

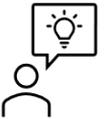
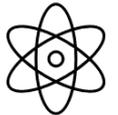


SAFETY ANALYSIS OF SMR WITH PASSIVE MITIGATION STRATEGIES - SEVERE ACCIDENT

ANALYSIS OF POSTULATED DBA AND SEVERE ACCIDENT SCENARIOS IN GENERIC INTEGRAL PWR SMALL MODULAR REACTORS IN THE FRAME OF THE HORIZON EURATOM SASPAM-SA PROJECT

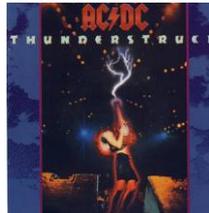
F. Gabrielli
on behalf of the SASPAM-SA WP2 Community

Karlsruhe Institute of Technology

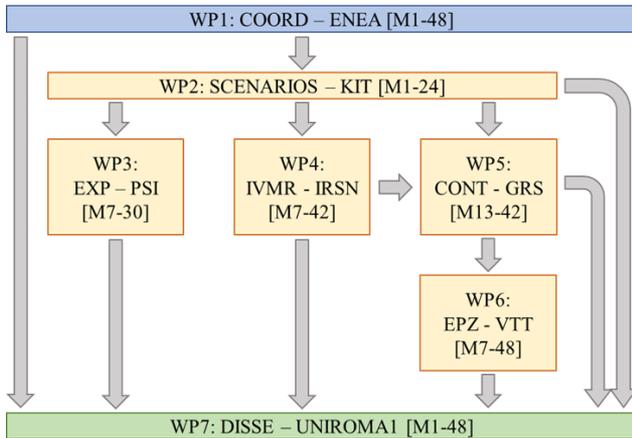


- 17 institutions: CIEMAT, EDF, ENEA, FZJ, GRS, IRSN, JRC, KIT, KTH, LEI, PSI, PSS RUB, RATEN, SSTC NRS, TRACTEBEL, VTT, UNIROMA1
- The SASPAM-SA WP2's Community

F. Mascari, A. Bersano, P. Maccari, S. Ederli, M. E. Cazado, V.H. Sanchez-Espinoza, M. Di Giuli, J. Bittan, N. Bakouta, M. Malicki, T. Lind, M. Makarenko, Yu. Yesipenko, O. Zhabin, D. Gumenyuk, S. Kelm, E.-A. Reinecke, C. Vázquez-Rodríguez, M. K. Koch, J. Krieger, G. Stahlberg, T. Jankowski, M. Garcia Martin, L. E. Herranz, N. Reinke, A. Bentaib, L. Carenini, J.-C. de la Rosa Blul, O. Papera Villacampa, A. Kaliatka, M. Valincius, M. Constantin, F. Giannetti, T. Sevon, P. Groudev
- The song of the WP2: AC/DC, Thunderstruck ('The Razors Edge', 1990, EMI)



- Pillars: elements not addressed in other on-going iPWR initiatives



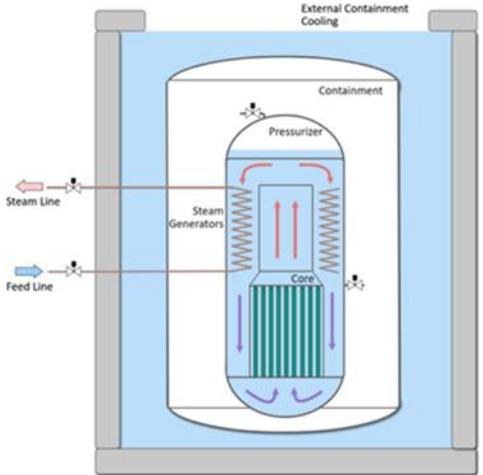
- **Input deck development and hypothetical SA scenarios assessment (SCENARIOS) (WP2)**

- Existing SA **experimental database** for iPWR Assessment (EXP) (WP3) (F. Mascari, session 6)
- Code capabilities to simulate the **IVMR** (WP4)
- Code capabilities to simulate **containment** phenomena and mitigation measures (CONT) (WP5)
- Characterization of **EPZ** (EPZ) (WP6)
- Education and Dissemination (DISSE) (WP7)

- Inside SASPAM-SA, the WP2 aims providing Input data/Boundary conditions for the activities foreseen in the other WPs

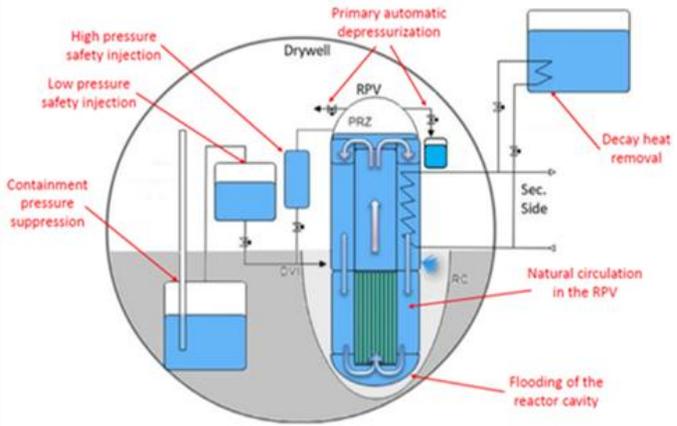
iPWR Design-1

Submerged containment, P~60 MWe



iPWR Design-2

Dry containment, several passive systems, P~300 MWe



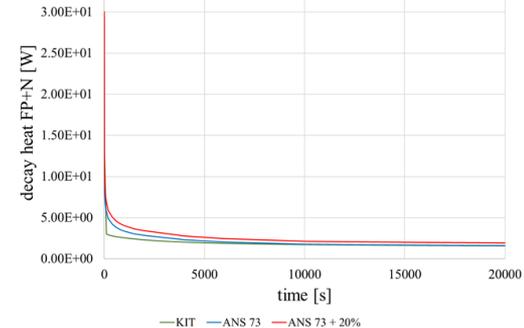
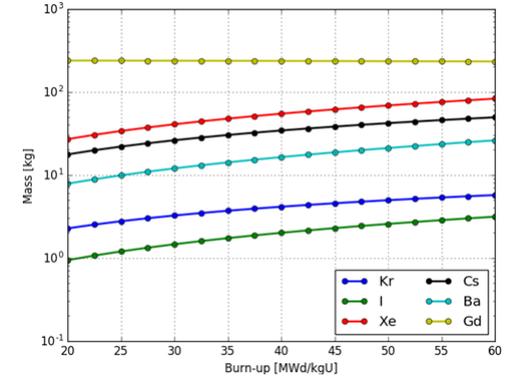
- The designs incorporate the main safety features of the most promising concepts ready for deployment in the European market
- **It is not the project's objective to assess the design of such concepts**



- Evaluating the capabilities of state-of-art European and non-European integral SA and CFD codes to simulate the key phenomena occurring in generic iPWR designs in hypothetical accident conditions
 1. Assessment of generic, but representative, SA and CFD codes' datasets of the iPWR Design-1 and Design-2
 2. Postulating DBA and SA sequences
 3. Analysis of the postulated DBA and SA scenarios

- Dedicated task also devoted to SA analyses employing ATF's cladding materials (FeCrAl)

- **Common database** of the generic iPWR Design-1 and Design-2 based on open literature to assess datasets
- **Fuel inventory and Decay Heat**
 - Depletion of a representative 2D fuel assembly of by means of CASMO5
 - Fuel inventories from 20 MWd/kgU to 60 MWd/kgU, with a burn-up step of 2.5 MWd/kgU composed of **300 isotopes**, i.e. isotope-wise mass [kg] and activity [Bq]
 - ANS73 and ANS73+20% decay data also considered



- **Postulated scenarios**
 - **No PSA assessments employed** → SA scenarios selected in terms of severity and not of probability to occur
- **Benchmarking the integral codes is NOT the main objective**
 - Starting from a common database, the partners were free also to explore the effect of modelling on the performance of the codes → **in line with the main goal of the WP2**
- **WP2's Keyword: SHARING**
 - The datasets are shared among the partners upon request

iPWR Design-1

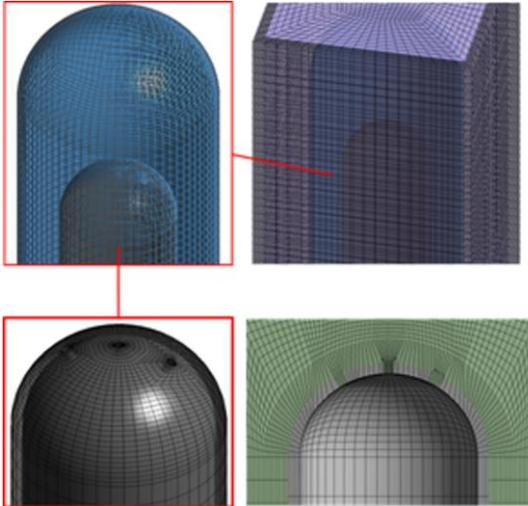
Partner	Code
EDF	EDF-MAAP5.04
GRS	Support to the AC ² users
IRSN	Support to the ASTEC users
KIT	ASTECv3.1
KTH	MELCORv2.2
PSI	MELCORv2.2
RATEN	Scenarios
RUB	AC²
SSTC NRS	ANSYS CFX (CFD)
TRACTEBEL	ASTECv2.2/v3.1

iPWR Design-2

Partner	Code
CIEMAT	MELCORv2.2
ENEA	ASTECv3.1/MELCORv2.2
FZJ	CAD and containmentFOAM
GRS	Support to the AC ² users
JRC	MAAP 5.06
IRSN	Support to the ASTEC users
LEI	AC²
RATEN	Scenarios
UNIROMA1	MELCORv2.2

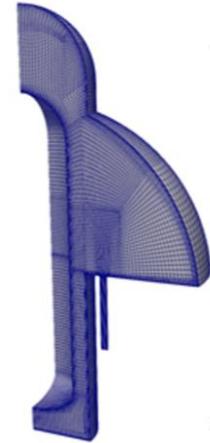
J

- **ANSYS CFX** model of the iPWR Design-1
- 370,000 nodes for the initial round of calculations



(courtesy of M. Makarenko, SSTC NRS)

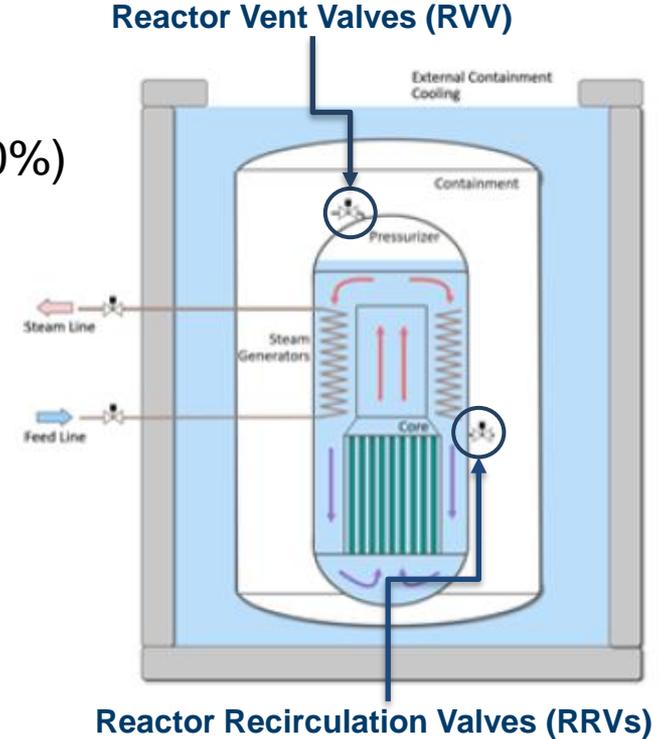
- **ContainmentFOAM** model of the iPWR Design-2
- Preliminary meshes using between 200,000 and 750,000 cells for representing one quarter of the Desing-2 containment



(courtesy of C. Vázquez-Rodríguez, S. Kelm, FZJ)

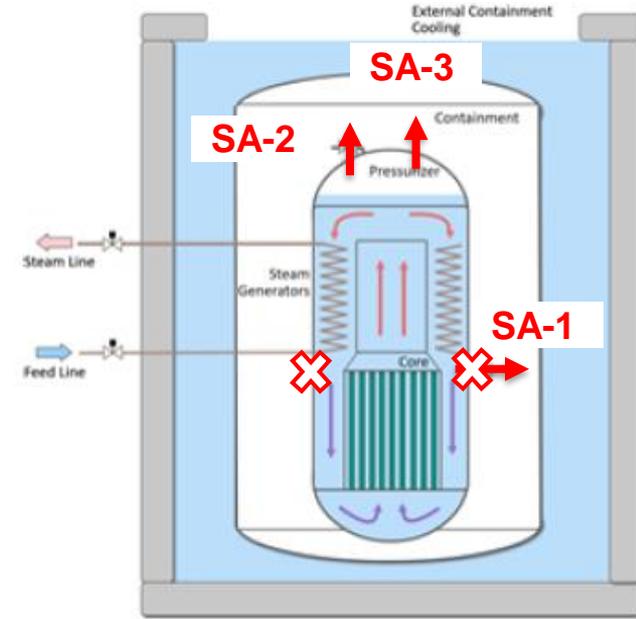
Chemical and Volume Control System make-up line break with loss of AC

- Break of different sizes (10%, 20%, 35%, 100%)
- Loss of AC @ $t = 0$ s
- Transient progression
 - Loss of FDW
 - Reactor SCRAM
 - Isolation of the MSL
 - Activation of the ECCS
 - $(P_{RPV} - P_{CNV} < 62 \text{ bar})$ & CNV level $> 5.8 \text{ m}$
 - Opening of 3 RVVs and 2 RRVs



- **SA-1: 100% break on the CVCS makeup line**
- **SA-2: Inadvertent opening of 1 RVV valve**
- **SA-3: 100% break on the Venting line**

- Loss of AC @ $t = 0$ s
- **Accident progression:**
 - Loss of FDW and Reactor SCRAM
 - Isolation of the MSL
 - Activation of the ECCS
 - ($P_{RPV} - P_{CNV} < 62$ bar) & CNV level > 5.8 m
 - Opening of 3 RVVs and **failure** of 2 RRVs



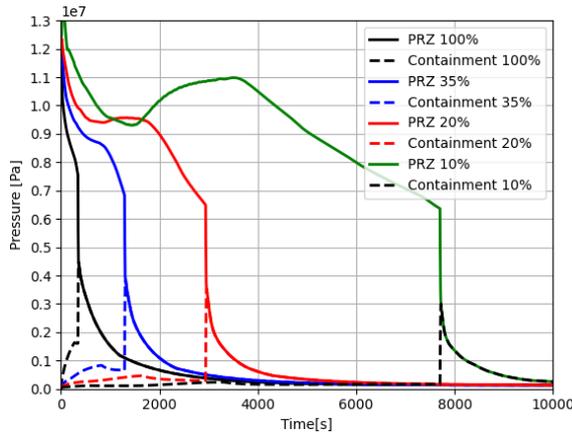
➤ Decay heat: WP2 (a), ANS73 (b), and ANS73+20% (c)

SAFETY ANALYSIS OF SMR WITH PASSIVE
MITIGATION STRATEGIES - SEVERE ACCIDENT

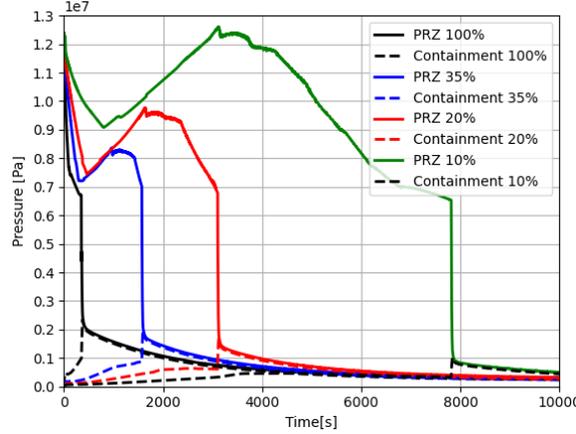
Scenario	DBA 100%	DBA 35%	DBA 20%	DBA 10%	SA-1	SA-2	SA-3
ASTECv2.2 (Tractabel)	b, c	b, c	b, c	b, c	b, c	b, c	b, c
ASTECv3.1 (Tractabel)	b	b	b	b	b	b	b
ASTECv3.1 (KIT)	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c	a, b, c
EdF-MAAP (EdF)	c	c	c	c	c	c	c
MELCORv2.2 (PSI)	b, c	b, c	b, c	b, c	b, c		
AC2 (PSS RUB)	c	c	c	c	c		
MELCORv2.2 (KTH)				b	b		
ANSYS CFX (SSTC)					b		



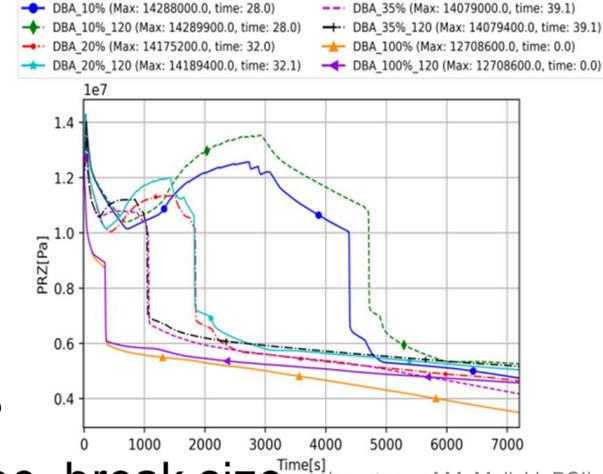
ASTECv3.1



EdF-MAAP

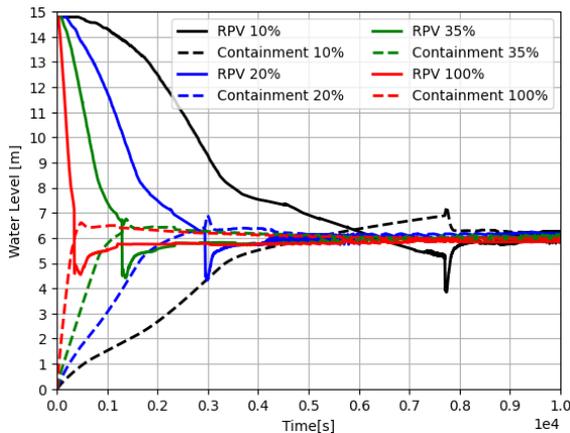


MELCOR

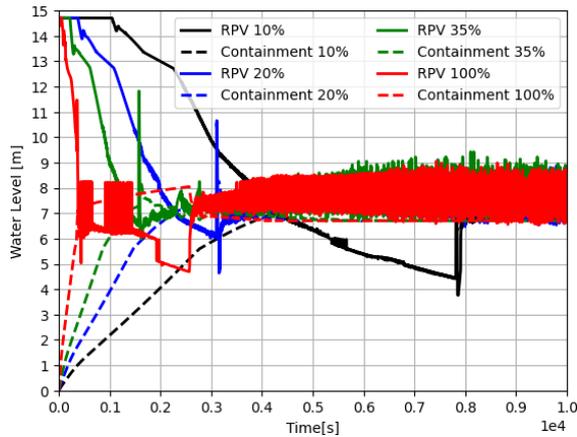


- Kinetics of the RPV depressurization depends on the break size (courtesy of M. Malicki, PSI)
- Only part of the decay heat evacuated through the break → pressure increase in the RPV
- When the ECCS valve opening → core refilled by gravity
- **Good agreement on the timing of the ECCS activation**

ASTECv3.1

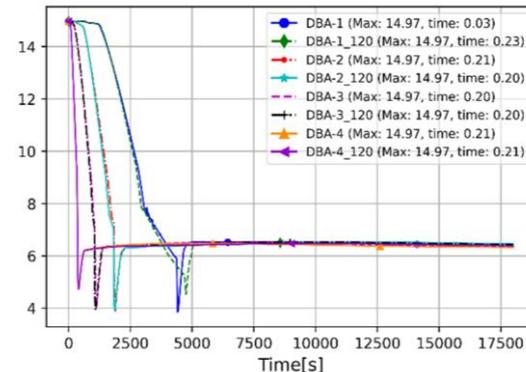


EdF-MAAP

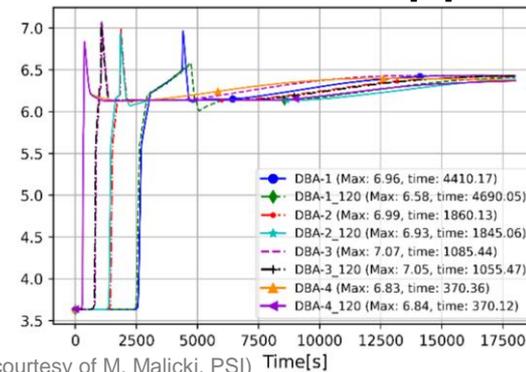


MELCORv2.2

Water Level RPV [m]



Water Level CNMT [m]

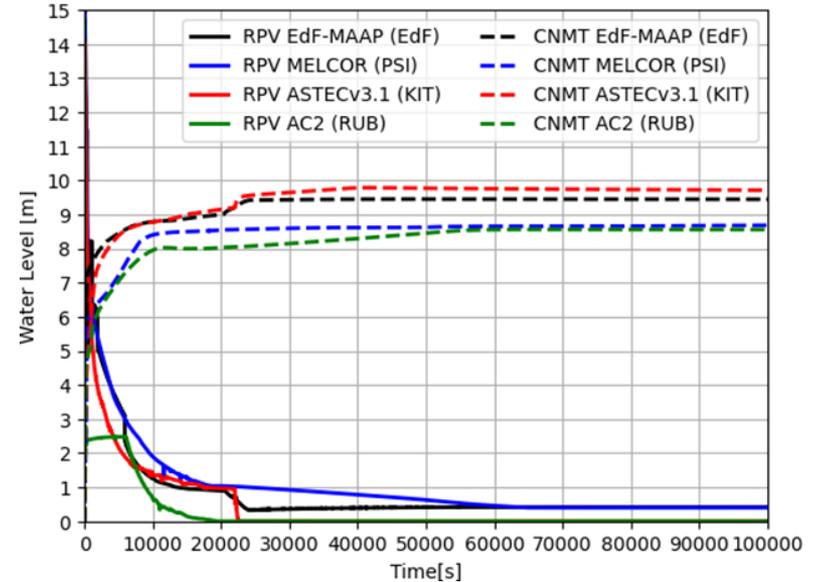


➤ Codes are able to predict the key TH phenomena, e.g., single and two-phase natural circulation in integral RPV

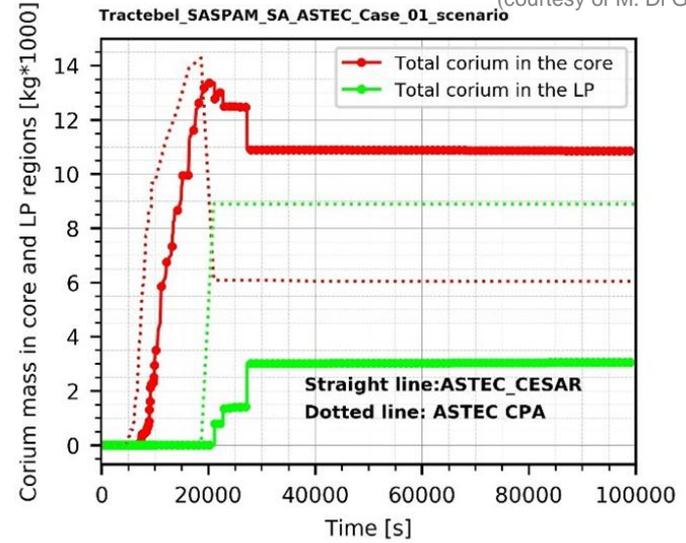
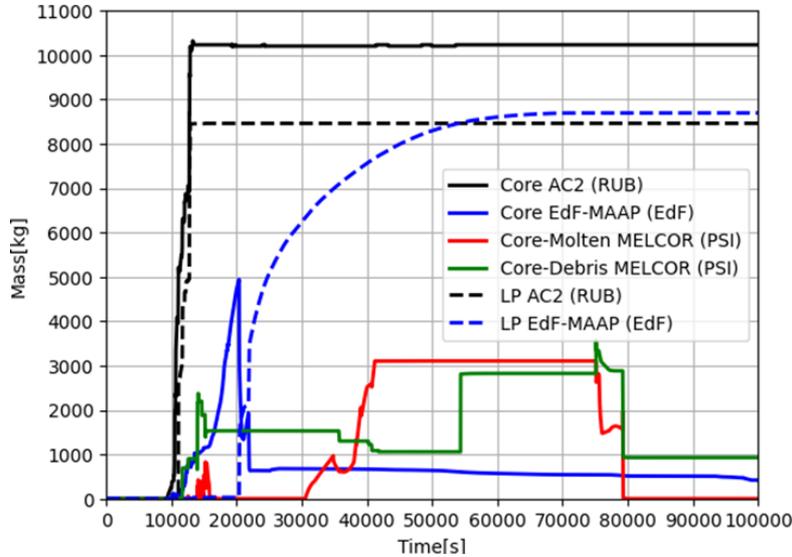
(courtesy of M. Malicki, PSI) Time[s]



- RPV depressurizes while the pressure in the CNTM increases up to equalizes to about 0.1 MPa
- Because of the stack of the RRVs, the core is isolated and the water level decreases below the TAF quite early and it is completely uncovered at about 25,000 s



(courtesy of M. Di Giuli, Tractebel)

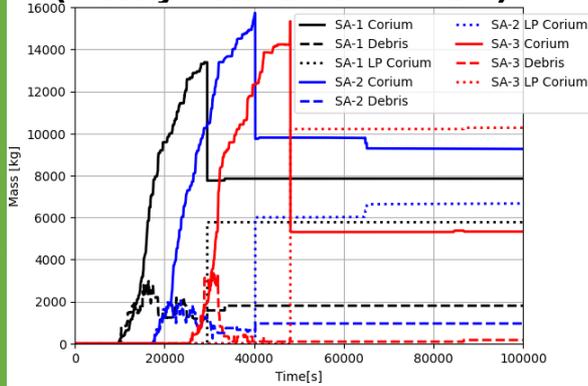


- The timing of the relevant phenomenological of the core degradation progress shows a reasonable agreement
- Degradation begins at 10,000 – 15,000 s
- Mass of material relocated in the LP 8.5 – 10.5 ton



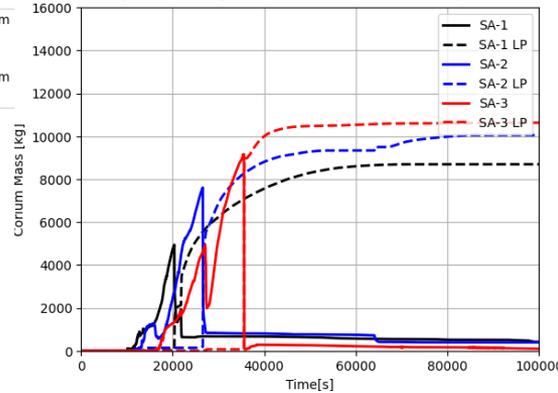
ASTECv3.1

(Decay heat SASPAM-SA)



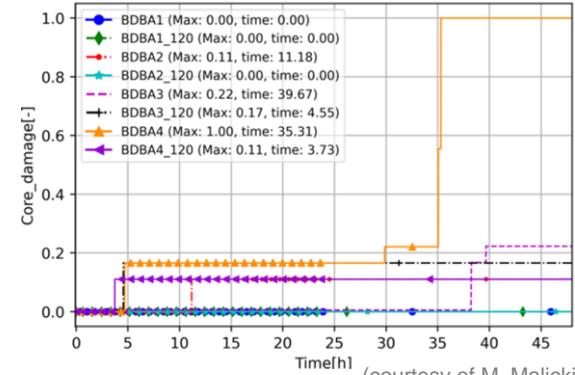
EdF-MAAP

(Decay heat ANS73)



MELCOR

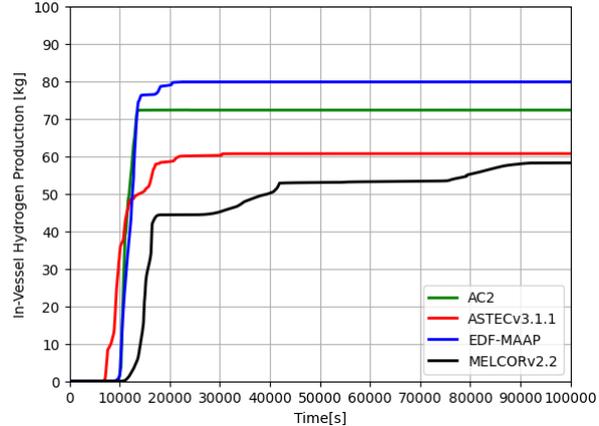
(Decay heat ANS73 and ANS73+20%)



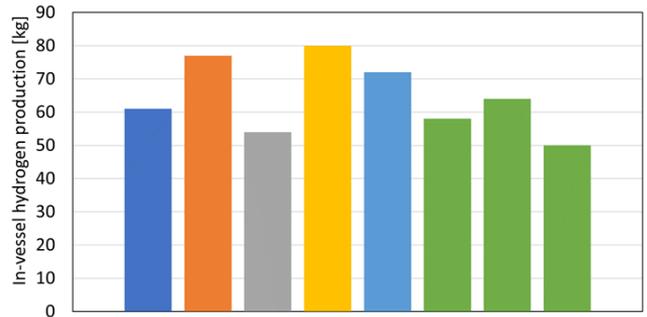
(courtesy of M. Malicki, PSI)

- No RPV failure is predicted by the codes for any of the postulated SA scenarios
- Deviation on the timing of material relocation to the LP is ~3,000 s, when using the same decay heat data

SA-1 (ANS73+20%)

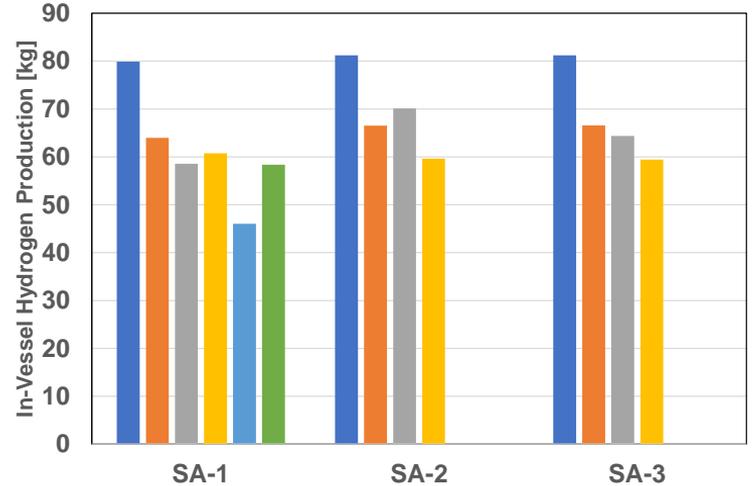


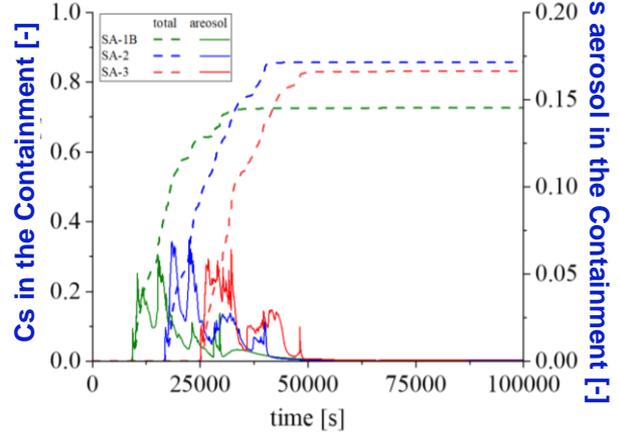
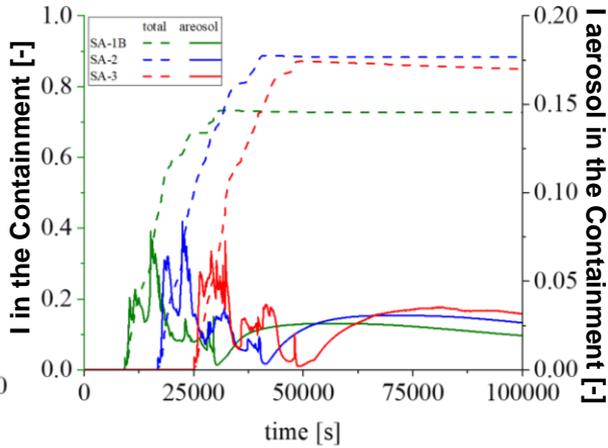
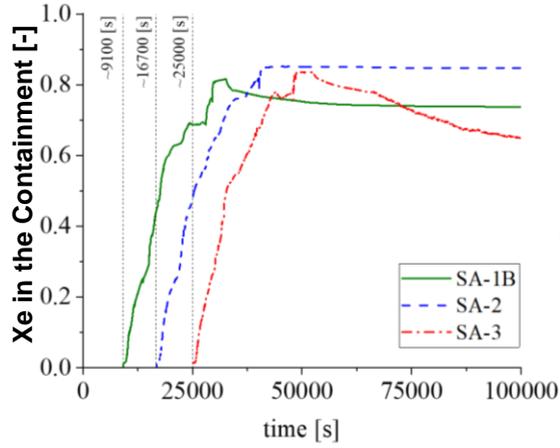
- ASTECv3.1 (KIT)
- ASTECv2.2 (CESAR, Tractebel)
- ASTECv3.1(Tractebel, CPA)
- EdF-MAAP (EdF)
- AC2 (RUB)
- MELCOR (PSI)



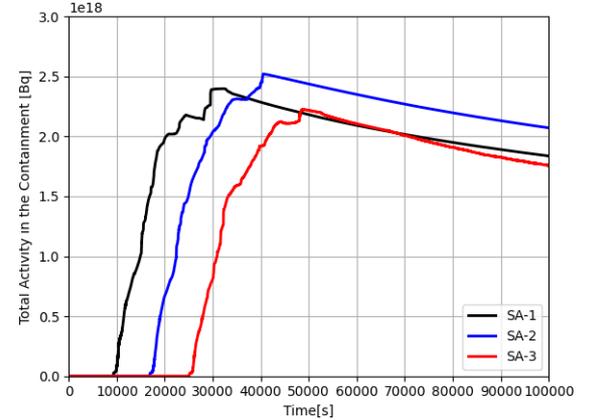
- Deviation among the codes:
 - On **H2 onset**, ~ 1,000-2,000 s when using the same decay heat data
 - On **H2 produced**, ~20 kg

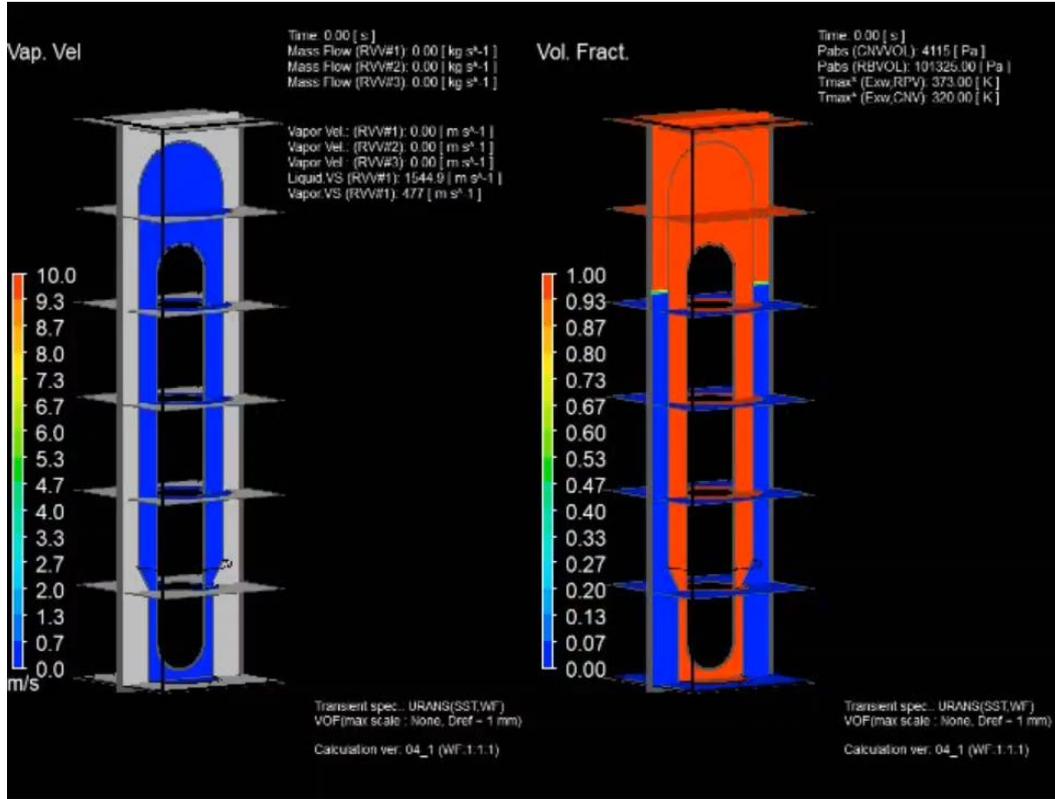
Codes and Decay Heat





- I and Cs aerosols released to the CNMT ~ 7.5% of the initial loading
- Maximum activity in the CNMT ~ 10% of the initial activity in the core ($2.3E+19$ Bq)





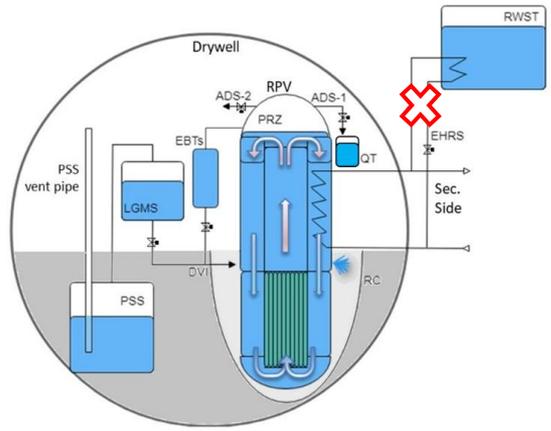
(courtesy of M. Makarenko, SSTC NRS)

- SA-2: 1000 s transient
- BCs from MELCOR (adjusted at the first 300 s to avoid choked flow)

- **DBA: Guillotine break of one Direct Vessel Injection (DVI) line**
- **Severe Accidents: DBA +**

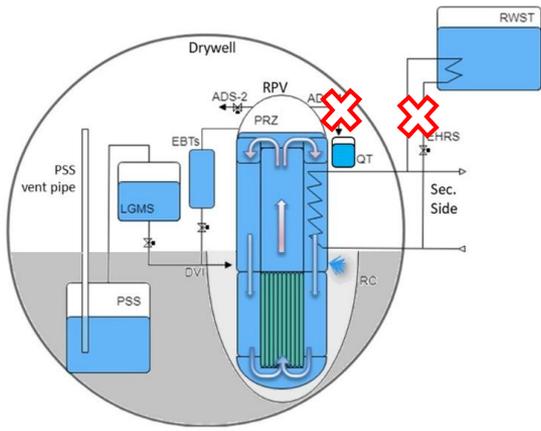
SA-1

Unavailability of EHR systems



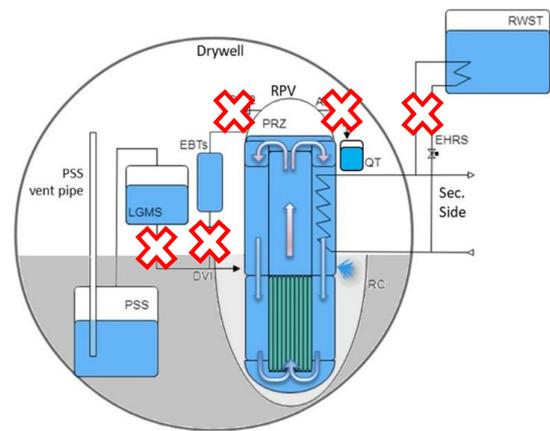
SA-2

Unavailability of EHR systems and ADS-1 systems



SA-3

Unavailability of ALL the safety systems



EHRs: Emergency Heat Removal System

(courtesy of A. Bersano)

➤ Decay heat from WP2 employed

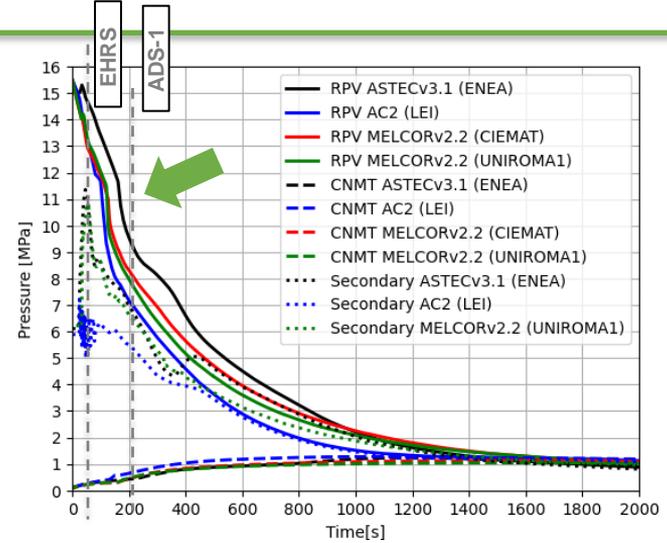
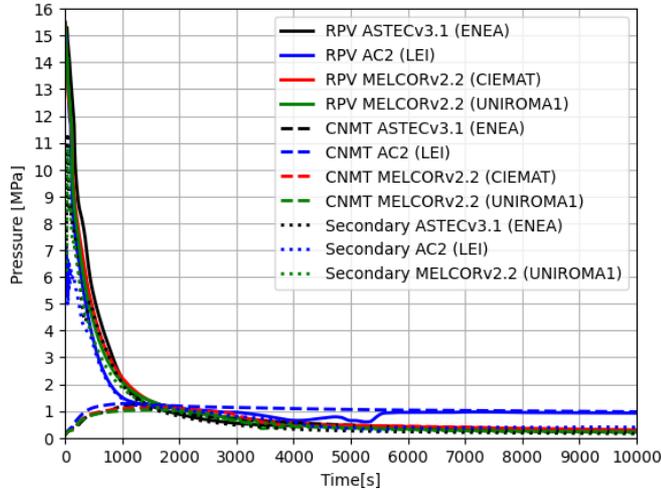
Scenario	ASTEC v3.1 (ENEA)	MELCOR v2.2 (UNIROMA1)	MELCOR v2.2 (CIEMAT)	MAAP V5.06 (JRC)	AC2 (LEI)
DBA	X	X	X	X	X
SA-1	X	X		X	
SA-2	X		X	X	
SA-3	X	X	X	X	X

IPWR Design-2: DBA Scenario results

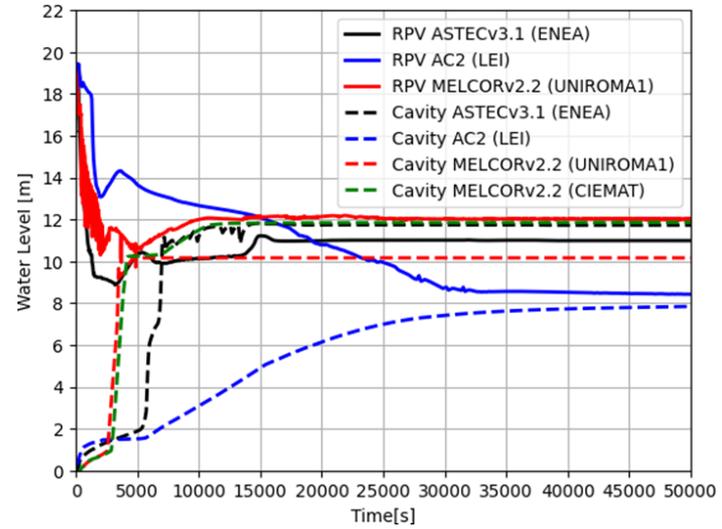
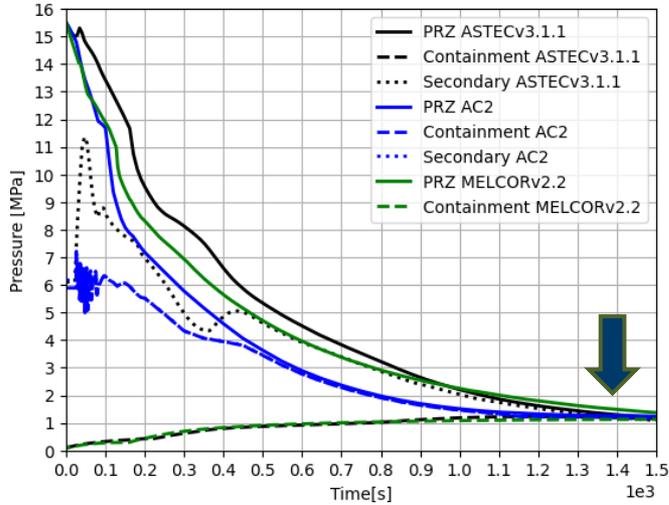
SAFETY ANALYSIS OF SMR WITH PASSIVE MITIGATION STRATEGIES - SEVERE ACCIDENT

Event	ASTECv3.1 (ENEA)	MELCORv2.2 (UNIROMA1)	MELCORv2.2 (CIEMAT)	MAAP5.06 (JRC)	AC ² (LEI)
Break of DVI line-A	0	0	0	0	0
High containment pressure setpoint (s)	20	27	28	31	28
↑SCRAM ↑Secondary system isolation ↑EHRs					
Low pressurizer level signal (s)	68	88		50	62
↑RCP coast-down ↑RI-DC valves opening					77
Low pressurizer pressure signal (s)	160	109	108	170	92
↑EBTs ↑ADS stage-1					
Low DP RPV-containment signal (s)	1466	1780	1750	1274	1904
↑LGMS					
Low LGMS mass signal (s)	13459	13295	11030	25920	14301
Start of reverse flow in the PSS (s)	4950	2850	4170	5050	15400
Collapsed Maximum liquid level in the containment (m)	11.76		11.8		8.44
Collapsed Minimum level in the core from LP bottom (m)	3.84	2.98	4.52		5.54
Core TAF refilled - collapsed (s)	5500	1000	5650	4320	





- Peak pressure in the secondary system quickly decreases (heat removal from the Refuelling Water Storage Tank)
- When the low PRZ level set-point is reached, the reactor coolant pumps coast-down occurs → **natural circulation in the RPV**
- **The low-pressure set-point in the PRZ triggers the ADS-1 → rapid decrease of the primary and secondary pressure**



- **RPV and drywell (DW) pressures equalization → Long term Gravity Make-up System (LGMS) to the RPV and the reactor cavity (RC)**
- DW pressure decreases below the Pressure Suppression System (PSS) pressure → PSS water pushed inside the PSS vent pipes and fills the RC
- **All the codes been able to predict most of the key TH phenomena**



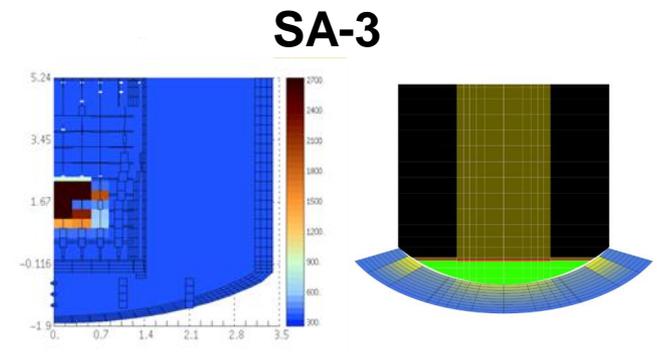
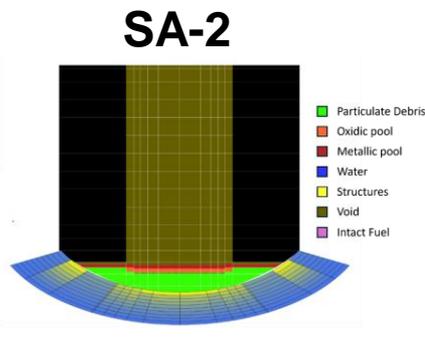
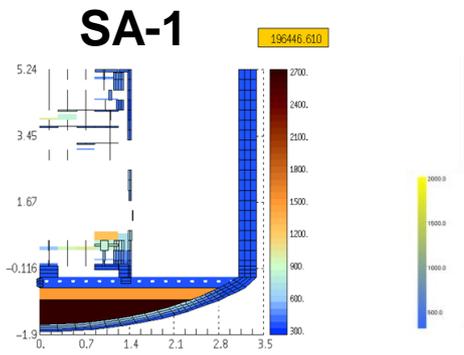
Event	SA-1	SA-2	SA-3
Start of the transient (t_0)	0	0	0
High containment pressure setpoint (s)	20	20	20
Low pressurizer level signal (s)	90	90	90
Low DP RPV-containment signal (s)	18581	45303	53532
Actuation of LGMS (s)	18586	45308	-
Low LGMS mass signal (s)	150174	133087	-
LGMS emptying (s)	18586	160000	-
Actuation of ADS-2 (s)	150174	133087	-
Containment failure	800	2500	4020
Start of reverse flow in the PSS (s)	815	2530	4060
RC collapsed level at DVI level (s)	1030	2800	4300
Core uncover (TAF reached), (s)	5830	2000	5280
Time of H2 production onset (s)	11500	8000	7294
Start of FPs release from fuel (s)	12528	9651	10386
Core uncover (BAF reached), (s)	-	76860	72960
First corium slump (s)	-	92900	74610

SA-1 unavailability of EHR systems	Event	ASTEC v3.1 (ENEA)	MELCOR v2.2 (UNIROMA1)	MAAP v5.06 (JRC)
	Containment failure*		800	680
Core uncover (TAF)		5830	3136	2804
H2 onset		11500	18138	4762
Start of FPs release		12528		19800
Core uncover (BAF)		-	58059	10231
First core failure		12528	35280	10231
First corium slump		-	67060	32700

SA-2 unavailability of EHRs and ADS-1 systems	Event	ASTEC v3.1 (ENEA)	MELCOR v2.2 (CIEMAT)	MAAP v5.06 (JRC)
	Containment failure*		2500	4630
Core uncover (TAF)		2000	610	2804
H2 onset		8000	12290	4762
Start of FPs release		9651	12610	19800
Core uncover (BAF)		76860	23970	10231
First core failure		9700	13450	10231
First corium slump		92900	29850	62192

➤ **No lower head vessel failure due to the ex-vessel reactor cooling**

SA-3 unavailability of all safety systems	Event	ASTEC v3.1 (ENEA)	MELCOR v2.2 (UNIROMA1)	MELCOR v2.2 (CIEMAT)	MAAP v5.06 (JRC)	AC ² (LEI)
		Containment failure*	4020	3090	5730	13327
	Core uncover (TAF)	5280	4250	1690	2675	3600
	H2 onset	7294	12290	9070	3980	7000
	Start of FPs release	10386	9390	9390		7000
	Core uncover (BAF)	72960	23800	18680	12411	11000
	First core failure	10386	14630	10270	9955	13500
	First corium slump	74610	27300	24300	13327	

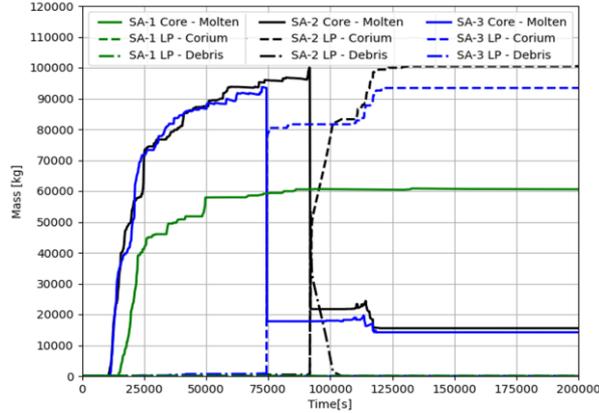


➤ No lower head vessel failure due to the ex-vessel reactor cooling

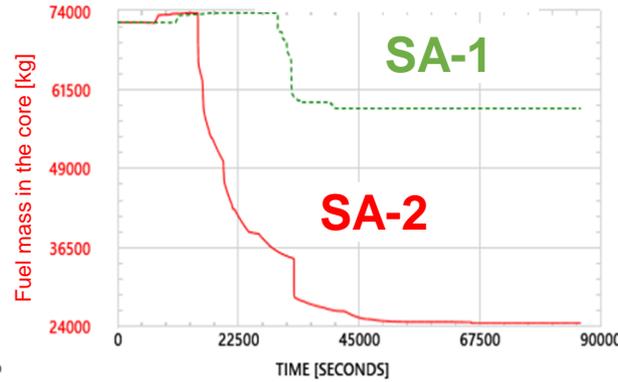
* Design pressure: ASTEC, MELCOR, AC2 (1.4 MPa), MAAP v5.06 (2.4 MPa)



ASTECv3.1

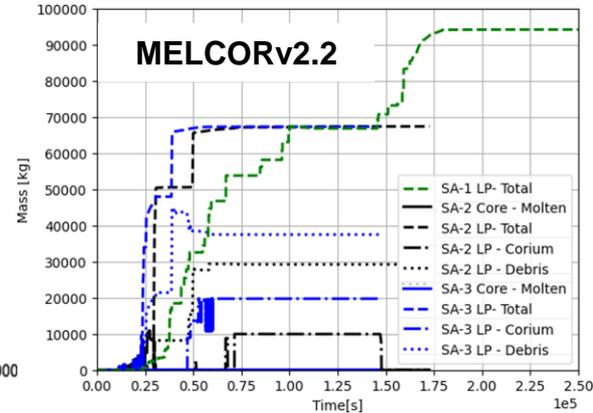


MAAP v5.06



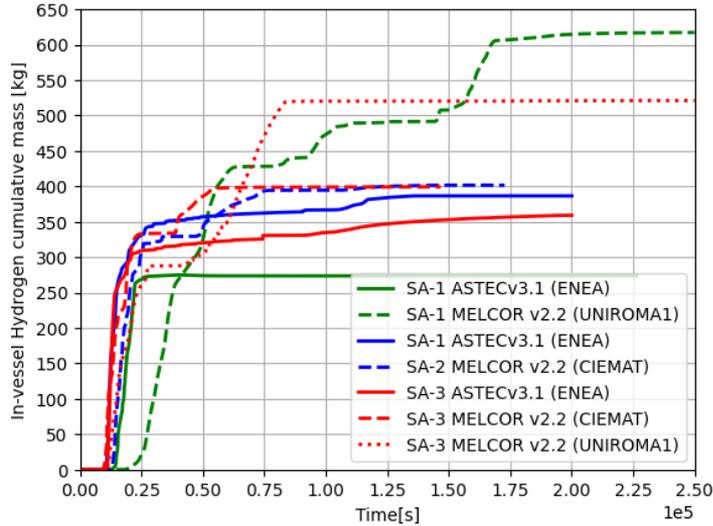
(courtesy of J. C. de la Rosa Blul, JRC)

MELCORv2.2

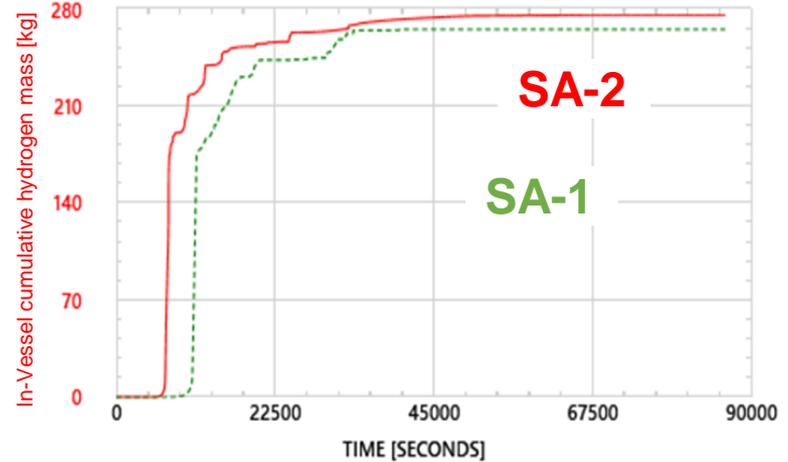


- Increase of the systems unavailability (SA-1 to SA-3) → Increase of the severity of the core degradation conditions
- **No RPV failure in any scenario**
- Deviation on mass relocated in the LP (SA-2 and SA-3) ~2 ton
- SA-1: different prediction on the relocation in the LP



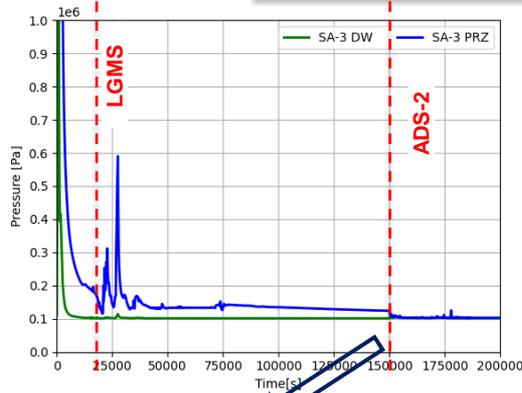


MAAP v5.06

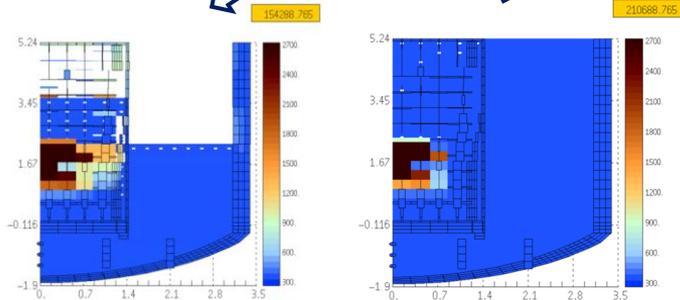


(courtesy of J. C. de la Rosa Blul, JRC)

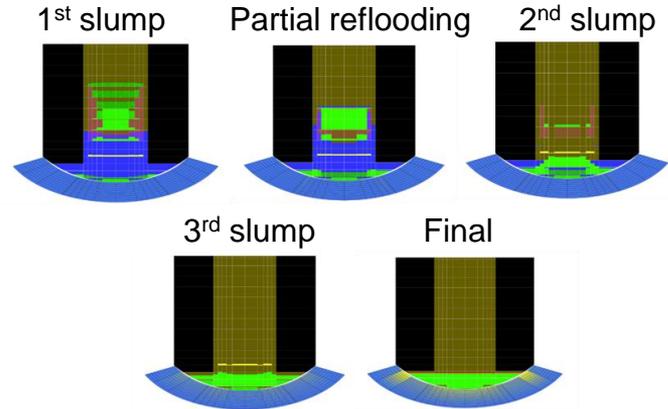
- H₂ production ranges from 280 (SA-1) to 400 (SA-3) kg
- MELCORv2.2 (UNIROMA1): higher production due to multiple corium slump



- ~ **150,000 s** → LGMS water level reached → triggering the Automatic Depressurization System-2 → RPV/containment pressure equalization
- Water begins re-entering from the RC though the break → core water refilling



MELCORv2.2



- Codes look able to reproduce the TH and in-core degradation phenomena before and after the refilling

iPWR Design-1

Partner	Code
KIT	ASTECv3.1
RUB	AC ²
VTT	MELCORv2.2

iPWR Design-2

Partner	Code
ENEA	ASTECv3.1
LEI	AC ²
UNIROMA1	MELCORv2.2

- Capabilities of integral codes to analyze hypothetical scenarios using ATF materials
- FeCrAl/Steam oxidation correlations from QUENCH Experiments

$$K = \begin{cases} 9.62 \times 10^{-12} [\text{g}^2/\text{cm}^4\text{s}], & T \leq 1473 \text{ K} \\ A_B \exp\left(\frac{-E_B}{RT}\right), & 1473 < T < 1648 \text{ K} \\ A_{Fe} \exp\left(\frac{-E_{Fe}}{RT}\right), & T \geq 1648 \text{ K (melting point of FeO)} \end{cases}$$

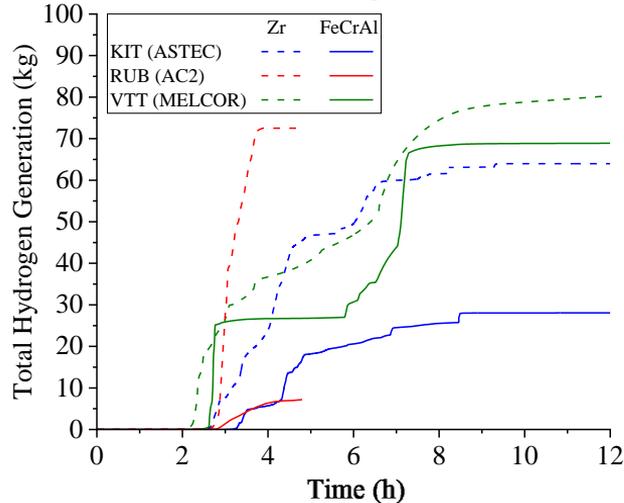
$$A_B = 3 \cdot 10^9 \text{ g}^2/\text{cm}^4 \text{ s} \quad E_B = 594354 \text{ J/mol}$$

$$A_{Fe} = 2.4 \cdot 10^6 \text{ g}^2/\text{cm}^4 \text{ s} \quad E_{Fe} = 352513 \text{ J/mol}$$

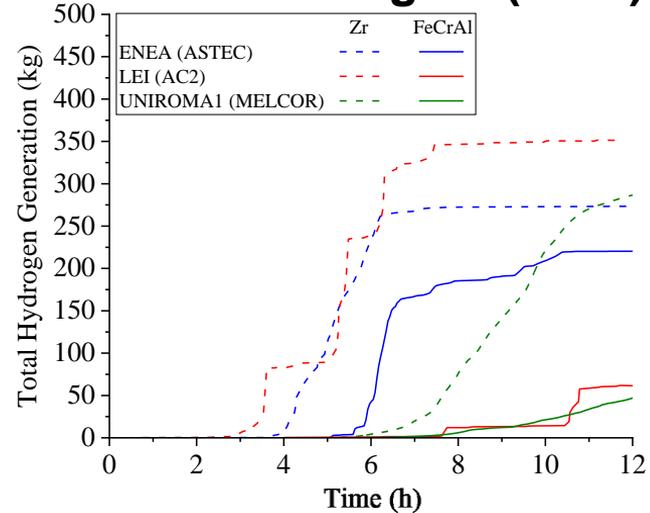
C. Kim, C. Tang, M. Grosse, Y. Maeng, C. Jang, M. Steinbrueck, Oxidation mechanism and kinetics of nuclear-grade FeCrAl alloys in the temperature range of 500–1500 °C in steam, Journal of Nuclear Materials, Volume 564, 2022, <https://doi.org/10.1016/j.jnucmat.2022.153696>

iPWR Design-1 (SA-1)

(courtesy of M. E. Cazado, KIT)



iPWR Design-2 (SA-1)



- FeCrAl implementation were successful for both designs and different codes
- H₂ production lower using ATF, although its effect is much more significant below the transition oxidation
- Delay of H₂-onset: ~1 hour (Design-1), ~1-2 hours (Design 2)

- SASPAM-SA unique project on iPWRs with respect to DiD levels 4 and 5
- Datasets of both state-of-art European and non-European integral codes and CFD tools for two generic iPWR designs assessed
- DBA and hypothetical SA scenarios have been postulated and analyzed
- **Integral codes able to predict the key TH phenomena occurring in iPWRs in the postulated scenarios**
- Results show a general good agreement among the codes
- Feedback from the users collected → codes' best practice, guidelines, and lessons learned provided and under review
- Large amount of results produced for the other investigations planned in the project, e.g., IVMR, Containment, EPZ



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