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Quantification of the Effectiveness of the Improved Severe Accident Management Measures Realized at German PWR

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Introduction

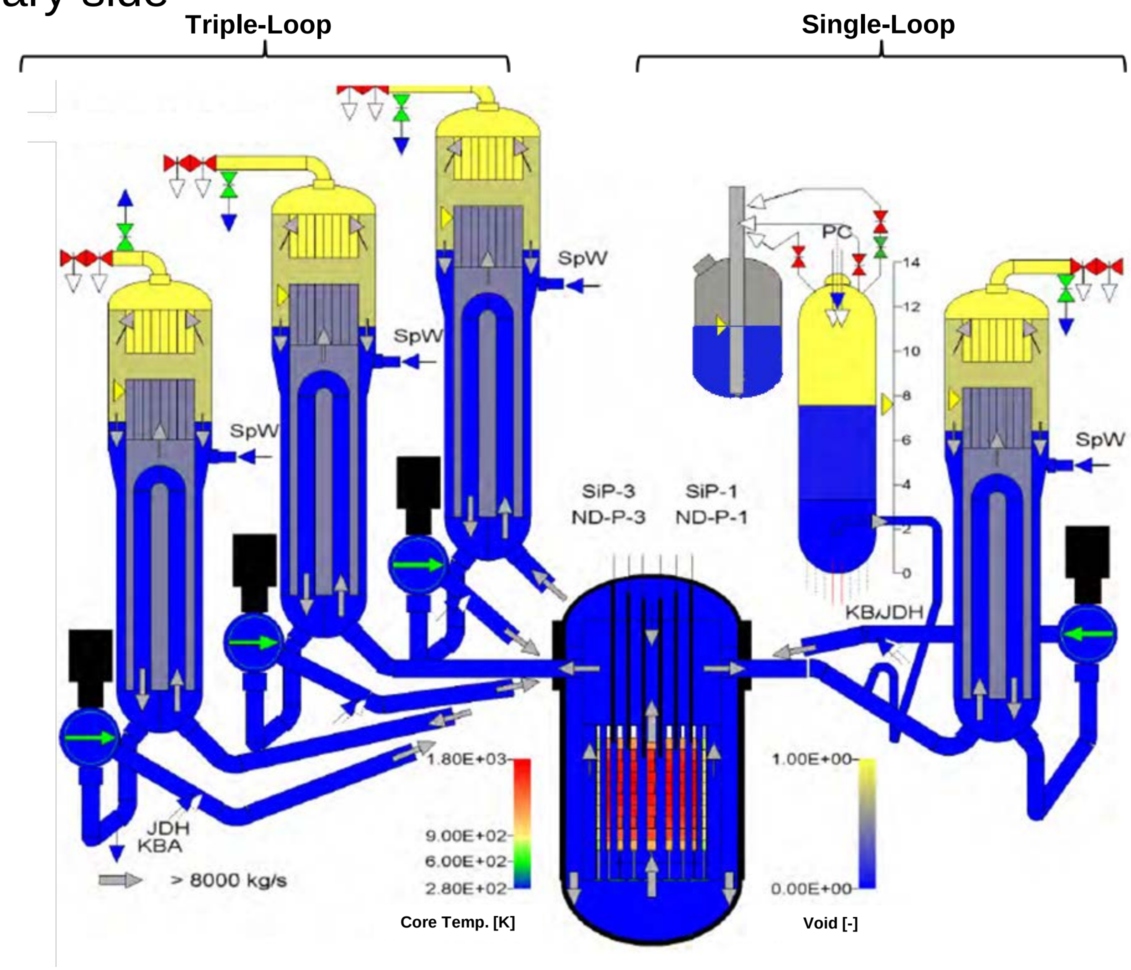
- Re-evaluation of Safety of the German NPPs has been done after the Fukushima accident.
- Main focus lay on the robustness of the plants and the optimization of severe accident management (SAM).
- SAM concept of German NPPs has been extended by additional measures for prevention and mitigation. Implementation of Severe Accident Management Guidelines (SAMG).
- SAM measures related to specific severe accident phenomena (H_2 and radionuclide behaviour) has been re-assessed.
- Two projects financially supported by the German Federal Ministry BMUB are performed at GRS in order to assess for PWR
  - the new SAM measures and
  - the H_2 and radionuclide behaviour outside the containment.
- Exemplarily, selected results of the two projects will be shown.

Assessment: New Preventive and Mitigative SAM Measures General Aspects

- Impact of the new SAM measures implemented in German PWRs has been examined by severe accident analyses with the MELCOR code ⇨ Quantification of the effectiveness of these SAM measures.
- New preventive measures ⇨ SA analyses of a long-term Station Blackout.
- Selected mitigative measures ⇨ SA analyses of a SB LOCA with 20 cm^2 break size and multiple failures of safety systems.
- Selected SA scenarios have been analysed under consideration of the plant status regarding SAM available in the plants before and after Fukushima.
- A comparative assessment of the results against the base cases have been performed and showed the efficiency of the new SAM measures and some limitations.
- Results regarding the examination of the new preventive measures are presented next.

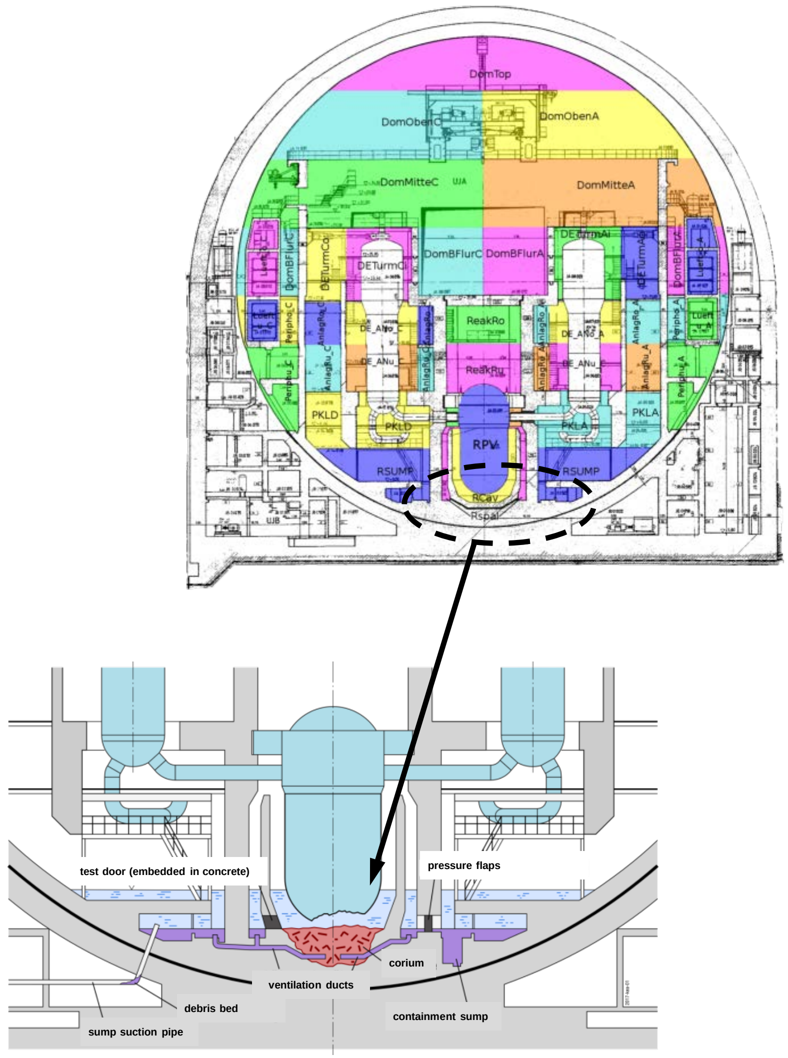
Assessment: New Preventive and Mitigative SAM Measures
MELCOR Plant Model Used

- Reactor circuit and secondary side
  - One single-loop and one triple-loop representation.
  - Consideration of the whole free volume and solid structures of RC.
  - Detailed modelling of RPV and its internal structures.
  - Core representation by 5 radial rings and 15 axial meshes.
  - Representation of the main functions of secondary side, e.g. feeding of steam generators and heat sinks.



Assessment: New Preventive and Mitigative SAM Measures MELCOR Plant Model Used

- Containment modelling:
  - Detailed thermal-hydraulic modelling (77 control volumes, 263 flow paths, and 228 heat structures).
  - Flow paths cover doors, ventilation ducts, drainages, pressure flaps.
  - Extended calculation of molten core concrete interaction due to consideration of a potential corium spreading from reactor cavity thru surrounding annular gap into containment sump.
  - 58 passive autocatalytic recombiners (PAR) distributed on 37 control volumes.
  - Filtered containment venting.

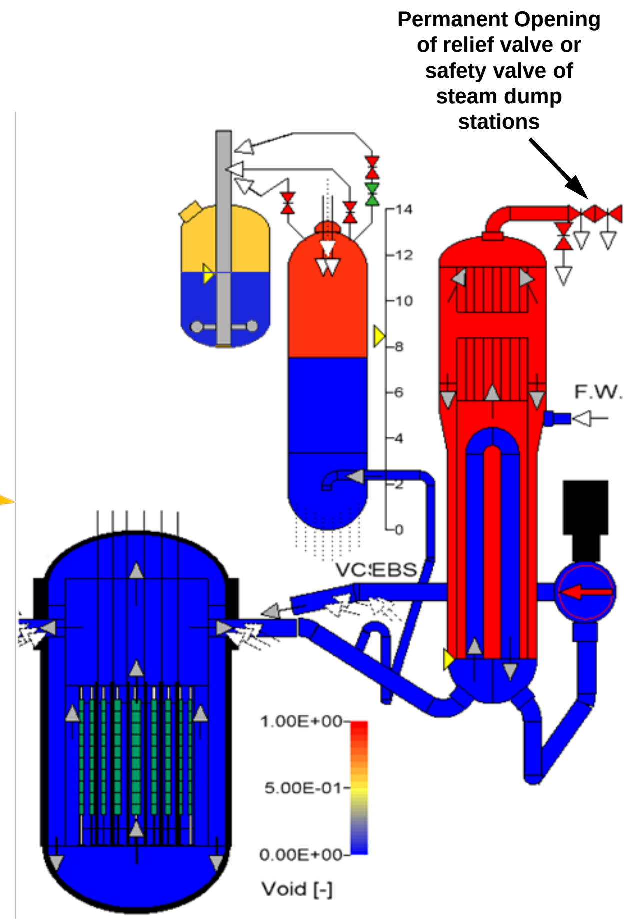


Assessment: New Preventive and Mitigative SAM Measures Analyses Long-term Station Blackout

- **Base case:** Analysis with preventive SAM measures (status-quo of SAM before Fukushima accident)
  - Secondary side bleed and passive injection from feed water system (Postulate: failure of existing mobile pump for SG feeding), and
  - primary side bleed and injection by eight accumulators.
- **Variation „2 EDGs":** in addition the new preventive measure „2 mobile emergency diesel generators (EDGs) " is available:
  - 10 h after event initiation EDGs are connected. Feeding from flooding tanks with:
    - 4 piston pumps of extra borating system (4x2 kg/s) powered by EDG1, and
    - 1 SFP cooling pump of ECCS (175 kg/s at 5 bar) powered by EDG2.
  - **Long-term goal of the new preventive measures**:
    - Recovery of core cooling, and
    - transition to "closed circulation cooling" mode by ECCS (SFP cooling pump + residual heat removal)

Assessment: New Preventive and Mitigative SAM Measures
Results Long-term Station Blackout

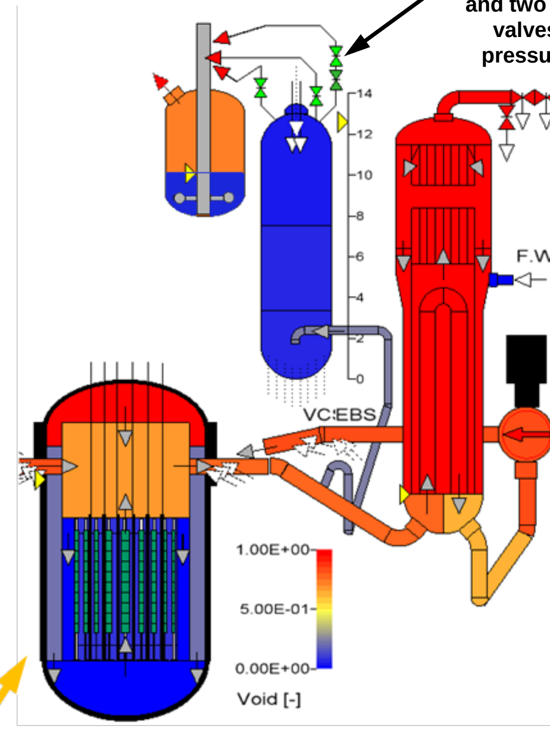
Calculated Progression [hh:mm:ss]	Base Case / 2 EDGs
Station Blackout	00:00:00
SCRAM	00:00:04
1st opening safety valve SGs (p_{MS} > 88.3 bar)	00:00:20
Water Levels SGs < 4 m	00:32:00
EOP: Secondary side bleed (SDE)	**01:10:30**
Start passive injection feedwater tank	01:41:00
Start injection of eight accumulators	02:25:00
Start periodic opening relief valve pressurizer	04:25:00
Water level RPV < lower edge hot leg	07:55:00
EOP: Primary side bleed (PDE)	**07:55:00**
Start core uncovery	07:58:00
Complete core uncovery	08:05:00
Start gap release	**08:15:00**
End of accumulator injection	09:28:00

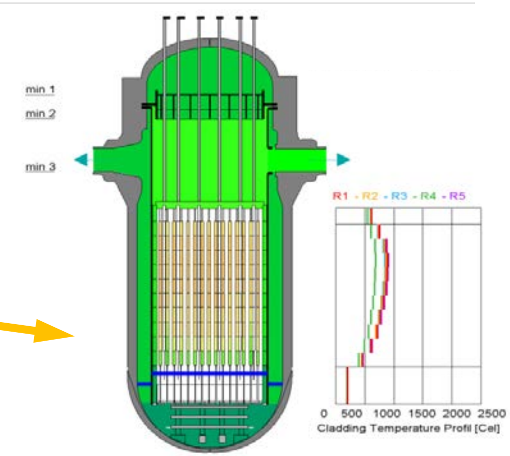


Assessment: New Preventive and Mitigative SAM Measures
Results Long-term Station Blackout

Calculated Progression [hh:mm:ss]	Base Case / 2 EDGs
Station Blackout	00:00:00
SCRAM	00:00:04
1st opening safety valve SGs (p_{MS} > 88.3 bar)	00:00:20
Water Levels SGs < 4 m	00:32:00
EOP: Secondary side bleed (SDE)	**01:10:30**
Start passive injection feedwater tank	01:41:00
Start injection of eight accumulators	02:25:00
Start periodic opening relief valve pressurizer	04:25:00
Water level RPV < lower edge hot leg	07:55:00
EOP: Primary side bleed (PDE)	**07:55:00**
Start core uncovery	07:58:00
Complete core uncovery	08:05:00
Start gap release	**08:15:00**
End of accumulator injection	09:28:00

Permanent opening of blow-off valve and two safety valves of pressurizer

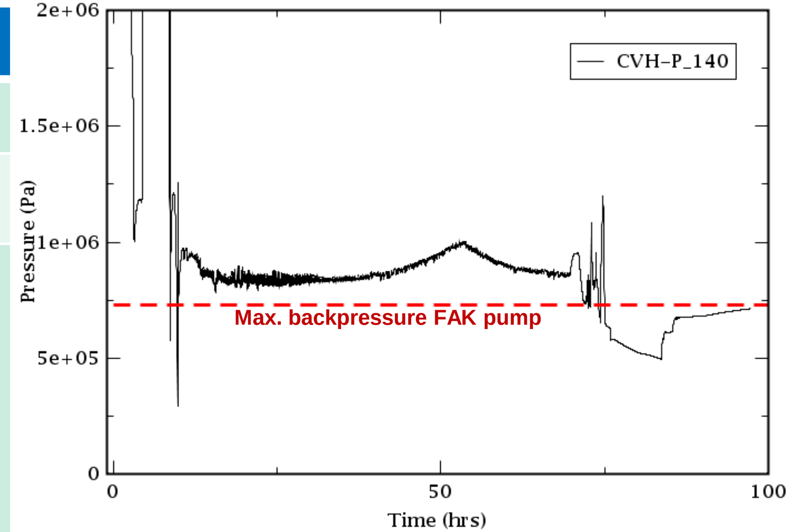




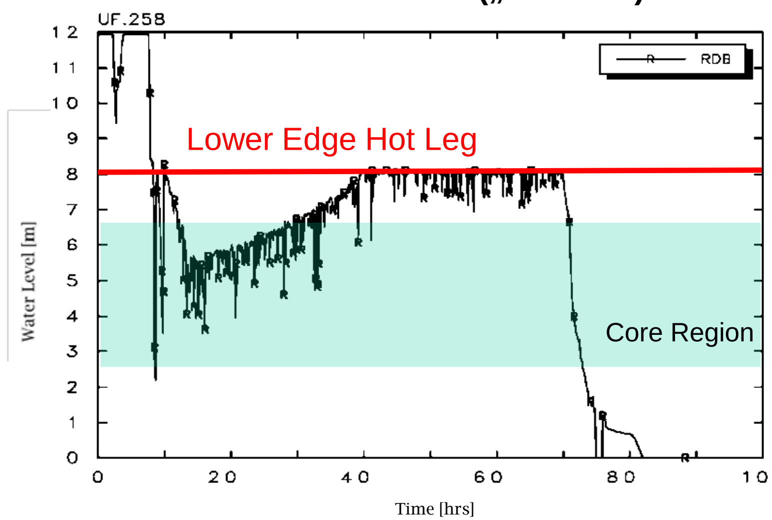
Assessment: New Preventive and Mitigative SAM Measures
Results Long-term Station Blackout

Calculated Progression [hh:mm:ss]	Base Case	2 EDGs
EOP: Mobile diesel generators available	-	10:00:00
EOP: Injection pumps extra borating system	-	10:01:00
Start failure lower support structure	12:34:00	
RPV failure	**13:55:00**	-
Start Molten Core Concrete Interaction - Reactor Cavity - Annulus / Containment sump	 13:55:00 17:03:00	
Start 1st filtered venting	**40:17:00**	**53:21:34**
EOP: End of injection extra borating system	-	69:44:00
Start failure lower support structure	see above	74:22:00
RPV failure	see above	**75:50:00**
Start Molten Core Concrete Interaction - Reactor Cavity - Annulus / Containment sump		 75:50:00 83:36:00
End of analysis	97:13:20	

Pressure RPV („2 EDGs“)



Water Level RPV („2 EDGs“)



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Assessment: New Preventive and Mitigative SAM Measures Conclusions

- **General findings:**
  - Application of the new SAM measures leads to a relevant gain in time regarding failure of RPV, start of evaporation of sump water, and first initiation of filtered containment venting (FCV).
  - Gain in time can be used for recovery actions for failed systems/components and transferring the plant in a safe and stable long-term state.
  - Hydrogen generation and release of radionuclides during FCV are reduced due to application of the additional preventive and mitigative measures.
- **Sequence specific findings:**
  - SBO: Injection of SFP cooling pump should be done first in order to reach the transition to closed circulation cooling more quickly.
  - SB LOCA: SAMG measures for mitigation initiated before RPV failure are more effective than the same measures initiated after RPV failure.

Assessment: Behaviour of Hydrogen
General Aspects

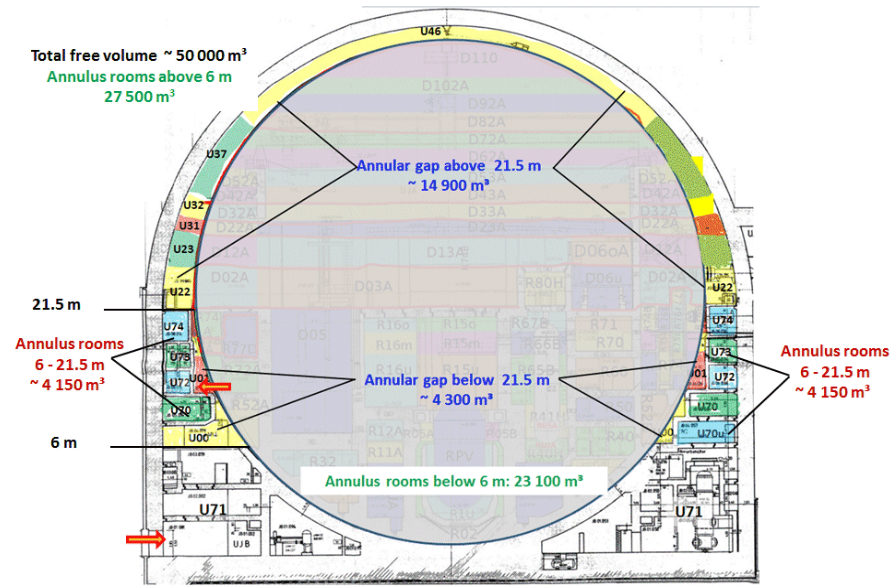
- **Main objectives**
  - Investigation of conditions inside RB annulus (e.g. hydrogen and radionuclide concentration) of a PWR plant of KONVOI type in case of a SA with increased containment leakages.
  - Elaboration of methods for detection of hydrogen and radioactive leakages from the containment into RB annulus.
  - Analysis of the efficiency of potential accident management measures (not yet implemented in the plants) to mitigate severe accident consequences.
- **Contribution to further improvement of planned mitigative SAM measures in case of increased containment leakages into RB annulus**
  - Recommendations to German Reactor Safety Commission (RSK)
- **Analyses are based on previous GRS investigations on:**
  - PAR concept inside the containment
  - Filtered containment venting concept

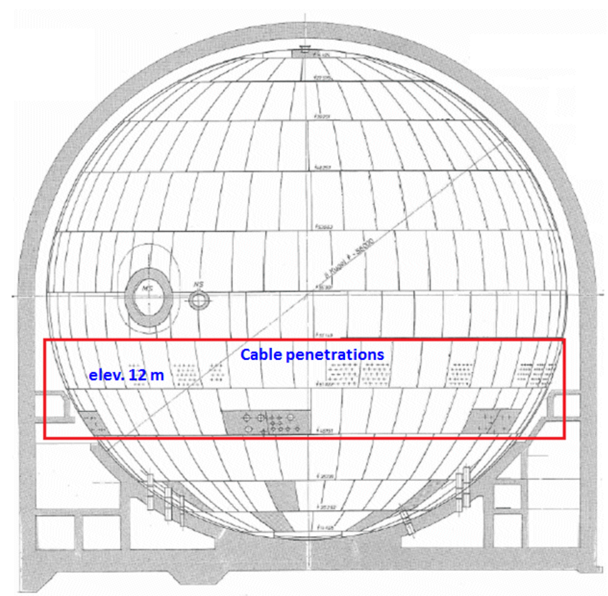
Assessment: Behaviour of Hydrogen
Selected Severe Accident Scenarios

- Selection of two representative SA scenarios (base cases), discussed here:
  - **MBL** – a medium break LOCA with a failure of ECCS after emptying the emergency water supply tank
- Investigation of specific aspects related to RB annulus conditions, discussed here:
  - Operation/Failure of RB annulus exhaust air system
  - Variation of size of containment leakages into RB annulus
    - Containment design leakage (base case)
    - 10 times larger containment leakage (variation)
- Analyses of efficiency of a mitigative SAM measure in RB annulus
  - Use of air supply/suction system (system for normal plant operation)
- Additional analysis of an alternative method for hydrogen reduction
  - Implementation of a small number of PARs in upper RB annulus

Assessment: Behaviour of Hydrogen
COCOSYS Plant Model

- COCOSYS containment model:
  - Detailed containment and RB annulus (free volume 50 000 m^3) model representing relevant plant design features:
    - Annular part of RB annulus and separated rooms located below 21.5 m,
    - fire protection doors, pressure flaps, drainages in RB annulus,
    - heat structures representing walls, floors, ceilings and metal internals,
    - containment leakages at the most unfavorable location in the area of cable penetrations at elevation 12 m,
    - filtered containment venting and PARs installed inside the containment, and
    - extended MCCI modelling for simulation of potential corium spreading from reactor cavity into sump.



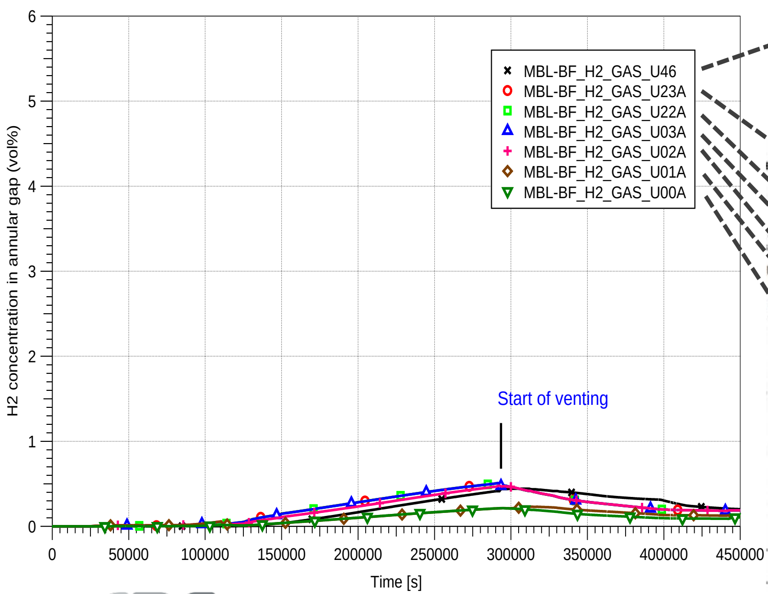


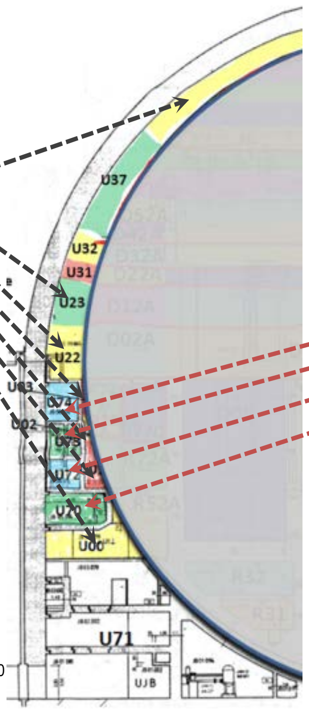
Assessment: Behaviour of Hydrogen

Results of Medium Break LOCA

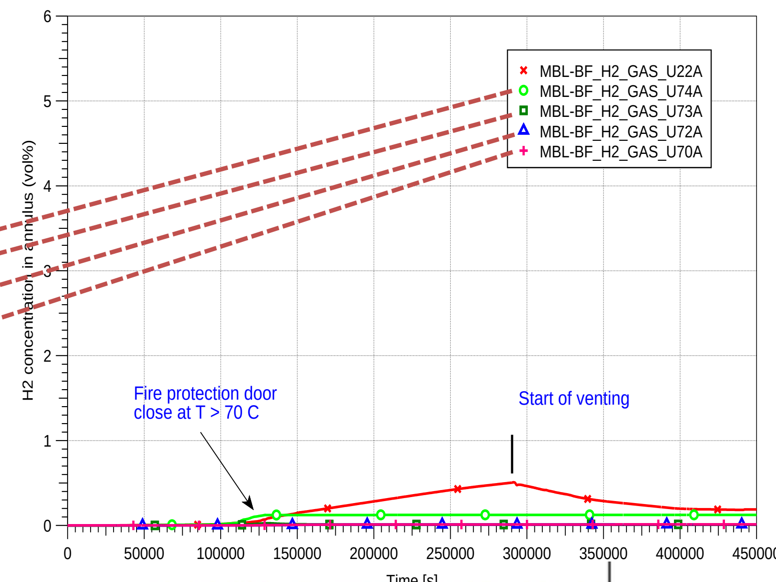
- Base case with containment design leakage
  - No formation of combustible gas mixtures (> 4 vol.-% hydrogen) in RB annulus
    ⇨ *Hydrogen concentration remains < 1 vol.-% due to operation of RB annulus exhaust air system.*
  - Separate RB annulus rooms are isolated at an early stage by automatic closure of fire protection doors, thus preventing a further increase in H_2 concentration.

Annular gap of RB annulus





Separate rooms of RB annulus

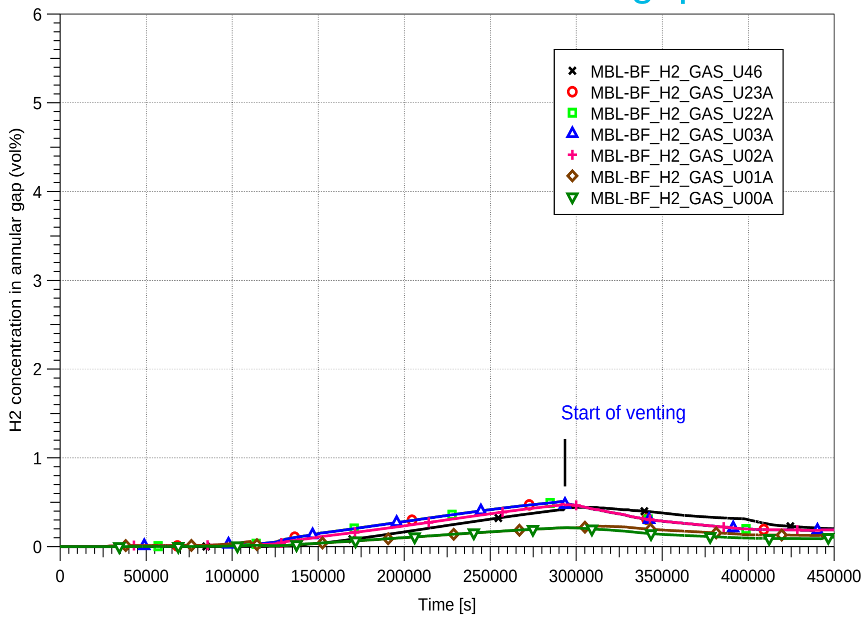


Assessment: Behaviour of Hydrogen

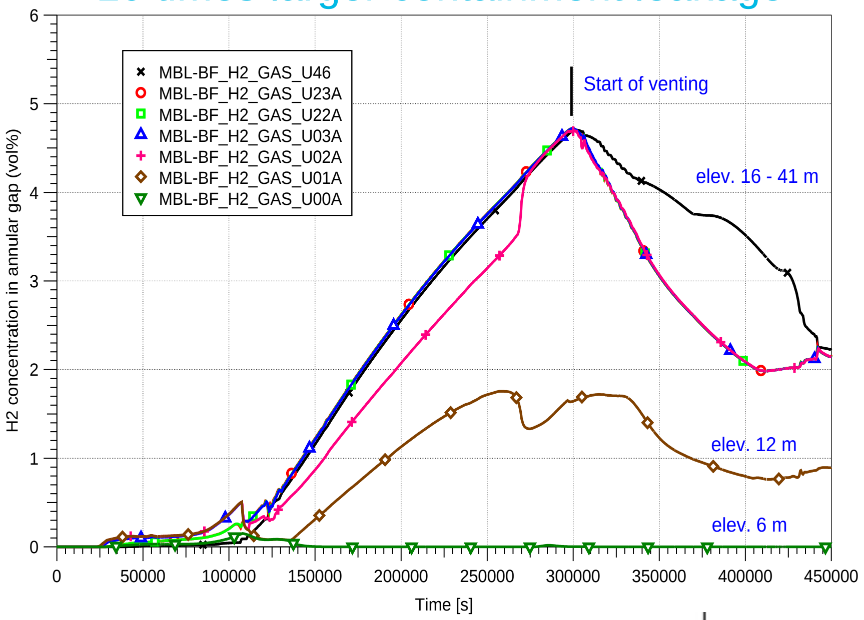
Results of Medium Break LOCA

- Variant calculation with a 10 times larger containment leakage
  - Formation of combustible gas mixtures (> 4 vol.-% hydrogen) in upper RB annulus
    ⇨ *RB annulus exhaust air system is not efficient enough to keep the hydrogen concentration below the lower combustible limit*
  - Establishment of gas concentration zones with different hydrogen concentrations along the height of RB annulus (stratification)

Base case for annular gap



10 times larger containment leakage

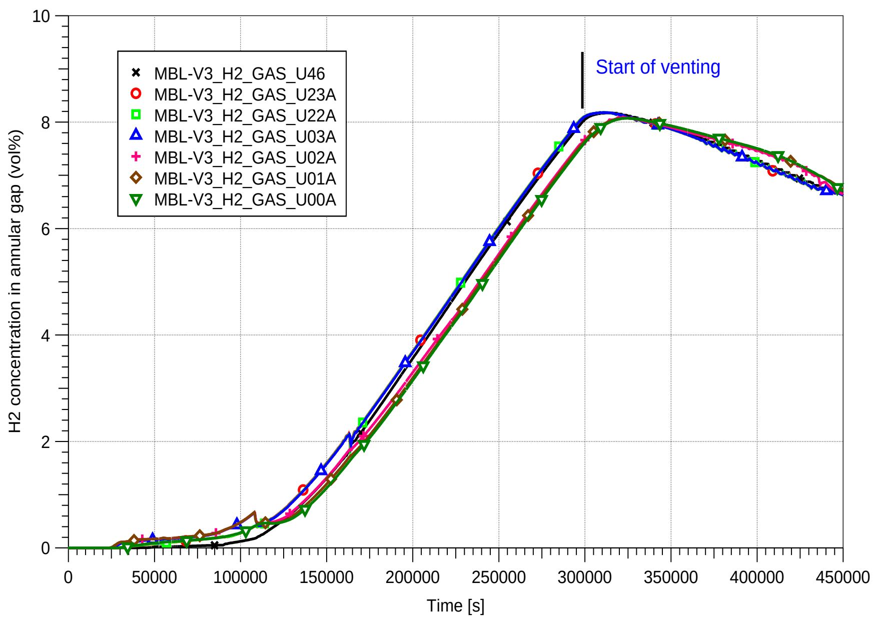


Assessment: Behaviour of Hydrogen

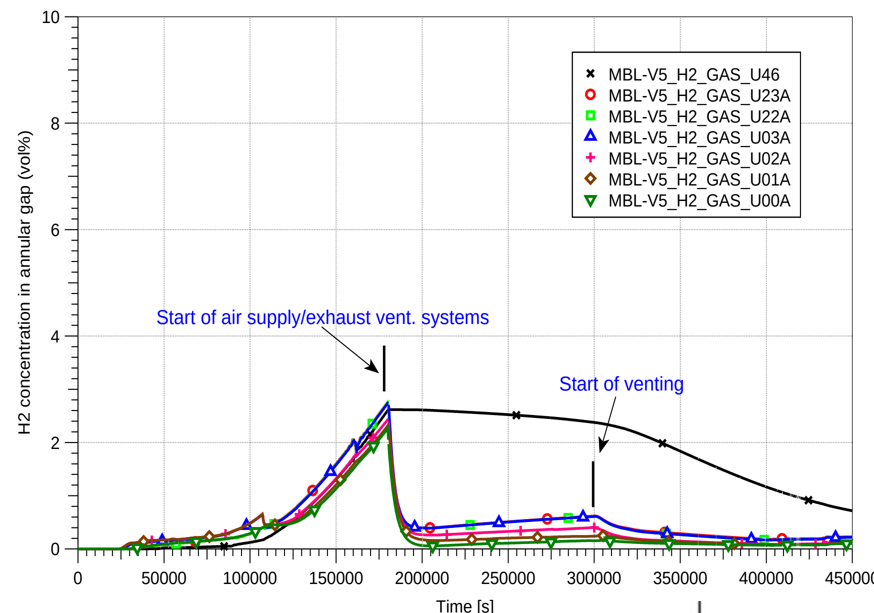
Results of Medium Break LOCA

- Variant calculations with a 10 times larger containment leakage and SAM measure: operation of RB air supply/exhaust systems at approx. 50 h
  - Use of RB supply/exhaust air systems significantly reduces the H_2 concentration and prevents formation of combustible gas mixtures in RB annulus rooms
    ⇨ *Hydrogen concentration remains < 1 vol.-% in the long-term*
  - Use of emergency air filtration system of the plant is needed in addition to limit the radionuclide releases into the environment

10 times cont. leakage, no RB air suction



10 times cont. leakage and SAM measure

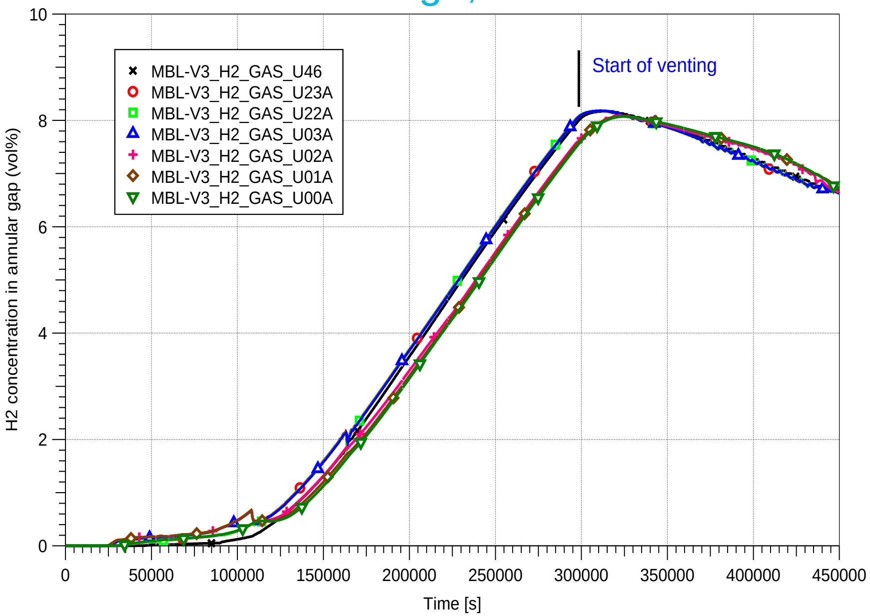


Assessment: Behaviour of Hydrogen

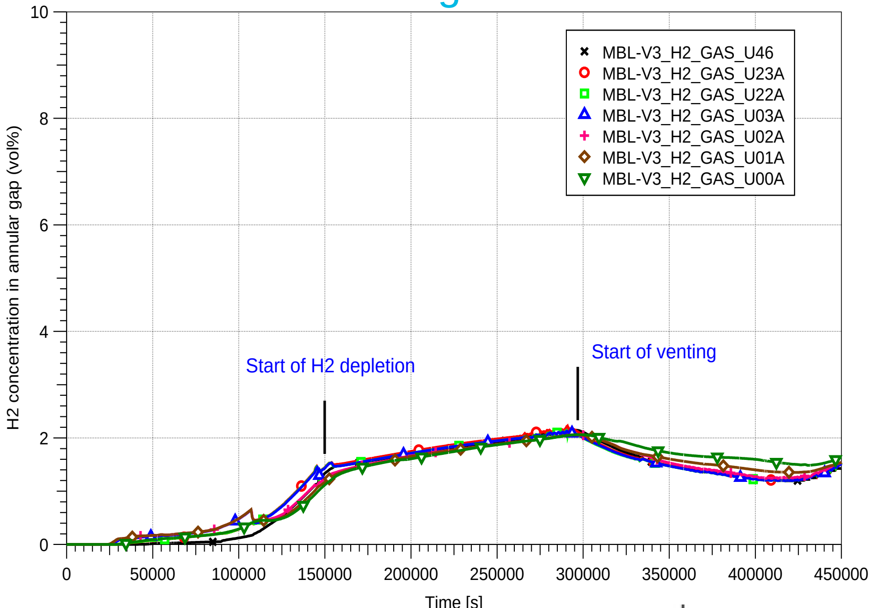
Results of Medium Break LOCA

- Variant calculations with a 10 times larger containment leakage and SAM measure: installation of a small number of medium size PARs in RB annulus
  - Use of PARs can significantly reduce the H_2 concentration in RB annulus and keep it well below lower combustible limits
    ⇨ *Hydrogen concentration remains < 4 vol.-% in the long-term*
  - Implementation of PARs is considered as a very efficient mitigation measure for preventing formation of combustible gas mixtures in RB annulus

10 times cont. leakage, no RB air suction



10 times cont. leakage and PARs in RB



Assessment: Behaviour of Hydrogen
Conclusions

- **General findings:**
  - **Base case with containment design leakage:**
    No formation of combustible gas mixtures in RB annulus.
    Isolation of separate RB annulus rooms at an early stage by automatic closure of fire protection doors, which prevents a further increase in H_2 concentration.
  - **Variant case with a 10 times larger containment leakage:**
    RB annulus exhaust air system is not efficient enough to prevent formation of combustible gas mixtures in upper RB annulus under all conditions.
- **Efficiency of different mitigative SAM measures in RB annulus**
  - Use of RB annulus air supply/suction systems is a very promising SAM measure for reducing the hydrogen concentration in RB annulus.
    Operation of emergency air filtration system is required to limit radioactive release into the environment.
  - Implementation of a small number of PARs in upper RB annulus would be a very efficient and fully passive mitigation measure without additional aerosol release into the environment.

Summary

- New SAM measures of German NPPs has been examined by deterministic severe accident analyses with the MELCOR and the COCOSYS code.
  - New preventive and mitigative SAM measures have been assessed.
  - The behaviour of hydrogen and radionuclides during SA sequences in the PWR RB annulus due to containment leakages has been examined.
- In general, the extended SAM measures have got a positive impact on the prevention and mitigation of the progression of SA sequences.
- Several sequence specific findings could be identified.

Thank you for your attention!
Questions?

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