Thermal and Dynamic Loads on the EPR Containment Due to Hydrogen Combustion

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Introduction

A major aspect of the EPR safety concept is to cope with severe accidents including core melt and to maintain the integrity of the containment even for those hypothetical events. One potential threat for the containment is related to the combustion of hydrogen, which may be produced in a large amount during core degradation.

The European Pressurized Water Reactor (EPR) hydrogen mitigation concept consists of about 44 recombiners, located mainly in the equipment rooms (only 4 recombiner are located in the dome area). Hydrogen mitigation is supported by two facts:

- Depressurisation of the reactor coolant system occurs directly into the containment atmosphere via a relief tank with rupture disc at two low locations on the elevation of the steam generator supports. This guarantees a large amount of well mixed steam in the containment for nearly all scenarios.
- The containment structure is relatively open allowing for good gas mixing.

In order to justify this concept against a set of criteria specified by GPR a close co-operation between research institutions, which develop and validate codes for hydrogen distribution and combustion, and the designer is beneficial. Such a combined effort allows the designer to use state-of-the-art codes with scientific support for the interpretation of the results and the research people to focus their work on realistic scenarios and real industrial needs. This paper is devoted to two important potenial threats on the containment related to hydrogen removal:

- Thermal loads resulting from recombiner action and/or combustion are of importance also with respect to the integrity of the local composite liner foreseen at some crucial locations of the containment.

- Dynamic loads resulting from fast deflagration may impair containment wall or internal walls even if the AICC (adiabatic isochoric complete combustion) pressure is below the design pressure.

Within the EPR project a large number of scenarios have been analysed with MAAP4 in order to provide boundary condition for the development of the EPR severe accident mitigation features, in particular, with respect to hydrogen mitigation, mass and energy release into the containment. Based on these calculations representative scenarios and bounding scenarios with additional aggravation, as reflood, have been specified.

Loss of off-site power scenario, with and without aggravation by reflood at the most unfavourable moment, and some small break loss of coolant accidents (SBLOCA) scenarios have then been analysed with the CFD code GASFLOW /1/ to assess temperature distributions, in the atmosphere and in the walls, and potential combustion modes. Experimentally based criteria for the exclusion of fast deflagration, or the exclusion of deflagration detonation transition (DDT) /2/ are included in GASFLOW.

- The "sigma" criterion, which relates the expansion ratio to a limit expansion ratio to exclude flame acceleration found in experiments
- The "lambda" criterion (characteristic length of the hydrogen cloud divided by 7 lambda, with lambda being the cell size) to exclude DDT.

Combustion is possible for some SBLOCA scenarios, where we have focussed on a 20 cm^2 break in the cold leg in three variants:

1. A scenario with fast secondary cool-down, which leads to low steam concentration in the containment
2. A scenario with partial cool-down and delayed depressurisation, which leads to large amount of in-vessel hydrogen because accumulators feed onto a hot core, and to high steam concentration
3. A scenario with partial cool-down to assess the risk from ex-vessel hydrogen combustion.

Two types of combustion calculations have been performed:

a) In cases, where fast deflagration cannot be excluded, combustion has been calculated with COM3D /3/, a special CFD code developed to calculate dynamic pressure loads on walls (see chapter 3), and

b) "Standing flame" combustion as well as recombination processes have been calculated with GASFLOW for bounding scenarios in order to evaluate maximum containment wall surface temperatures for cases of long-lasting combustion, mainly with emphasis on the application of a partial liner (see chapter 2).

Thermal Loads

With respect to the assessment of thermal loads the development of GASFLOW continued during the investigation period: a radiation model has been implemented in the GASFLOW code /4/ and the partial liner is now modelled explicitly

Thermal Loads Due to Recombiners

The following table summarises the major results on containment wall temperatures due to recombination, that means without combustion (even in case of high recombiner exhaust temperatures).

Scenario, main boundary conditions	Major Findings	Conclusion
SBLOCA with fast secondary cool-down Radiation 760 kg H_2 released	<80 °C in the upper (cylindrical) part <70 °C in the lower part (below the hatch) Gas temperature close to the wall < 120 °C	100°C as upper bound for containment wall surface temperatures
LOOP with reflood No radiation 960 kg H_2 released	Surface temperature between 90 °C and 120 °C. Gas temperature close to the wall< 200 °C.	180 °C as upper bound for the containment wall surface temperatures (from the difference between LOOP/R and SBLOCA gas temperature) 150 °C for the containment part around material hatch)

Neglecting ignition at the recombiner exit no significant thermal loads to the containment wall can be identified. In case of ignition the thermal loads will be covered by the loads from accidental ignition assumed at the worst location and time (see chapter 2.2). It is worthwhile to be noted that most of the recombiners are located in the equipment rooms close to the hydrogen source and heat will be generated far from the containment shell.

Thermal Loads Due to Accidental Ignition

Concerning accidental combustion (no igniters are foreseen within the containment) three calculations have been performed, all with the radiation model:

1. SBLOCA with fast secondary cool-down with:

- an early ignition in the dome area above the steam generator (SG) compartment of the broken loop, which leads to slow but continuous combustion during the whole release period
- a late ignition, at the same location, after accumulation of more than 500 kg hydrogen, which leads to a rapid, but by far incomplete combustion.

2. SBLOCA with delayed depressurisation: accidental ignition assumed at the top of the SG compartment shortly after onset of the hydrogen release (continuous combustion), as soon as the mixture is ignitable.

3. SBLOCA with partial cool-down with ex-vessel release of 700 kg hydrogen. Continuous combustion above reactor pit and spreading area is possible due to the high gas temperature, which is far above the autoignition temperature.

As the liner was not modelled explicitly in case 1, the following discussion focus on the last two scenarios.

SBLOCA with Delayed Depressurisation

It is assumed that the mixture ignites whenever it is ignitable in a predefined ignition area above the SG tower of loop 2. As a result, combustion starts very early, just after onset of hydrogen release at about 7840 sec after onset of the accident. Despite the flame moved down towards the break and combustion continued near the different release locations of loop2. The combustion was terminated at about 8050 sec, which is well after the hydrogen release peak at 7950 sec. Major hydrogen release is terminated at 8100 sec.

At 8033 sec, just before combustion terminates, the containment pressure has its maximum: 4.3 bar. Maximum average containment atmospheric temperature is reached around that time and amounts to 337°C. The maximum concrete surface temperature as well as the maximum steel temperature is reached at the same time with peak values of 387 °C and 567 °C, respectively. As combustion occurs close to the break these values refer to inner structures of the containment and not to the containment shell. The containment shell itself is exposed to hot gases raising from the combustion location through the SG tower. At liner location maximum liner surface temperature is below 180 °C.

The amount of 620 kg hydrogen is burnt within 210 sec (3.5 min).

Figure 2.2.1 shows the histories for maximum wall surface temperatures (local hot spots) and the average atmospheric temperature,

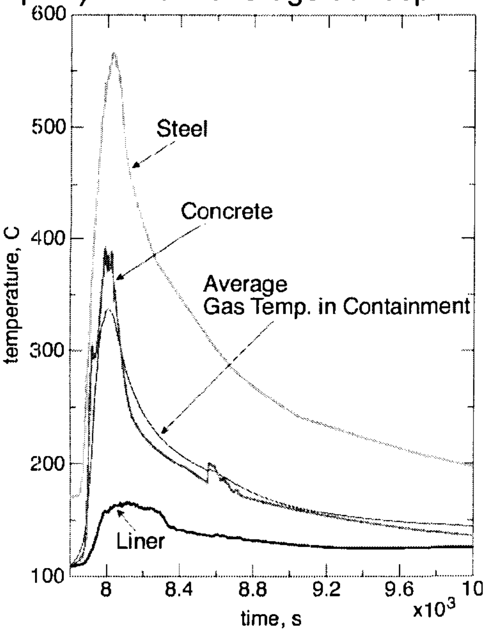


Figure 2.2.1 Temperature histories in case of ignition at the top of the SG tower and combustion close to the break

The reason for this moderate combustion process is the high amount of steam present in the atmosphere. A calculation with arbitrarily reduced content of steam (from around 50 to 40 vol%), performed to analyse the influence of steam to combustion, revealed a completely different picture: Assuming the same location for the ignition combustion could now occur at lower hydrogen concentration, where downward movement is not possible at the beginning. Thus, more energy is released into the dome area leading to maximum containment wall surface temperatures of 440 °C locally.

Ex-Vessel Release in Case of SBLOCA with Partial Cool-down

Ex-vessel hydrogen results from the dissolution of sacrificial concrete used in the reactor pit and the spreading compartment to guarantee spreading and long-term stabilization of the melt. About 700 kg hydrogen are released over a period of 1.7 hours with release rates of up to 1 kg/s. Maximum hydrogen release occurs just after vessel failure and at the end of the spreading process, where the erosion of the concrete is driven by the metal phase.
Combustion will occur as soon as sufficient oxygen is available, which is the case within the pit in the first phase (convection through the ventilation ducts) and downstream to the spreading area in the second phase because hydrogen is released at temperature well above autoignition temperature and, in addition, hot particles may be enclosed in the released gas stream. The results are as follows:

Pressure:	1st period after vessel failure: max. pressure after 50 sec.: 4 bar 2nd period after spreading: max. pressure after 20 sec: 4 bar
Temperature:	
Until gate failure:	inner concrete walls < 700°C, liner: < 150°C, steel < 390 °C, average atm. < 270 °C
After gate failure:	inner concrete (ceiling of the spreading compartment) < 450 °C, liner < 220 °C, steel < 510 °C, average atm. <320 °C

Figure 2.2.2 shows the temperature histories for ignition in the reactor pit (left hand side)and in the spreading room (right hand side), where ceiling temperature maximum is 450°C.

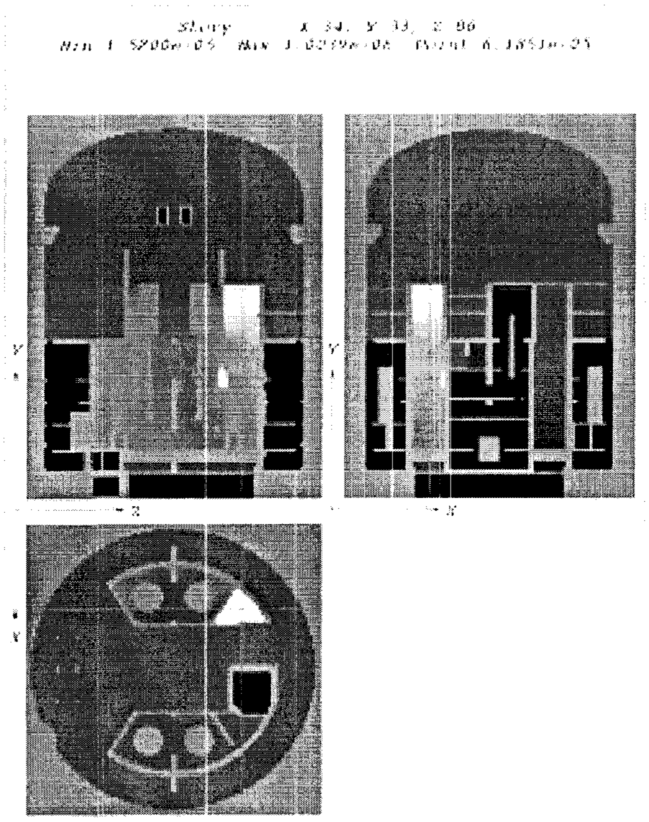


Figure 3.1.1 Distribution of the maximum pressure

The following observations can be made:

- Initial pressure is 1.52 bar; this is the minimum pressure on the other side of the wall (for the assessment of the differential pressure)
- Peak pressure at different location range between 2.2 and 4 bar (somewhere, at the top of the upper pump room, maximum is be 6 bar)
- Pulse width is about 0.07 sec
- Highest peak pressures occur at the earliest time (0.06 sec)
- Only one remarkable peak occurs at one location (no long-lasting pressure oscillations with high pressure peaks)

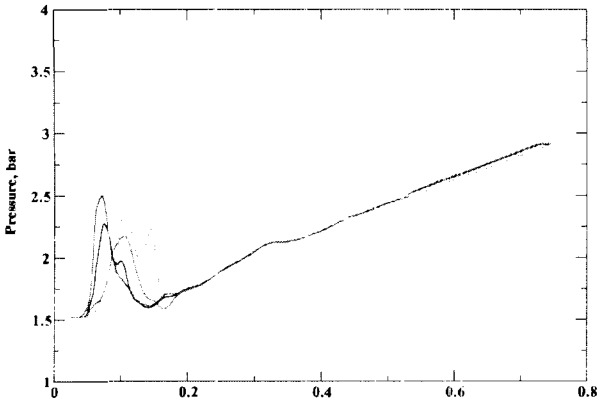


Figure 3.1.2 Pressure histories for internal walls

considerably broadens validity domain of combustion simulations. For the evaluation of mean reaction rate the modified EBU model /5/ is used.

In the high level turbulence limit the model is extended by switching to an Arrhenius-type reaction with effective constants.

Two base cases have been analysed:

- SBLOCA with fast secondary cool-down, which resulted, according to MAAP4 analysis, in slow release of about 800 kg hydrogen into a dry atmosphere (around 20 vol% steam)
- SBLOCA with delayed depressurisation, which was originally considered as a bounding case due to the high release rate and the large amount of hydrogen. However, the large amount of steam significantly reduces the combustion loads. This scenario has therefore been taken as basis scenario for a set of parametric calculations performed to see influence of steam concentration and other parameter on flame acceleration.

SBLOCA with Fast Secondary Cool-down

Combustion has been initiated close to the break in the cold leg. Flame acceleration occurred in the loop compartments above the break in both SG compartments and upper pump room, where pressure pulses typical for a fast deflagration have been calculated. On its way through the containment the flame seems to be decelerated due to the lower mixture quality in the dome compared to the loop compartments. Only at a level close to the top of the SG tower, e.g. top of the cylindrical part of the containment, dynamic effects can be seen. At the top and at the bottom of the containment the pressure rise is quasi-static.
Figure 3.1.1 shows the maximum pressures that occurred during the calculation period of 0.785 sec in two vertical and 1 horizontal cut. The pressure values, marked here with different colours (bright colours: high pressure, dark colours: low pressure), indicate the maximum pressure that occurred at any time at this location. Thus, this figure informs about the spatial distribution of the maximum pressure. Maximum pressure occurs in the upper pump room of the affected loop (6 bar), whereas containment walls are exposed to lower pressures.

Contrarily to the containment shell inner walls of the affected loop are exposed to high peak pressure, with the typical shape of a dynamic pressure load. The maximum pressure, as indicated in figure 3.1.1, reaches 6 bar and occurs at the wall surface at the top of the upper pump room, which is a dead end room. As the locations, at which pressure time histories should be recorded, must be defined before beginning of the calculation it is not possible to present the pressure time history with the maximum peak pressure; the maximum pressure recorded is close to 4 bar. Figures 3.1.2. shows some of these pressure histories.

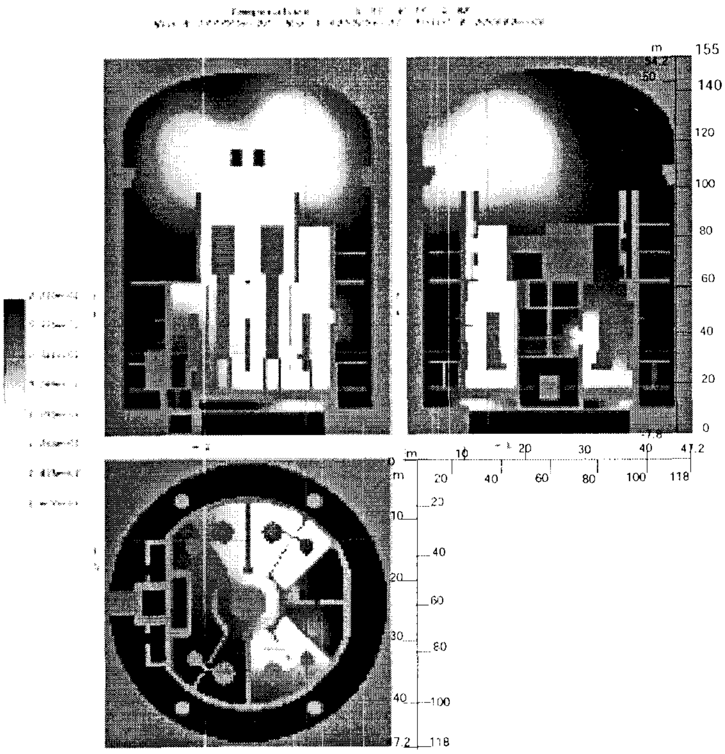


Figure 3.2.1 Atmospheric temperature distribution within the containment 1 sec after ignition

Fig. 3.2.2 shows some typical pressure histories at different location. Continuous combustion of the H2/air/steam mixture produces pressure waves, which propagate with speed of sound from the combustion location in all directions towards the containment structures. Contrarily to 1-dimensional tube experiments the strength of the pressure waves weaken during the propagation in the 3-dimensional space due to the moderate combustion rate and it does not result in amplification of the pressure wave and to higher loads. The peak pressure difference on internal walls is about 500 mbar. The quasi-static pressure increase is about 0.8 bar within the first second. Extrapolating the burning rate to complete combustion a pressure increase of 3.2 bar is expected. Adding the 3.2 bar to the initial pressure of 2.9 bar the calculated AICC pressure is obtained. Note that COM3D is adiabatic because of the short period of calculation time for fast deflagration.

The maximum differential pressure occurs again between the upper pump room and the SG compartment and amount to 0.5 bar, which can be compared to 4.5 bar in case of fast secondary cool-down (20 vol% steam). Hence, two additional calculations have been performed reducing the steam concentration to 40 vol% and 30 vol% by keeping the amount of hydrogen constant (thus increasing the hydrogen concentration and reducing the initial pressure). Reduction of the steam concentration in this range may result from accidental activation of the spray system, which is needed for the EPR only in the long-term to avoid over-pressurisation of the containment.

In general, the combustion can be called a mild fast deflagration starting quite violent within the affected loop, but is then damped on its way towards the containment walls due to the lower hydrogen concentration at higher elevation.

SBLOCA with Delayed Depressurisation

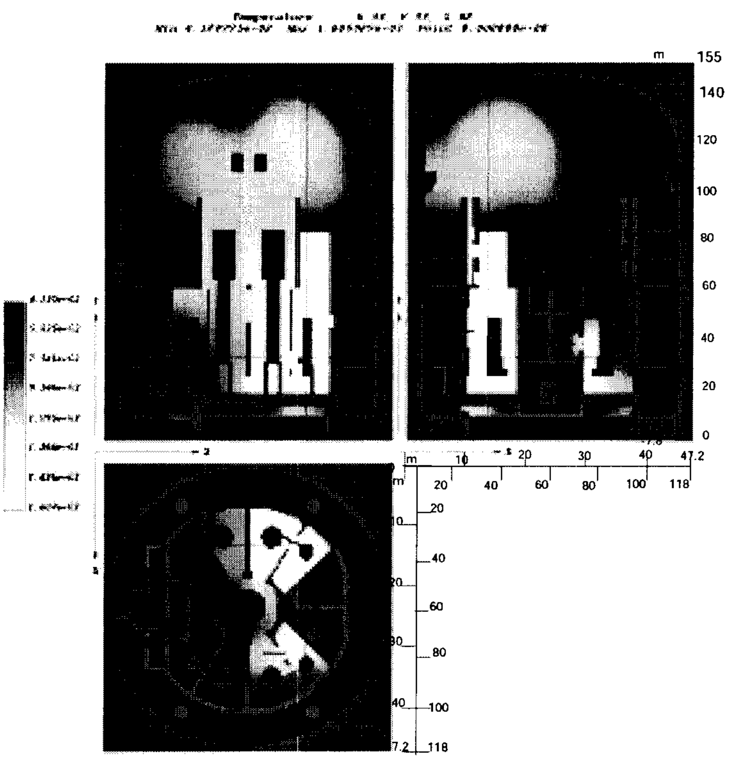
As a consequence of the calculation presented in chapter 3.1, where high internal pressure loads occurred in a dead end room above the break, it was decided to provide openings from this room to the adjacent SG compartment. With this layout improvement a new set of calculations was performed for the bounding scenario with delayed depressurisation.

Because of the high release rate the hydrogen concentration is very inhomogeneous throughout the release period. Local violation of both criteria, for the exclusion of flame acceleration and for the exclusion of DDT, occur early, just after onset of the hydrogen release. An ignition moment has been selected, which is a compromise between maximum amount of hydrogen available for combustion and maximum violation of the criteria: 180 sec after onset of hydrogen release: 680 kg of hydrogen (out of max. 800 kg) is present in the containment; the moment is 70 sec after maximum lambda index and 100 sec before end of hydrogen release.

Hydrogen release occurs at three locations: release from the relief tank at the bottom of loop2 and loop3 and the break, assumed in loop2. Thus, loop2 is exposed to a superposition of two releases and ignition location is assumed just above the break.

The basic calculation has been performed for 1 sec. Less than 200 kg hydrogen burnt in this period of time, corresponding to a maximum burning rate of 240 kg/s. Maximum flame velocity is always around or slightly above 60 m/s. Thus no significant dynamic loads are expected, neither for the containment wall nor for the inner walls.

Figure 3.2.1 shows the temperature distribution after 1 sec in two vertical and one horizontal cut. Hence, this figure identifies the area in the containment where combustion had taken place. At that time the flame has just touched the containment shell at one side. Loop 2, where ignition took place, is located on the upper right side of the horizontal cut, on the right side of the left hand side cut and on the left side of the right hand side cut. In addition to moving upwards to the dome the flame moved also downwards (hydrogen concentration above 10 vol%) to one of the two PRT discharge locations and from there to the opposite loop, where the second PRT discharge is located. One second after ignition the flame is just moving upwards in the pump room of this loop 3 (top right cut, right hand side). Maximum temperature is about 1600 K (inner pump rooms) and 750 K for the gas touching the containment wall.



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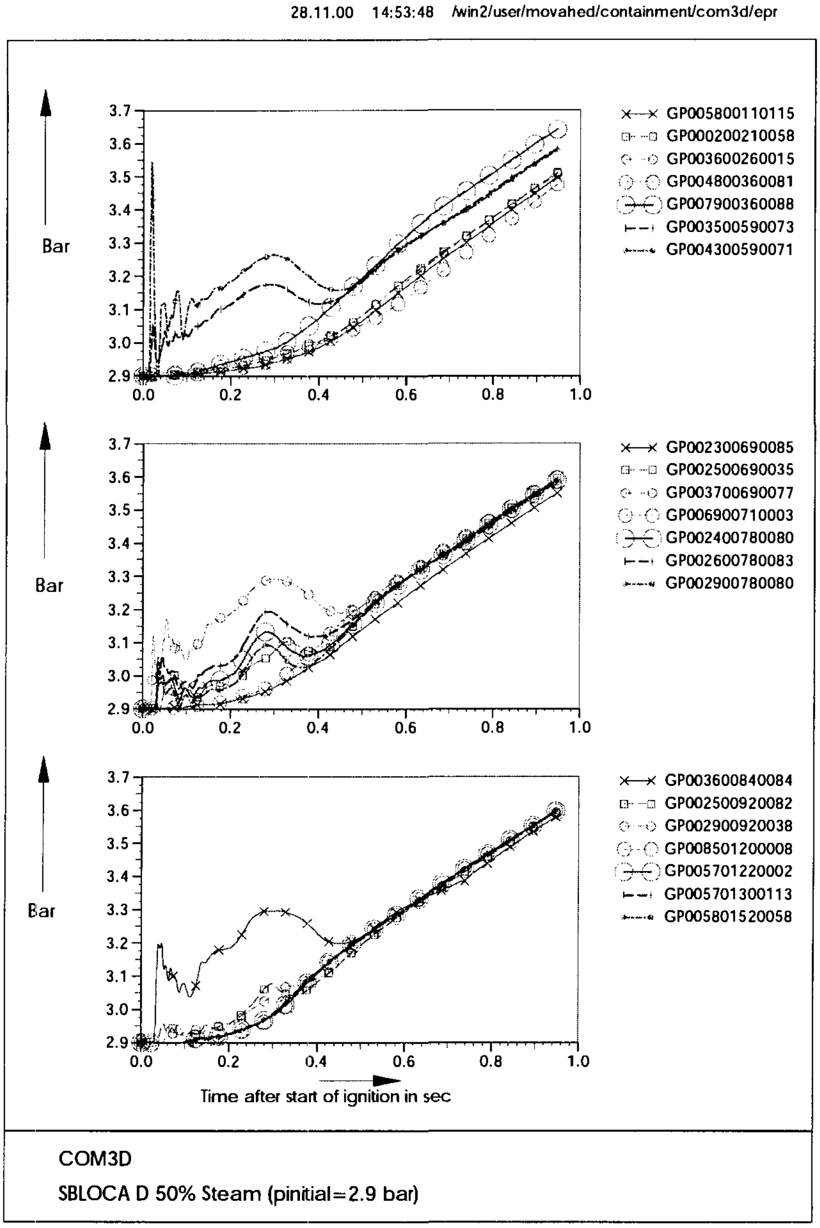

Figure 3.2.2 Pressure histories at different locations

Following these calculations no impair of the containment is expected due to fast combustion even for the worst case with only 30 vol% steam. The response of the internal walls to the pressure history is now being analysed with the commercial finite element code TRIMAS.

The case with medium steam concentration was taken as basis for a set of additional parameter calculations to find bounding pressure levels:

- Reassessing containment delineation to also consider smaller structures down to cell size (40 cm), which may serve as obstacles and turbulence generator and thus cause flame acceleration. Maximum pressure difference stayed below 1.2 bar.
- The initial turbulence of the atmosphere was increased to its maximum value simulating a high turbulent atmosphere. Maximum pressure differences stayed

below 1.8 bar.

- Ignition location was changed towards the top of the SG tower. Pressure differences are marginal because no downward movement of the flame occurs as in the GASFLOW calculation with 40% steam (chapter 2).
- Closed SG tower in order to simulate situation close to tube experiments: in the SG tower
- Closed SG tower in addition with high initial turbulence
- Reduction of the temperature (because most experiments have been performed at lower temperature)

The last three parametric studies result in higher flame speed and thus in higher loads to the walls.

Conclusion on Combustion Loads

Because of the depressurisation of the reactor coolant system directly into the containment atmosphere via a relief tank and rupture discs a high concentration of steam is available for nearly all scenarios. For these scenarios no threat to internal walls is expected based on the combustion loads identified by the analyses presented here. In case of fast secondary cool-down a large amount of energy is removed to the secondary side of the SG and less steam is available in the containment. As a consequence, combustion, even in case of low hydrogen release rate and therefore relative homogeneous gas distribution, is more violent and causes high pressure loads to dead end rooms. Additional openings in those rooms towards the adjacent SG compartments, however, will reduce these loads.

No threat to the containment shell resulting from fast deflagration could be identified by these calculations and maximum containment pressure is thus not higher than the corresponding AICC pressure, which has been calculated to be less than the design pressure in any case.

Literature

/1/ J. R. Travis, J.W. Spore, P. Royl, "GASFLOW": A Computational Fluid Dynamics Code for Gases, Aerosols and Combustion" Report LA-13357-M and FZK-5994, Vol I-III, Oct. 1998

/2/ W. Breitung et. al.: State of the art report on flame acceleration and deflagration to detonation transition in nuclear safety
OECD-report to be published1999

/3/ A. Kotchourko et. al.:
Reactive Flow Simulations in Complex 3D Geometries using the COM3D code
Jahrestagung Kerntechnik 1999

/4/ J. R. Travis: A Computationally Efficient Thermal Radiation Transport Model for the GASFLOW Code
5^{th} SMIRT Post Conference Seminar on Containment of Nuclear Reactors,
Hoam Convention Centre, Seoul, Korea, Aug 23-24, 1999

/5/ R. Said and R. Borghi: A simulation with a cellular automation for turbulent combustion modeling
22th Symp. (Int) on combustion pages: 569-577
University of Washington, Seattle, USA, 1988