MELCOR Application to the Analysis of SMR

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Outline

- Introduction
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- SMR Steam Generator
  - TH model
  - CHF condition calculation
- SMR Check Valves
  - Control Function definition
- Collapsed Water Level
  - Sensitivity on bubble rise velocity
- 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)

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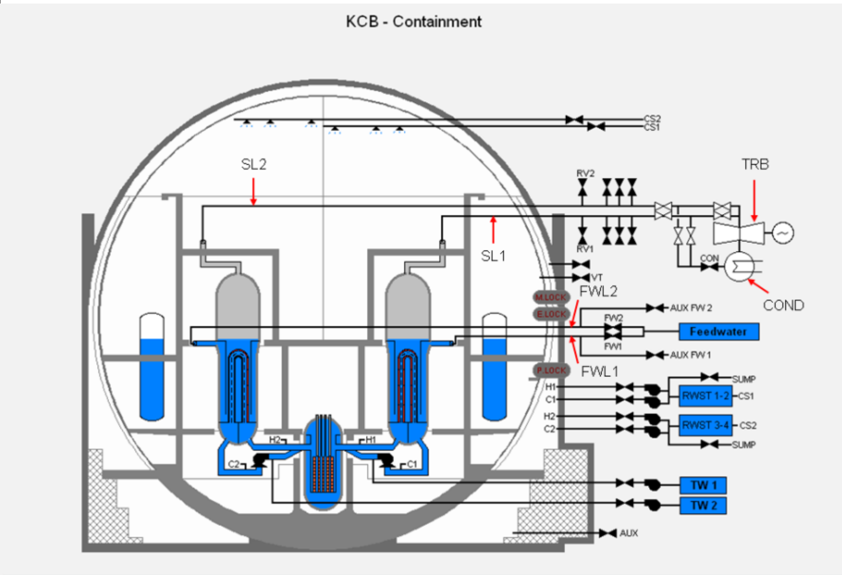
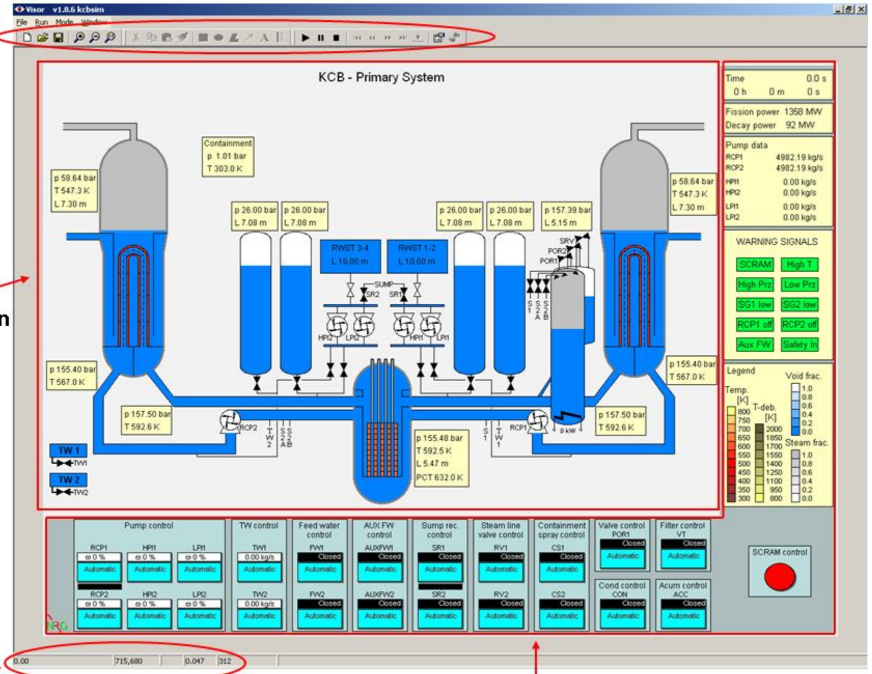
Introduction

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



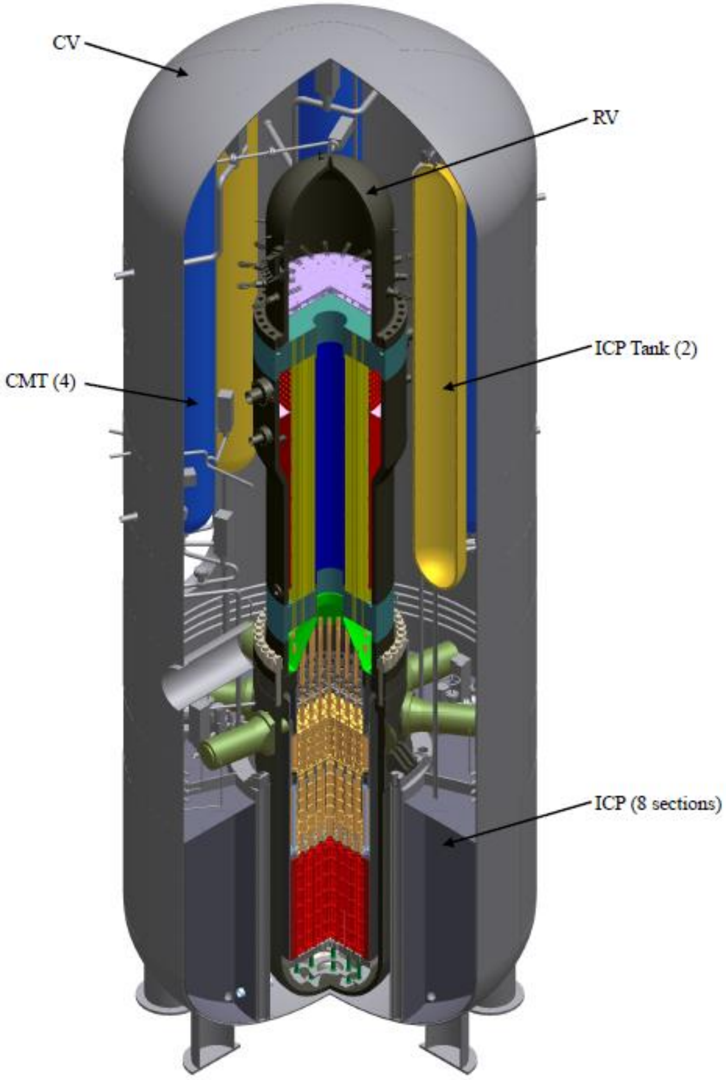
Plant mimic screen

Window information

Plant control and display board

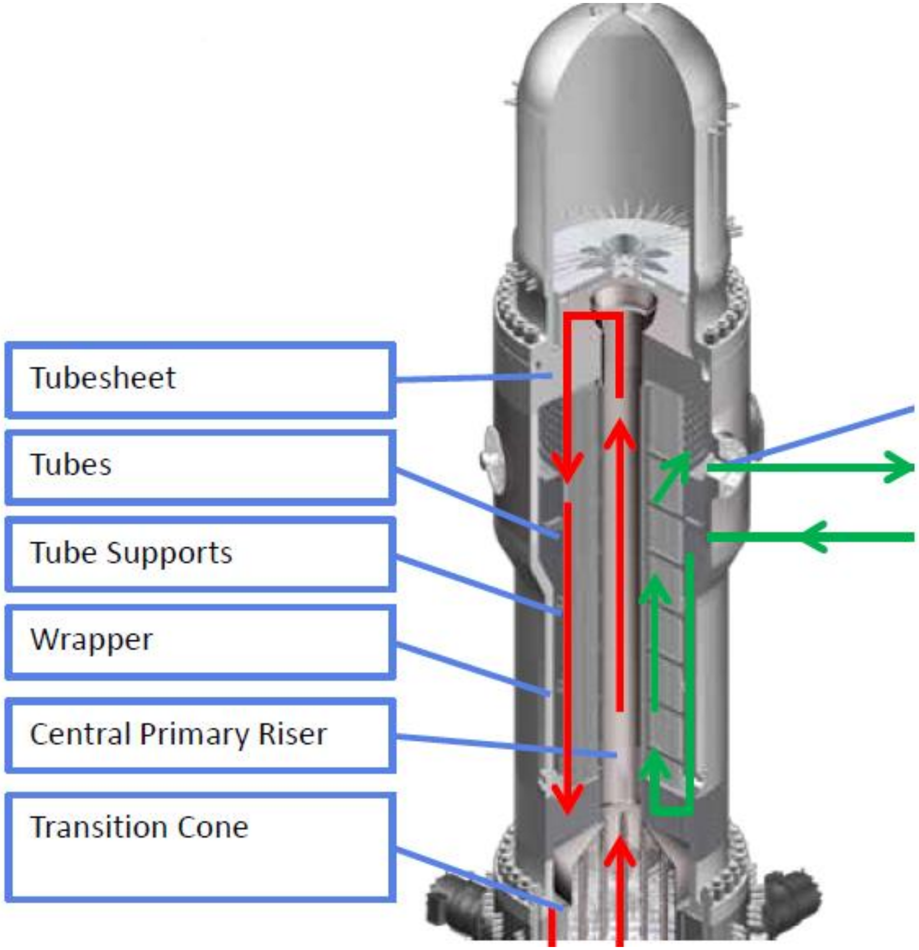
Westinghouse SMR

- ☐ **Westinghouse SMR is an integral PWR nuclear system**
- ☐ **The Pressure Vessel and most of the passive safety system components are contained inside a Containment Vessel**
    - ➢ The Containment Vessel is immersed in a pool of cold water (OCP)
    - ➢ The atmosphere inside the Containment Vessel is highly depressurized under NC
- ☐ **The Passive Safety System (PXS) is made of:**
    - ➢ The In-Containment Pool (ICP);
    - ➢ Four Core Makeup Tanks (CMT), each containing a PRHR heat exchanger;
    - ➢ Two Sump Injection Tanks (SIT), connected to the ICP
    - ➢ A two-stage automatic depressurization system (ADS)
    - ➢ An Upper Internal Storage Tank (UIST)
    - ➢ An Out-Containment Pool (OCP) housing the CV



SMR Steam Generator

- ❑ **The MELCOR model of the SMR Steam Generator**
  - ➢ HX power: 800 MW
  - ➢ Once-through tube-shell HX
  - ➢ The TH nodalization consists of 10 uniform axial nodes for the CVs (both tubes and shell)
  - ➢ The tubes wall is modelled with 10 heat structures with the same node geometry of the boundary CVs
- ❑ **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

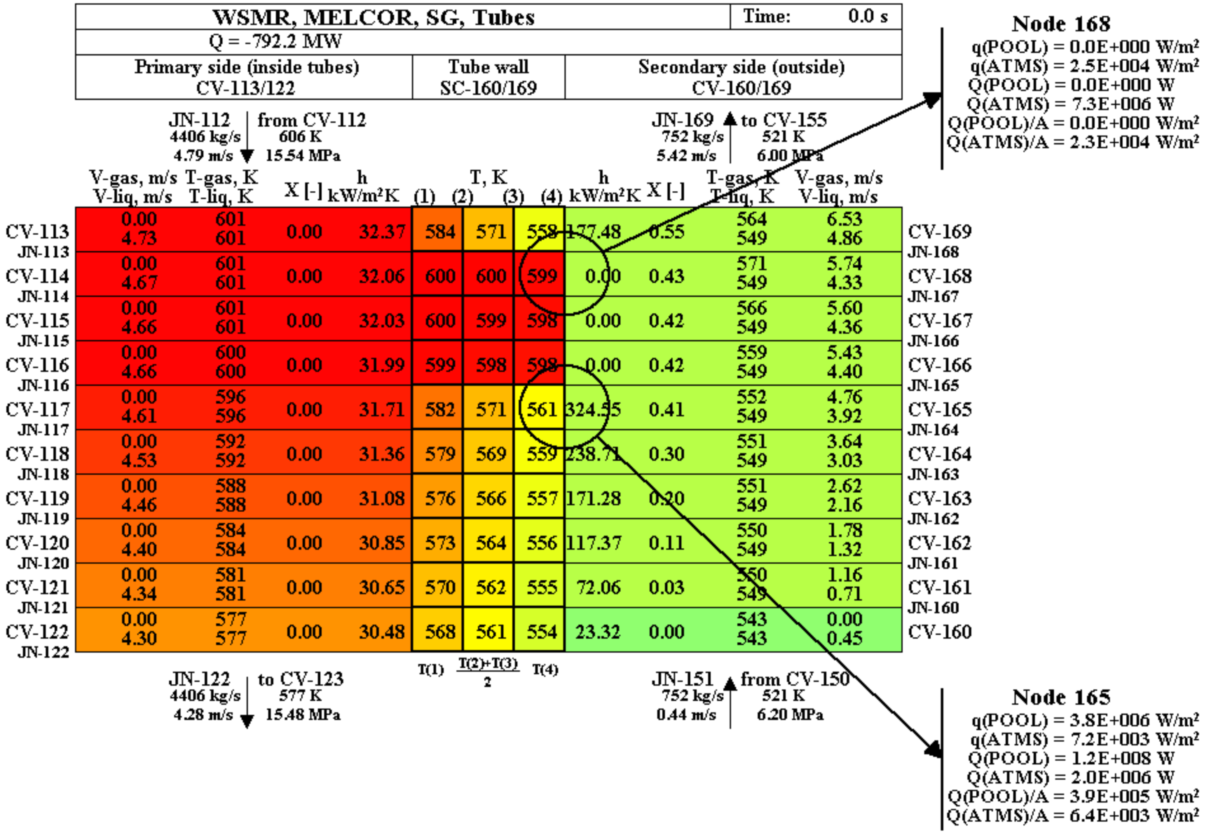


SMR Steam Generator

- ❑ **Post-CHF regime in the upper part of SG!**

$$q_{atms} = \frac{Q_{atms}}{A_{atms}}, \quad q_{pool} = \frac{Q_{pool}}{A_{pool}}$$

- ❑ **Heat flux definition:**
- ❑ **MELCOR result, node 165:**
  - **q = 3.8 MW/m^2 (close to CHF)**
  - **Q = 120 MW**
  - **Q/A = 0.37 MW/m^2**
- ❑ ***q* definition appropriate for stratified flow**
- ❑ **Bubbly flow (~90% void) → overestimation of heat flux by about a factor of 10**



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				
	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 JN-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-168
CV-114 JN-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-167
CV-115 JN-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-166
CV-116 JN-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-165
CV-117 JN-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-164
CV-118 JN-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-163
CV-119 JN-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-162
CV-120 JN-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-161
CV-121 JN-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-160
CV-122 JN-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
					T(1)	$\frac{T(2)+T(3)}{2}$	T(4)					

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

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

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

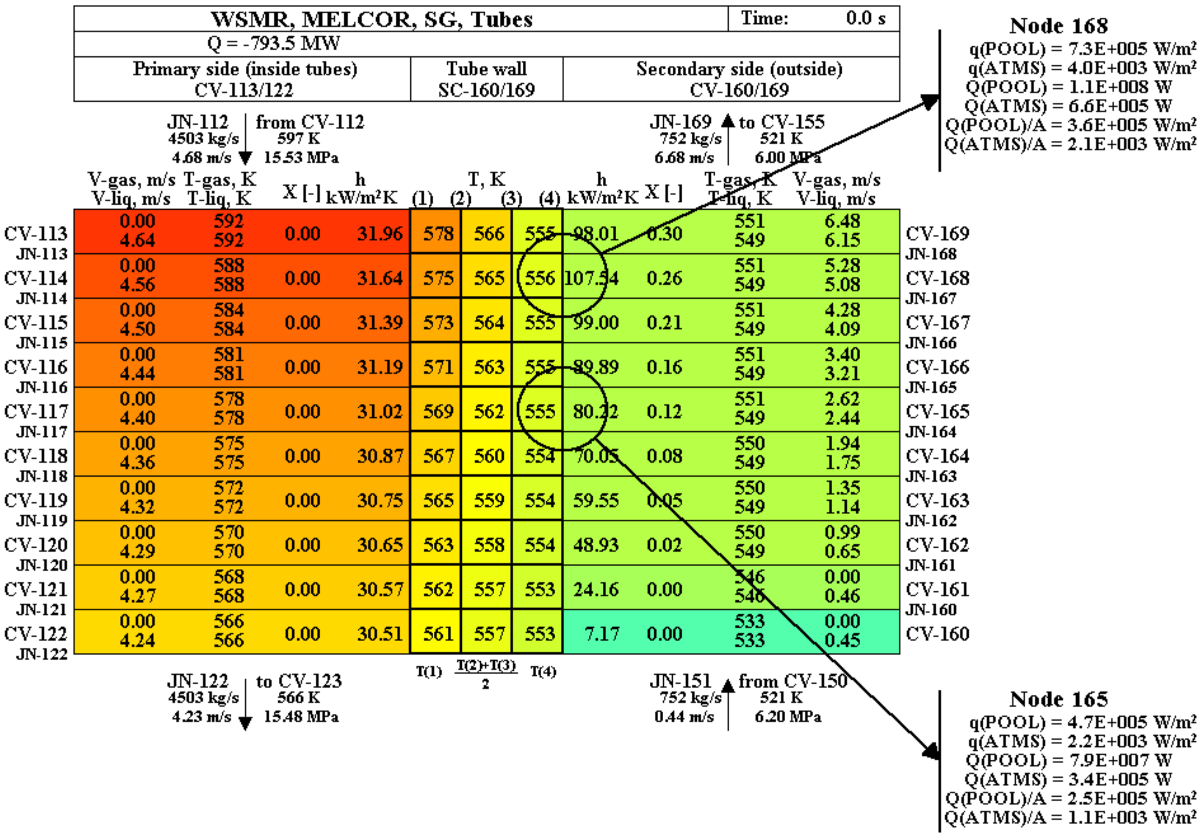
JN-151 from CV-150
752 kg/s 521 K
0.44 m/s 6.20 MPa

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

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



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 JN-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-168
CV-114 JN-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-167
CV-115 JN-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-166
CV-116 JN-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-165
CV-117 JN-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-164
CV-118 JN-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-163
CV-119 JN-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-162
CV-120 JN-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-161
CV-121 JN-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-160
CV-122 JN-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
					T(1)	$\frac{T(2)+T(3)}{2}$	T(4)					

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

- ❑ **Comparison with other TH codes:**

Node 165	**MELCOR**	**MELCOR**	**RELAP**	**SPECTRA**	
	$\alpha_{MAX} = 0.40$	**$\alpha_{MAX} = 0.95$**			
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	MELCOR	RELAP	SPECTRA	
	$\alpha_{MAX} = 0.40$	**$\alpha_{MAX} = 0.95$**			
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 $\alpha_{MAX}=0.95$,
    - ✓ 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

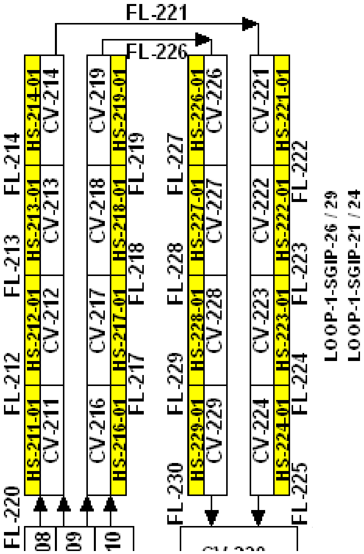
- ☐ **Results of 1300 MW_{th} PWR, KCB, MELCOR 2.1**
  - ➢ Secondary side modeled by a single volume, CV-300
- ☐ **Summary**
  - ➢ No overestimation of heat flux
- ☐ **Conclusion**
  - ➢ No effect in typical PWR SG geometry and modeling approach. Seems to be SMR-specific.
  - ➢ Is dividing secondary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

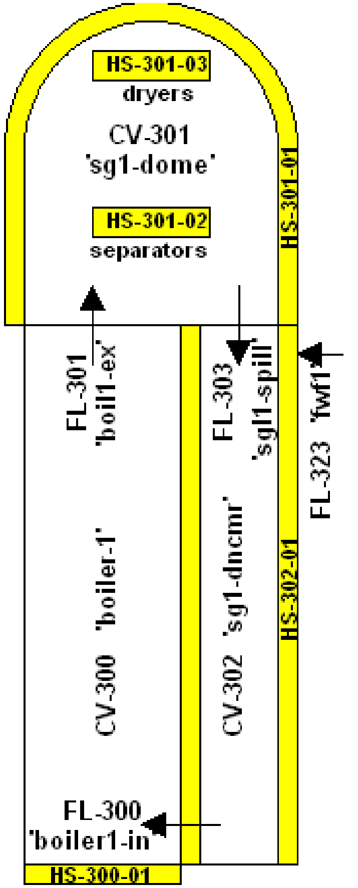
Node 214
q(POOL) = 1.8E+005 W/m^2
q(ATMS) = 0.0E+000 W/m^2
Q(POOL) = 5.8E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 1.8E+005 W/m^2
Q(ATMS)/A = 0.0E+000 W/m^2

Node 221
q(POOL) = 1.5E+005 W/m^2
q(ATMS) = 0.0E+000 W/m^2
Q(POOL) = 4.7E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 1.5E+005 W/m^2
Q(ATMS)/A = 0.0E+000 W/m^2

Node 211
q(POOL) = 3.0E+005 W/m^2
q(ATMS) = 0.0E+000 W/m^2
Q(POOL) = 6.7E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 2.9E+005 W/m^2
Q(ATMS)/A = 0.0E+000 W/m^2

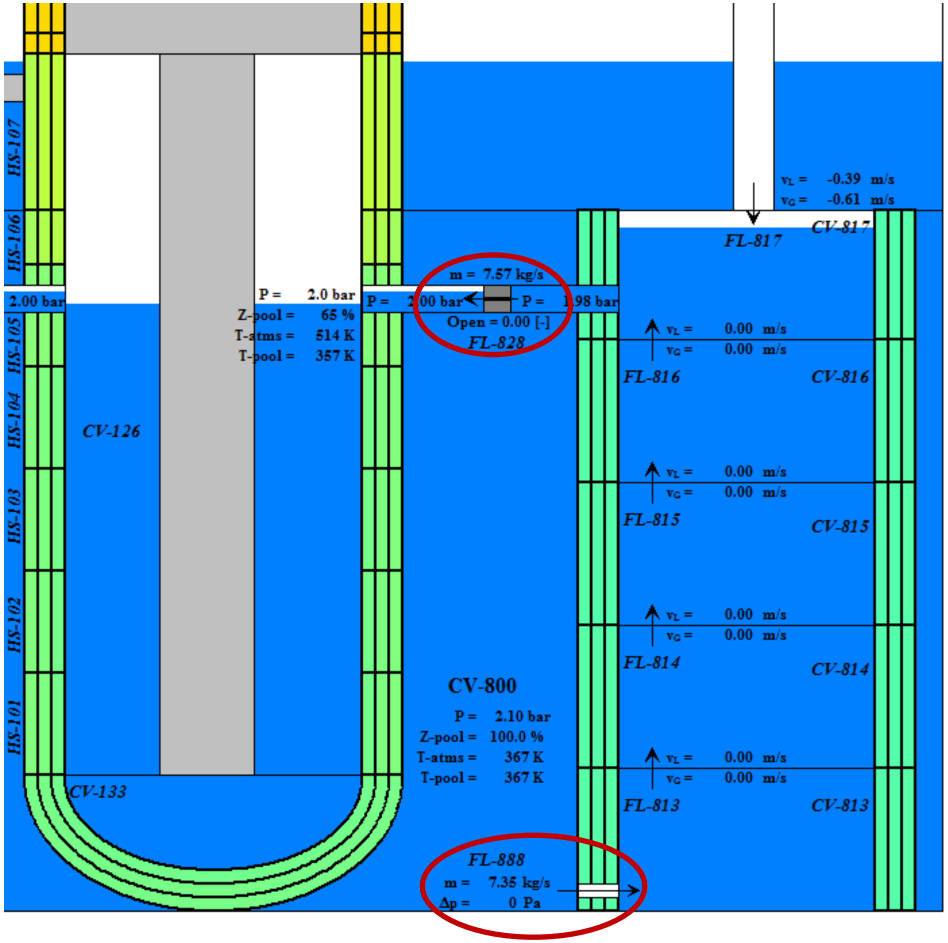
Node 224
q(POOL) = 9.8E+004 W/m^2
q(ATMS) = 0.0E+000 W/m^2
Q(POOL) = 2.2E+007 W
Q(ATMS) = 0.0E+000 W
Q(POOL)/A = 9.7E+004 W/m^2
Q(ATMS)/A = 0.0E+000 W/m^2





Sump Recirculation in SMR

- ❑ **The SMR makes use of gravity-driven passive safety features for postulated accidents**
  - ➢ Heat removal through the four PRHR loops connected to the RPV
  - ➢ Water injection in the RPV from the SITs
  - ➢ Recirculation of water from the sump
- ❑ **The sump recirculation is triggered by hydrostatic pressure in the CV**
  - ➢ After a LOCA, discharged coolant is condensed in the CV
  - ➢ The pressure differential between the CV and the ICP opens the sump check valves
  - ➢ The water is injected in the RPV downcomer through the ICP-to-RPV lines

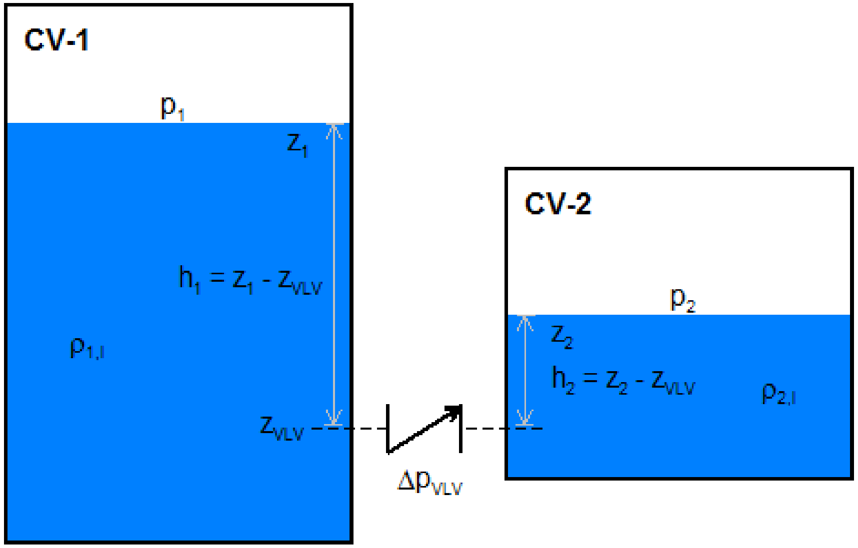


Check Valve Model

- **The CF that triggers the check valve opening was based on the difference of upstream and downstream CV pressure, at first**
  - The opening never occurred during the transient
  - The opening was experienced with other TH codes
- **The reason was the lack of the contribution of the hydrostatic head in the CVs**
- **When passive systems governed by natural circulation are concerned the hydrostatic head plays a fundamental role**
- **Suggestion: why not consider the junction elevation directly in the valve model (e.g.: define junction pressures)?**

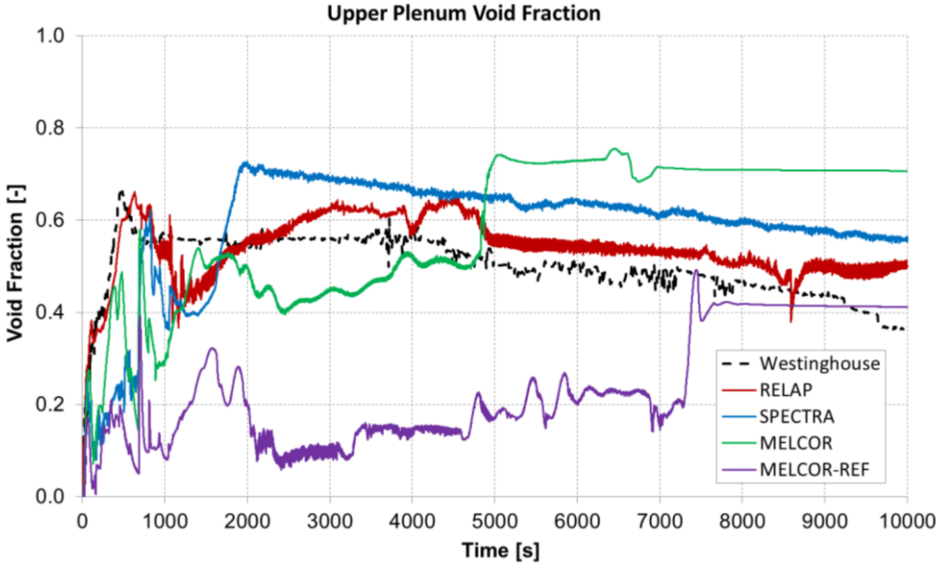
Old model: $\Delta p_{VLV} = p_2 - p_1$

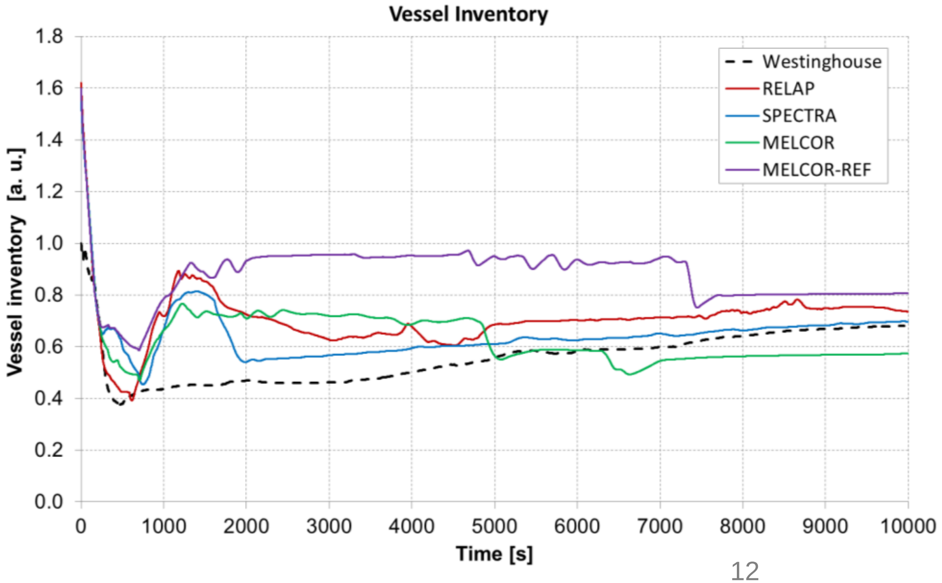
New model: $\Delta p_{VLV} = (p_2 + \rho_{2,l} g h_2) - (p_1 + \rho_{1,l} g h_1)$



Core Flooding

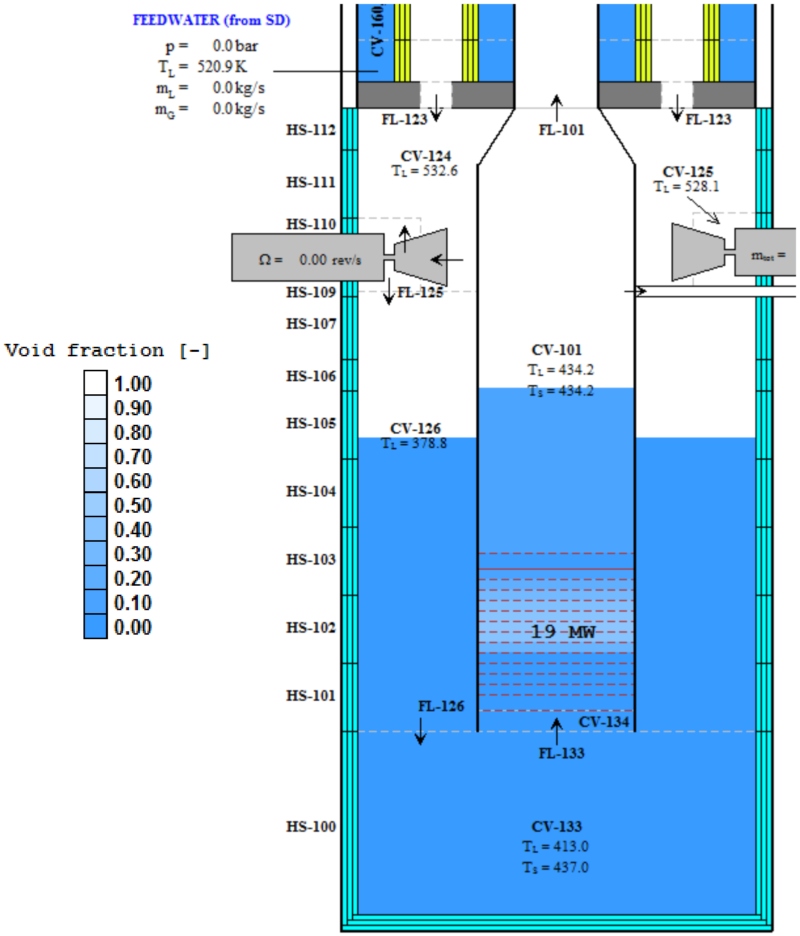
- ❑ **Safety injections provide the flooding of the core**
  - ➢ The decay heat removal is obtained by water evaporation
  - ➢ The amount of liquid in the core is sensitive to the value of the bubble rise velocity in CVs
- ❑ **Generally bubble rise velocity in a boiling RVP is ~ 1 m/s**
  - ➢ The MELCOR default value is 0.3 m/s
  - ➢ The default value results in underestimation of the void fraction in the upper plenum
  - ➢ The value was decreased to 0.1 m/s resulting in a better agreement with the other codes

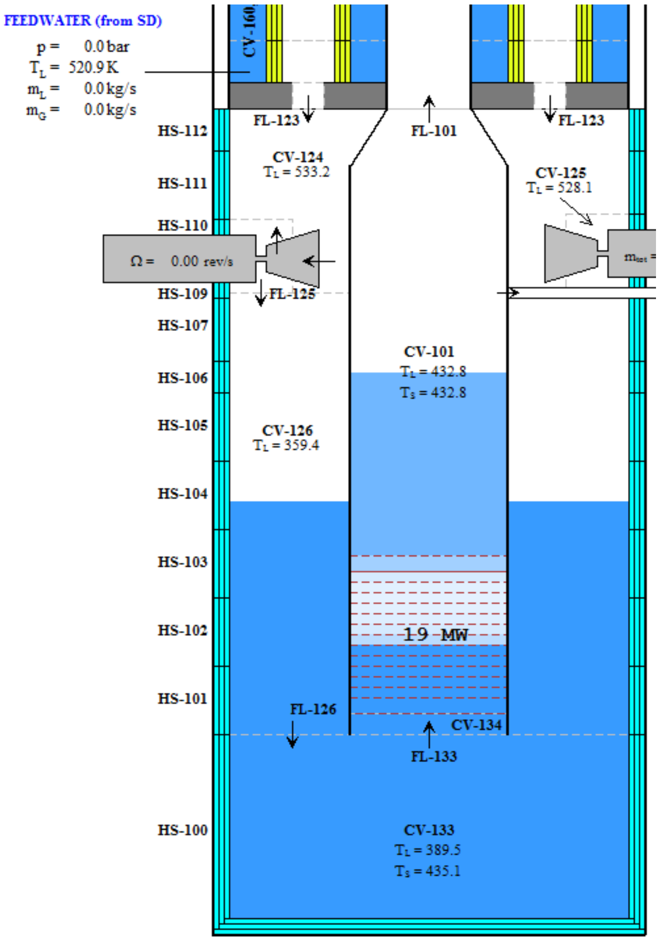




Core Flooding

- ☐ **Sensitivity coefficient SC 4407 item 1: default v_{BUB} = 0.3 m/s (left), modified v_{BUB} = 0.1 m/s (right)**





Conclusions

Issues and comments

- ☐ **CHF Condition:**
  - ➢ SMR SG secondary side: fine CV nodalization can lead to CHF condition encountered in high void fraction volumes when high heat flux is involved
  - ➢ A fine CV/HS nodalization is not envisaged in such situations
- ☐ **Check Valve Model:**
  - ➢ Hydrostatic head plays a fundamental role in the actuation of passive safety systems that rely on natural convection or stored potential energy
  - ➢ Control logic of check valves has to consider hydrostatic head for adequate modelling
  - ➢ Can the FL package internally account for junction elevation in valves?
- ☐ **Collapsed Water Level:**
  - ➢ The default value of the bubble rise velocity (0.3 m/s) in CVs results in a general underestimation of the CV void fraction
  - ➢ A sensitivity calculation was performed with a modified value (0.1 m/s) which resulted in a better agreement in terms of RPV inventory, collapsed water level and void fraction

Thank you for your attention!
Questions?