MELCOR Application in the NPP Krško Safety Upgrade Program

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  - Support calculations for the safety upgrade program (SUP)
  - Status of MELCOR NPP Krško (NEK) model and calculation
  - Comparison MELCOR vs. MAAP for NEK SBO PCFV
- Simple SFP TH analysis
  - Fuel assembly dryout analysis
  - SFP water level instrumentation status (equipment survivability)
  - Dose rates calculation with SCALE
- Containment MSLB Analysis
  - Comparison with Gothic calculation
  - Within the scope of the equipment qualification program

NPP Krško (NEK)

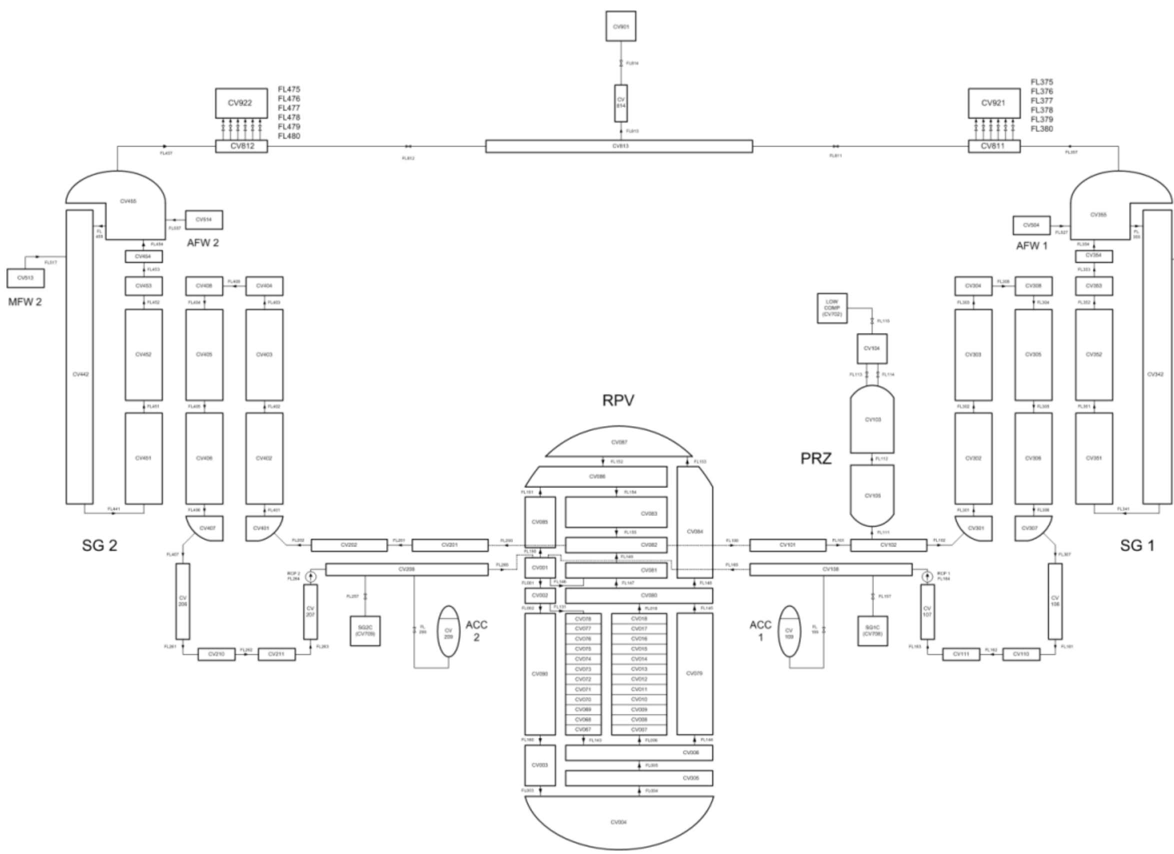
- **PWR 2-Loop Plant with 700 MW electrical output**

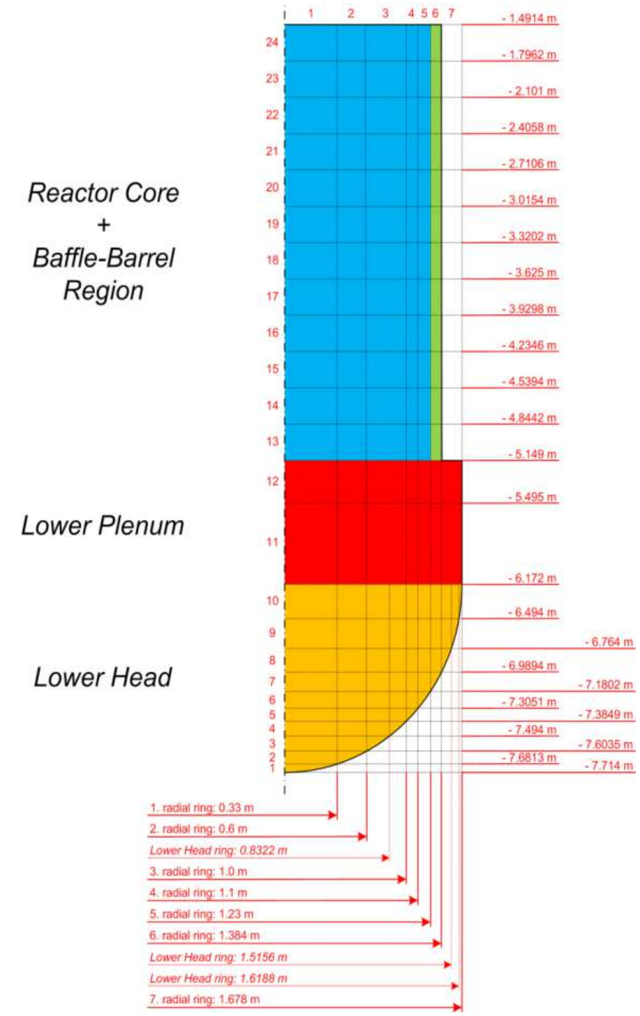
MELCOR Support Calculation for SUP

- Following Fukushima accident, NPP Krško decided to upgrade the plant safety
  - Instalation of PARs and the PCFV system
- Supporting calculations performed with MAAP 4.0.7 and MELCOR 1.8.6
- SBO accident scenario based on Westinghouse calculation used to design the PARs and the PCFVS
- System thermal hydraulics, core degradation, containment corium behaviour covered
- Simple PCFVS model, no aerosol/FP calculation

MELCOR NEK RCS/Core Model

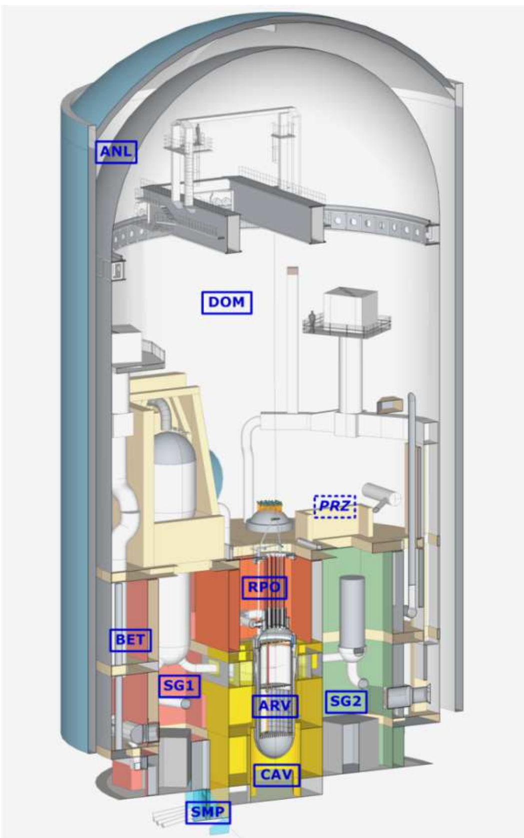
The primary and secondary systems, including regulation systems and control volumes that represent boundary conditions, consist of 104 thermal-hydraulic control volumes, 125 flow junctions and 48 heat structures.

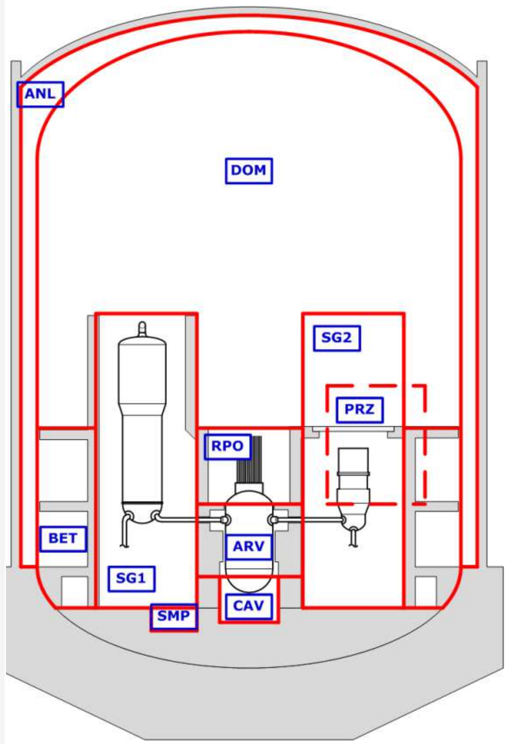


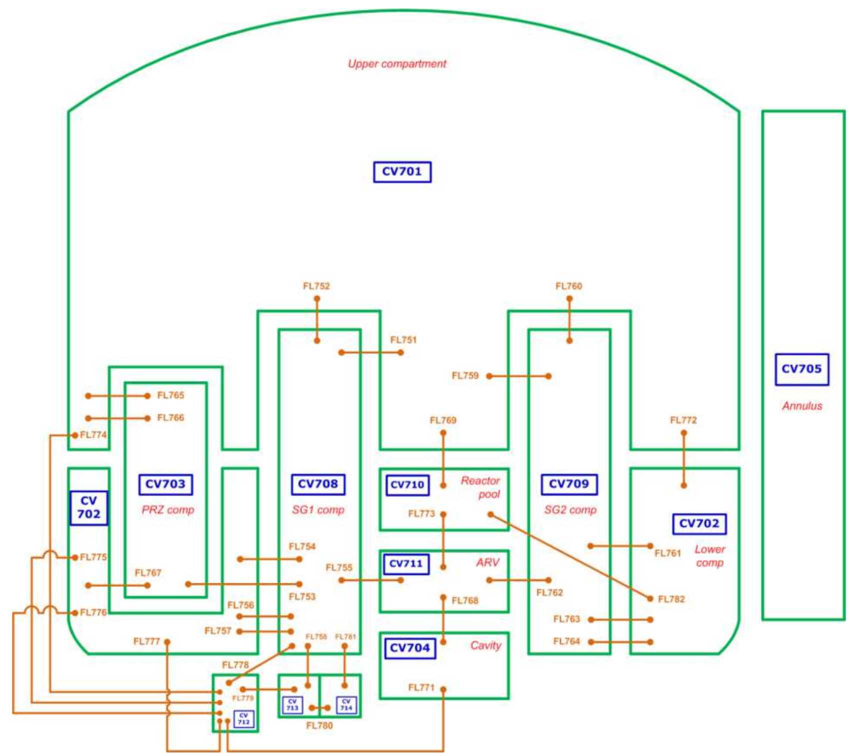


MELCOR NEK Containment Model

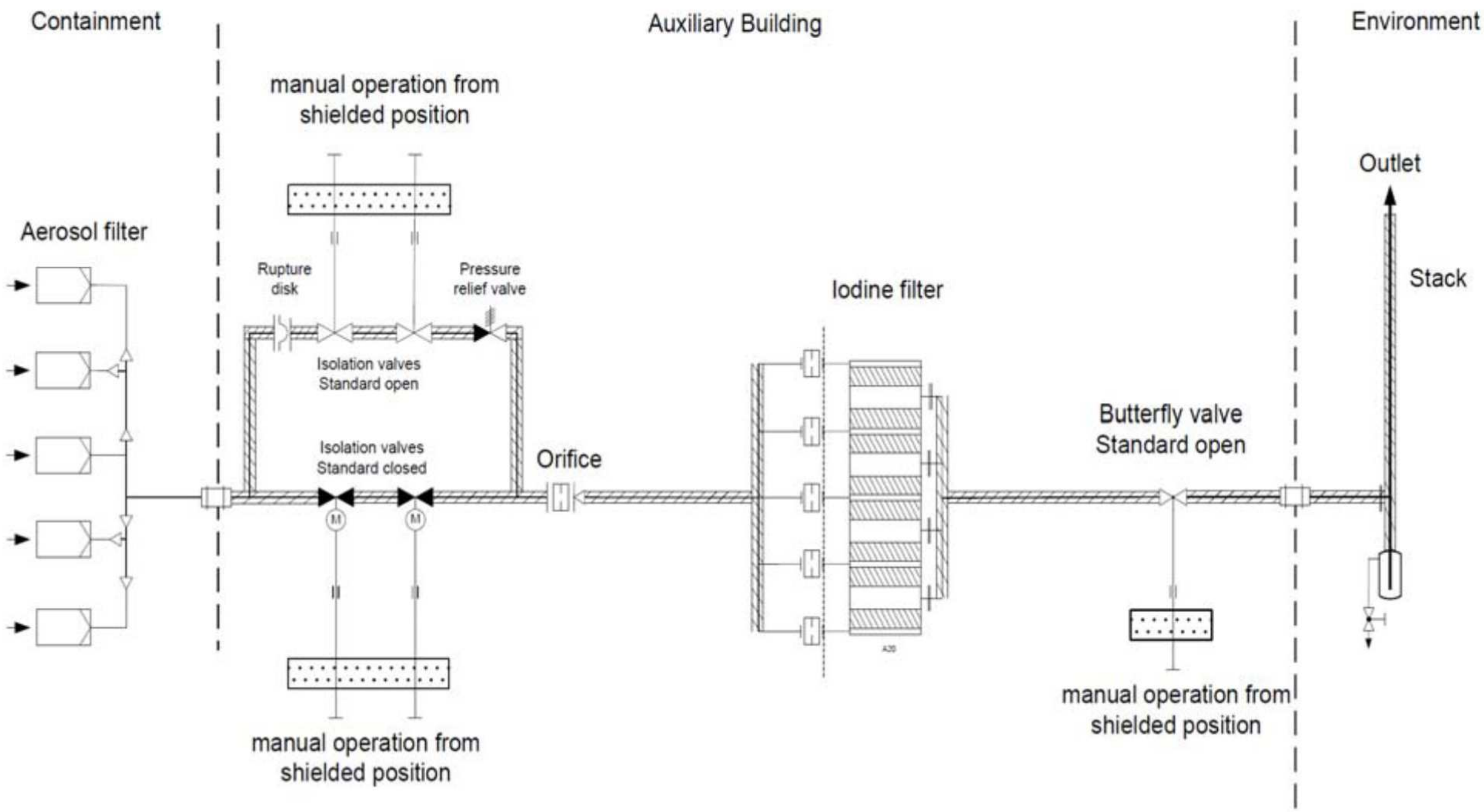
- **12 control volumes, 20 heat structures, 30 junctions**



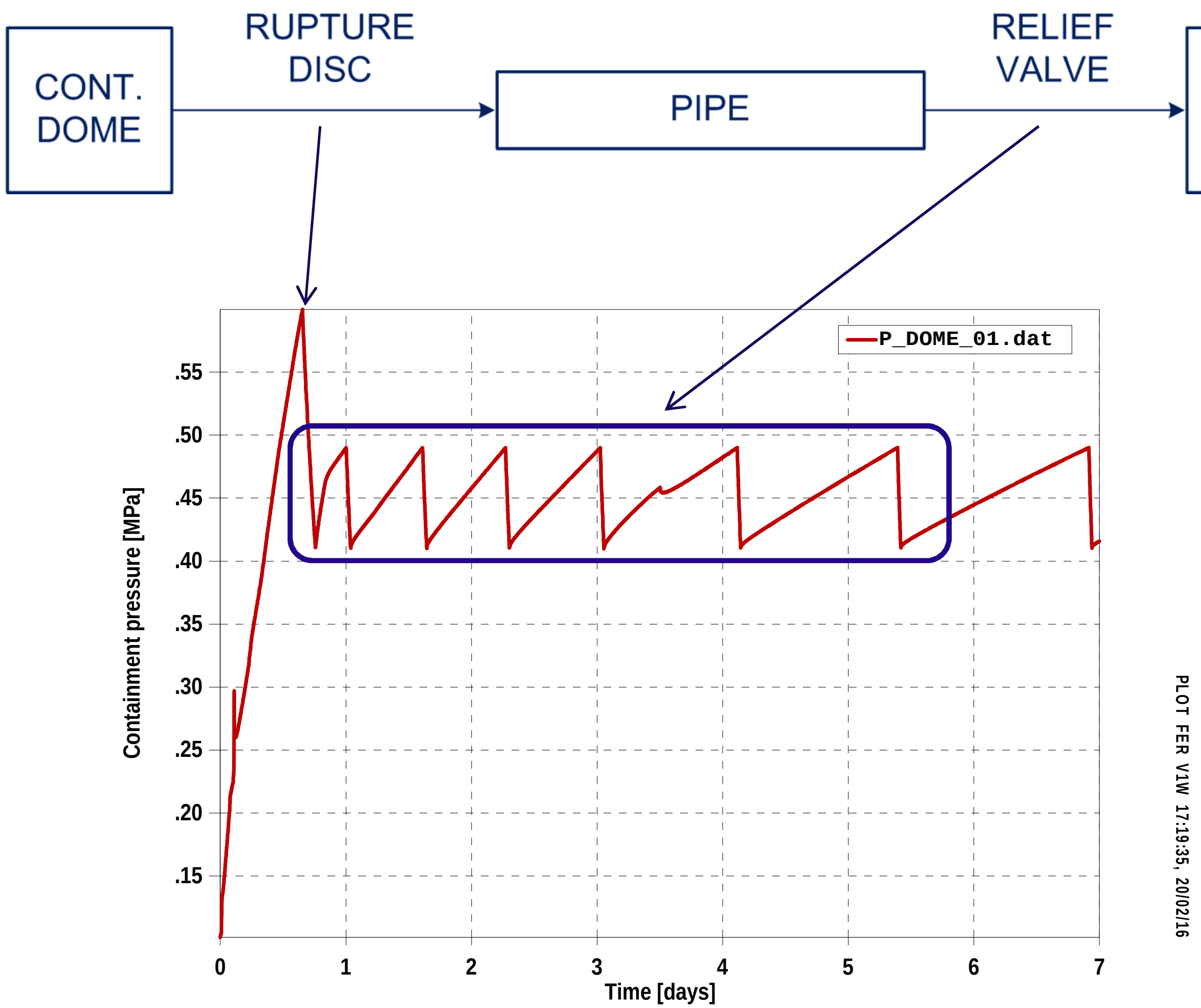




Passive Containment Filtered Vent (PCFV) System



PCFV System – Modelling

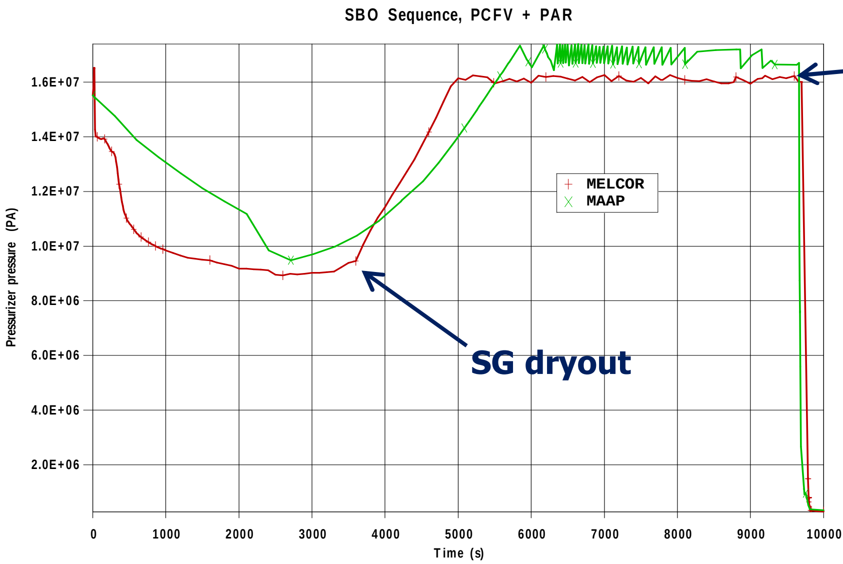


- 6 bar – rupture disc failure
- PCFV relief valve cycling between 4.1 bar and 4.9 bar

Transient Description

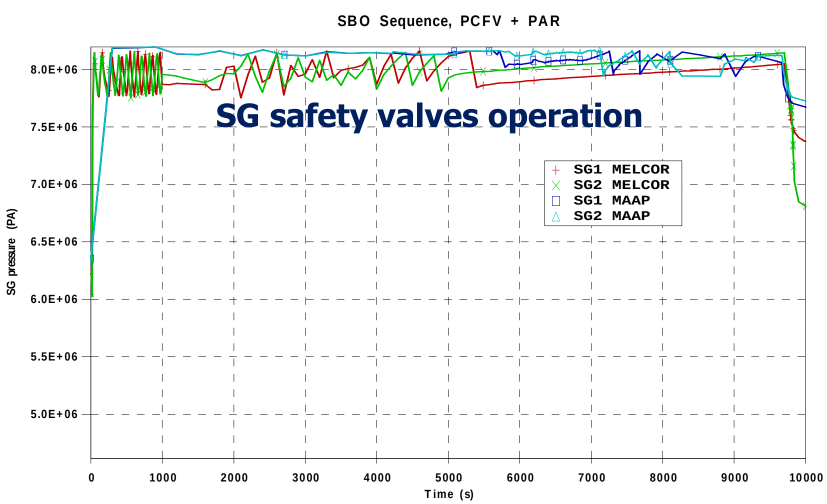
- Followed by a 1000 sec. steady state
- Station blackout accident, nothing works scenario
- SB LOCA - coolant loss through the RCPs (21 gpm/RCP) due to degradation of pump seals (unavailability of seal cooling)
  - asymmetrical breaks (letdown relief valve opened)
- RCS coolant is released to SG containment compartments
- Hot leg creep break presence
- Blockage of a pipe connecting the sump with the cavity after release of corium from the RPV
- MELCOR 1.8.6 vs. MAAP 4.0.7 calculation

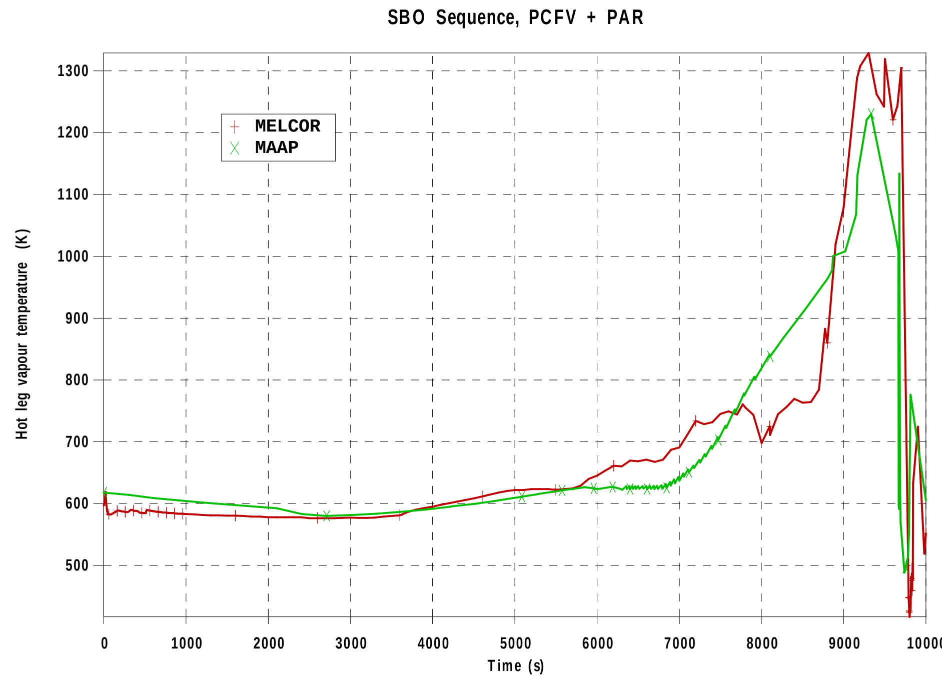
Pressurizer, SG Pressures and the Hot Leg Vapour Temperature



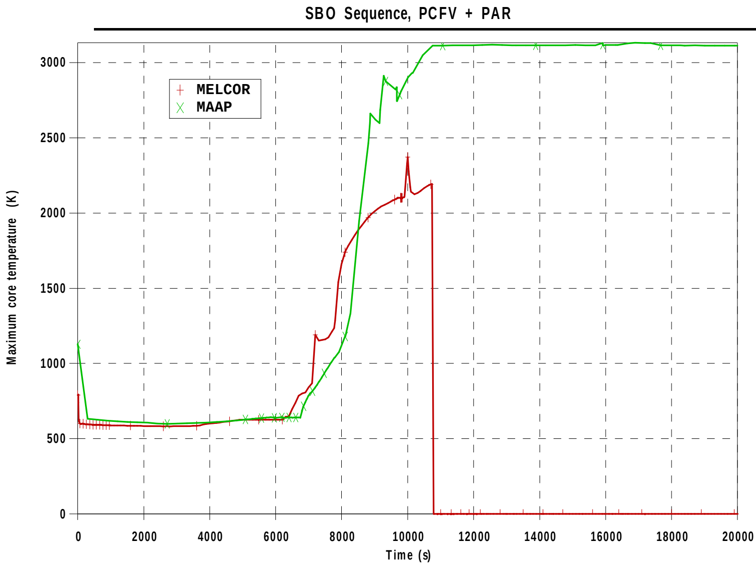
Hot leg creep failure at 9700 sec.

- high pressure sequence
- no accumulator injection prior to the hot leg creep rupture

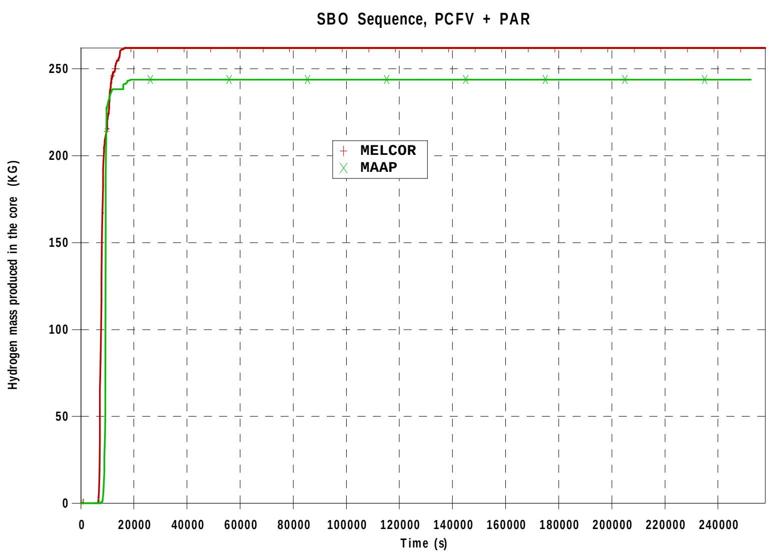


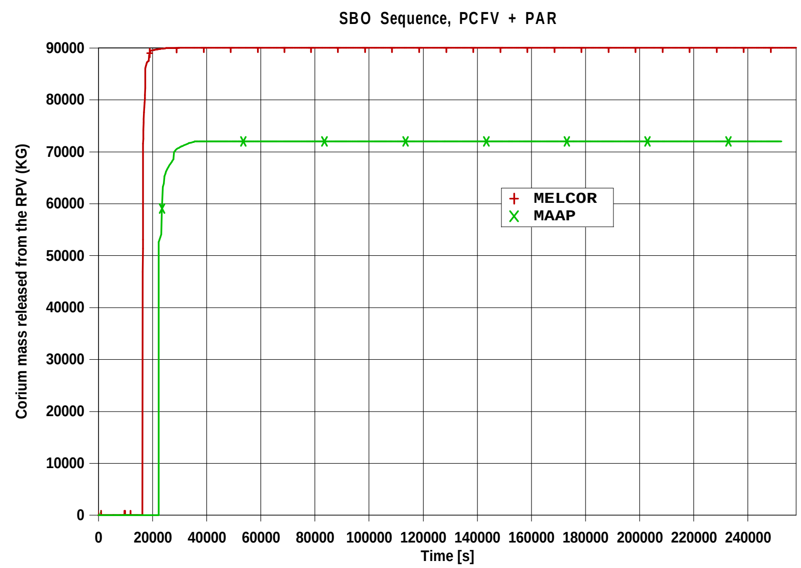


Core Temperature, Hydrogen Production and Corium Release

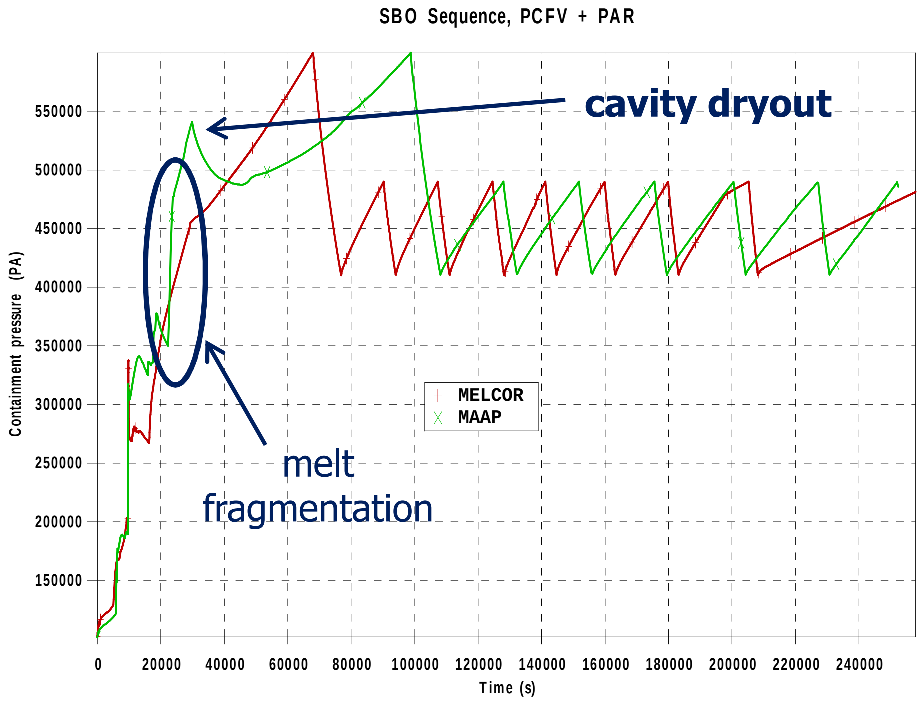


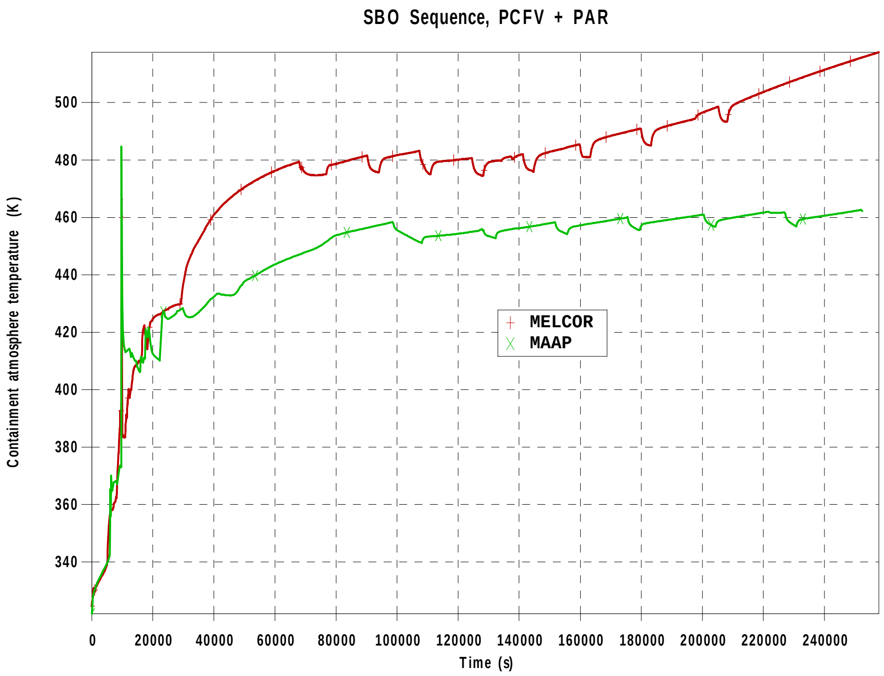
- as more and more water was discharged from the RCS to the containment, the core started to uncover and to heat up
- the upper core levels uncovered at 6000 s, and the lower levels at 7500 s
- early core meltdown and corium slump in the lower head at approximately 9000 s (700 s before accumulator injection)





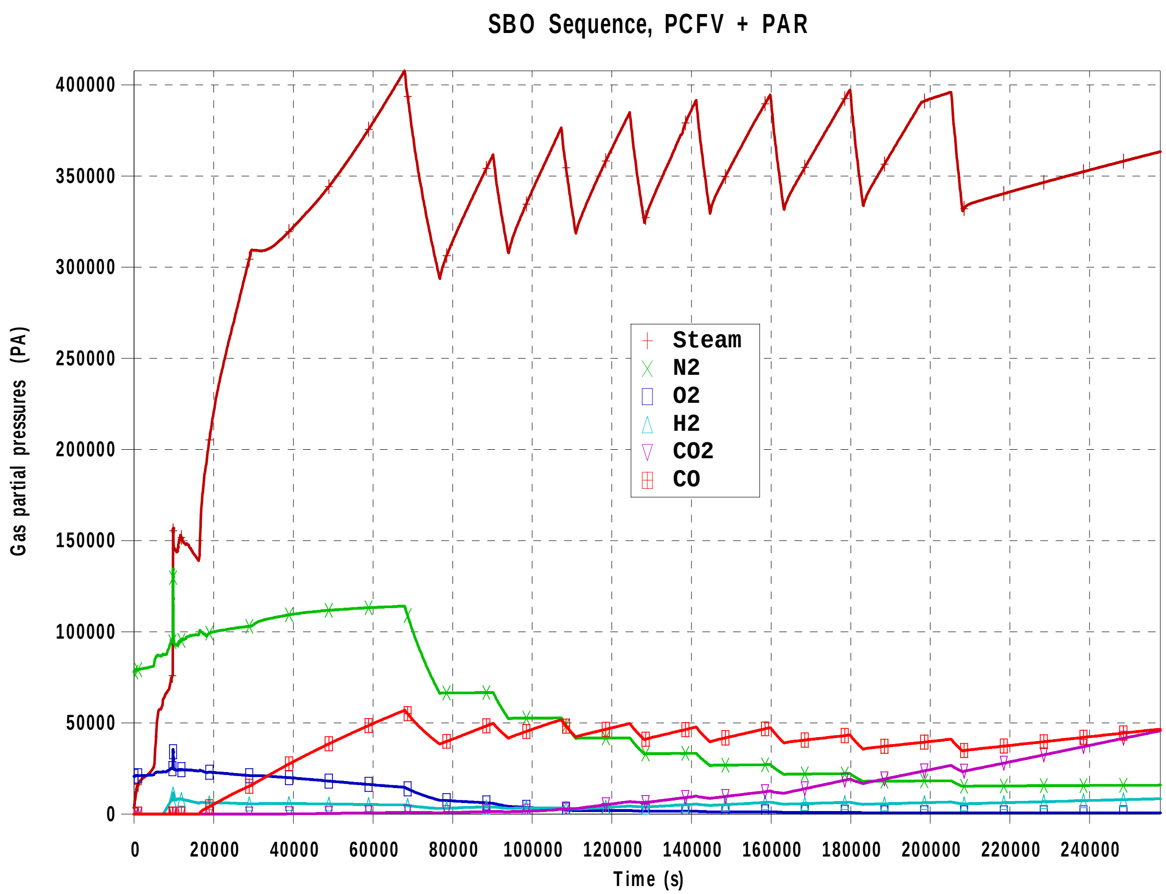
Pressure and Temperature in the Containment Upper Plenum



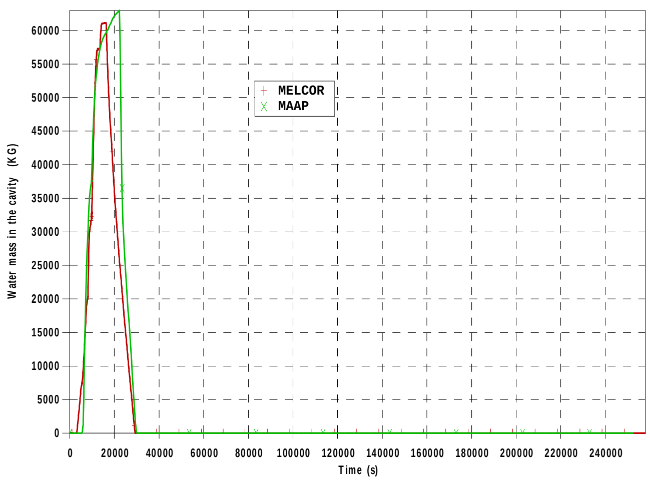


- initially, high pressure increase due to melt fragmentation in MAAP, no fragmentation in MELCOR
- quenching of the melt particles
- heatup of particles after water evaporation, delay in pressurization and later opening of the PCFV relief valve

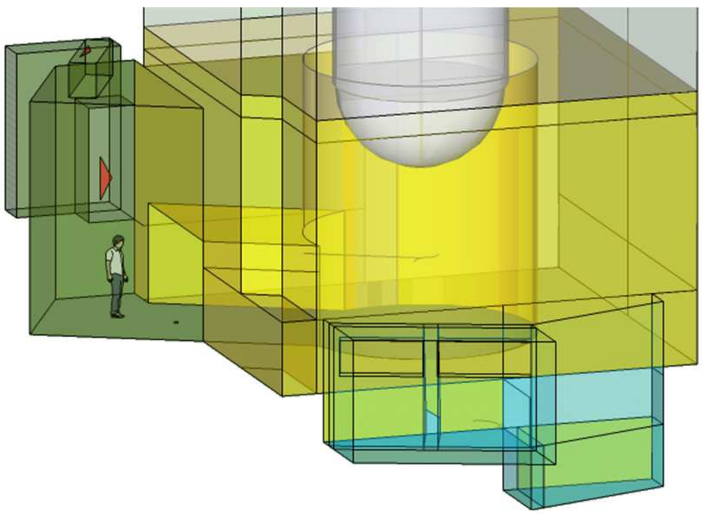
Gas Partial Pressures in the Containment and the Cavity Water Mass

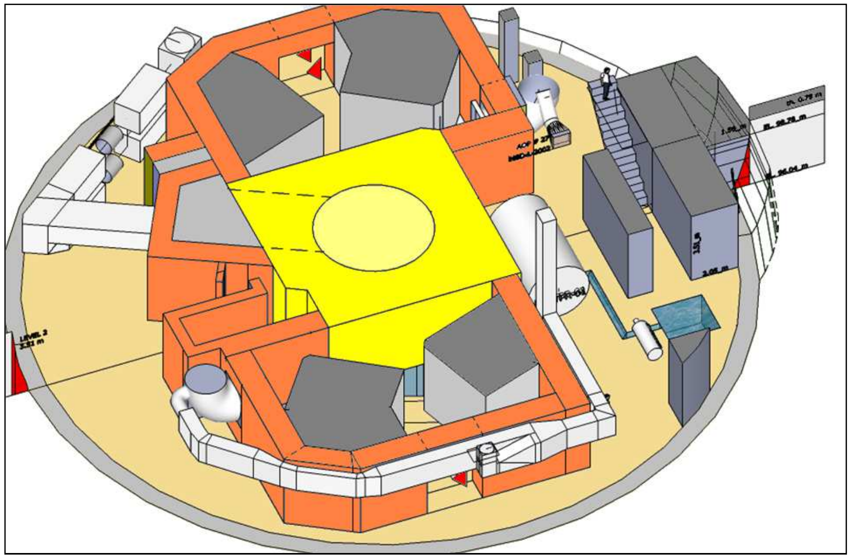


- steam partial pressure has dominant influence on the total pressure
- nitrogen and oxygen fractions decreasing due to release of hydrogen, CO and CO_2 during MCCI
- oxygen starvation because of PARs operation



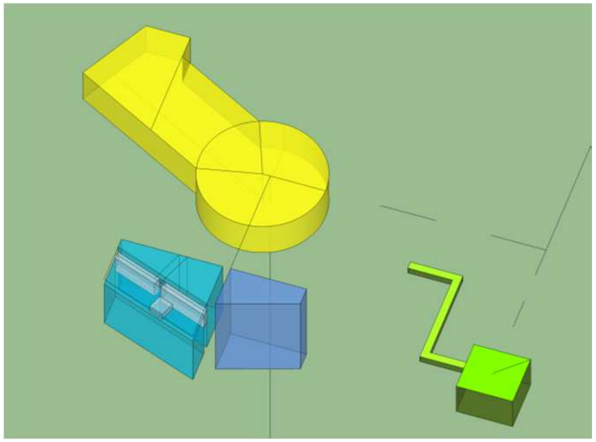
Cavity Layout and the MCCI



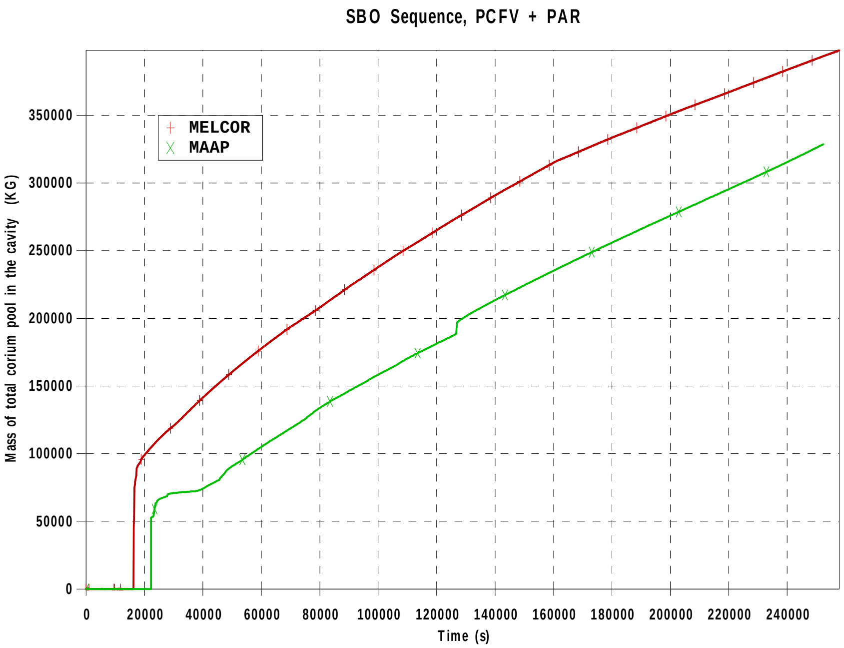


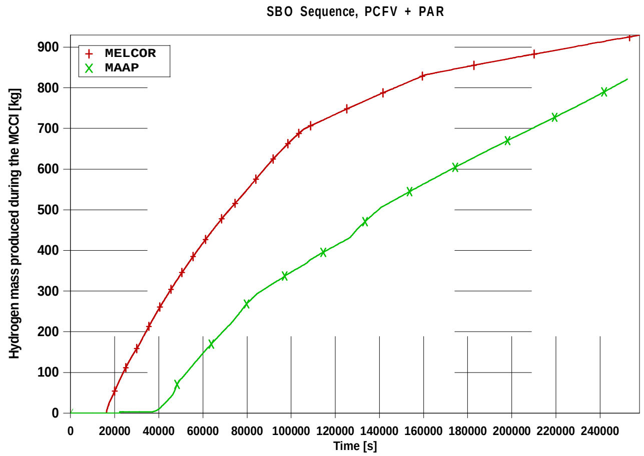
Concrete decomposition
(at temperatures 873 – 1173 K):
$CaCO_3 \rightarrow CaO + CO_2$ (endothermic reaction)

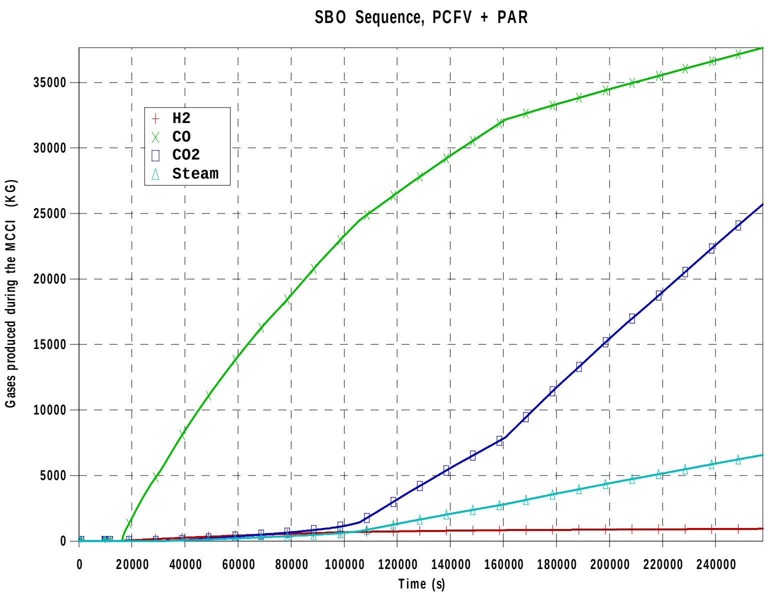
Iron rebar oxidation
(600 kg of iron in the 1 m^3 of the concrete):
$Fe + H_2O + 3.0\ kJ/kg_{(Fe)} \rightarrow FeO + H_2$
$Fe + CO_2 + 480\ kJ/kg_{(Fe)} \rightarrow FeO + CO$



MCCI Concrete Degradation and Release of Gases

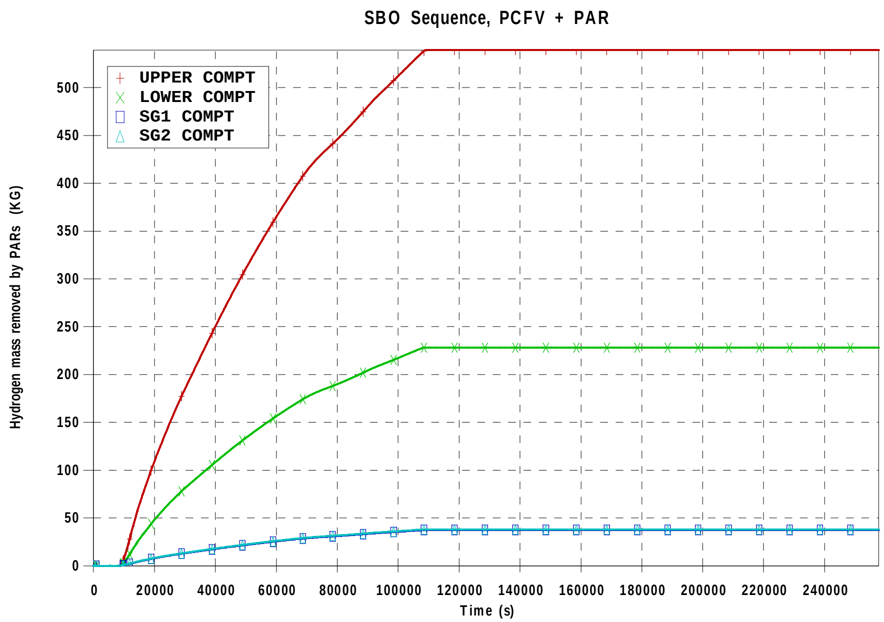






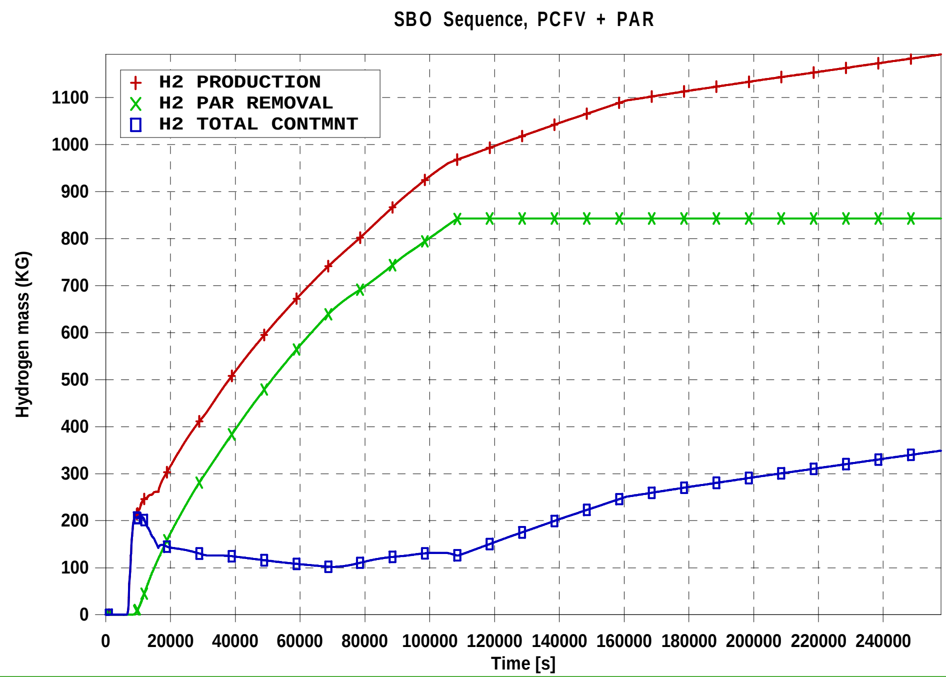
- MCCI in MELCOR starts immediately after corium release, in MAAP not before total water evaporation in the cavity

PAR Performance



Hydrogen mass removed by PAR operation, MELCOR calculation

Hydrogen production, hydrogen mass removed by PARs and total hydrogen mass in the containment, MELCOR calculation

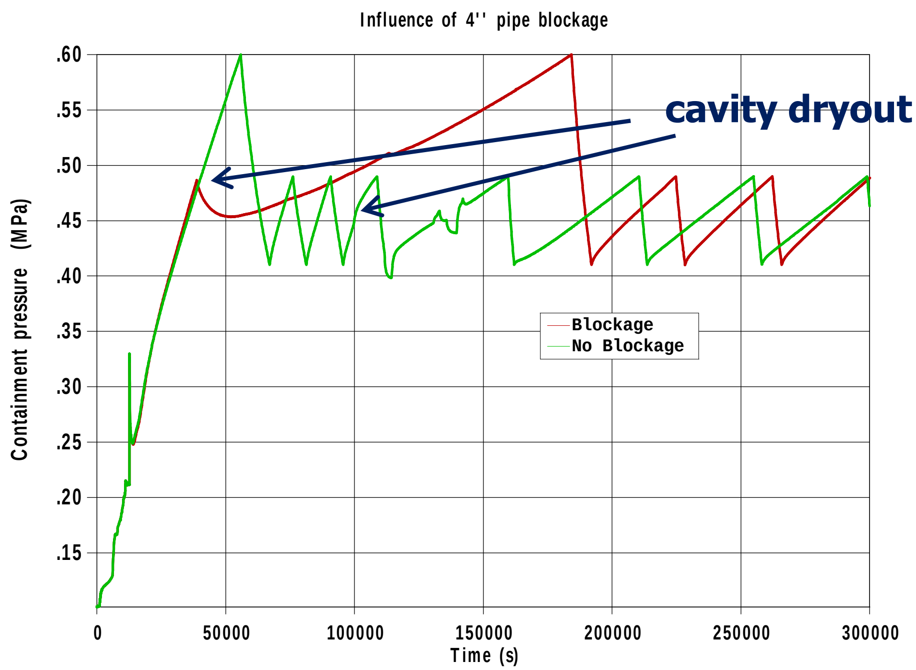


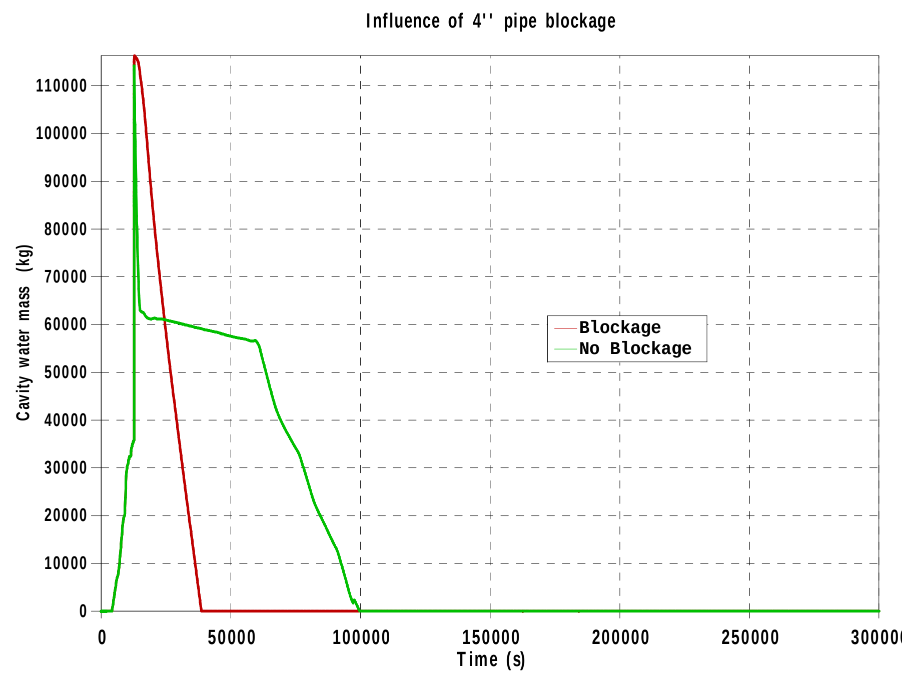
- NIS PAR model, 22 PARs
- PAR operation started when hydrogen mole fraction reached value of 0.02 and stopped after oxygen mole fraction dropped to 0.005
- During PAR operation 80% of hydrogen produced due to the oxidation in the core and the MCCI was removed by the recombiners

Time sequence of the main events

Parameter	MELCOR	MAAP
Loss of the SG heat sink	1.0 h	1.4 h
Core has uncovered	1.6 h	1.8 h
Increase of the core temperature	1.7 h	1.9 h
Start of the oxidation and production of hydrogen in the core	1.8 h	2.0 h
Start of the core melt	2.0 h	2.2 h
Hot leg creep failure	2.7 h	2.7 h
Melt relocation in the lower head	3.0 h	4.4 h
RPV rupture	4.5 h	6.2 h
PCFV rupture disk broken	18.8 h	27.3 h
Second PCFV system opening	25.0 h	35.5 h

Sensitivity Case – Influence of the Sump-Cavity Pipe Blockage





- no blockage – water enters from the sump into the cavity as long as the upper elevation of water in the sump is higher than the bottom of the cavity
- excess water evaporation leads to continuous containment pressurization

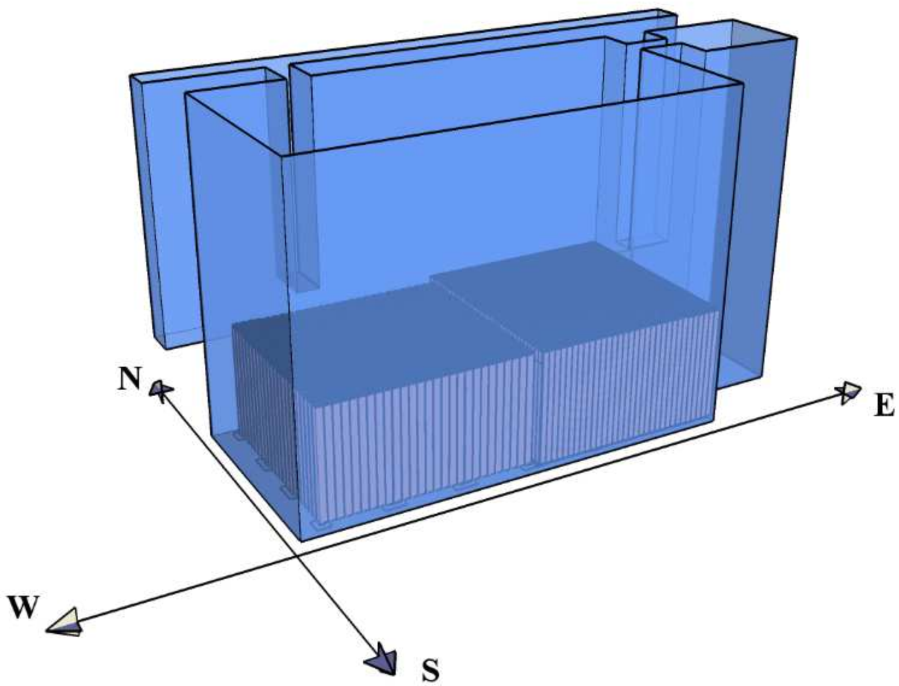
Spent Fuel Pool Analysis

Simple SFP Heatup Model

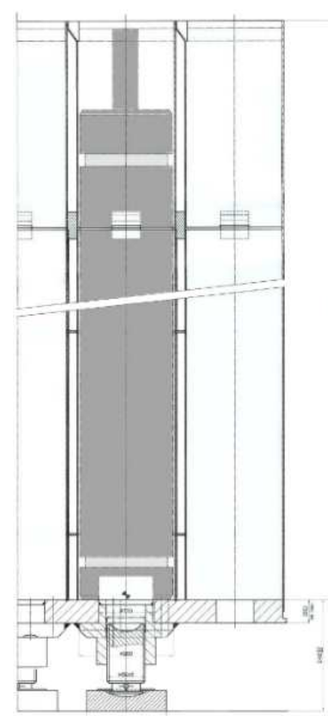
- NEK Equipment survivability for DEC (SFP water level instrumentation status)
- Thermal-hydraulics calculation using MELCOR 2.1
- Different racks in old and new (reracked) part of the pool
- Simple model to calculate time to boiling, time of FA uncover and FHB temperature and pressure
- Transfer channel and cask loading area excluded
- 16×16 type fuel assembly
- Heat load (ANS) based on real number of FAs during operation and during refueling

SFP Layout

- SFP layout

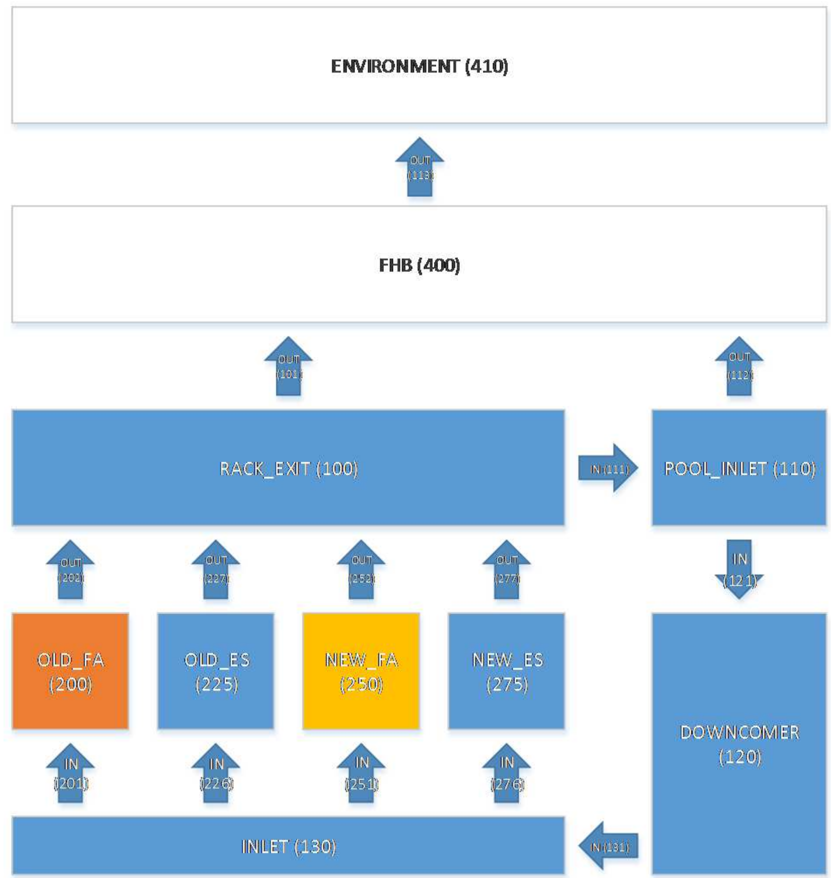


- SFP rack vertical cross section



SFP Nodalization

- Lumped volumes
- Full and empty cells in old and new SFP part based on rack cell geometry and FA characteristics
- Water above racks
- Downcomer channel based on real geometry
- Water below bottom rack openings
- FHB empty space
- Leak to the environment



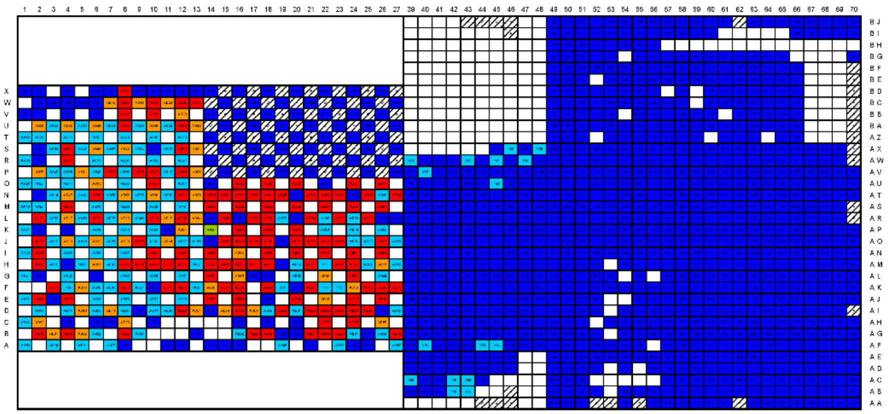
Model Heat Structures

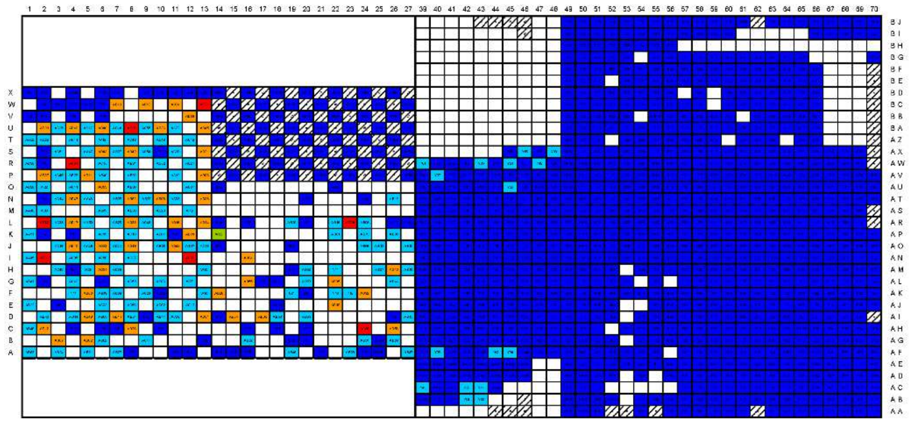
- Equivalent fuel rod structure for full old and new cells
- Steel liner HS for full and empty old and new cells
- Steel liner for SFP walls and bottom
- FHB concrete
- No radiative heat transfer
- Different heat source for old and new part; for "at power" and refueling mode

	Refueling	At power
Old racks with FAs	417	296
Old empty cells	140	261
New racks with FAs	857	857
New empty cells	201	201

Layout of Full and Empty Cells and Total Heat Loading

- Refueling (5 MW total)
- At power (2 MW total)



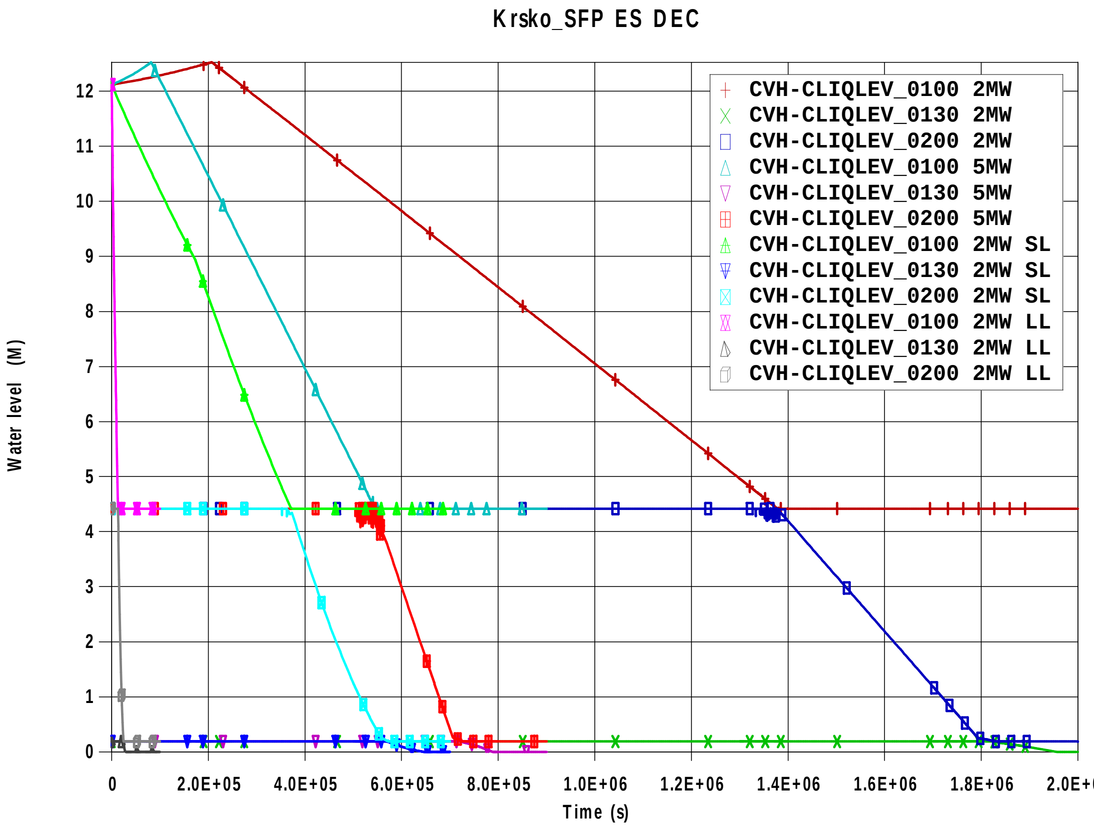


Red colour: last unloaded fuel from the reactor (large decay heat)
Blue colour: old “cold” fuel assemblies

Simulation Scenarios

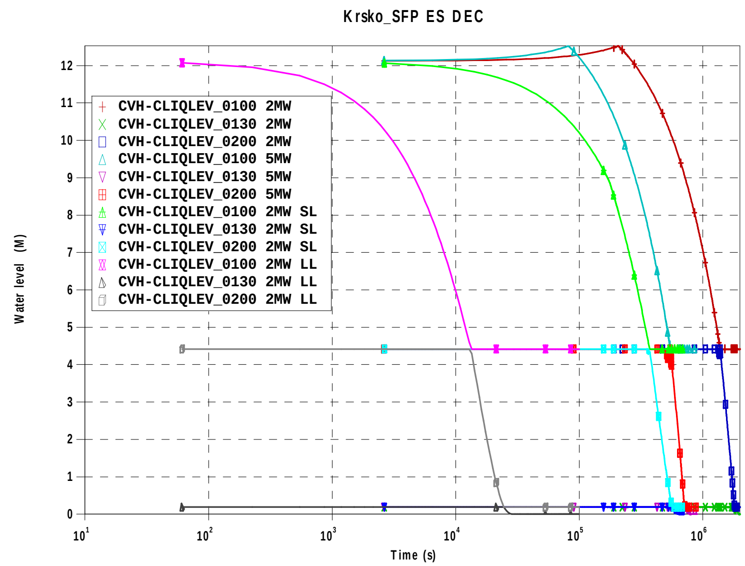
- Heatup
  - SFP heat loading during operation at power (2 MW total)
  - SFP heat loading during refueling (5 MW total)
- Leakage
  - SFP heat loading during operation at power small leak 2.85e-4 m^2
  - SFP heat loading during operation at power large leak 7.85e-3 m^2
  - No leakage during refueling
- Initial conditions
  - SFP water level 12.12 m
  - SFP temperature 40 °C
  - Environment at 25 °C, 101.325 kPa

SFP Water Level

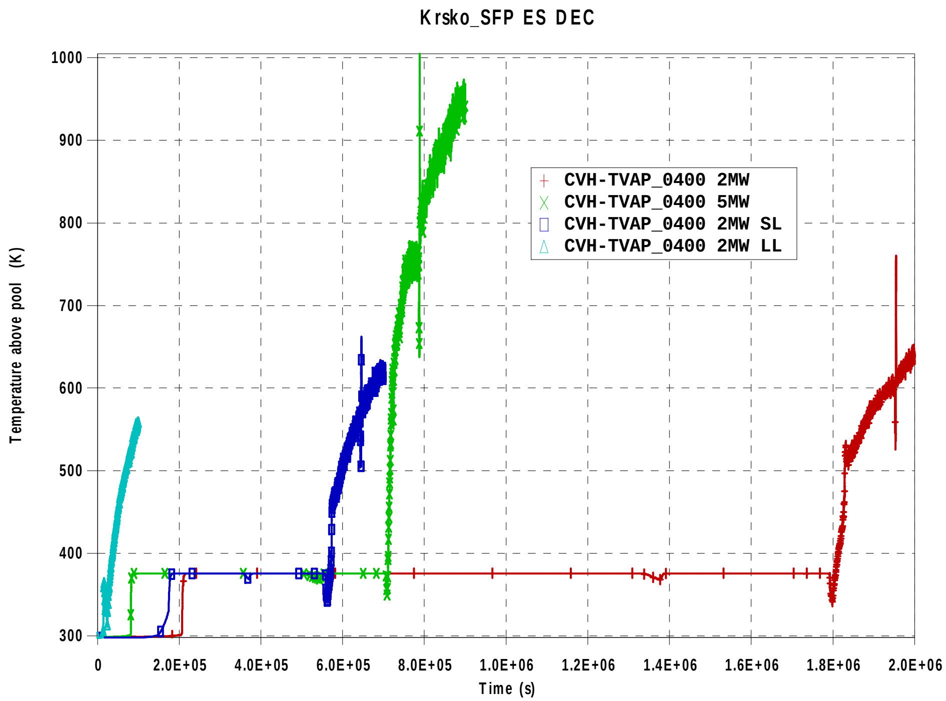


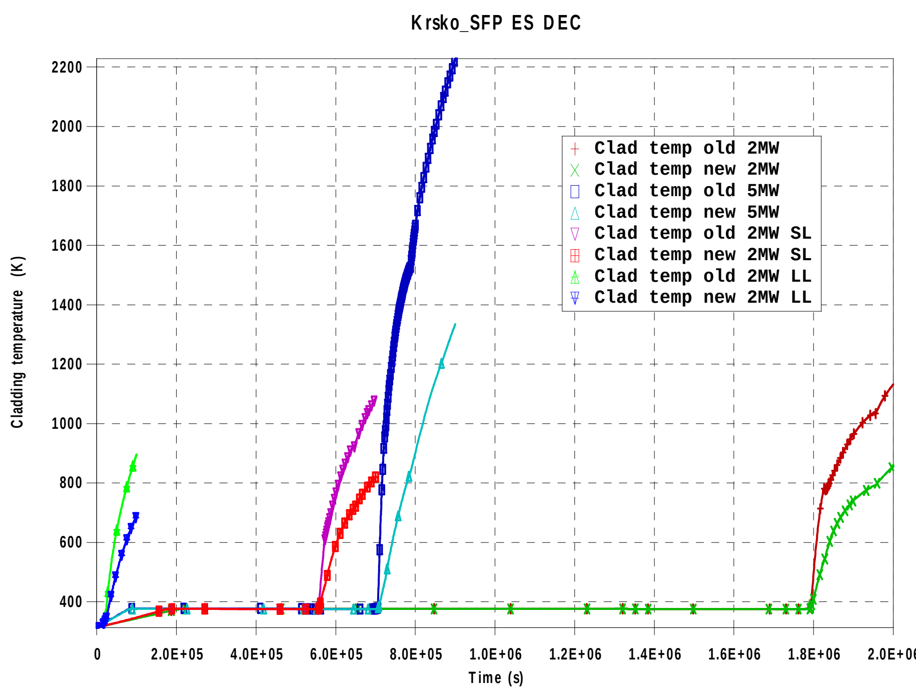
12 days

24 days



Atmosphere and Fuel Cladding Temperatures





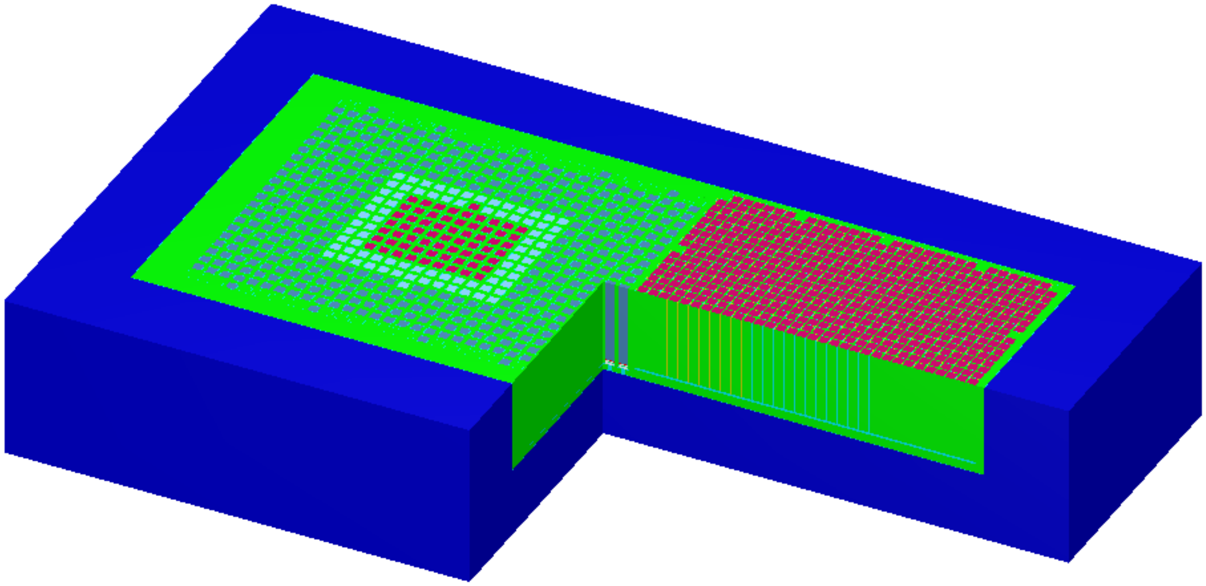
Results Summary

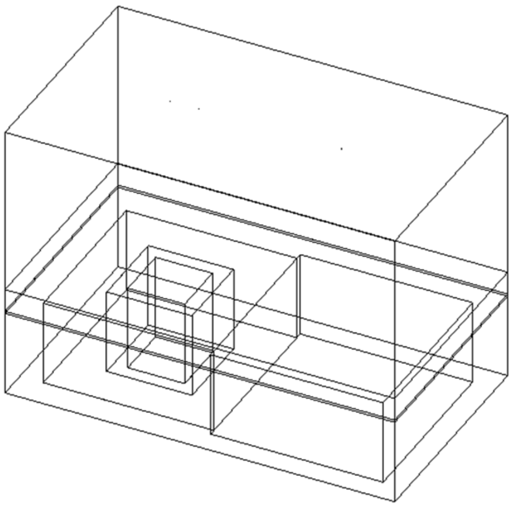
Scenario	Time to boiling (h)	Fuel rack uncover (h)	Fuel dryout (h)
5 MW	22.84	151.65	201.23
2 MW	58.03	382.10	508.64
2 MW small leak	48.40	102.88	159.01
2 MW large leak	-	3.69	6.82

Simple SFP Shielding Model

- Shielding calculation using SCALE 6.2b4 MAVRIC
- Gamma source calculated using ORIGEN for typical plant's high burnup fuel assembly
- Old and new (reracked) part of the pool
- Old part: 3 homogenized rings
  - Inner ring: 64 FAs, 60 days cooling time
  - Middle ring: 80 FAs, 1 year cooling time
  - Outer ring: 432 FAs, 5 years cooling time
- New part: 1 homogenized region
  - Full: 1088 FAs, 10 years cooling time

Simple SFP Shielding Model

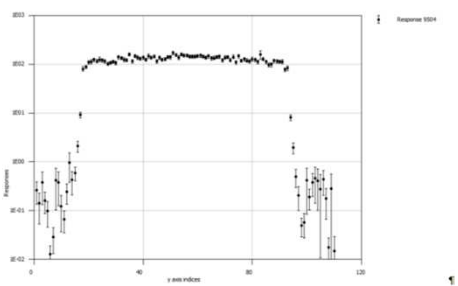


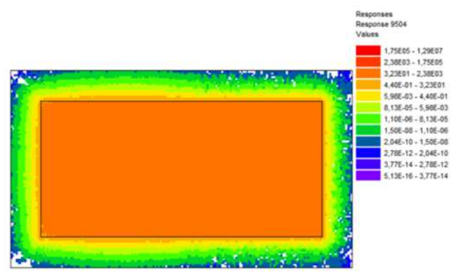


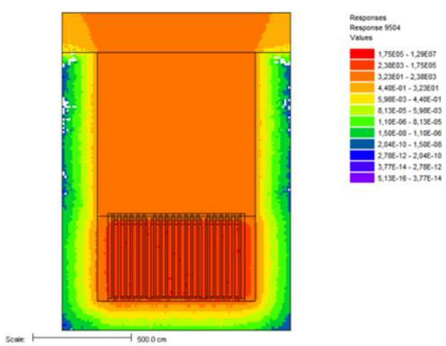
- At the top of FA – 10 cm iron based shield with equivalent density (Fe+water) of 1.4 g/cm^3 to simulate FA top nozzle
- Two cases: without water above FA or 1 m water layer

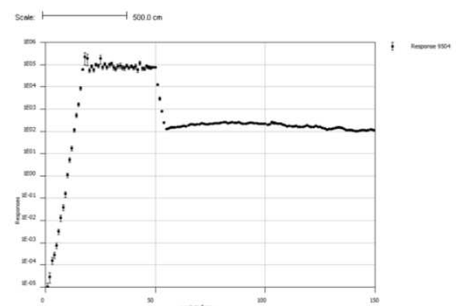
Gamma Dose Rate at the Top of the SFP

Gamma dose rate mGy/h	Empty	1 m of water
Old part center	5.49e4	1.63e2
Old part side	4.28e4	1.03e2
New part center	3.06e4	5.65e1
New part side	2.46e4	4.06e1









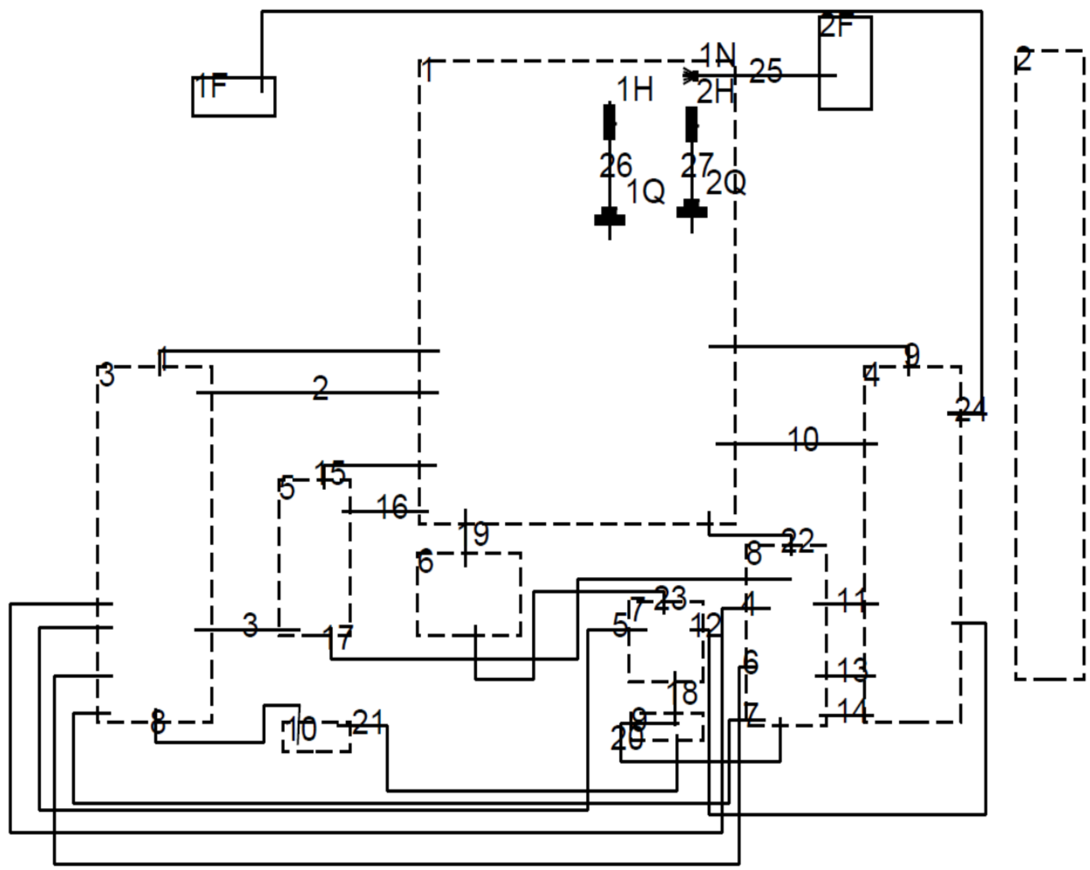
MELCOR Analysis in Support of Equipment Qualification

NEK DBA and Equipment Qualification (EQ)

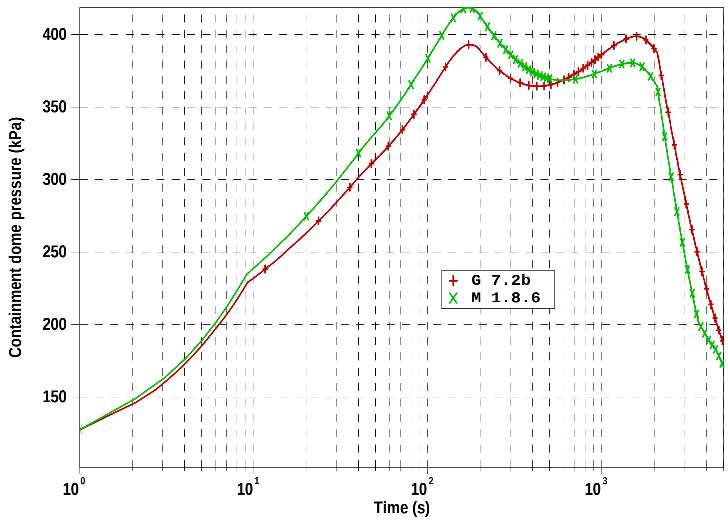
- Gothic 7.2.b qa used for DBA and EQ calculations
- Both single volume licensing model (containment + annulus) and 10 volumes BE model
- Large Double Ended (LDER) MSLB from 70% Pn
- RELAP5 used to calculate MER (Table functions)
- Two RCFC s started in accident mode at 39.4 s
- One spray train started at 80.9 s, off at 3600 s
- RCFC heat transfer rate adjusted using sensitivity coefficients in order to get proper power

Gothic Multivolume Model

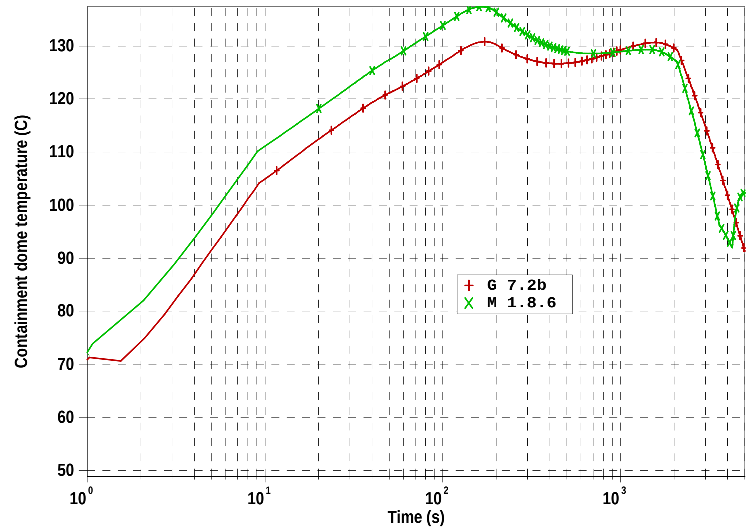
- Nodalization:
  - 10 control volumes
  - 2 boundary conditions
  - 27 flow paths
  - 74 heat structures
  - 2 RCFC units (volumetric fan + HX)
  - 1 spray train



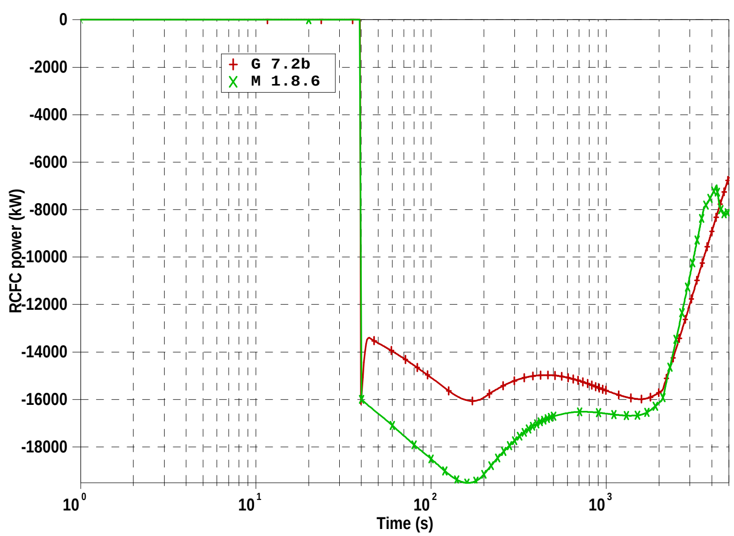
Results



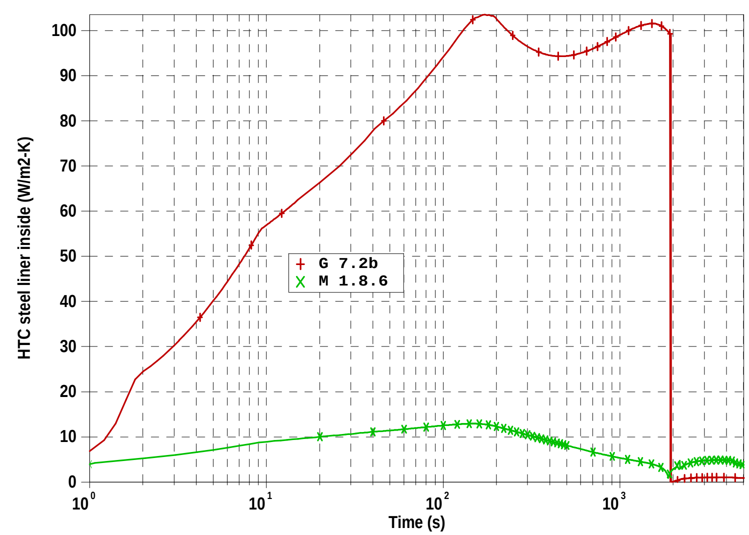
Containment dome pressure (kPa)
Time (s)
G 7.2b
M 1.8.6



Containment dome temperature (C)
Time (s)
G 7.2b
M 1.8.6



RCFC power (kW)
Time (s)
G 7.2b
M 1.8.6



HTC steel liner inside (W/m2-K)
Time (s)
G 7.2b
M 1.8.6

Conclusion

- PCFV Analysis: Overall prediction is similar to prediction used in PCFV design calculation except for time of first PCFV actuation. That time is very sensitive to status of 4" communication between cavity and sump and to relief paths between cavity and rest of the containment.
- MELCOR running times much longer than MAAP ones
- Preparation and maintenance of nodalization more complicated in MELCOR case
- Empirical models and many user-defined coefficients present in the MAAP code
- Equipment survivability and equipment qualification programs: Potential for MELCOR use, need for model adjustements