MELCOR Modelling and Experience at NRG

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Outline

- Introduction
  - MELCOR use @ NRG
- Fukushima-Daiichi Unit-4 SFP
  - BWR vs SFP-BWR Models
  - Analysis of the Results
- SMR Steam Generator
  - TH modelling
  - CHF condition calculation
- Zircaloy Oxidation Model
- Conclusions

Introduction

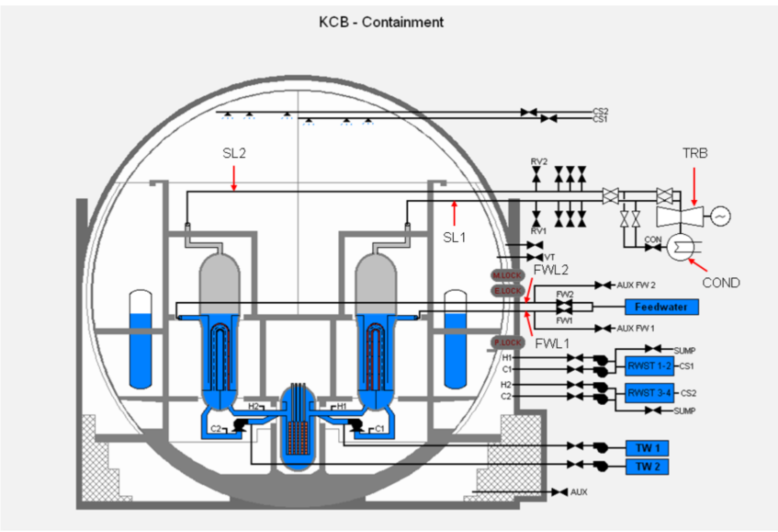
Uses of MELCOR @ NRG:

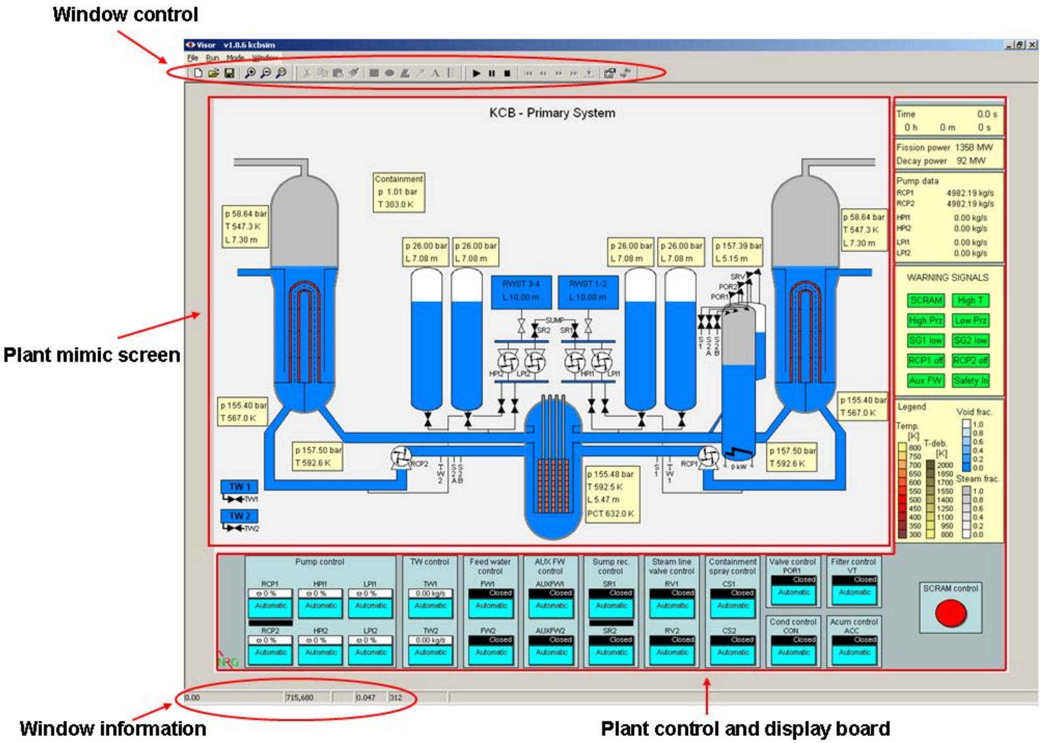
- **Post-Fukushima SFP analyses**
  - Spent Fuel Pool analyses in MELCOR (and other codes) in order to assess the coolability after a SFP LOCA scenario
- **Severe accident analysis for KERENA**
  - (Part of) PSA Level 2 analysis
  - Safety analyses for shutdown and power scenarios
- **HFR calculations 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

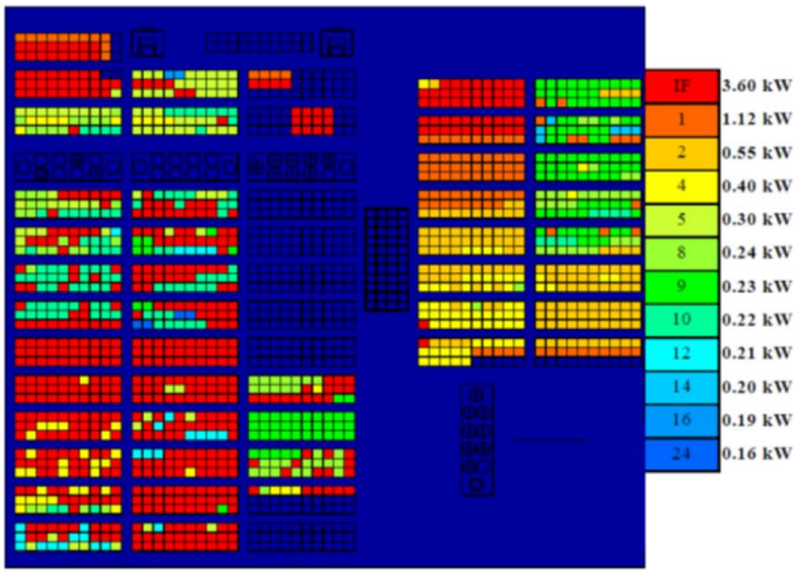
- TH codes: MELCOR, RELAP, MAAP and SPECTRA (NRG code)
- Visor: NRG visualization software compatible with the most widespread TH codes

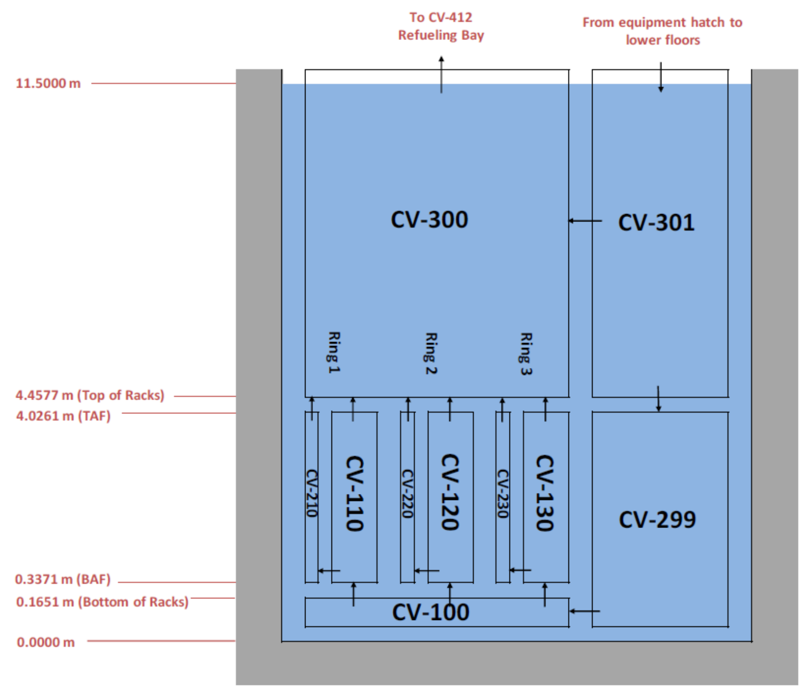




Fukushima SFP4

- SFP boil-off scenario with roof explosion (no water refilling)
- Low SFP initial water level (for speed-up purposes only)
- Model of the plant: SFP, refueling bay and environment
- CORE: 3 rings × 11 axial levels (6 for active fuel)
- Comparison between BWR and SFP-BWR reactor type (MELCOR 2.1)





Fukushima SFP4

- **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
EDIT OF NS AND SS SUPPORT AND FAILURE OPTIONS IA **** IR = 1 2 3 4 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.)	EDIT OF NS AND SS SUPPORT AND FAILURE OPTIONS IA **** IR = 1 2 3 4 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

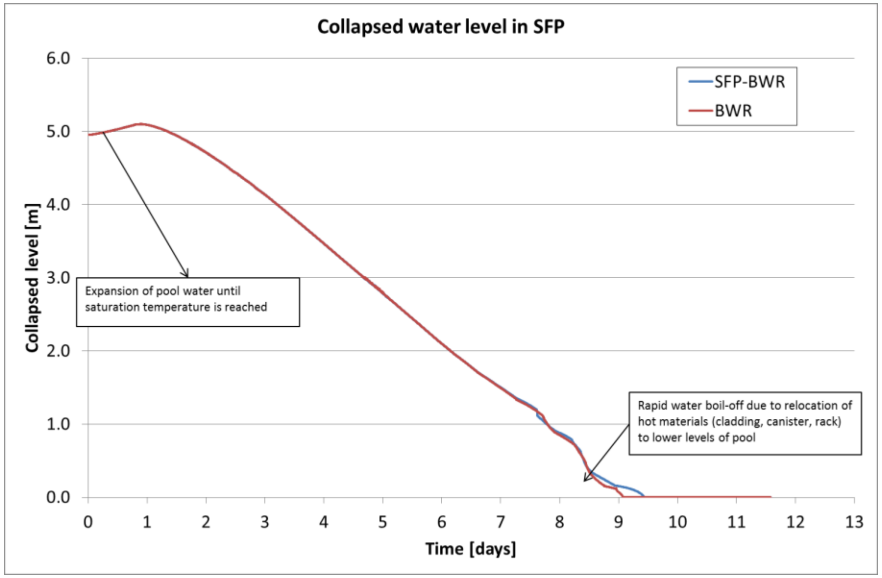
Fukushima SFP4

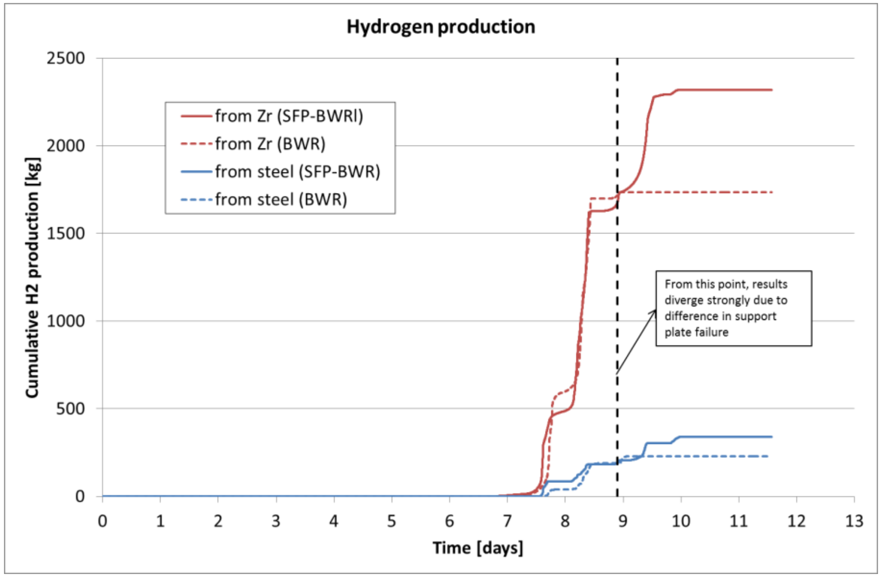
Sequence of events of the accident scenario

Event	SFP-BWR	BWR
Gap release in rod group 1	648,300 s	654,200 s
Gap release in rod group 2	711,100 s	717,500 s
Core support structure has failed in cell ia= 2 ir= 3	722,400 s failure was by over-temperature	
Core support structure has failed in cell ia= 2 ir= 1	843,900 s failure was by creep rupture	773,700 s failure was by yielding
The lower head in segment 1 of ring 1 has failed from thru-wall yielding	843,400 s	
Beginning of debris ejection to cavity	843,400 s	
Core support structure has failed in cell ia= 2 ir= 2	855,700 s failure was by creep rupture	
The lower head in segment 2 of ring 2 has failed from thru-wall yielding	855,700 s	
The lower head in segment 3 of ring 3 has failed from thru-wall yielding	855,700 s	
End of calculation	1,000,000 s	1,000,000 s

Fukushima SFP4

- **The two models evolve similarly up to the rack base plate failure**
- **Rack base plate failure:**
  - SFP-BWR: over-temperature + creep rupture
  - BWR: yielding
- **Relocation of core material determines the base plate failure (highly variable process)**
- **SFP-BWR:**
  - Failure of support plate in ring 3! (no core material above)
  - Radial relocation of core debris (is it meaningful for SFP application?)
  - Disable radial relocation by COR_TST card: code crash

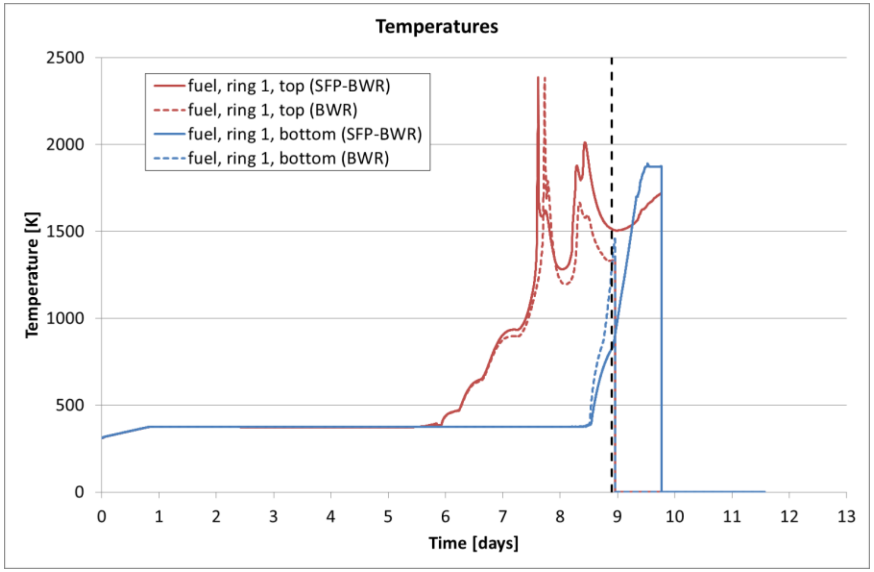




Fukushima SFP4

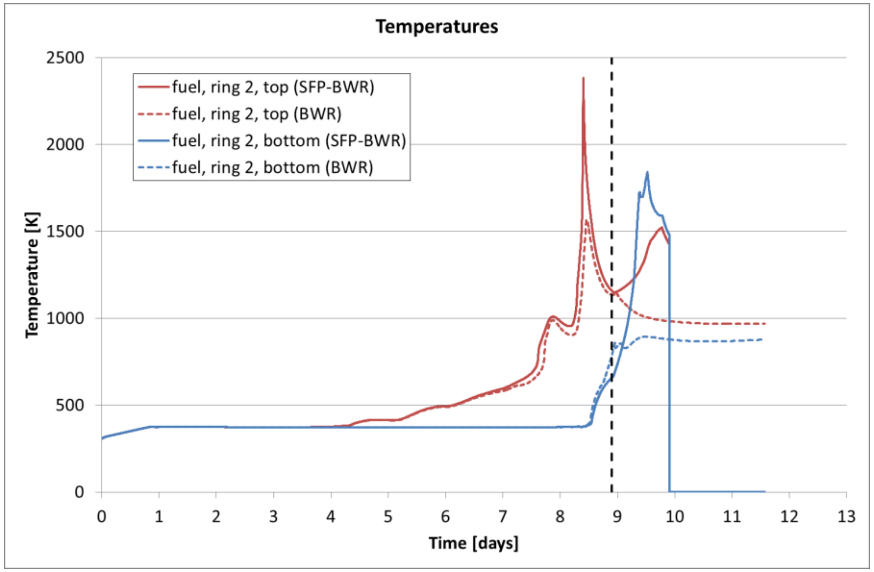
Ring 1:

- **Top of the fuel**
  - Fuel temperature peaks are caused by exothermic reaction of Zr and steam
- **Bottom of the fuel**
  - Failure of the ring 1 support plate occurs at different time in the two models



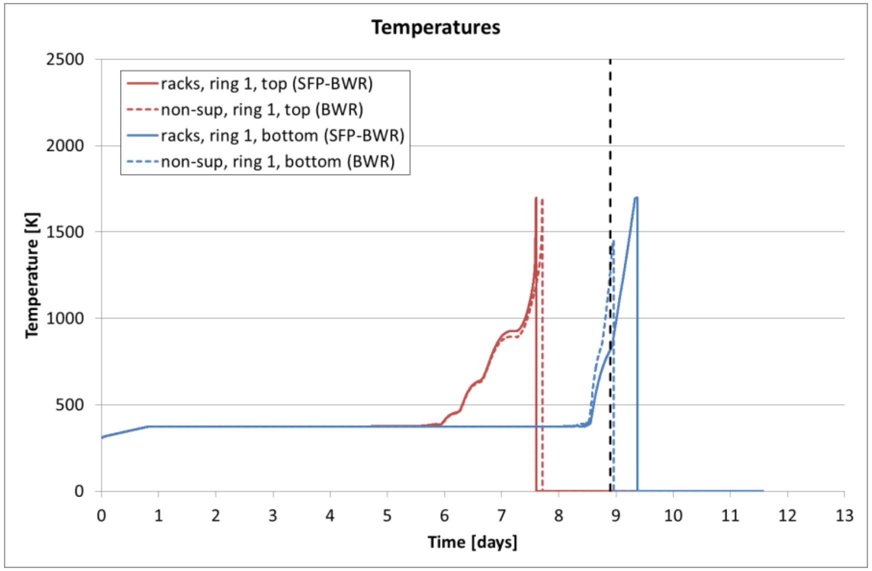
Ring 2:

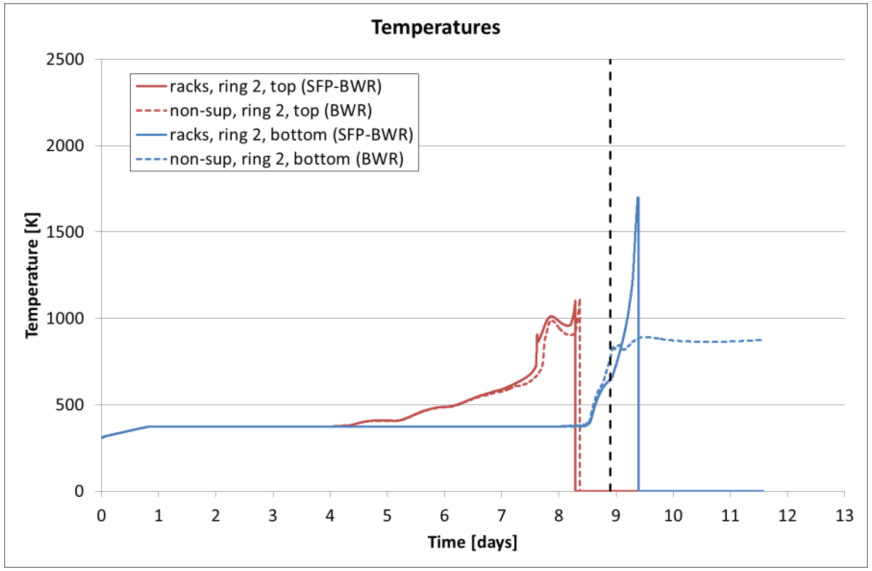
- **Top of the fuel**
  - Fuel temperature is lower in the BWR-type model due to relocation of the cladding
  - Fuel temperature in lower cells where cladding is still present is over 2000 K
- **Bottom of the fuel**
  - Different behaviour because in the BWR-type model the support plate in ring 2 does not fail



Fukushima SFP4

- ❑ **Rack model:**
  - ➢ BWR: standard NS non-supporting structure
  - ➢ SFP-BWR: dedicated rack component
- ❑ **Rack temperature evolution is surprisingly similar**
  - ➢ It seems that there is no particular differences in the COR model between the rack component and the standard NS structure



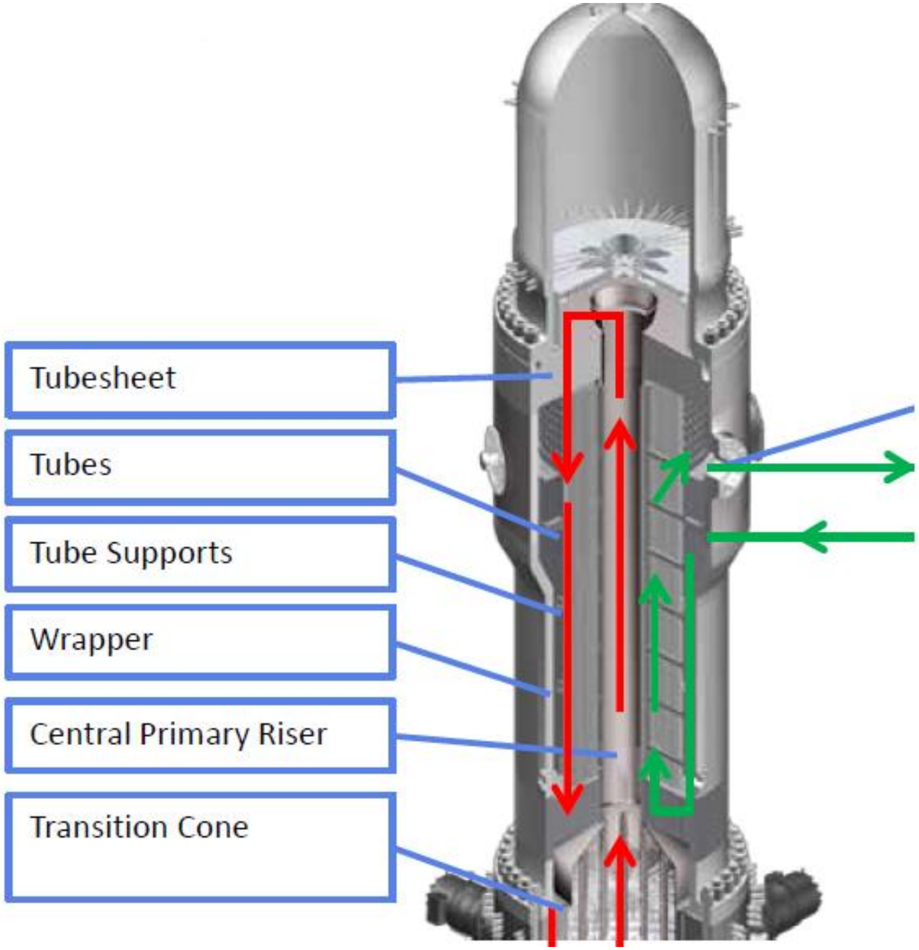


Fukushima SFP4

- **MELCOR has been used to simulate a severe accident evolution of the Fukushima Daiichi Unit-4 spent fuel pool**
- **SFP applications of MELCOR lack of full validation (SNL analysis on Fukushima SFP4 only covers the boil-off phase)**
- **The new 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
- **The SFP-BWR and SFP-PWR reactor types require the SFP to be modelled as a reactor core:**
  - The radial ring model is not generally adequate for SFP application (generally the FAs are arranged in a checkerboard pattern alternating recently unloaded FAs with very old ones, for better coolability and criticality purposes)

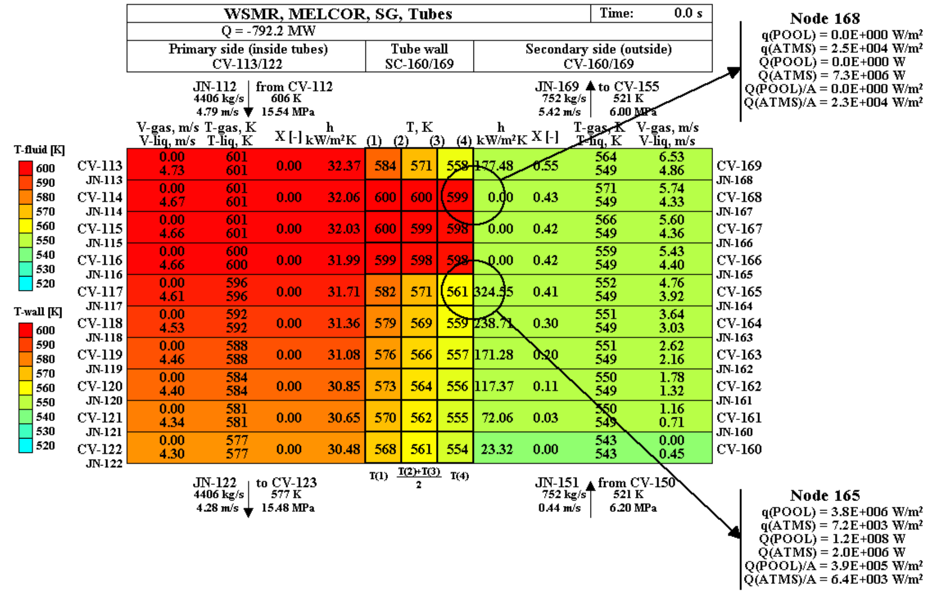
SMR Steam Generator

- **Westinghouse SMR is an integral PWR system**
- **The steam production is a two-stage process:**
  - The primary coolant heat is removed in a tube-shell HX (straight tubes) inside the RPV
  - The steam is separated from the secondary two-phase mixture in a dedicated component
- **The SMR SG MELCOR model comes automatically from the SPECTRA code**
  - HX power: 800 MW
  - 9188 tubes, heated length ~ 6.1 m
  - The nodalization consists of 10 uniform axial nodes for the CVs (both tubes and shell) and HSs

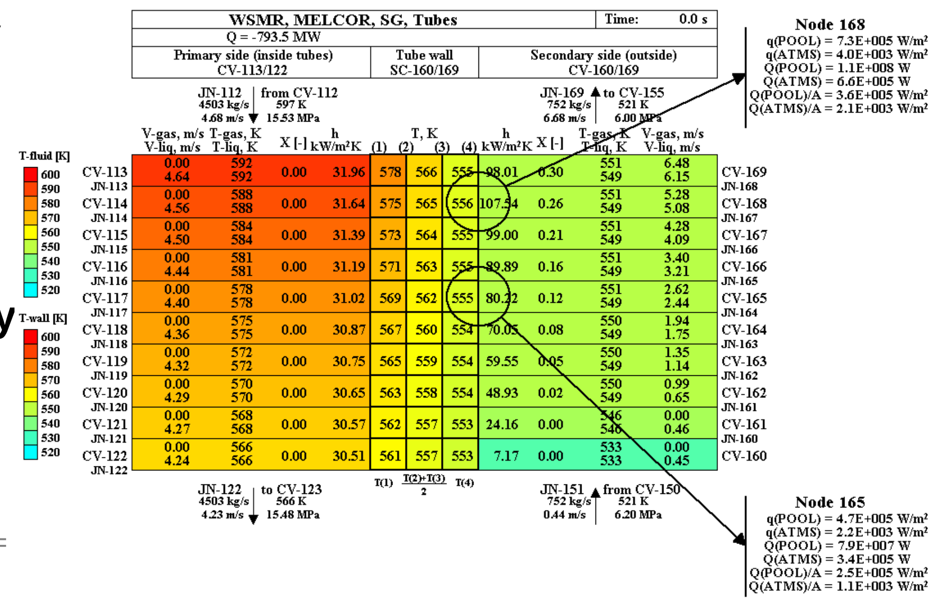


SMR Steam Generator

- Post-CHF regime in the upper part of SG!
- Heat flux definition: $q_{atms} = \dfrac{Q_{atms}}{A_{atms}}, \quad q_{pool} = \dfrac{Q_{pool}}{A_{pool}}$
- MELCOR result, node 165:
  - q = 3.8 MW/m² (close to CHF)
  - Q = 120 MW
  - Q/A = 0.37 MW/m²
- *q* definition appropriate for stratified flow
- Bubbly flow (~90% void) → overestimation of heat flux by about a factor of 10



- Problem can be partly remedied by changing the void fraction limit (sensitivity coefficient SC 4407, item 11):
  - default: α_{MAX} = 0.40
  - changed to: α_{MAX} = 0.95
- New results: no CHF.
- However, heat flux is still overestimated, by about factor of 2. Node 168:
  - q = 0.73 MW/m² (close to CHF)
  - Q/A = 0.36 MW/m²



SMR Steam Generator

- Sensitivity coefficient SC 4407 item 11: default $\alpha_{MAX} = 0.40$

WSMR, MELCOR, SG, Tubes	Time: 0.0 s
Q = -792.2 MW	

Primary side (inside tubes) CV-113/122	Tube wall SC-160/169	Secondary side (outside) CV-160/169

JN-112 4406 kg/s 4.79 m/s — from CV-112 606 K 15.54 MPa

JN-169 752 kg/s 5.42 m/s — to CV-155 521 K 6.00 MPa

	V-gas, m/s / V-liq, m/s	T-gas, K / T-liq, K	X [-]	h kW/m²K	T, K (1) T(1)	T, K (2) (3) $\frac{T(2)+T(3)}{2}$	T, K (4) T(4)	h kW/m²K	X [-]	T-gas, K / T-liq, K	V-gas, m/s / V-liq, m/s	
CV-113	0.00 / 4.73	601 / 601	0.00	32.37	584	571	558	177.48	0.55	564 / 549	6.53 / 4.86	CV-169
JN-113												JN-168
CV-114	0.00 / 4.67	601 / 601	0.00	32.06	600	600	599	0.00	0.43	571 / 549	5.74 / 4.33	CV-168
JN-114												JN-167
CV-115	0.00 / 4.66	601 / 601	0.00	32.03	600	599	598	0.00	0.42	566 / 549	5.60 / 4.36	CV-167
JN-115												JN-166
CV-116	0.00 / 4.66	600 / 600	0.00	31.99	599	598	598	0.00	0.42	559 / 549	5.43 / 4.40	CV-166
JN-116												JN-165
CV-117	0.00 / 4.61	596 / 596	0.00	31.71	582	571	561	324.55	0.41	552 / 549	4.76 / 3.92	CV-165
JN-117												JN-164
CV-118	0.00 / 4.53	592 / 592	0.00	31.36	579	569	559	238.71	0.30	551 / 549	3.64 / 3.03	CV-164
JN-118												JN-163
CV-119	0.00 / 4.46	588 / 588	0.00	31.08	576	566	557	171.28	0.20	551 / 549	2.62 / 2.16	CV-163
JN-119												JN-162
CV-120	0.00 / 4.40	584 / 584	0.00	30.85	573	564	556	117.37	0.11	550 / 549	1.78 / 1.32	CV-162
JN-120												JN-161
CV-121	0.00 / 4.34	581 / 581	0.00	30.65	570	562	555	72.06	0.03	550 / 549	1.16 / 0.71	CV-161
JN-121												JN-160
CV-122	0.00 / 4.30	577 / 577	0.00	30.48	568	561	554	23.32	0.00	543 / 543	0.00 / 0.45	CV-160
JN-122												

JN-122 4406 kg/s 4.28 m/s — to CV-123 577 K 15.48 MPa

JN-151 752 kg/s 0.44 m/s — from CV-150 521 K 6.20 MPa

T-fluid [K]: 600, 590, 580, 570, 560, 550, 540, 530, 520

T-wall [K]: 600, 590, 580, 570, 560, 550, 540, 530, 520

Node 168
q(POOL) = 0.0E+000 W/m²
q(ATMS) = 2.5E+004 W/m²
Q(POOL) = 0.0E+000 W
Q(ATMS) = 7.3E+006 W
Q(POOL)/A = 0.0E+000 W/m²
Q(ATMS)/A = 2.3E+004 W/m²

Node 165
q(POOL) = 3.8E+006 W/m²
q(ATMS) = 7.2E+003 W/m²
Q(POOL) = 1.2E+008 W
Q(ATMS) = 2.0E+006 W
Q(POOL)/A = 3.9E+005 W/m²
Q(ATMS)/A = 6.4E+003 W/m²

SMR Steam Generator

- Sensitivity coefficient SC 4407 item 11: modified α_{MAX} = 0.95

WSMR, MELCOR, SG, Tubes	Time: 0.0 s
Q = -793.5 MW	

Primary side (inside tubes) CV-113/122	Tube wall SC-160/169	Secondary side (outside) CV-160/169

JN-112: 4503 kg/s, 4.68 m/s — from CV-112: 597 K, 15.53 MPa

JN-169: 752 kg/s, 6.68 m/s — to CV-155: 521 K, 6.00 MPa

	V-gas, m/s / V-liq, m/s	T-gas, K / T-liq, K	X [-]	h kW/m²K	T, K (1)	(2) (3)	(4)	h kW/m²K	X [-]	T-gas, K / T-liq, K	V-gas, m/s / V-liq, m/s	
CV-113	0.00 / 4.64	592 / 592	0.00	31.96	578	566	555	98.01	0.30	551 / 549	6.48 / 6.15	CV-169
JN-113												JN-168
CV-114	0.00 / 4.56	588 / 588	0.00	31.64	575	565	556	107.54	0.26	551 / 549	5.28 / 5.08	CV-168
JN-114												JN-167
CV-115	0.00 / 4.50	584 / 584	0.00	31.39	573	564	555	99.00	0.21	551 / 549	4.28 / 4.09	CV-167
JN-115												JN-166
CV-116	0.00 / 4.44	581 / 581	0.00	31.19	571	563	555	89.89	0.16	551 / 549	3.40 / 3.21	CV-166
JN-116												JN-165
CV-117	0.00 / 4.40	578 / 578	0.00	31.02	569	562	555	80.22	0.12	551 / 549	2.62 / 2.44	CV-165
JN-117												JN-164
CV-118	0.00 / 4.36	575 / 575	0.00	30.87	567	560	554	70.05	0.08	550 / 549	1.94 / 1.75	CV-164
JN-118												JN-163
CV-119	0.00 / 4.32	572 / 572	0.00	30.75	565	559	554	59.55	0.05	550 / 549	1.35 / 1.14	CV-163
JN-119												JN-162
CV-120	0.00 / 4.29	570 / 570	0.00	30.65	563	558	554	48.93	0.02	550 / 549	0.99 / 0.65	CV-162
JN-120												JN-161
CV-121	0.00 / 4.27	568 / 568	0.00	30.57	562	557	553	24.16	0.00	546 / 546	0.00 / 0.46	CV-161
JN-121												JN-160
CV-122	0.00 / 4.24	566 / 566	0.00	30.51	561	557	553	7.17	0.00	533 / 533	0.00 / 0.45	CV-160
JN-122												
					T(1)	$\frac{T(2)+T(3)}{2}$	T(4)					

T-fluid [K]: 600, 590, 580, 570, 560, 550, 540, 530, 520

T-wall [K]: 600, 590, 580, 570, 560, 550, 540, 530, 520

JN-122: 4503 kg/s, 4.23 m/s — to CV-123: 566 K, 15.48 MPa

JN-151: 752 kg/s, 0.44 m/s — from CV-150: 521 K, 6.20 MPa

Node 168
q(POOL) = 7.3E+005 W/m²
q(ATMS) = 4.0E+003 W/m²
Q(POOL) = 1.1E+008 W
Q(ATMS) = 6.6E+005 W
Q(POOL)/A = 3.6E+005 W/m²
Q(ATMS)/A = 2.1E+003 W/m²

Node 165
q(POOL) = 4.7E+005 W/m²
q(ATMS) = 2.2E+003 W/m²
Q(POOL) = 7.9E+007 W
Q(ATMS) = 3.4E+005 W
Q(POOL)/A = 2.5E+005 W/m²
Q(ATMS)/A = 1.1E+003 W/m²

SMR Steam Generator

- **Summary:**

Node 165	MELCOR $\alpha_{MAX} = 0.40$	MELCOR $\alpha_{MAX} = 0.95$	RELAP	SPECTRA	
q (code output)	3.8	0.47	0.30	0.25	MW/m^2
Q/A (hand-calc.)	0.39	0.25	0.30	0.25	MW/m^2

Node 168	MELCOR $\alpha_{MAX} = 0.40$	MELCOR $\alpha_{MAX} = 0.95$	RELAP	SPECTRA	
q (code output)	CHF	0.73	0.34	0.35	MW/m^2
Q/A (hand-calc.)	~0	0.36	0.34	0.35	MW/m^2

- **Conclusion:**
  - In bubbly flow regime MELCOR overestimates heat flux
    - ✓ by ~10 for default α_{MAX},
    - ✓ by ~2 for α_{MAX}=0.95,
    - ✓ no effect of α_{MAX} above 0.95.
  - Effectively MELCOR underestimates CHF by the above mentioned ratios.
  - This conclusion was reached with MELCOR 1.8.6.
    Input converted to MELCOR 2.x → approximately the same results obtained with MELCOR 2.1.5540.

PWR SG MELCOR Model

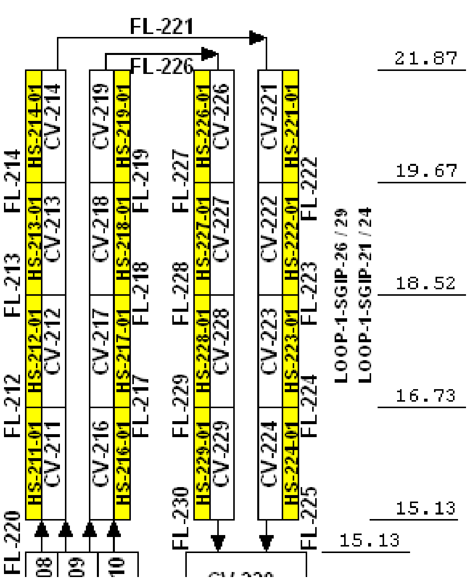
- **Results of 1300 MW_{th} PWR, KCB, MELCOR 2.1**
  - **Secondary side modeled by a single volume, CV-300**
- **Summary**
  - **No overestimation of heat flux.**
- **Conclusion**
  - **No effect in typical PWR SG geometry and modeling approach. Seems to be SMR-specific.**
  - **Is dividing secondary side of SG into a number of nodes (Control Volumes) a good idea?**

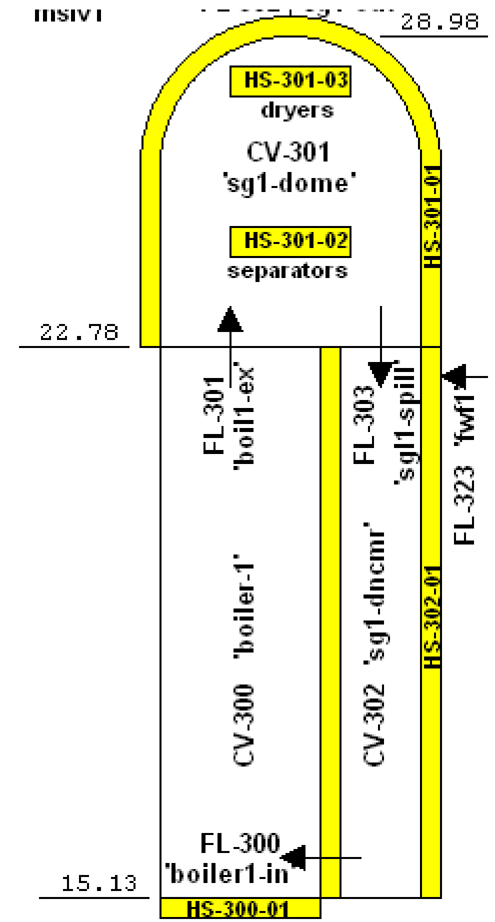
Node 214
q(POOL) = 1.8E+005 W/m²
q(ATMS) = 0.0E+000 W/m²
Q(POOL) = 5.8E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 1.8E+005 W/m²
Q(ATMS)/A = 0.0E+000 W/m²

Node 221
q(POOL) = 1.5E+005 W/m²
q(ATMS) = 0.0E+000 W/m²
Q(POOL) = 4.7E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 1.5E+005 W/m²
Q(ATMS)/A = 0.0E+000 W/m²

Node 211
q(POOL) = 3.0E+005 W/m²
q(ATMS) = 0.0E+000 W/m²
Q(POOL) = 6.7E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 2.9E+005 W/m²
Q(ATMS)/A = 0.0E+000 W/m²

Node 224
q(POOL) = 9.8E+004 W/m²
q(ATMS) = 0.0E+000 W/m²
Q(POOL) = 2.2E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 9.7E+004 W/m²
Q(ATMS)/A = 0.0E+000 W/m²





Zircaloy Oxidation Model

MELCOR model:

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

Life function (T ≠ const):

$$LF = \int_0^t \frac{\vartheta}{\tau} \mathrm{d}\vartheta = 1$$

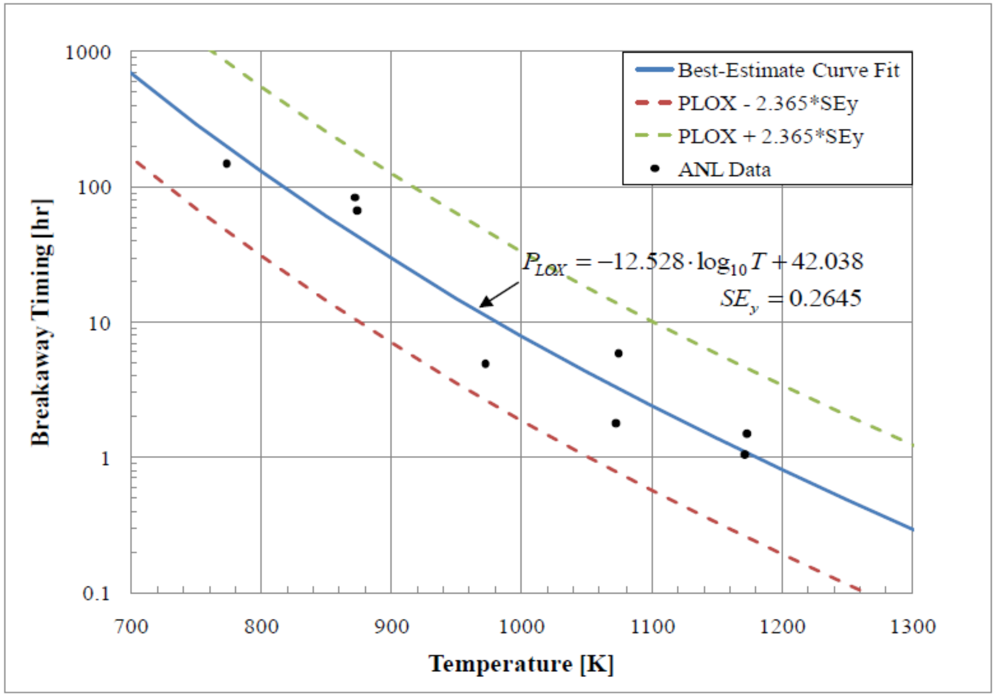
$$t = \sqrt{2\tau}, \qquad T = const$$

- 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

Modification of documentation:

$$LF = \int_0^t \frac{\mathrm{d}\vartheta}{\tau} = 1$$

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

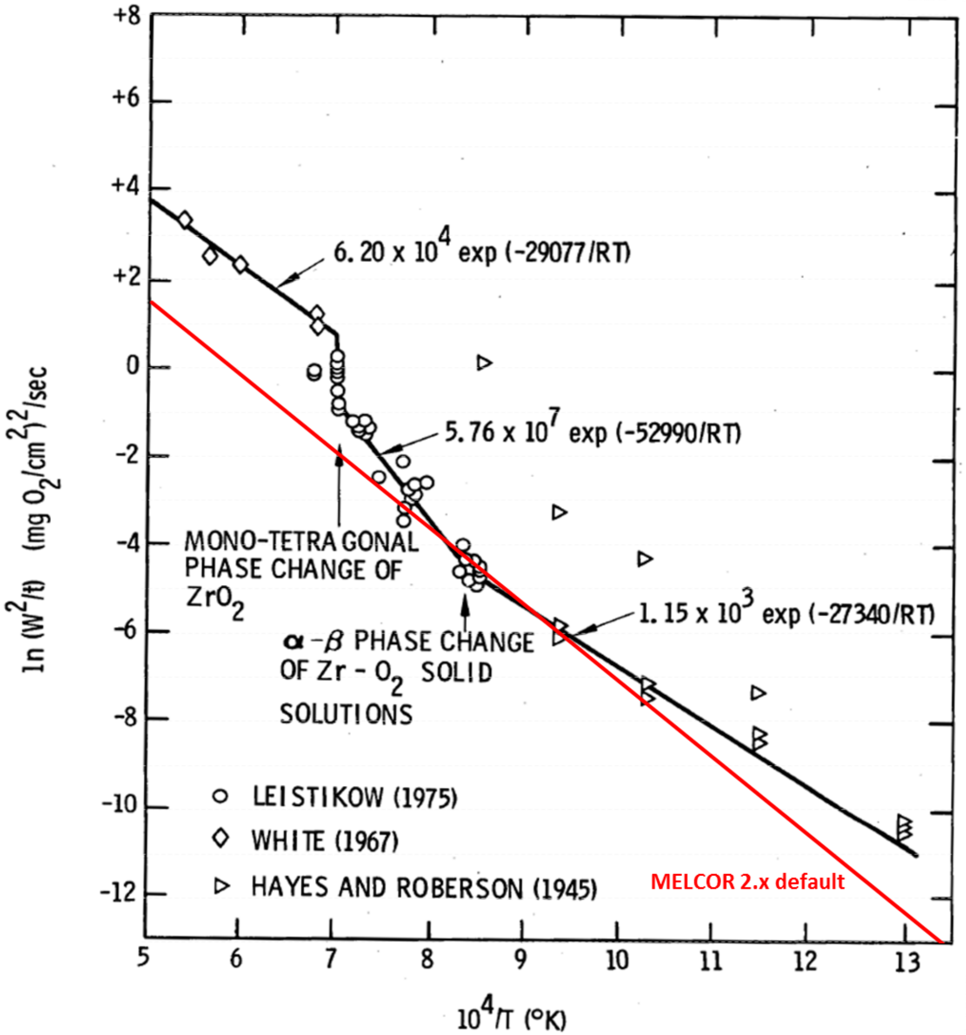


R. Gauntt et al., Fukushima Daiichi Accident Study, SAND2012-6173

Zircaloy Oxidation Model

MELCOR 2.1 breakaway option (COR_OXB):

- By default the code adopts the pre-breakaway model (red line in the plot) without rising warnings, which is non-conservative for safety assessment
- MELCOR 1.8.6 uses Powers model (NUREG/CR-0649) by default for oxidation, which has a different behaviour wrt version 2.1)
- <u>It is envisaged to adopt post-breakaway model by default (more consistent with code version 1.8.6)</u>



Conclusions

Troubles and Issues

- **Fukushima SFP4:**
  - SFP-BWR reactor type: radial core debris relocation option failure (Word 10 of COR_TST card set to value ISPR=3, disable the two radial relocation models)
- **SMR Steam Generator:**
  - SG secondary side: fine CV nodalization can lead to CHF condition encountered in high void fraction volumes when high heat flux is involved
- **Oxidation Model:**
  - Misdescription of the life function for time to breakaway in MELCOR 2.1 documentation
  - Different default behaviour for the treatment of post-breakaway oxidation model with respect to the previous MELCOR 1.8.6

Summary

- **Wide range of applications of MELCOR**
- **Many years of user experience: code versions from 1.8.2, 1.8.3, 1.8.4, 1.8.6 (mostly used in the past) to recent 2.x applications**

NRG

Thank you for your attention!
Questions?