RE-EVALUATION OF PAR CONCEPT IN GERMAN PWR WITH REVISED PAR MODEL

M. Sonnenkalb, S. Band, H. Nowack
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Schwertnergasse 1, 50667 Köln, Germany
Martin.Sonnenkalb@grs.de, Sebastian.Band@grs.de, Holger.Nowack@grs.de

S. Schwarz
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH
Forschungsgelände, 85748 Garching, Germany
Siegfried.Schwarz@grs.de

ABSTRACT

Consideration and analysis of Beyond Design Basis Accidents (BDBA) and Severe Accident (SA) of NPPs is an essential component of the defence-in-depth approach used in nuclear safety. A set of Severe Accident Management (SAM) measures and guidelines is today applied to existing NPPs to be taken to prevent the SA or to mitigate its consequences. A basic concept for hydrogen mitigation inside the PWR containment of German plants by a large number of Passive Autocatalytic Recombiners (PAR) has been examined by GRS within the frame of projects sponsored by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) already in a period up to 2001. The PAR concepts have been realized in all German PWRs thereafter, while a re-evaluation of the concept was done at GRS more recently.

Based on PSA level 2 results additional accident scenarios have been considered within the re-evaluation process. The GRS code COCOSYS has been applied again for the analyses with an updated input deck including the latest code models available, especially the new PAR model. Within recently finished OECD/NEA THAI projects several new tests related to hydrogen recombination using different PAR types (Areva, AECL, NIS) have been performed, which allowed a significant improvement of the PAR models used in COCOSYS and other codes, including CFD codes. The COCOSYS calculations were conducted according to the state-of-the-art of the computer code as well as based on experiences gained in the meantime of the validations on experiments.

The analyses results for the German PWR underlined the efficiency of the implemented PAR concept even under more challenging severe accident conditions; still local hydrogen combustion processes could not be avoided in all cases and were analyzed with COCOSYS for the first time. Various ignition criteria were applied, like a presumed ignition of the gas mixture by a PAR, to determine the most challenging conditions (worst case) with regard to the combustion process and the resulting pressure peak. A summary of the results of the re-evaluation of the PAR concept for a German PWR is presented together with recommendations on appropriate code application for the development of PAR concepts in large dry, multi-compartment PWR containments. Further reference is made to a recently published OECD/NEA SOAR report on "Hydrogen Management and Related Computer Codes" in which the German regulatory requirements related to hydrogen mitigation are summarized.

KEYWORDS
Lumped parameter code application, severe accidents, hydrogen mitigation concepts, PWR

1. INTRODUCTION

Consideration and analysis of Beyond Design Basis Accidents (BDBA) and Severe Accident (SA) of NPPs is an essential component of the defence-in-depth approach used in nuclear safety. Hydrogen mitigation measures, as part of the Severe Accident Management (SAM), have been implemented in many NPPs worldwide, starting already after the Chernobyl accident [1]. The Fukushima accident in March 2011 triggered further activities in such countries which had not considered hydrogen mitigation measures yet, such as PAR or igniter concepts. Their objective is to prevent mechanical and thermal loads, resulting from hydrogen combustions, which could threaten containment integrity. Therefore, depending on the NPP type, different hydrogen mitigation measures are designed to meet specific safety criteria and requirements. More details are provided in the recently published OECD/NEA SOAR report on "Hydrogen Management and Related Computer Codes" [2, 3], where the German regulatory requirements and the status of the implemented hydrogen mitigation measures are summarized as well.

First requirements for a SAM programme regarding BDBA and SA during power operation for German NPPs were already published in autumn 1988 after intensive discussions within the German Reactor Safety Commission (RSK). Within the German SAM concept necessary hardware modifications have been considered, as e.g. the installation of a Filtered Containment Venting (FCV) system and the implementation of Passive Autocatalytic Recombiners (PAR) in German PWR containments [4]. The paper focusses on the assessment and analyses made for the PAR concept evaluation for German PWR.

Within the scope of the experimental OECD/NEA THAI projects [6, 7] significant progress in knowledge has been achieved on the behaviour of different types of commercial PARs (Areva, AECL, NIS) under conditions typical of a severe accident. The qualification of the PAR has been done by the manufacturer already in the 90s, and was complemented by new experiments studying phenomena like onset of recombination, recombination rate and limiting conditions like oxygen starvation or poisoning by aerosols, and finally studying its ignition potential. A highly important result achieved by the OECD/NEA THAI projects is that PAR ignition potential is limited to a relatively small area of mixture compositions in the air-hydrogen-steam ternary diagram capable to provide the high catalyst temperatures required for ignition [6, 7]. Using results from the OECD/NEA THAI projects allowed a re-evaluation of PAR model [13] used within the German containment code COCOSYS [8], what is summarized here.

A basic PAR concept for German PWR plants has been analyzed by GRS already in a period up to 2001 [9]. More recently extended reference analyses by COCOSYS for the PAR concept were conducted. Based on PSA level 2 results additional accident scenarios have been considered [10]. The GRS code COCOSYS has been applied again for the analyses with an updated input deck including the latest code models available, especially the new PAR model. The analyses results underlined the efficiency of the implemented PAR concept even under more challenging severe accident conditions; still local H_2 combustion processes could not be avoided in all cases and were analysed with COCOSYS for the first time using various ignition criteria; a summary is presented here. The COCOSYS calculations were conducted according to the state-of-the-art of the computer code as well as based on experiences gained in the meantime by code validation on experiments [11, 15-17].

2. PWR CONTAINMENT BEHAVIOUR

The size of Western PWRs covers ranges from two-loop 1365 MWt to large four-loop 4270 MWt units. The typical German PWR containment consists of a steel containment within a surrounding concrete reactor building (Figure 1). In contrast to other PWR designs no spray systems are installed in the German PWR containments [2].

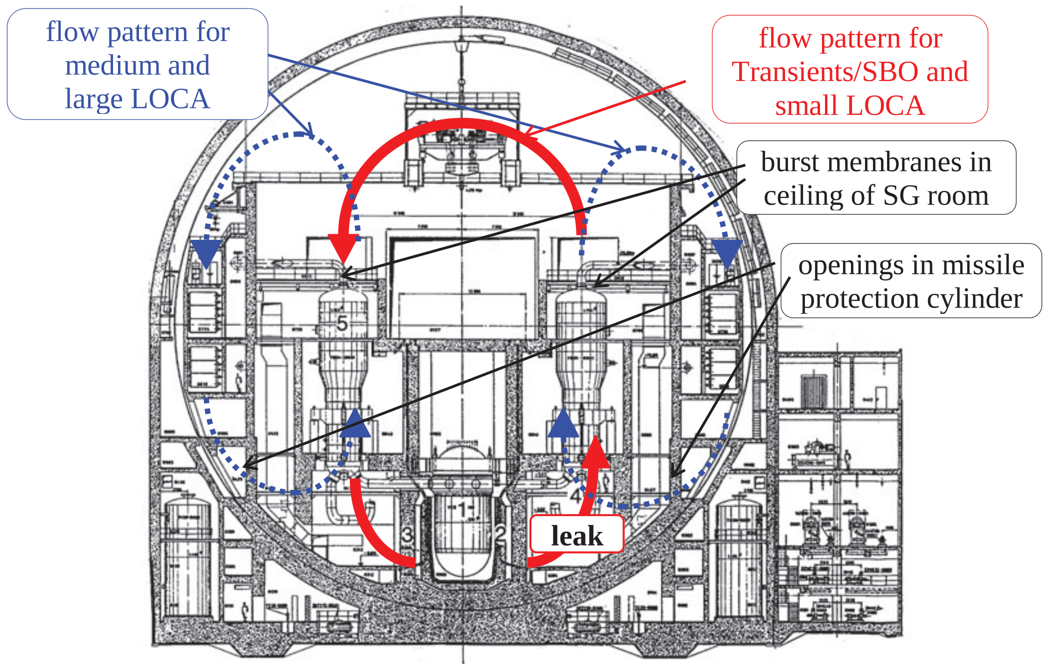


Figure 1. Main convection flow pattern in German PWR containments.

The conditions inside the containment in case of an SA are strongly dependent on the amount of energy released from the primary circuit, the size and location of the releases, the main convection flow pattern, the local gas concentration, and the operation of safety systems and of PARs. Due to the specific design of the German PWR containments, the convection flow regime inside the containment is strongly determined by the initial event and the release location from the primary circuit. Mainly in case of Medium Break (MB) or Large Break (LB) LOCA, two main convection flow patterns exist (blue arrows in Figure 1), while in other cases like Small Break (SB) LOCA or transient scenarios like Station Black-Out (SBO) only one main convection flow pattern exists (red arrow in Figure 1). The reason for this plant specific behaviour is the different pressure peak caused by different leak sizes which determines the resulting pressure difference between the inner and outer containment part and therefore the number of burst membranes or doors, which will be destroyed. Many burst membranes are located in the ceiling of both Steam Generator (SG) compartments, while inside the missile protection cylinder stronger burst membranes and doors are located, which will be opened only in case of significant pressure peaks. Analyses results showed that in MB and LB LOCA cases the global convection inside the containment is more intensive and the homogenisation process of gases (e.g. steam, H_2) released into the containment is much faster, while in other cases steam inertisation in the containment in rooms above the leak location may exist. Such plant specifics have to be considered in the analyses done for the definition of the PAR concept, as well as for the selection of different scenarios to be analysed, and for the input deck set-up. In addition, the possibility of gas stratification processes in the containment has to be analysed.

3. REQUIREMENTS FOR THE IMPLEMENTATION OF HYDROGEN MEASURES

3.1 General Recommendations of RSK related to PAR Concepts

In the recently published OECD/NEA SOAR report on "Hydrogen Management and Related Computer Codes" [2] the German regulatory requirements related to hydrogen mitigation are summarized. In all German PWR containments, PARs are installed to remove the hydrogen generated in SAs, following the respective German Reactor Safety Commission (RSK) recommendations [4]. It should be noted that besides other requirements no specific criteria related to the remaining maximum or average hydrogen concentration in the containment were applied nor was it practicably possible to request to prevent any hydrogen combustion in PWR containment by the PAR concept. It was recommended that the number of PARs to be installed in a PWR containment, and their locations, have to be determined based on best estimate analyses using representative SA scenarios taking into account different hydrogen release rates and characteristic gas transport times within the containment. Further, numerical analyses with lumped parameter codes and engineering estimates related to the distribution, the number and the locations of the required PARs are specified to be appropriate. The RSK assumed that the analysis results are further supported by CFD code analysis, what was done for one case by GASFLOW [5].

These RSK recommendations related to SAM and especially hydrogen mitigation [4] are still in line with the currently used nuclear rules and regulations within the scope of the "Safety Criteria for Nuclear Power Plants" [12] completed end of 2012. The new nuclear rules and regulations comply with the related recommendations of the IAEA and the Western European Nuclear Regulators Association (WENRA).

3.2 Practical Application of Requirements related to Development of PAR Concept for PWR

GRS carried out detailed investigations by the COCOSYS code (or its predecessor RALOC), supporting the discussions in Germany about the basic requirements for the implementation of a PAR concept in large dry PWR containments [9]. Based on the results of these investigations, the implementation of PARs in large dry containments was recommended by the German Reactor Safety Commission RSK in 1997, realised by the NPPs thereafter [2, 3], and reconfirmed by the latest analyses of GRS [10].

The following specific topics have been investigated by GRS analyses [9, 10]:

- Positioning of PARs in a multi-compartment PWR containment and development of generic criteria,
- Local and overall capacity of a PAR system needed to prevent H_2 accumulation and global H_2 combustions challenging the containment integrity,
- Influence of the PAR system on the gas distribution, convection flow processes, extent of gas mixing in the containment under SA conditions and the local and average gas temperatures,
- Consequence of a failure of some PARs e.g. due to blow-down forces or catalytic poisons.

The following main criteria have been used for selection of representative severe accidents, as the determination of one or two bounding cases and/or the application of conservative assumptions is impossible and not recommended for those analyses of PAR concepts in general:

- The range of steam and non-condensable gas release rates into the containment through core oxidation and core concrete interaction (MCCI) has been analysed for different SA scenarios (analysed within PSA level 2) to determine:
  - Peak gas release rates (H_2, steam) from core oxidation,
  - Long-term average gas release rates (H_2, CO, CO_2, steam) from concrete erosion,
  - Maximum release rate of H_2 and CO together with steam from both processes.
- Different release locations from reactor circuit into the containment have been analyzed with regard to the pre-conditioning of the containment atmosphere (question of steam inertisation) prior to H_2 and CO releases to determine:
  - Local steam and oxygen concentration, and possible gas stratification and steam inertisation,
  - Pre-conditioning related to structure temperatures, potential for steam condensation etc.,
  - Conditions of openings between rooms and areas supporting natural convection (burst membranes and doors) in the containment dependent on the accident scenario,
  - Influence of other plant specific aspects of the PWR containment design.
- The probability of the selected representative SA sequences and the assumptions related to the use of ECCS systems e.g. have to be determined, so that relevant scenarios are not neglected for the selection of representative scenarios for PAR design analyses.

4. CONTAINMENT NODALISATION AND PAR MODEL

4.1 General Requirements on Containment Nodalisation for Lumped Parameter Codes

As mentioned above, the calculations have been performed mainly with the GRS containment code COCOSYS [8] and general requirements on containment nodalisation have been developed. In principle the containment was subdivided into two halves (Figure 2), considering the specific design and the location of the two SG compartments. Smaller rooms have been modelled separately while large open compartments, e.g. the dome region of the containment, which dominates the possible convection flow regime, are modelled by several control volumes. This was done to allow the calculation of temperature and gas distribution and a possible stratification to some extent. Other general requirements derived related to the containment nodalisation are summarized as follows:

- High degree of detail concerning the containment nodalisation:
  - Large detail of modelling of compartments allowing consideration of local positioning of PARs,
  - "Center elevation" of volumes modelling rooms located at a similar level should be the same,
  - Modelling of existing flow connections between the different compartments,
  - Consideration of long-term convection flows in the containment after days with ongoing MCCI.
- Appropriate consideration of release locations for mass and energy into the containment (e.g. break location, cavity).
- Consideration of all types of flow connections between the compartments (size, location, direction):
  - Existing free openings between rooms,
  - Δp dependent openings: like burst membranes and doors,
  - Connections via the air ventilation system ducts inside containment,
  - Drainage flow paths from the individual rooms down into containment sump,
  - Containment leakage(s) to the annulus.

4.2 PWR Containment Nodalisation used in Lumped Parameter Code COCOSYS

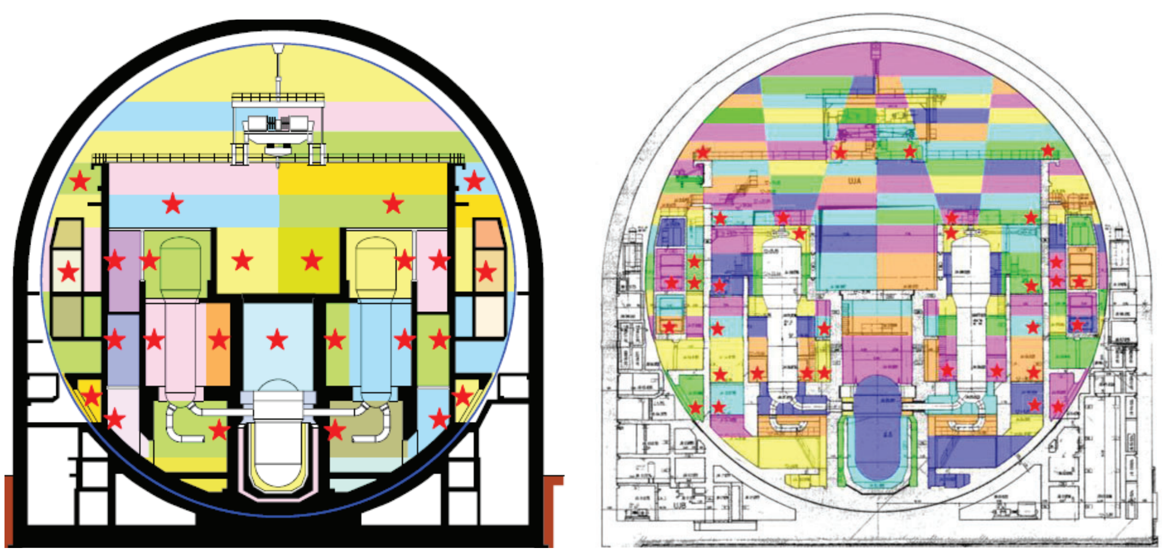


Figure 2. COCOSYS nodalisation schemes with PAR location (red stars); left: "basic PAR concept" and scheme used first [9], right: "realized PAR concept" and scheme used for re-evaluation [10].

Two slightly different nodalisation schemes have been used for the analyses (Figure 2). The "simpler one", still consisting of more than 100 zones inside the containment, was used for the first analyses [9] at a time when the computers have been less powerful than today. The latest nodalisation used in the re-evaluation process [10] considers all plant specific aspects even with more detail. The nodalisation of the containment system consists of up to 200 zones, app. 240 structures and more than 550 junctions. Both schemes also have a detailed nodalisation of the surrounding annulus, which is not shown in Figure 2. At least two different PAR concepts have been studied (see Figure 2), starting with a “basic concept” of ~50 PARs of different size used in the first analyses [9], and the final concept for the large dry German PWR containment consisting of ~65 PARs used in the analyses of the re-evaluation process [10].

4.3 PAR Model developed for Lumped Parameter Code COCOSYS

The PAR models in COCOSYS are developed for the simulation of plate type recombiners (Areva and AECL). A PAR can be simulated with a detailed 1D-junction model or by using simplified correlations that only calculate the depletion of H_2 (and CO) based on derived equations from the detailed model or the one provided by Areva. The model used in COCOSYS in the earlier PAR concept analyses [9] was based on an Arrhenius type reaction kinetic. The previous validation was done based on the BMC Gx4 experiment. The comparison of the model with latest OECD/NEA THAI results showed unexpected discrepancies, especially a partially strong overestimation of recombination rates (Figure 3) [13].

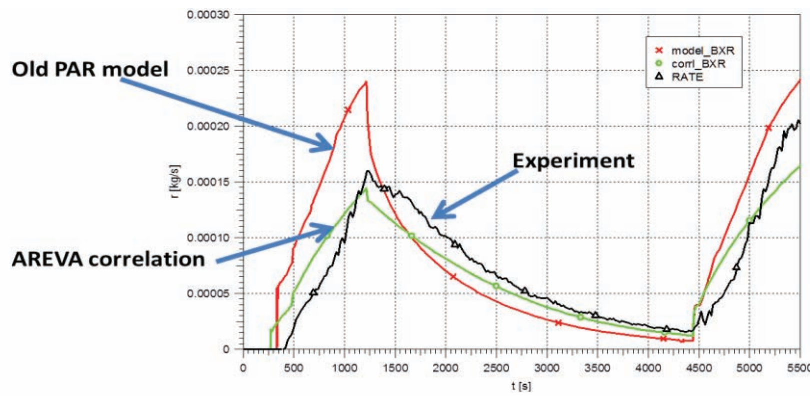


Figure 3. H_2 recombination rate, no steam: THAI HR-5 3.3 bar [13].

Latest findings at Forschungszentrum Jülich (FZJ) [14] show that reaction kinetics inside a PAR is not Arrhenius typical, but driven by the diffusion of hydrogen (and CO) towards the catalytic plates. So the model was revised [13] and in the re-evaluation of the PAR concept this diffusion based model derived from the REKO-DIREKT code [14] is used. The model uses the following main equations:

$$\dot{r} = \beta \, (C_{wall} - C) \tag{1}$$

$\dot{r}$: reaction rate [mol/(m²s)], β: mass transfer coefficient [m/s],
C_{wall}: H_2 concentration near the PAR plate [mol/m³], C: H_2 concentration in gas phase [mol/m³]

Two further assumptions are to be made: complete H_2 depletion at the PAR plate $C_{wall} = 0$ and the mass transfer coefficient β differs along PAR plate axis leading to:

$$\dot{r} = \frac{1}{A} \sum_{x=0}^{X} - \beta_x C_x A_x \tag{2}$$

The new PAR model in COCOSYS uses a subdivision of the plate into 100 axial parts and calculates the H_2 concentration in the gas phase C_n as a function of plate height:

$$C_n = C_{n-1} \frac{v_{n-1}}{v_n} - \beta_n C_{n-1} \frac{A_{kat}}{A} \tag{3}$$

C: concentration [mol/m³], v: velocity [m/s], A_{kat}: catalytical surface [m²], A: inlet surface [m²]

New validation [13] used OECD/NEA THAI results as exemplarily shown below (Figure 4 – Figure 6), but as well the old BMC Gx4 experiment; all show very good results also for oxygen starved conditions.

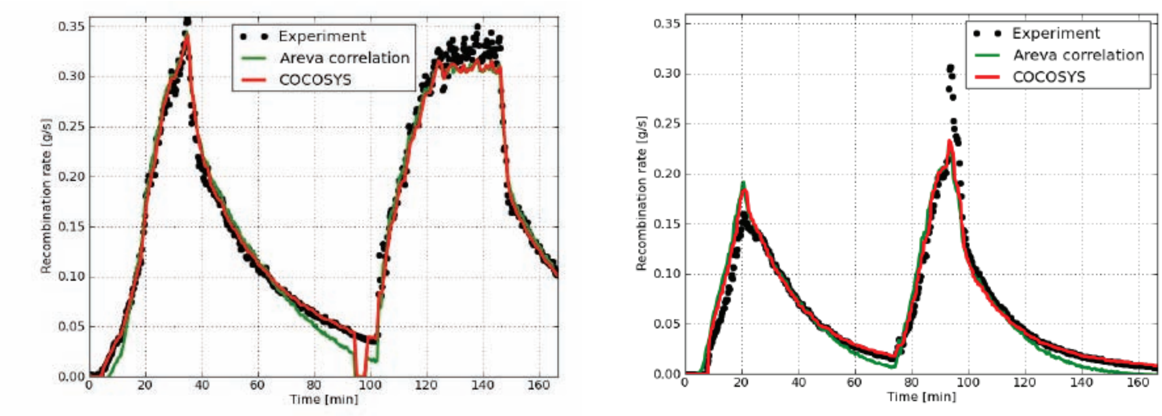


Figure 4. Comparison of measured and calculated H_2 recombination rate, experiments without steam: THAI HR-2 1.0 bar (left); THAI HR-5 3.3 bar (right) [13].

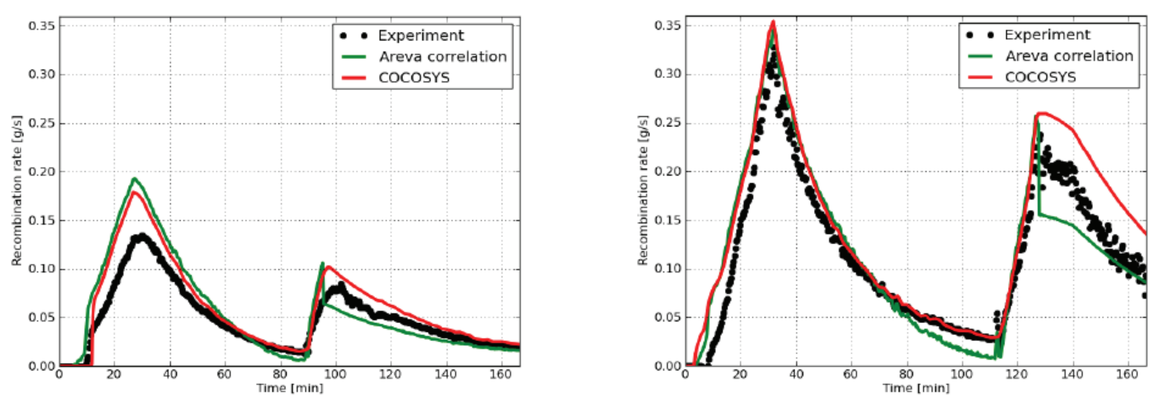


Figure 5. Comparison of measured and calculated H_2 recombination rate, experiments with 60 % steam: THAI HR-13 1.0 bar (left), THAI HR-12 3.0 bar (right) [13].

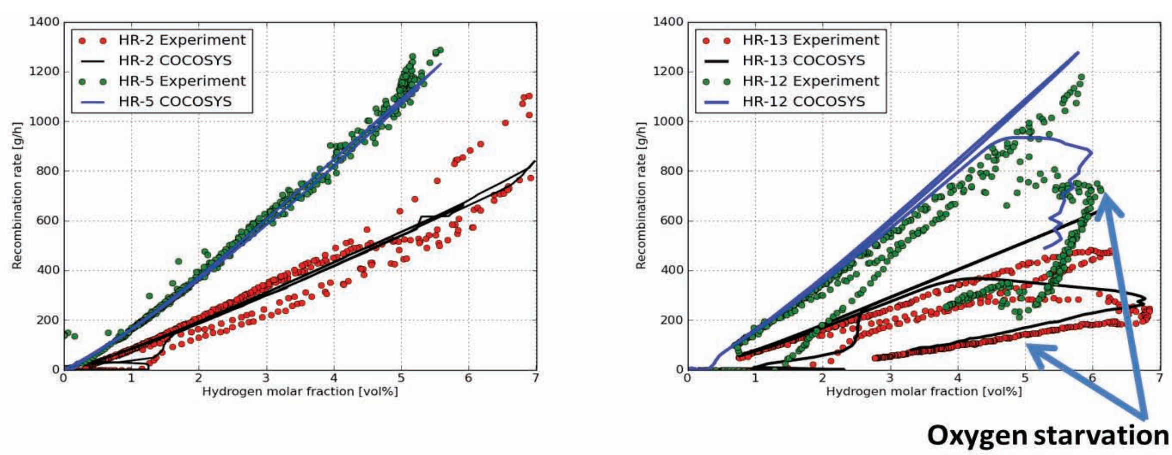


Figure 6. Comparison of measured and calculated H_2 recombination rate versus H_2 molar fraction in different THAI HR experiments, without steam (left) and with saturated conditions (right) [13].

5. RE-EVALUATION OF THE PAR CONCEPT FOR PWR – ANALYSES RESULTS

5.1 Selection of Representative Scenarios

Out of a set of more than 10 different severe accident sequences being analyzed with conditions as realistic as possible (no conservative assumptions) with the code MELCOR, four different cases were selected and analysed by COCOSYS within the first stage of the PAR concept analyses [9]. These are cases with assumed failure of ECCS injection except accumulators before core melting:

- Fast core degradation process (0.5 – 1.5 h): LB LOCA, 2A break of pressurizer surge line,
- Intermediate core degradation process (1 – 3 h): SB LOCA, leak of 50 cm^2, hot leg, with failure of Steam Generator (SG) depressurization and heat removal,
- Slow core degradation process (> 3 h): Loss Of SG Feed Water supply (LOFW) with primary side depressurization, high release location through pressurizer relief tank,
- Slow core degradation process (> 3 h): SB LOCA, leak of 50 cm^2, hot leg, with available SG depressurization and heat removal.

Within the re-evaluation of the PAR concept [10] the spectrum of analyses was extended by two cases with available ECCS and accumulator injection before core melting. Such cases lead to non-inerted containment conditions prior to the hydrogen release:

- Late core degradation process (> 6 h): MB LOCA, leak of 200 cm^2, hot leg, with available SG depressurization and heat removal,
- Extremely late core degradation process (> 22 h): SB LOCA, leak of 10 cm^2, hot leg, with available SG depressurization and heat removal.

It should be pointed out that due to the existing preventive SAM actions of secondary and primary bleed and feed in German PWR plants high pressure core melt sequences were not taken into account for the design of a PAR system. The LOFW scenario is a transient similar to an SBO, which has a higher probability and was therefore selected in the re-evaluation process together with the first analysed LB LOCA scenario. So again a selection of representative cases was made for the re-evaluation and the description of some analyses results in the following comprises of three parts. First results of a "test case" with the used containment nodalisation are presented. The purpose was to demonstrate the ability to predict light gas stratification (H_2 stratifications) and its dissolution by a steam plume released from a lower position as studied in THAI experiments and others. The main part is related to COCOSYS analyses results for the PAR concept re-evaluation as described in [10] and finally an example is shown for a H_2 combustion calculation done with COCOSYS within the same project.

5.2 Nodalisation Test for Modelling Gas Stratification and Dissolution in PWR Containment

Possible build-up of a light gas stratification and its dissolution by steam plume have been experimentally analysed within the THAI facility as part of ISP-47 or HM2 benchmark [11, 15] or in the PANDA facility at PSI in Switzerland within OECD/NEA SETH and SETH-2 project [16, 17]. Such behaviour might occur under specific SA conditions (see Figure 7 left part for illustration) and implies e.g. the late reflooding of a heavily damaged reactor core or the quenching of melt in the cavity by flooding with water resulting in strong steam release finally. The experimental data have been widely used for code comparison using lumped parameter and CFD codes. The thermal hydraulic phenomena of the experiments have typically been predicted well by the codes; however, the time intervals needed to dissolve the stratification have often been either under- or over-predicted especially in the blind predictions. Reasons are user effects in setting up the nodalisation, the detail of the nodalisation used in lumped parameter codes or the choice of turbulence and heat radiation models in CFD applications. Open predictions have been used to improve the analyses results and to gain further knowledge on appropriate code usage. COCOSYS was applied successfully for such kind of analyses [11, 15].

The updated PWR containment nodalisation described in chapter 4.2 (here without PARs) was tested related to its ability to simulate H_2 stratification and dissolution processes. A scenario was defined in analogy to the experiments [11, 15] as follows: After an initialization phase of 5 000 s, a H_2 injection phase followed (0.03 kg/s H_2 into the upper SG box A, 5 000 – 47 000 s) through a break in a high position (orange arrow in Figure 7). After a gas layer stabilization phase the dissolution of the H_2 layer by steam injection was simulated (3.5 kg/s steam into the cavity, 50 000 – 74 000 s), assuming melt in the cavity was flooded by water (blue arrow in Figure 7). The simulation stops at 80 000 s.

The results related to the H_2 concentration in different rooms of the containment (Figure 7) qualitatively reproduce the experimental findings very well: H_2 released into the dry containment atmosphere at an elevated location with a temperature similar to the containment atmosphere results in H_2 stratification above the release location. Steam release simulated at a low position in the cavity will dissolve the layer within a given time starting from below. This demonstrates that the nodalisation chosen is able to predict such stratifications if its occurrence under SA conditions would have to be expected (see next chapter).

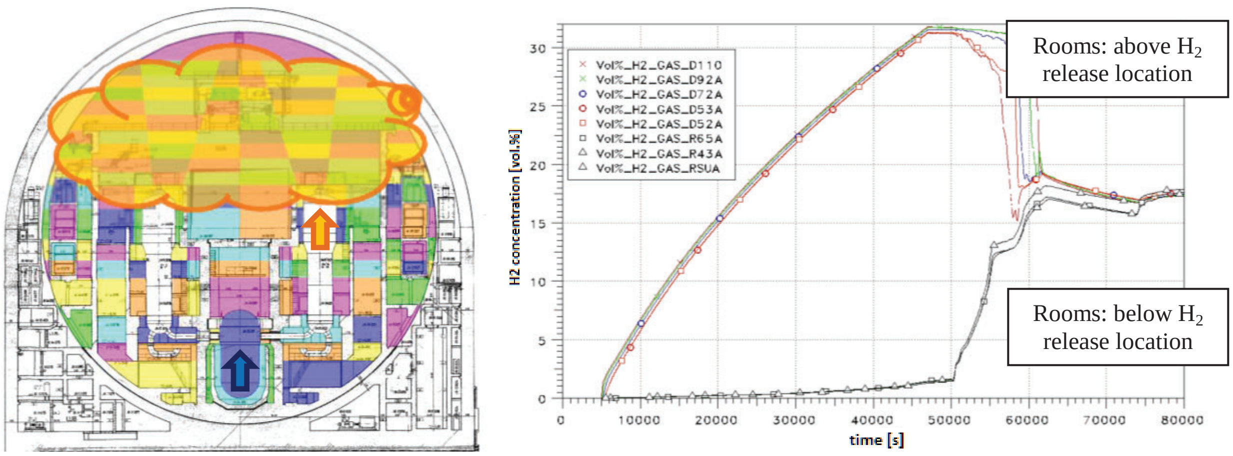
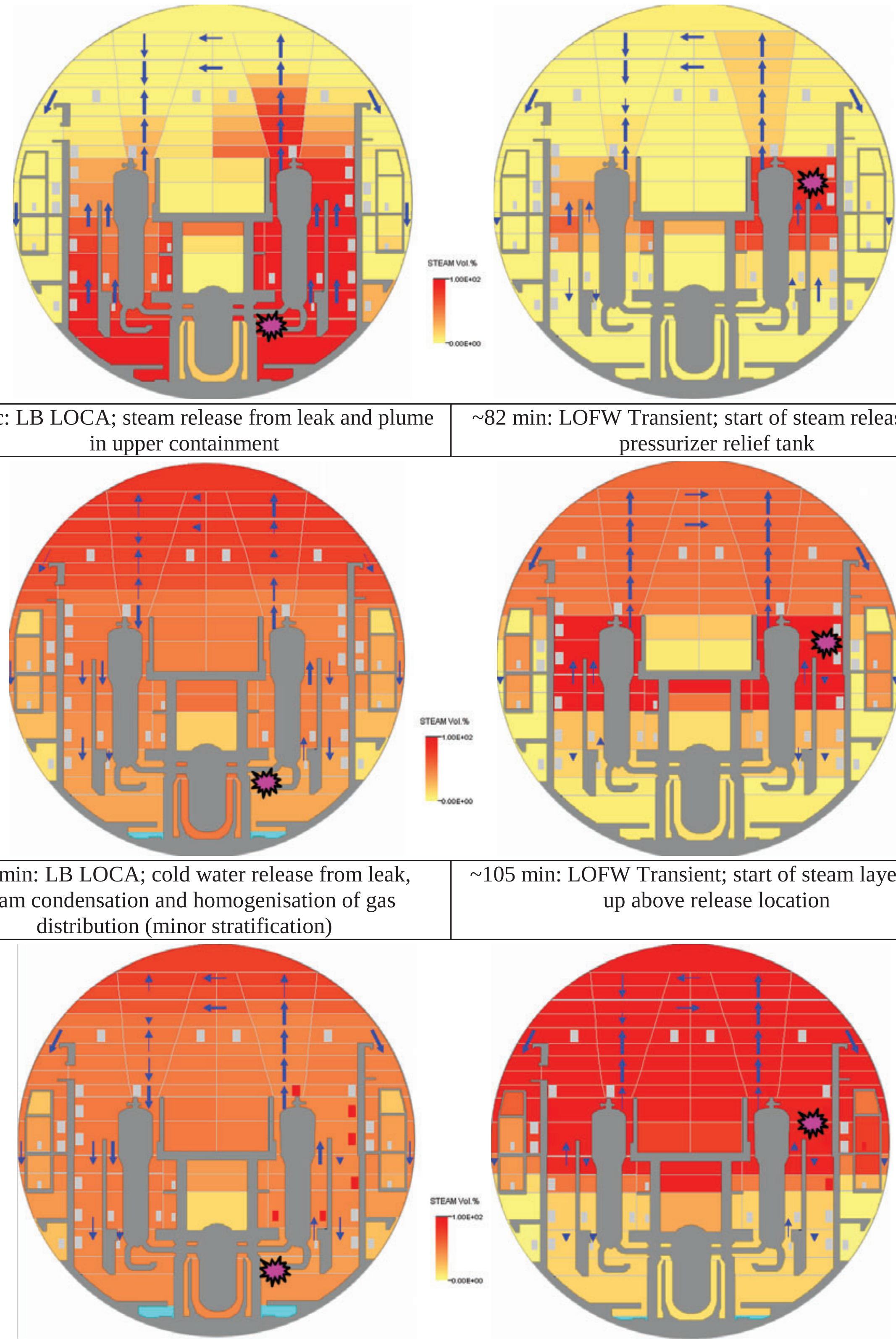


Figure 7. Test of PWR nodalisation to reproduce build-up of H_2 stratification above release location and dissolution by steam release from cavity; right: H_2 concentration in different rooms [10].

5.3 Exemplary Results of two Different SA Cases analysed for PAR Concept Re-evaluation

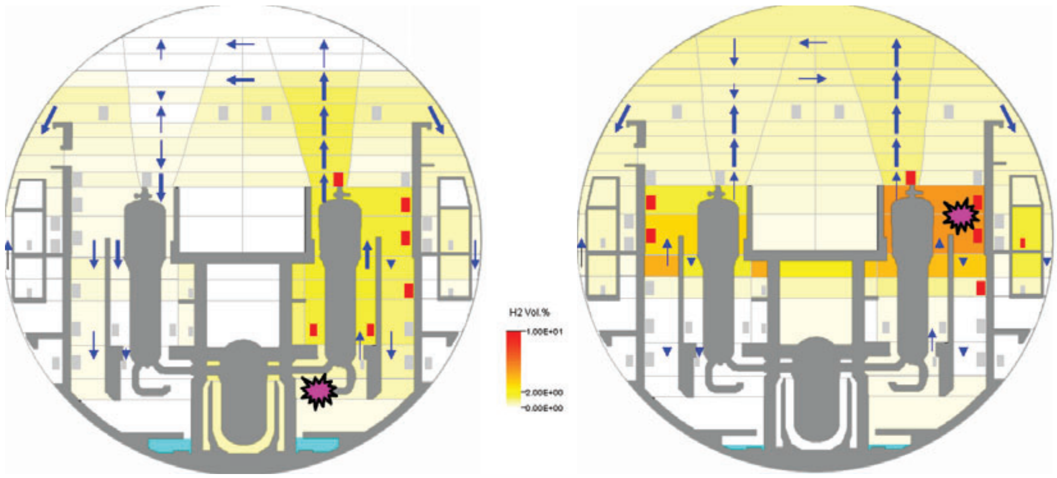
Characteristic events of two scenarios: LB LOCA and LOFW analysed through the concept re-evaluation [10] have been chosen to show typical results. The two scenarios are different with regard to the timing of the events: LB LOCA - early core degradation, LOFW - late core degradation, the flow conditions: LB LOCA - good, LOFW - limited convection, and the steam concentration during H_2 release: LB LOCA - no steam inertisation, LOFW - steam inertisation in upper part of containment. The release locations also vary: LB LOCA - low leak position at RCS, LOFW - high(est) release position at pressurizer relief tank. Figure 8 and Figure 9 (next pages) show the steam concentration (range: 0 – 100 vol.%) respectively the H_2 concentration (range: 0 – 10 vol.%) in the containment. The operation of PARs is visualized by either "gray boxes" - no recombination or "red boxes" - ongoing recombination. Please notice that the position of the release through the pressurizer relief tank (LOFW) is not visible as it is behind the SGs.

All calculations performed showed that the implemented PAR concept was powerful enough to prevent global H_2 combustions challenging the containment integrity [10]. The examination was done for each room by using Shapiro diagrams. The number of PARs and their location was modified several times through the initial analyses [9], before the final set-up was defined and re-evaluated [10]. Stratified conditions with high H_2 concentration have not been found. The flammability limits will be exceeded only for short time periods during the early core degradation phase if no steam inertisation is given, and typically rooms are affected in the inner containment part close to the H_2 release location (chapter 5.4.)

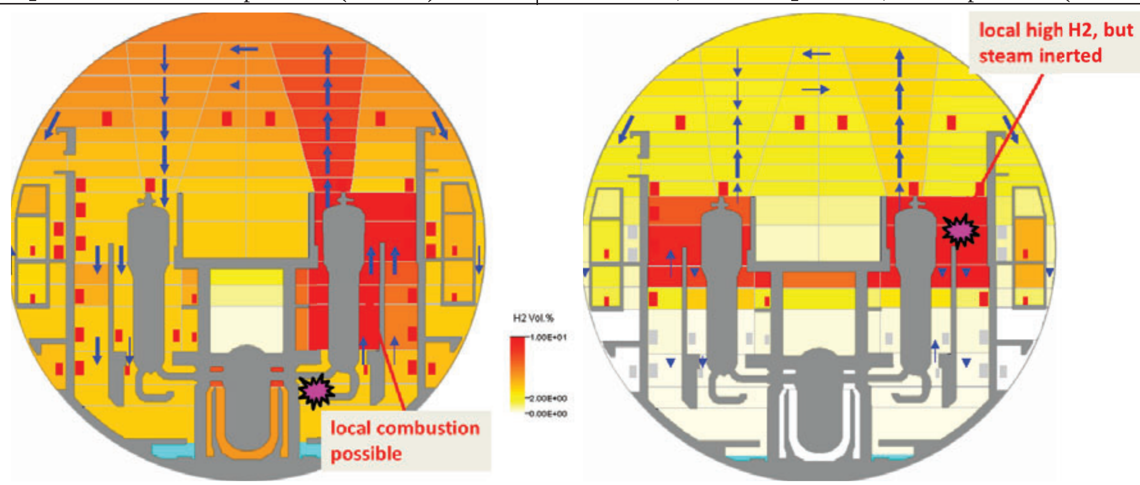


~10 sec: LB LOCA; steam release from leak and plume in upper containment	~82 min: LOFW Transient; start of steam release from pressurizer relief tank
~13 min: LB LOCA; cold water release from leak, steam condensation and homogenisation of gas distribution (minor stratification)	~105 min: LOFW Transient; start of steam layer build-up above release location
~30 min: LB LOCA; no steam inertisation, start of H_2-release, PAR operation (red box)	~213 min: LOFW Transient; steam inertisation/ stratification, start of H_2-release, PAR operation (red box)

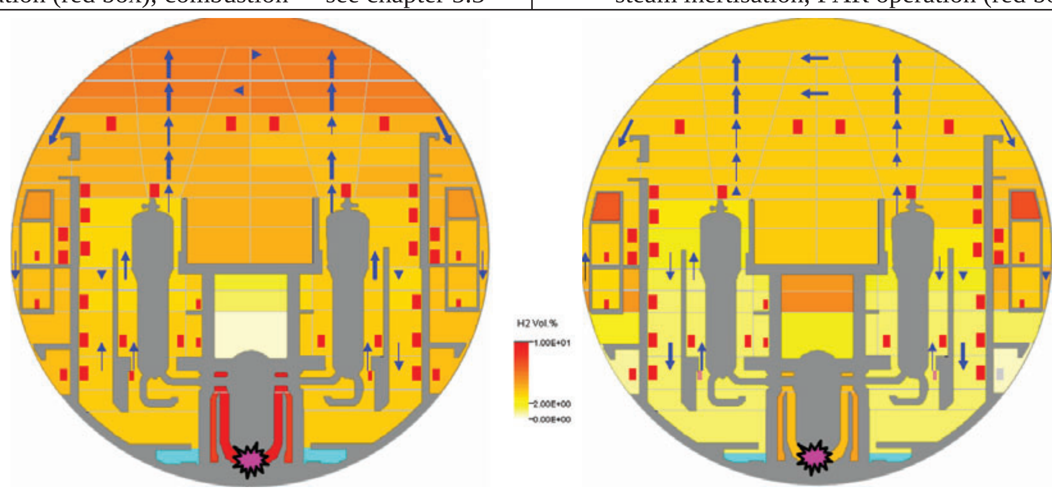
Figure 8. Steam concentration in PWR containment prior to H_2 release.



~30 min: LB LOCA; no steam inertisation, start of H_2-release and PAR operation (red box)	~213 min: LOFW Transient; steam inertisation/ stratification, start of H_2-release, PAR operation (red box)



~100 min: LB LOCA; strong short H_2 & steam release due to core relocation into lower plenum; all PARs in operation (red box), combustion -> see chapter 5.3	~239 min: LOFW Transient; strong short H_2 & steam release during core oxidation, no combustion due to steam inertisation, PAR operation (red box)



~110 min: LB LOCA; RPV failure, MCCI -> H_2/CO release, all PARs in operation, slight stratification	~390 min: LOFW Transient; RPV failure, MCCI -> H_2/CO release, nearly all PARs in operation

Figure 9. H_2 concentration in PWR containment during core degradation and MCCI.

5.4 Exemplary Results of H_2 Combustion Analyses performed with PAR Concept Re-evaluation

Possible H_2 combustion processes were analysed with COCOSYS for the first time. The combustion model FRONT was validated e.g. through participation in ISP-49 of OECD [19]. Various ignition criteria were implied in the analyses, like e.g. a presumed ignition of the gas mixture by any PAR at different H_2 concentrations between 8 vol.% and 10 vol.% according to the range experimentally observed at the THAI facility [6]. An attempt was made to find the “worst-case scenario” which assumes a combustion may start at any time and any location (ignition source needed!) and which would result in the largest flame propagation and therefore in the largest pressure peak due to the combustion – assumed to be the most challenging one for the containment integrity. Combustions are only possible in some scenarios. Exemplarily results of the LB LOCA case are shown inFigure 10 below with regard to the containment pressure (left) and H_2 mass burned (right). Figure 11 shows the combustion process based on the flame propagation for the “worst-case” starting in the cavity at ~10 vol.% H_2 (zone with red number 1) and “running” upwards through one SG tower to the dome where it stops (zone with red number 42 or 43).

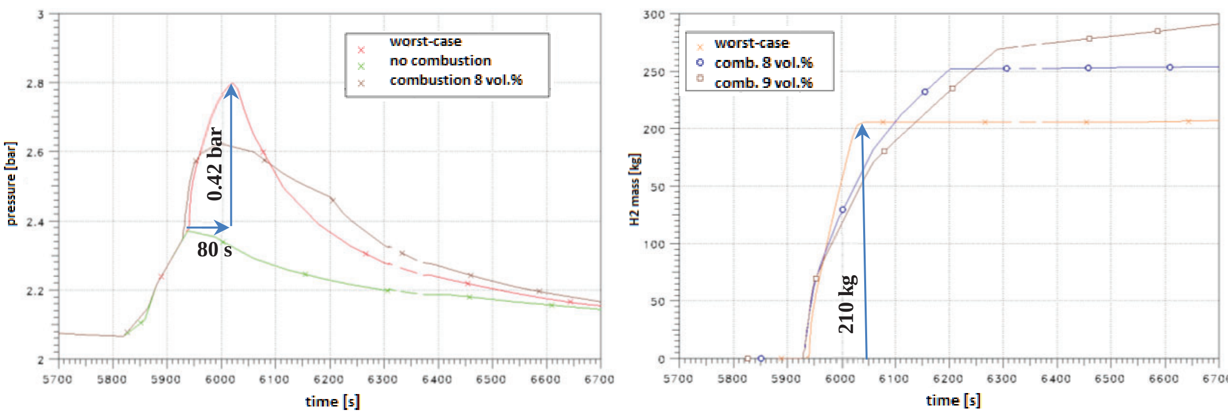


Figure 10. Containment pressure (left) and H_2 mass burned (right) in case of local H_2 combustion initiated at different conditions, LB LOCA [10].

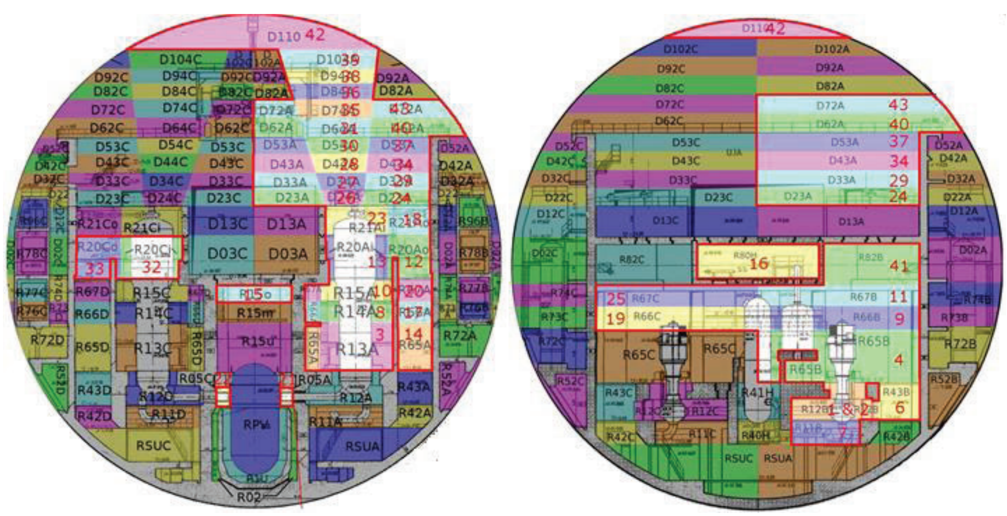


Figure 11. Flame propagation (red numbers from 1-50) through containment (front view and 90^{O} view) with combustion initiated in the cavity, “worst-case” scenario, LB LOCA [10].

The pressure increase calculated for these local H_2 combustion processes with assumed ignition sources was always lower than 0.5 bar, whereby the required combustion time ranges between 15 s (LB LOCA, ignition at 8 vol.% H_2, Δp ~0.25 bar), 30 – 45 s (MB LOCA, ignition at 10 vol.% H_2, Δp ~0.5 bar), and

80 s (LB LOCA, "worst-case scenario", Δp ~0.42 bar). The calculated flame speed respectively combustion time needed is in the range of data measured at the THAI facility [6]. Despite remaining inaccuracies of the calculated pressure increases, large margins exist until the design basis pressure of the containment will be reached, since ignitable gas mixtures only occur during the early stages of the accident sequence (strong core oxidation), when the pressure in the containment is still low.

For the evaluation, whether in case of severe accident loads due to increase of internal pressure and temperature the integrity of the containment as leak-tight barrier is endangered, structure mechanical calculations are necessary, in which the determination of safety margins against the loss of integrity respectively the limit load bearing capacity of the containment constitutes a priority. Within the project [10] such structure dynamical elastoplastic calculations were conducted with the finite element computer code ADINA, having been tested for such issues. Characteristic loading assumptions were determined as peak-like pressure and temperature sequences from already available test results and the COCOSYS calculations. Results of the structural mechanics analyses have been presented in [18] and underline the efficiency of the installed PAR concept in the PWR plants under SA conditions.

6. SUMMARY

With the concept of catalytic combustible gas recombination, a further risk reduction was achieved in case of BDBA and of SA. The PAR concept was judged to be compatible with the existing safety concept for PWRs and that it could be retrofitted without causing any operational restrictions. Based on the findings from available extensive analytical and experimental studies, the RSK recommended already in 1997 [4] that an appropriate PAR concept should be implemented in NPPs with PWR in Germany. The main findings of the analyses of [9, 10] are summarized as follows. The PAR concept calculations for large dry PWR containments demonstrate a high safety profit. An active PAR system results in a lower containment pressure in the long-term due to the mol reduction and steam condensation. The continuous recombination of H_2 and O_2 mitigates always potential threats to the containment, as it starts at low concentrations even under steam inerted conditions. CO released from core concrete interaction is recombined as well. The integral recombination rate depends on the local and global convection flow pattern inside the containment, which should be appropriately calculated, considering all plant specifics especially the numerous pressure dependent openings. The temperature level is thereby only slightly increased due to the exothermic O_2-H_2 respectively CO reaction (~20 – 30 K). Mainly in the inner containment (inside missile shield) combustible gas mixtures exceeding 10 vol.% H_2 could be developed locally for short times even with the PAR system. In some scenarios steam inertisation prevents any combustion, in others maybe not, as PARs could act as an igniter (see OECD/NEA THAI experiments [6]), but would ignite the mixture at relatively low H_2 concentrations, well below the detonation limit. App. 1 day after the start of the H_2 release the containment atmosphere of a German PWR becomes inert due to the complete O_2 consumption by the catalytic reaction (unmitigated scenario assumed).

A detailed containment nodalisation considering all plant specific aspects together with a well validated code and a selection of representative severe accident scenarios for the analysis of the PAR concept are recommended and were applied at GRS. SAM guidance should be provided in case a containment spray system is used together with the PAR system, what is not the case in German PWR. In the view of the RSK [4], as well as of many experts, the distribution of H_2, which is the decisive factor for determining the number and position of the required PARs, could be calculated adequately by means of lumped parameter codes and engineered judgment. As a result of the first analyses [9] generic recommendations for PAR locations within complex German PWR containments have been derived, which are confirmed in general by the re-evaluation [10]. More details in this regard are provided in the recently published OECD/NEA SOAR report on "Hydrogen Management and Related Computer Codes" [2].

ACKNOWLEGEMENT

The work related to the PAR concept development was done by GRS within projects sponsored by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) and the work related to the COCOSYS development within projects sponsored by the German Federal Ministry of Economics and Technology (BMWi).

REFERENCES

1. OECD/NEA, *“Implementation of Severe accident management measures – Summary and conclusions”*, NEA/CSNI/R(2002)12, (2002)
2. OECD/NEA, *“Status Report on Hydrogen Management and Related Computer Codes”*, NEA/CSNI/R(2014)8, (2014)
3. Z. Liang, M. Sonnenkalb, A. Bentaib, M. Sangiorgi, “Hydrogen Management Strategies and Analysis Codes implemented by the OECD/NEA Member Countries”, *16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16)*, Hyatt Regency Chicago, Chicago, IL, USA, (2015)
4. RSK, „Maßnahmen zur Risikominderung bei Freisetzung von Wasserstoff in den Sicherheitsbehälter von bestehenden Kernkraftwerken mit Druckwasserreaktor nach auslegungsüberschreitenden Ereignissen,“ *Empfehlung der RSK*, Deutschland, (Dezember 1997)
5. Dr. W. Zeiss, „Hydrogen Management in Beyond Design Accident Conditions in NPP Neckar 2“, *7th International Conference on Nuclear Engineering (ICONE)*, Tokyo, Japan, (April 1999)
6. OECD/NEA, *“OECD/NEA THAI Project: Hydrogen and Fission Product Issues Relevant for Containment Safety Assessment under Severe Accident Conditions”*, NEA/CSNI/R(2010)3, (2010)
7. OECD/NEA, “OECD/NEA THAI 2 project,” http://www.oecd-nea.org/jointproj/thai2.html
8. GRS, “COCOSYS short description”, http://www.grs.de/en/content/cocosys (2015)
9. J. Rohde, B. Schwinges, M. Sonnenkalb (GRS), “Implementation of PAR-Systems in German LWRs”, *OECD Workshop on the Implementation of Severe Accident Management Measures*, Paul Scherrer Institut (PSI), Villigen, Switzerland, (September 2001)
10. S. Band, S. Schwarz, M. Sonnenkalb (GRS), *„Nachweis der Wirksamkeit von H2-Rekombinatoren auf der Basis ergänzender analytischer Untersuchungen mit COCOSYS für die Referenzanlage GKN-2“*, Vorhaben 3609R01375: Anforderungen an den Nachweis der Wirksamkeit von H2-Rekombinatoren auf der Basis ergänzender analytischer Untersuchungen, GRS-A-3652, (März 2012)
11. Schwarz, S. et. al. (GRS), “Benchmark on Hydrogen Distribution in a Containment based on the OECD-NEA THAI HM-2 Experiment”, *Nuclear Technology* pp. 594 – 603 (September 2011)
12. BMUB, *“Safety Criteria for Nuclear Power Plants”*, Germany, http://regelwerk.grs.de/ (Nov. 2012)
13. H. Nowack, W. Klein-Heßling, *“Development and Qualification of PAR Models for COCOSYS based on the OECD-NEA THAI HR Experiments”*, OECD/NEA THAI Seminar 2010, GRS Cologne, (October 2010)
14. J. Böhm, *„Modelling of the Processes in Catalytic Recombiners“*, Schriften des Forschungszentrums Jülich, Energy Technology, Volume 61 (2006)
15. H.-J. Allelein et al., *“International Standard Problem ISP-47 on Containment Thermal Hydraulics”*, Final Report, NEA/CSNI/R(2007)10, (2007)
16. de Cachard, F. et al., *“OECD-SETH Project: Large-scale Experimental Investigation of Gas Mixing and Stratification in LWR Containments”*, Paul Scherrer Institut, (2007)
17. OECD/NEA, *“OECD/SETH-2 Project PANDA and MISTRA Experiments, Investigation of Key Issues for the Simulation of Thermal-Hydraulic Conditions in Water Reactor Containment”*, final summary report, NEA/CSNI/R(2012)5, (2012)
18. J. Sievers, J. Arndt, H. Grebner, P. Bachmann, (GRS), *“Failure Assessment Methodologies for Components under Severe Accident Loading”*, EUROSAFE Forum 2012, Brussels, (Nov. 2012)
19. OECD/NEA, *“ISP-49 on Hydrogen Combustion”*, final report, NEA/CSNI/R(2011)9, (2012)