378,310	16.0	
Gap release in rod group 3	1,396,770	16.2	
Core support structure has failed in cell ia= 2 ir= 1	1,443,720	16.7	Failure was by yielding at axial level 2 and radial ring 1
The lower head in segment 1 of ring 1 has failed from creep rupture	1,455,220	16.8	
Core support structure has failed in cell ia= 2 ir= 2	1,458,230	16.9	Failure was by yielding at axial level 2 and radial ring 2
The lower head in segment 2 of ring 2 has failed from thru-wall yielding	1,458,230	16.9	
Core support structure has failed in cell ia= 2 ir= 3	1,472,450	17.0	Failure was by yielding at axial level 2 and radial ring 3
The lower head in segment 3 of ring 3 has failed from thru-wall yielding	1,472,450	17.0	
End of calculation	2,592,000	30.0	Normal termination by end time reached.

SFP Loss of Cooling

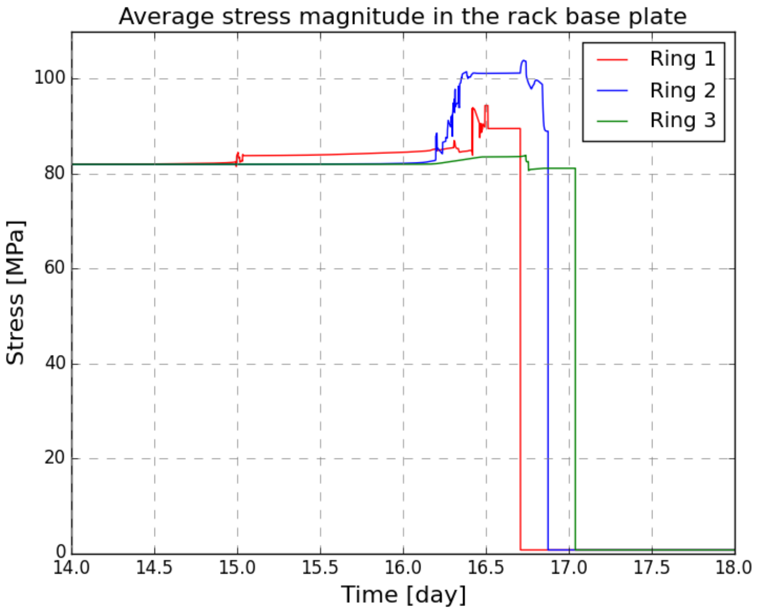
- ❑ Saturation conditions are reached after about 1 day
- ❑ Fuel elements uncovery starts after about 10 days

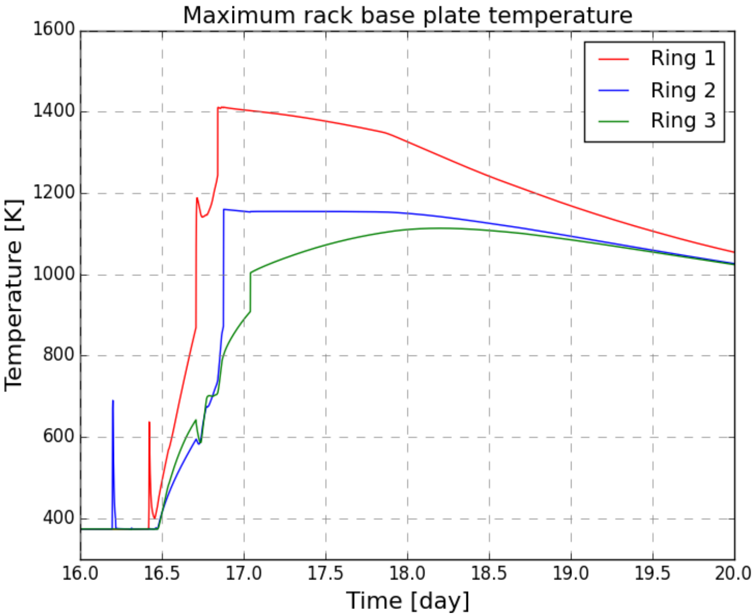




SFP Loss of Cooling

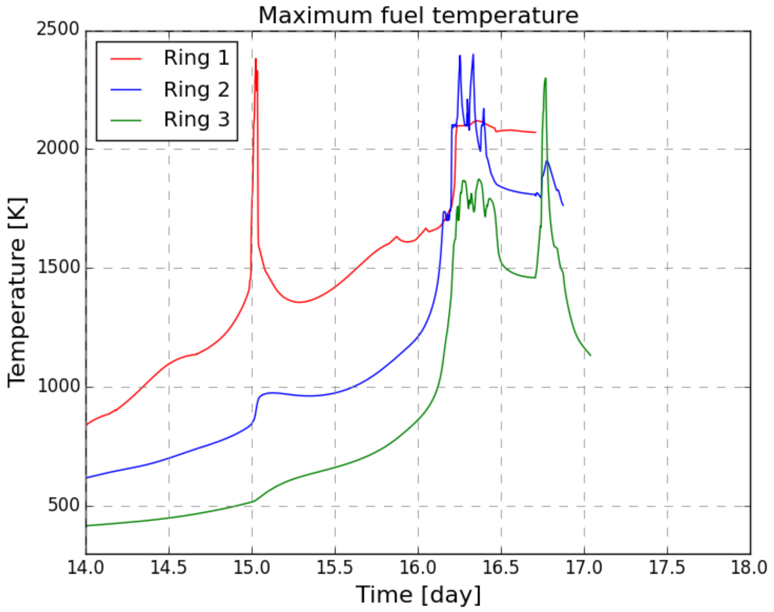
- ❑ **Failure of the rack base plate occurs in all three radial rings**
- ❑ **The event is highly dependent on the rack temperature**

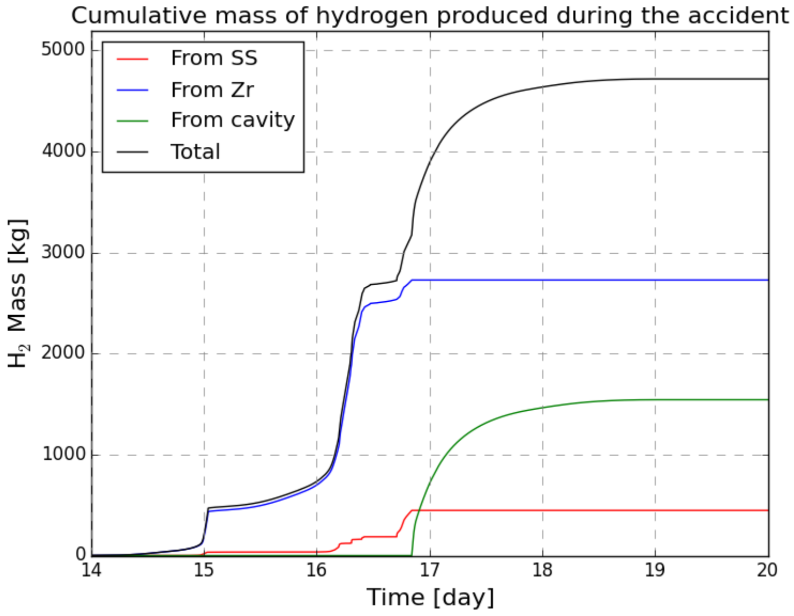




SFP Loss of Cooling

- ❑ Peak fuel temperature are reached as a consequence of oxidation breakaway
- ❑ The rate of hydrogen production increases in correspondence of cladding temperature increase


Maximum fuel temperature


Cumulative mass of hydrogen produced during the accident

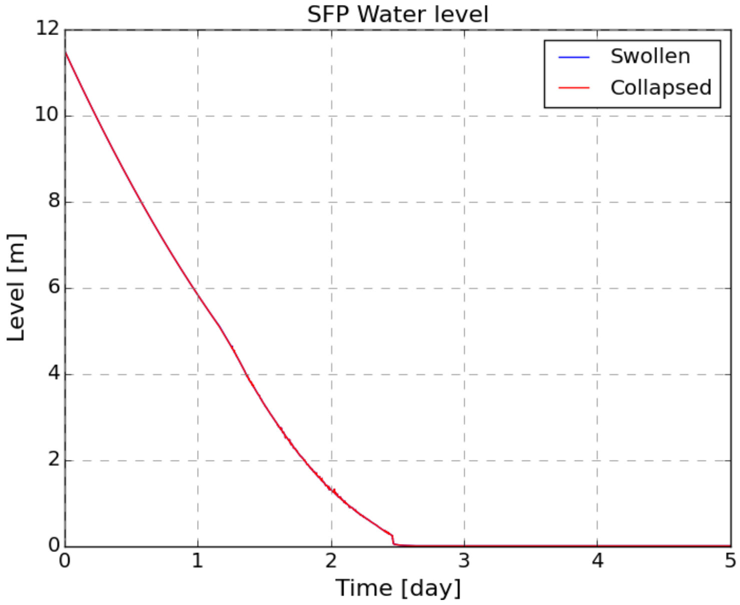
SFP LOCA

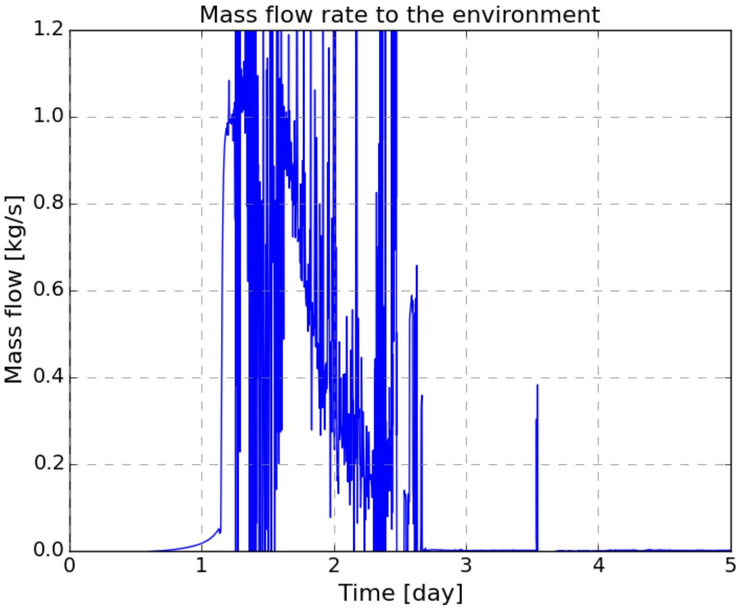
- ☐ Sequence of events of the Scenario 2
- ☐ Rack base plate failure occurs in radial rings 1 and 2 (corresponding to the powered FAs)
- ☐ During the LOCA the FAs are almost immediately exposed to air, while in the Scenario 1 they are exposed mainly to steam

Event	Time [s]	Time [days]	Remarks
Gap release in rod group 1	191,384	2.22	
Core support structure has failed in cell ia= 2 ir= 1	212,964	2.46	Failure was by yielding at axial level 2 and radial ring 1
The lower head in segment 1 of ring 1 has failed from thru-wall yielding	212,965	2.46	
Gap release in rod group 2	227,904	2.64	
Core support structure has failed in cell ia= 2 ir= 2	305,385	3.53	Failure was by yielding at axial level 2 and radial ring 2
End of calculation	432,000	5.00	Normal termination by end time reached.

SFP LOCA

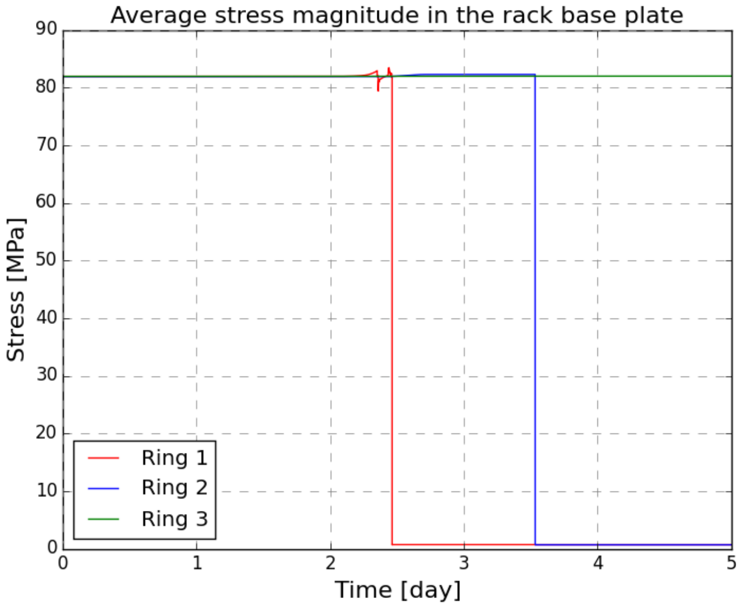
- ☐ **Saturation conditions are reached during the blowdown phase**
- ☐ **Fuel elements uncovery starts after about 2.5 days**

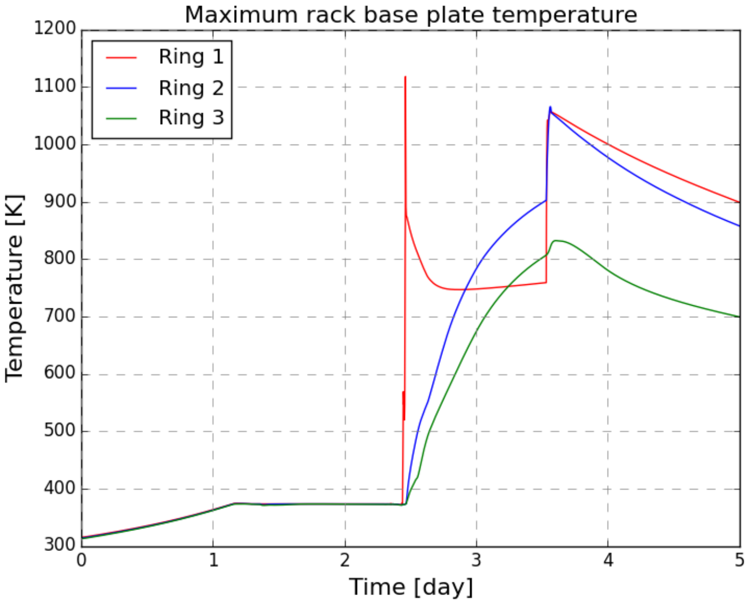




SFP LOCA

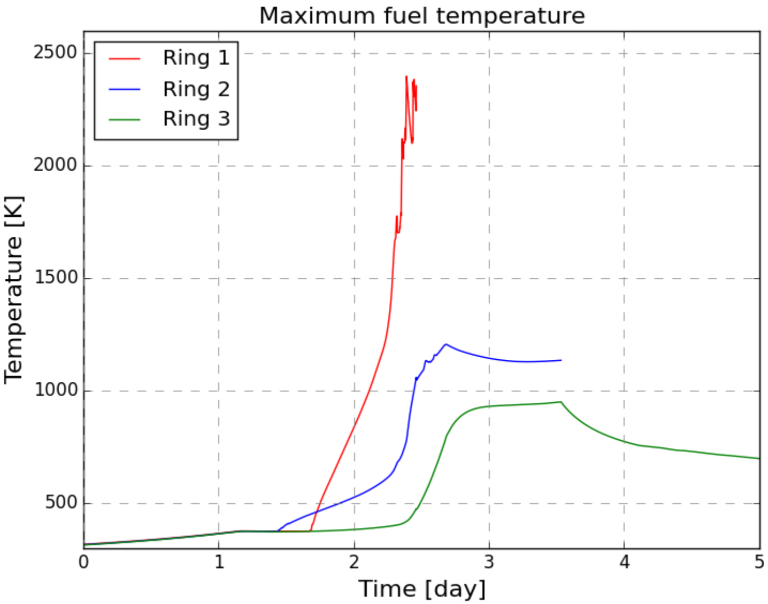
- ☐ **Failure of the rack base plate occurs in radial rings 1 and 2 (only powered FAs)**
- ☐ **The event is highly dependent on the rack temperature**

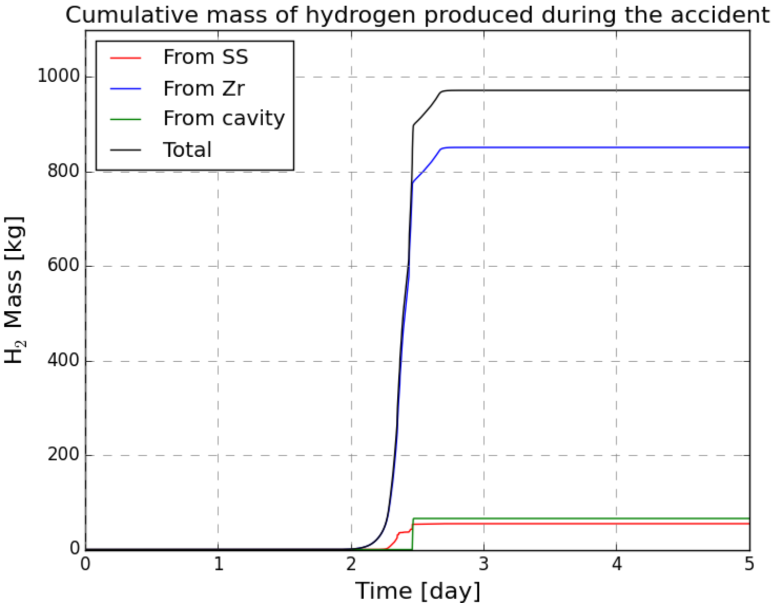




SFP LOCA

- ❑ Peak fuel temperature are reached as a consequence of oxidation breakaway
- ❑ The rate of hydrogen production increases in correspondence of cladding temperature increase





Modelling Issues

SFP Reactor Type

- **Rack component model:**
  - SFP-BWR: new component type ‘rack’ (mass in COR_KRK, surface in COR_RSA cards)
  - BWR: generic NS SUPPORT component
- **Different treatment of the loads on the structures (other differences?)**

SFP-BWR	BWR
11 NS SUPPORT FIXED FIXED FIXED - - - METAL STEEL STEEL STEEL DRMIN(M) 1.00E-04 1.00E-04 1.00E-04 TMAX (K) 1700.00 1700.00 1700.00 10 NS SUPPORT FIXED FIXED FIXED - - - METAL STEEL STEEL STEEL DRMIN(M) 1.00E-04 1.00E-04 1.00E-04 TMAX (K) 1700.00 1700.00 1700.00 9 NS SUPPORT FIXED FIXED FIXED - - - (etc.)	11 NS SUPPORT BELOW BELOW BELOW - - - METAL STEEL STEEL STEEL DRMIN(M) 1.00E-04 1.00E-04 1.00E-04 TMAX (K) 1700.00 1700.00 1700.00 10 NS SUPPORT BELOW BELOW BELOW - - - METAL STEEL STEEL STEEL DRMIN(M) 1.00E-04 1.00E-04 1.00E-04 TMAX (K) 1700.00 1700.00 1700.00 9 NS SUPPORT BELOW BELOW BELOW - - - (etc.)
EDIT OF CORE COMPONENT MASSES (KG) (...) *** LOAD (kg) CARRIED BY SUP-STR = 1.5696E+05 *** STRESS IN SUP-STR = 1.2647E+07	EDIT OF CORE COMPONENT MASSES (KG) (...) *** LOAD (kg) CARRIED BY SUP-STR = 1.8738E+05 *** STRESS IN SUP-STR = 1.5098E+07

Modelling Issues

Zircaloy Oxidation

☐ **MELCOR lifetime of Zircaloy:**

$$\log_{10}\tau = 42.038 - 12.528 \cdot \log_{10} T$$

☐ **Life function for breakaway:**

$$\boxed{LF = \int_0^t \frac{t'}{\tau(T)} \mathrm{d}t' = 1}$$

$$t = \sqrt{2\tau}, \qquad T = const$$

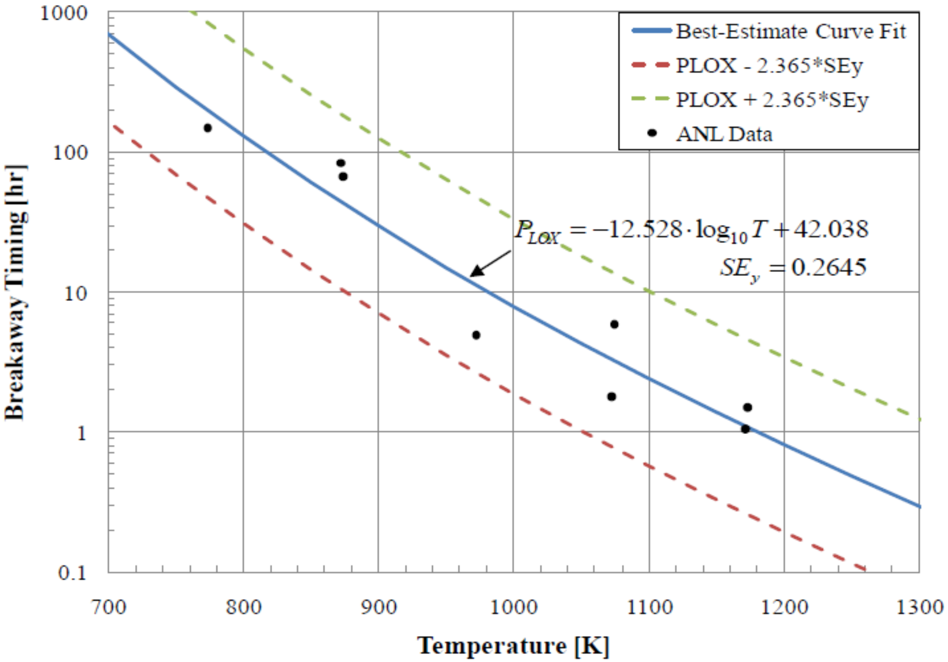
- LF is dimensional [s] (?)
- A test calculation (T = 963 K) results in $t \approx$ 40,000 s (in agreement with the Figure), while from the formula results $t \approx$ 283 s

☐ **Suggested modification of User's Guide (COR_OXB):**

$$\boxed{LF = \int_0^t \frac{\mathrm{d}t'}{\tau(T)} = 1}$$

$$t = \tau, \qquad T = const$$

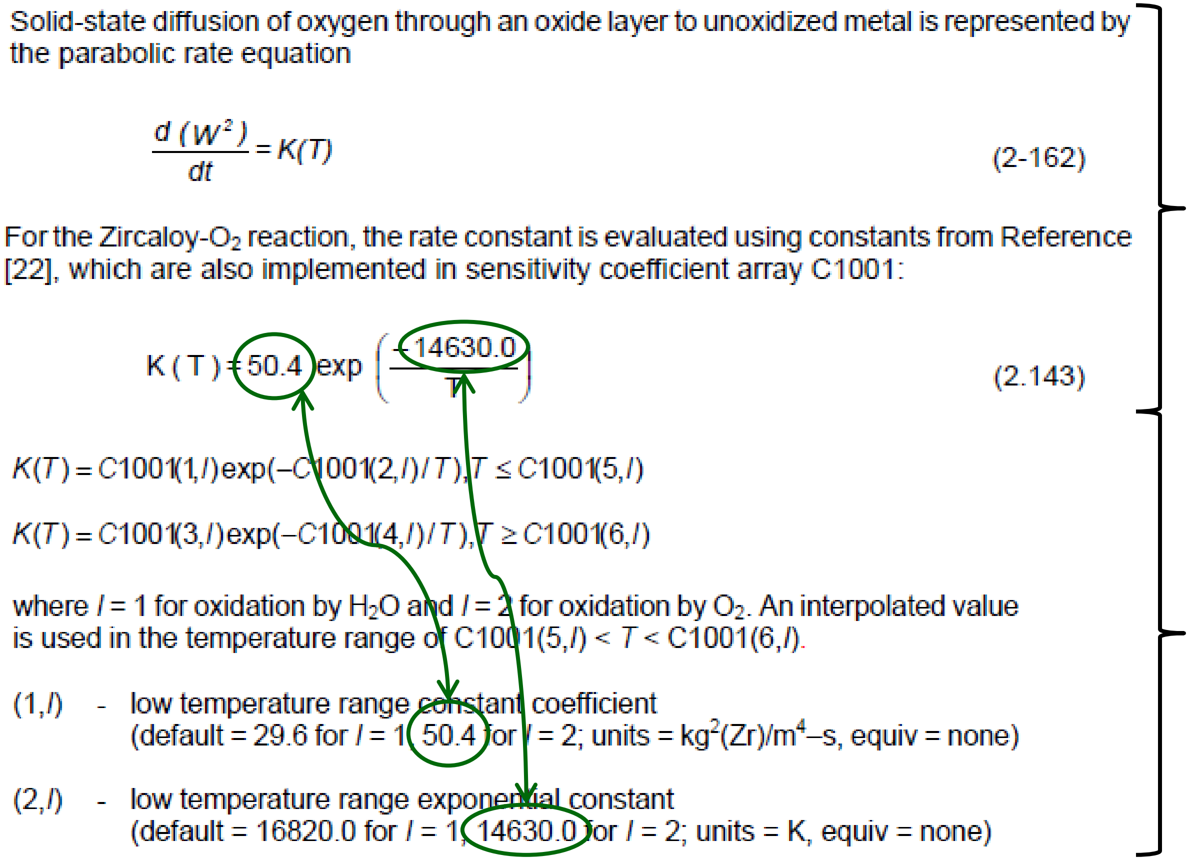
R. Gauntt et al., Fukushima Daiichi Accident Study, SAND2012-6173



Modelling Issues

Zircaloy Oxidation

- **The zircaloy oxidation section (2.5.1) of the COR package reference manual has not been modified since version 1.8.6 (September 2005)**



Solid-state diffusion of oxygen through an oxide layer to unoxidized metal is represented by the parabolic rate equation

$$\frac{d\,(W^2)}{dt} = K(T) \qquad (2\text{-}162)$$

For the Zircaloy-O_2 reaction, the rate constant is evaluated using constants from Reference [22], which are also implemented in sensitivity coefficient array C1001:

$$K\,(\,T\,) = \boxed{50.4}\ \exp\left(\frac{\boxed{-14630.0}}{T}\right) \qquad (2.143)$$

Reference Manual (ver. 1.8.6)

$$K(T) = C1001(1,l)\exp(-C1001(2,l)/T), T \le C1001(5,l)$$

$$K(T) = C1001(3,l)\exp(-C1001(4,l)/T), T \ge C1001(6,l)$$

where $l = 1$ for oxidation by H_2O and $l = 2$ for oxidation by O_2. An interpolated value is used in the temperature range of $C1001(5,l) < T < C1001(6,l)$.

(1,*l*) - low temperature range constant coefficient
(default = 29.6 for *l* = 1, $\boxed{50.4}$ for *l* = 2; units = $kg^2(Zr)/m^4$–s, equiv = none)

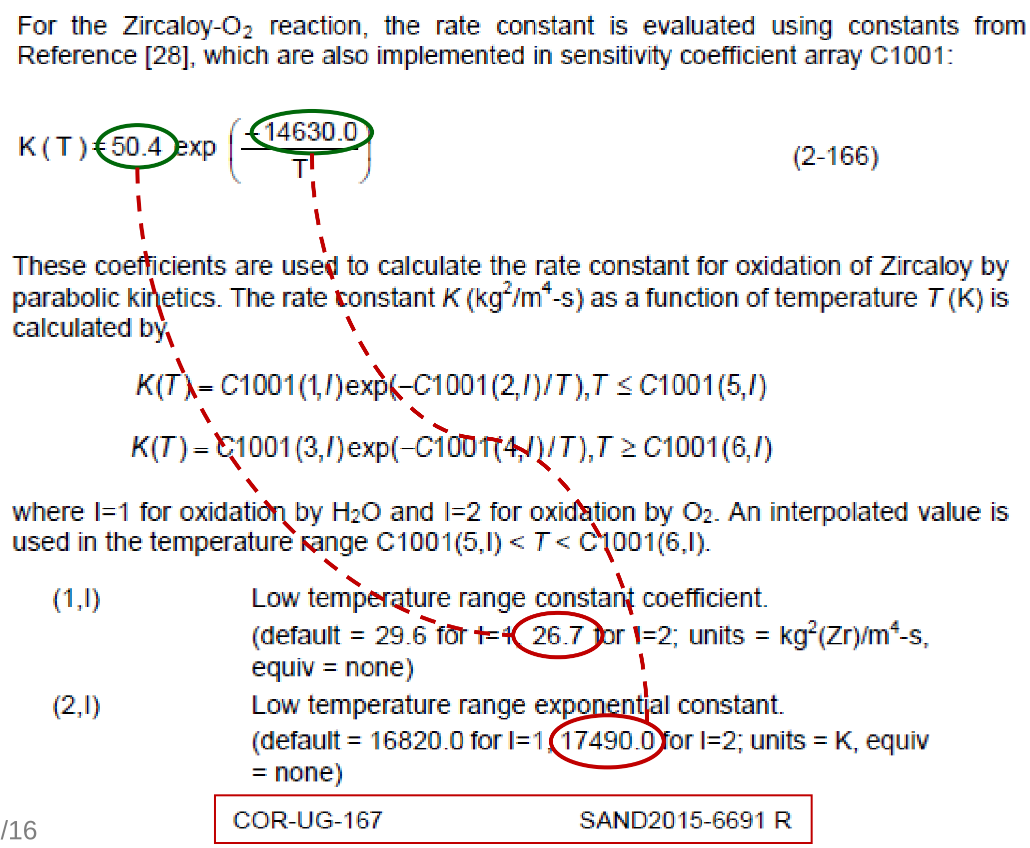
(2,*l*) - low temperature range exponential constant
(default = 16820.0 for *l* = 1, $\boxed{14630.0}$ for *l* = 2; units = K, equiv = none)

User's Guide (ver. 1.8.6)

Modelling Issues

Zircaloy Oxidation

- From MELCOR version 2.1 (build 3166) the default values of the sensitivity coefficients for zircaloy-air oxidation have been changed
- No information is given in the Reference Manual regarding the new correlation!



For the Zircaloy-O_2 reaction, the rate constant is evaluated using constants from Reference [28], which are also implemented in sensitivity coefficient array C1001:

$$K(T) = 50.4 \exp\left(\frac{-14630.0}{T}\right) \qquad (2\text{-}166)$$

Reference Manual (ver. 2.1)

These coefficients are used to calculate the rate constant for oxidation of Zircaloy by parabolic kinetics. The rate constant *K* (kg^2/m^4-s) as a function of temperature *T* (K) is calculated by

$$K(T) = C1001(1,I)\exp(-C1001(2,I)/T), T \le C1001(5,I)$$

$$K(T) = C1001(3,I)\exp(-C1001(4,I)/T), T \ge C1001(6,I)$$

where I=1 for oxidation by H_2O and I=2 for oxidation by O_2. An interpolated value is used in the temperature range C1001(5,I) < *T* < C1001(6,I).

(1,I)	Low temperature range constant coefficient. (default = 29.6 for I=1, 26.7 for I=2; units = $kg^2(Zr)/m^4$-s, equiv = none)
(2,I)	Low temperature range exponential constant. (default = 16820.0 for I=1, 17490.0 for I=2; units = K, equiv = none)

COR-UG-167 SAND2015-6691 R

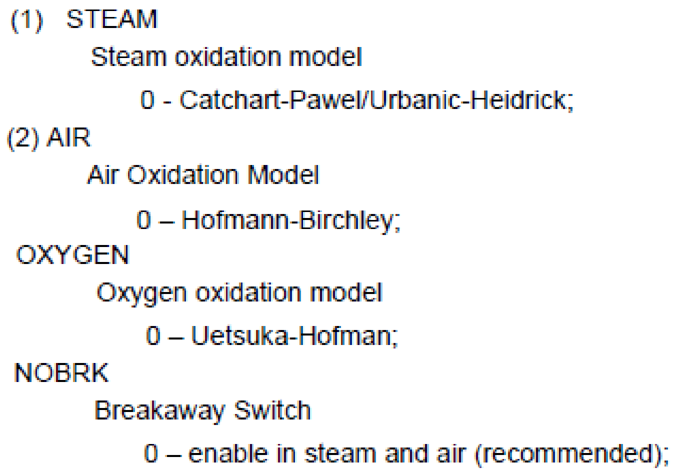
User's Guide (ver. 2.1)

Modelling Issues

Zircaloy Oxidation

- ❑ **From MELCOR version 2.1 (build 6840) a new model option for zircaloy oxidation is available (COR_OX)**
- ❑ **No description is given in the Reference Manual regarding the new correlations!**

```
!     PSI Oxidation breakaway model
!          active   H2O   Air   O2   breakaway
cor_ox     1        0     0     0    0
```



(1) STEAM

Steam oxidation model

0 - Catchart-Pawel/Urbanic-Heidrick;

(2) AIR

Air Oxidation Model

0 – Hofmann-Birchley;

OXYGEN

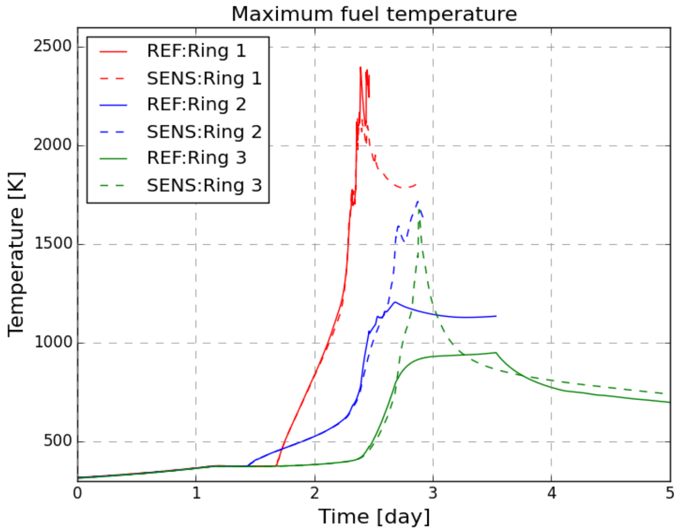
Oxygen oxidation model

0 – Uetsuka-Hofman;

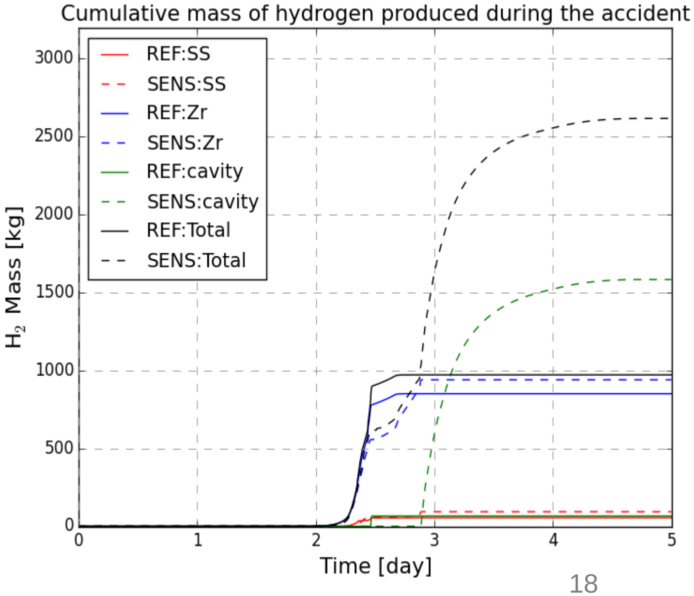
NOBRK

Breakaway Switch

0 – enable in steam and air (recommended);



Maximum fuel temperature



Cumulative mass of hydrogen produced during the accident

Conclusions

- **MELCOR has been used to simulate severe accidents evolution of a generic SFP within the framework of the NUGENIA+ project**
- **SFP applications of MELCOR lack of full validation (SNL analysis on Fukushima SFP4 only covers the boil-off phase)**
- **The MELCOR 2.1 reactor types SFP-BWR and SFP-PWR includes a few enhancements towards SFP modelling application:**
  - The new rack component is not considered in the load calculation of the support plate, which is consistent for SFP applications
  - There are not evidences that the rack component and the standard NS structures are treated differently in the COR package
- **Some deficiencies/inconsistencies in the MELCOR 2.1 Reference and User's Guide manuals have been found in regards of the zircaloy oxidation model**
  - In MELCOR version from (at least) 2.1.3166 the coefficients of the oxidized metal rate correlation are different between the Reference Manual and User's Guide
  - In MELCOR version 2.1.6843 the PSI oxidation model has been introduced but no information is given about the correlations adopted by the code

Thank you for your attention! Questions?