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Conference Paper

HYDROGEN MIXING ANALYSES FOR A VVER CONTAINMENT

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ABSTRACT

Hydrogen combustion may represent a threat to containment integrity in a VVER-440/213 plant owing to the combination of high pressure and high temperature. A study has been carried out using the GASFLOW 2.1 three-dimensional CFD code to evaluate the hydrogen distribution in the containment during a beyond design basis accident.

The VVER-440/213 containment input model consists of two 3D blocks connected via one-dimensional (1D) ducts. One 3D block contains the reactor building and the accident localization tower with the suppression pools. Another 3D block models the air traps. 1D ducts represent the check valves connecting the accident localization tower with the air traps. The VVER pressure suppression system, called "bubbler condenser," was modeled as a distributed heat sink with water thermodynamic properties. This model accounts for the energy balance. However, it is not currently possible to model dynamic phenomena associated with the water pools (e.g., vent clearing, level change).

The GASFLOW 2.1 calculation gave detailed results for the spatial distribution of thermal-hydraulic parameters and gas concentrations. The range and trend of the parameters are reasonable and valuable. There are particularly interesting circulation patterns around the steam generators, in the bubbler tower and other primary system compartments. In case of the bubbler tower, concentration and temperature contour plots show an inhomogeneous distribution along the height and width, changing during the accident. Hydrogen concentrations also vary within primary system compartments displaying lower as well as higher (up to 13 - 20% and higher) values in some nodes. Prediction of such concentration distributions was not previously possible with lumped parameter codes.

GASFLOW 2.1 calculations were compared with CONTAIN 1.2 (lumped parameter code) results. Apart from the qualitatively similar trends, there are, for the time being, quantitative differences between the results concerning, for example, pressure histories, or the total amount of steam available in the containment. The results confirm the importance of detailed modeling of the containment, as well as of the bubbler condenser and sump water pools.

The study showed that modeling of hydrogen distribution in the VVER-440/213 containment was possible using the GASFLOW 2.1 code with reasonable results and remarkable physical insights.

KEYWORDS: containment, VVER, accident, hydrogen, CFD, simulation

INTRODUCTION

The AGNES program for "Reassessment of the Safety of the Paks NPP ” was carried out in Hungary during 1991-1994. Among the broad range of issues addressed, AGNES focused on issues pertaining to the robustness of the containment, including containment loads and containment performance. The AGNES program addressed the issue of the magnitude of containment loads arising from both design-basis accidents (DBA) and beyond-design-basis-accidents (BDBA). It was identified that hydrogen combustion may be a dominant threat to containment integrity in a VVER-440/213 owing to the combination of high pressure and high temperature. To better assess the extent of the threat to containment integrity, a need was identified to perform analyses of hydrogen mixing and combustion for Paks using state-of-the-art codes. A multi-dimensional mixing code is needed to assess hydrogen distributions under various accident conditions.

Analyses have already been performed at VEIKI in Hungary addressing steam/water discharge rates and hydrogen production/discharge rates for a number of accident sequences with the MAAP code and the MELCOR code. The results of these analyses have been used as input to the GASFLOW 2.1 mixing code to evaluate combustible gas distributions and flammability conditions in the VVER-440/213 containment.

1 THE PAKS VVER-440/213 CONTAINMENT

The functional requirements for VVER-440/213 containment to restrict the release of radionuclides are based on internationally accepted principles. However, the architecture including the rectangular building with the localization tower is substantially different from Western-type containments.

1.1 Architecture

The primary circuit and its components are placed in the hermetically sealed main building. The steam generator room is a rectangular, reinforced concrete structure. The outer walls are 1.5 m thick; the inner walls are generally 0.8 m thick. Diagonal reinforced concrete walls are located in the corners. These walls reduce the ceiling span and fulfill the function of missile shielding. Inside the upper portion of the steam generator room there is an annular shaped pump room, located around the reactor shaft. The electric motors of the six primary coolant pumps and the electric drives of the primary system isolation valves are situated in this room. A plan view of the containment at 10.5 m level is shown in Fig. 1.

The reactor vessel is installed in the cylindrical reactor cavity shaft. The shaft wall is 2.5 m thick with multiple layers of steel reinforcement. The steam generator room and the connected neighboring compartments are connected to the localization system by a horizontal channel.

1.2 Accident Localization System

The accident localization system consists of the bubbler condenser and the air traps. The function of this system is to decrease the maximum peak pressure and to ensure a near atmospheric containment pressure after a pipe break. The localization tower contains 1500 m^3 of water, which is distributed among 12 levels of bubbler condenser trays. The air volume of the condensers is connected to four air traps. Between the air traps and the air volume of the trays there are check valves. The check valves are closed if the pressure in the air traps is higher than that in the trays. That means that the air will be contained in the air traps with a total volume of about 17 000 m^3. The total volume of the containment building is about 49000 m^3.

2 MODELING OF THE VVER-440/213 CONTAINMENT WITH GASFLOW 2.1

2.1 The GASFLOW 2.1 Code

GASFLOW 2.1 is a best estimate, special purpose computer code developed at Los Alamos National Laboratory (LANL) and Forschungszentrum Karlsruhe (FzK) to predict the transport, mixing and combustion of hydrogen and other gases, liquid droplets and aerosols in nuclear reactor containments and other non-nuclear buildings.

Two coordinate systems are available in GASFLOW 2.1: rectangular (Cartesian) and cylindrical. For the present model, the rectangular coordinate system was used, because the VVER-440 containment basically consists of rectangular compartments. The computational domain or 3D block is discretized using a rectangular finite difference mesh consisting of computational cells. Selection of this option means that cylindrical components like the reactor, the steam generators or the hydroaccumulators should also be modeled in a rectangular mesh. It is possible to define several 3D blocks, which are connected via one-dimensional ducts.

2.2 Model of the VVER-440/213 Containment

The developed model of the VVER-440/213 containment consists of two 3D blocks connected with 1D ducts.

- Block 1

Block 1 contains the steam generator room (SG box), the primary system rooms connected to the SG box (pressurizer room, hydroaccumulator rooms, cable channels, etc.), the pump deck, the connecting corridor, the bubbler tower shaft and the bubbler condenser trays. The block consists of 27x29x22=17 226 real cells. Cells, which are not part of the hermetic zone, are blocked out by obstacles (mobs). The total net (free) volume of the block is 31 175 m^3.

- Block 2

Block 2 contains the four air traps. The block consists of 23x1x22=506 real cells. The total net (free) volume is 17 552 m^3.

- 1D ducts

The air traps and the twelve bubbler condenser trays are connected via check valves. Twelve 1D ducts, representing the check valves, connect Block 1 and Block 2. The diameter of one duct is 50 cm, its length is 1 m. Ducts open at 500 Pa pressure difference and they are closed in the reverse direction. The elevations of the ducts correspond to the level of trays.

The check valve model is essential for the correct description of the operation of the bubbler condenser system.

- Computational Mesh Grid

The applied mesh grid is shown in different planes in Figs. 2 and 3. Fig. 1 shows the plan view of the containment at the 10.5 m level. The mesh view (Fig. 2) can be compared to the plan view of the containment at the same level (Fig. 1). The outside walls, shown in the mesh, form the containment boundary. The vertical view of the mesh grid is shown in Fig. 3. Inside walls of the containment are also modeled in the mesh.

Primary system components, like the reactor pressure vessel, steam, hydroaccumulators, pressurizer and main circulating pumps are modeled by obstacles (mobs). Obstacles consist of an arbitrary number of cells through which no fluid flow is allowed. No heat conduction is allowed through the obstacles: these structures are assumed to be insulated.

The primary coolant system components are represented as rectangular objects. Diagonal steam generators are set up of shifted rectangular mesh cells. A finer mesh grid would certainly lead to a better approximation of curvilinear components. However, computation time, which largely depends on the number of applied mesh cells, sets another limit to the mesh grid definition. This input involves only the main primary system components. Smaller components including piping are not currently modeled.

- Heat Structures

Heat conducting structures in the containment are modeled according to GASFLOW 2.1 modeling options. Walls are modeled as thin surfaces dividing two adjacent layers of fluid that forbid flow across them. Their temperature profile is determined by the adjacent fluid cell temperatures on both sides, and by their heat capacity and conductivity. Floors and ceilings are modeled as concrete slabs. Slabs are considered so thick that within the problem time scale, the temperature gradient never penetrates deep enough to affect the temperature profile near their back side. Construction steel in the containment is modeled as distributed sinks - heat structures, which are assumed to be distributed within the fluid cell.

- Bubbler Condenser Model

There is no suppression pool model currently available in GASFLOW 2.1. At the same time, the pressure suppression pool containing 1500 m3 of water is a major heat sink influencing the thermal hydraulic behavior of the containment. Modeling of this system is important for a reasonable description of containment phenomena.

The bubbler condenser pools were modeled in this study as distributed heat sinks. Suppression pool heat transfer is very effective, therefore the sink thickness is defined as 1mm. Material properties of this sink are the same as those of water, and the sink mass is equal to the mass of the bubbler condenser water pool. This model can describe the energy transfer from the steam-water mixture to the water.

However, the sink model has its own limitations. Sinks are modeled as a separate matter distributed in the whole volume of the bubbler condenser chamber. Therefore, dynamic phenomena associated with the pools (e.g., vent clearing, level change) cannot currently be modeled.

Geometrical modeling of the bubbler condenser is shown in Fig. 3. The 12 bubbler condenser chambers located in the bubbler tower shaft are modeled as rectangular boxes with distributed sinks inside. Flow area from the shaft to the bubbler condenser is defined with the fractional area option of the code. On the other side, connection to the air traps through check valves is modeled with the 1D duct option of the code.

- Initial and Boundary Conditions

Initially the containment pressure is 0.993 bar, the temperature is 323 K, relative humidity is 60%. Wall, slab and sink temperatures are equal to the atmosphere temperature. At boundaries of the computational domains, a rigid free-slip boundary condition is defined. This means that the entire computational volume is enclosed within rigid, impenetrable walls at which there is free slip or the gradient of the tangential velocity component is zero. This is a good approximation, because the computational boundaries are solid surfaces and the mesh resolution is not fine enough to represent the near-wall velocity gradients.

Hydrogen burns were suppressed to analyze the hydrogen mixing behaviour during the whole transient.

3 ACCIDENT SEQUENCE AND HYDROGEN SOURCE

The calculated unmitigated sequence is a medium break LOCA with failure of safety injection, and containment heat removal. As an initiating event a 100 mm break in the hot leg was considered. It was assumed that the engineering safety systems (low and high pressure emergency core cooling, and containment spray systems) were not available.

In-vessel calculations were performed by the MAAP4/VVER code. This code provided the blowdown source of water, steam and hydrogen to the containment, which was used as input to the GASFLOW 2.1 code as function of time. The total amount of hydrogen generated during the in-vessel period is 304 kg. The bulk of hydrogen is generated before support plate failure (274 kg). The maximum hydrogen generation rate is 1.11 kg/s, but the max. release rate from the primary system is about 0.4 kg/s.

The blowdown source is shown in Fig. 4. Until 236 s the source contains only water. Between 236 s and 753 s a mixture of steam and water is discharged. From this time on, only steam and H_2 is discharged. The H_2 source starts at 1240 s and it practically finishes at 3470 s. During this time 265 kg of H_2 is released. An additional 8 kg of H_2 is released between 3470 s and 4775 s, the last entry in the source table.

The location of the blowdown source is situated in the left part of the SG box in the centerline in y-direction, at elevation of 10 m, facing to the reactor (to east, cf. Fig. 6). The isenthalpic expansion option of GASFLOW 2.1 was used to calculate the expansion process from the primary system pressure to the containment pressure.

4 RESULTS OF GASFLOW 2.1 CALCULATION

The calculation was performed on a SUN SPARC 20 workstation at ANL. The problem time of the calculation was 3600 s. Total computational time took almost six weeks.

4.1 Thermal Hydraulic Transient Results

After the start of the accident, the pressure rises rapidly in the containment. The pressure distribution is quite homogenous in the whole containment, except the air traps, where the pressure buildup is slower, and it reaches its maximum value of 2 bar at 200 s (Fig 5.). After 200 s the mass flow rate of the source drops significantly, therefore the pressure also decreases. Between 550 and 750 s a mixture of steam and water is released with a mass flow rate one order of magnitude less than before, and the pressure drops again. After 750 s, only steam is released with continuously decreasing mass flow rate. The heat removal from the containment atmosphere due to condensation on heat structures is higher than the energy input, which results in pressure decrease. The average pressure in the containment at 3600 s is about 1.3 bar. The pressure in the localization tower drops below that of the air traps at about 1100 s and the check valves close. This occurs before the hydrogen release starts.

The average temperature of the containment atmosphere rises rapidly and reaches its maximum value of about 372 K at 500 s then it decreases to 360 K at about 3600 s.

The spatial distribution of the temperature is influenced by the flow patterns within the containment, and therefore it is less homogeneous than the pressure distribution. In the first seconds, when the primary coolant is discharged at high pressure, there is a strong flow through the corridor to the bubbler tower. The velocity of the flow is about 2 to 4 m/s. Temperature contour plots at 10 m level at 200 s are shown in Fig. 6. The plots show how the temperature decreases with the distance form the break location. There are high temperatures, about 170 to 180 C near the break. The temperature values are between 110 and 130 C in the bulk of the containment. Temperatures in the upper part of the bubbler tower do not exceed 100 C. Vertical temperature distributions show that the hottest part is located at the entrance to the localization shaft. The hot gases flow upward in the localization tower and then return cooled down, as reflected very well by the flow pattern. The temperature decreases with the elevation in the hydroaccumulator and pressurizer rooms.

After 500 s, when the discharge flow decreases drastically, and the source contains mainly steam, the flow pattern changes in the corridor. Until 500 s the gases move towards the localization tower trough the whole cross section of the corridor. Starting from 500 s the hot gases move towards to the tower at the upper part of the corridor and cooler gases return to the steam generator room in the lower region. This difference between the two sides of the corridor disappears after 500 s.

After 1000 s, a relatively stable flow pattern can be observed. The source stream is redirected by the reactor vessel, turning around, downward and southward. A portion of the flow goes through the upper part of the corridor to the localization tower. Here the gases rise around the centerline and flow back at both sides, then they return to the SG room at the bottom of the corridor. Another portion of the source stream flows to the right part of the SG box. There is a circulation around the steam generators, in the accumulator rooms and in the pressuriser room.

4.2 Hydrogen Concentration Distribution

The hydrogen appears in the containment at 1240 s. Before this time only steam and air are present in the atmosphere. Before 700 s a substantial amount of liquid water is also present. Fig. 7 shows contour plots of steam concentrations in a vertical cut of the localization shaft at 1000 s. The highest steam concentration near the break exceeds 95%, and it is higher than 75% in all primary system compartments except the pump deck. Steam concentrations in other parts of the containment are between 30% and 65%. Generally less steam is present in the localization tower, except the region of the connection of the corridor where the concentration exceeds 70%. The lower bubbler condenser trays receive more steam than the upper ones. Steam concentrations on the lower levels are about 40%, while upper tray concentrations do not reach 20%. After 1500 s the steam concentrations decrease as the condensation rate exceeds the generation rate.

The hydrogen release rate increases after 1700 s, which is reflected also in the hydrogen concentration in the containment. Steam concentration decreases with the rise of the hydrogen concentration. Around the break location the steam concentration remains above the inerting limit of 55%, but below the break elevation the gas mixture becomes flammable in some nodes at about 1800 s. Hydrogen concentration exceeds 13% at 1900 s in some nodes of the SG box with steam and oxygen concentrations adequate for burning. Very close to the break, the hydrogen concentration is more than 20%, but the steam concentration is still above the inerting limit there. At 2000 s the gas mixture is flammable also in some nodes of the corridor. There are some nodes in the right part of the SG box where the mixture is flammable with hydrogen concentrations higher than 6%. At 2300 s almost the whole left side of the SG box and the major part of the right side of the SG box contain flammable gas mixture. The hydrogen concentration exceeds 13% in several nodes. There are also cells in the localization tower, where hydrogen burning is possible. At 2800 s, the criteria for hydrogen burn are met practically in the whole containment (except the air traps). The gas mixture also becomes flammable in the vicinity of the bubbler condenser trays. At 3000 s the hydrogen concentration exceeds 11% in major part of the left side of the SG box. After 3000 s, the hydrogen release rate decreases below 0.05 kg/s and after 3500 s it is almost zero. At this time, the hydrogen concentrations become more equilibrated. Below the break elevation, in the corridor, and in the localization tower, the concentration levels are about 8 to 11%, above the break elevation are about 11 to 13%.

A certain vertical stratification can be observed within the SG box and the neighboring compartments. At the bottom, the hydrogen concentration is less and it is increasing with the height. This is true for both sides of the SG box and other primary system compartments as well. There is no stratification in the localization tower, because there is a massive circulation pattern, which transports and mixes the hydrogen. The highest hydrogen concentration is observed in the lower part, where the hydrogen arrives from the SG box. The contour plots of hydrogen concentrations in a vertical cut of the localization shaft at 3000 s are shown in Fig. 8.

The check valves to the air traps close before the hydrogen release starts, therefore, there is no hydrogen present in the air traps.

5 COMPARISON WITH CONTAIN 1.2 RESULTS

For purpose of comparison, a CONTAIN 1.2 input deck was set up with volumes, flow areas and heat structure surfaces according to the GASFLOW 2.1 input. There is a significant difference in the modeling of the pressure suppression system. CONTAIN 1.2 has a built-in model for suppression pools, which is used in the CONTAIN calculation. The initial conditions and the blowdown source are the same as in GASFLOW 2.1.

In the first phase (i.e., during the intensive water and steam blowdown), GASFLOW 2.1 calculates higher average pressure in the primary system compartments than CONTAIN 1.2 (Fig. 5). At about 1250 s the mass flow rate of the source drops below 10 kg/s, and the pressure decreases. There is almost no more liquid water in the atmosphere. The pressure decreases more in GASFLOW 2.1 than in CONTAIN 1.2. Also the steam mass in the atmosphere is less according to the GASFLOW 2.1 results. There are two major modeling differences between the codes, which contribute to this behavior.

(a) The difference in suppression pool modeling. CONTAIN 1.2 models condensation in the bubbler tray until the pressure difference between the shaft and the tray is less than the height of the water column on the tray. In GASFLOW 2.1, condensation is modeled with heat sinks without taking account of the hydrostatic resistance of the water. As a consequence, condensation continues, further decreasing the containment pressure.

(b) There is no modeling currently available in GASFLOW 2.1 for pools that collect the condensate runoff and the droplet rainout from the atmosphere. In contrast, CONTAIN 1.2 has this model available. Pool evaporation influences the results significantly: according to CONTAIN predictions, an amount of about 2200 kg water evaporates from the pools and trays between 1250 and 3600 s, contributing to the atmosphere pressure.

Temperature histories are more difficult to compare because CONTAIN 1.2 uses average temperature in each cell, while GASFLOW 2.1 calculates temperature field which may vary significantly within a compartment. Figure 9 shows the temperatures at 3000 s for each cell calculated by CONTAIN 1.2 and the temperature range of GASFLOW 2.1 for the corresponding compartments. The columns reflect the minimum and maximum values only and not the spatial distribution of temperatures. The wide range for ‘Box left’ reflects the high temperature of the blowdown source near the break location.

During the period of the intensive discharge (before 1000 s) the temperatures calculated by CONTAIN 1.2 lie within the temperature range of GASFLOW 2.1. After 1000 s, the two calculations show more differences. CONTAIN 1.2 predicts higher temperatures in the compartments of the left side of the containment (where the break is located), than in the right side. GASFLOW 2.1 calculates lesser difference between these two parts of the containment (except for the ‘Box left” = break location). The reason is the different modeling of flow patterns in the codes. CONTAIN 1.2 predicts the hot gases move towards the bubbler tower shaft in the left part of the corridor and flow back in the right side. GASFLOW 2.1 models a back flow of cool gases in the lower part of both sides. This difference between the two sides becomes less significant at the end of the calculation.

The most interesting issue is the prediction of gas distributions, especially the hydrogen concentration. The main purpose of employing a 3D calculation is to identify locations within the compartments where hydrogen can accumulate. This is not possible with lumped parameter codes like CONTAIN 1.2, because these codes treat the cells (compartments) as well-mixed volumes and characterize the entire volumes with lumped values. Figure 10 shows the fractions of the total volume (columns -z-axis) of the left steam generator compartment (‘Box left’) in which the hydrogen concentration corresponds to a given range (y-axis) at selected times (x-axis). Left columns represent the results of CONTAIN 1.2, and the right columns show those of GASFLOW 2.1. For example, at 2300 s CONTAIN 1.2 predicts hydrogen concentration of 10.9% in the entire left side of the box. GASFLOW 2.1’s prediction is more detailed: it says that there are regions within the box where the concentration is less the 4% (about 18% of the box volume), and there are regions where the concentration exceeds 13% (4% of the box volume).

There are qualitative differences in the flammable conditions predicted by the codes. CONTAIN 1.2 predicts higher steam concentrations. Until the end of the calculation (3600 s), it does not decrease below the inerting limit of 55%, except for the pump deck. GASFLOW 2.1 keeps less steam in the atmosphere. Therefore, the gas mixture attains the flammability conditions in several region of the containment. Figure 11 shows the flammability conditions in the left steam generator compartment. The columns indicate the fraction of the total volume of the corresponding compartment, where the hydrogen concentration is within the given range and other flammability criteria are also met (i.e., steam is less than 55%, oxygen is more than 5%). For example, CONTAIN 1.2 predicts non-flammable mixtures in this compartment. On the contrary, GASFLOW 2.1 calculates flammable conditions in some parts at different times. (Note that the concentration values are valid under the assumption that no hydrogen burn occurs.)

6 CONCLUSIONS

The GASFLOW 2.1 calculation gave detailed results for the spatial distribution of thermal-hydraulic parameters and gas concentrations. Hydrogen concentrations vary within the primary system compartments displaying lower as well as higher (up to 13 - 20% and higher) values in some nodes during the accident. Steam concentrations decrease with the rise of the hydrogen concentration, and the gas mixture becomes flammable in some nodes from 1800 s. Prediction of such concentration distributions was not previously possible with lumped parameter codes. Application of the GASFLOW 2.1 calculations to safety analysis of the plant would need, however, further efforts concerning input deck development and innovative use of available modeling options.

GASFLOW 2.1 calculations were compared with CONTAIN 1.2 (lumped parameter code) results. Apart from the qualitatively similar trends, there are, for the time being, quantitative differences between the results concerning, for example, pressure histories, or the total amount of steam available in the containment. The results underline the importance of a more detailed modeling of the bubbler condenser and sump water pools, as well as a refined treatment of atmosphere or wall condensation. These modeling problems should be resolved with further efforts.

7 ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy, National Nuclear Security Administration. The U.S. Government makes no endorsement of the results of this work. The authors express gratitude to Jay W. Spore (LANL) for the development of the check valve option in the 1D duct model and for a number of important suggestions facilitating the accomplishment of this work.

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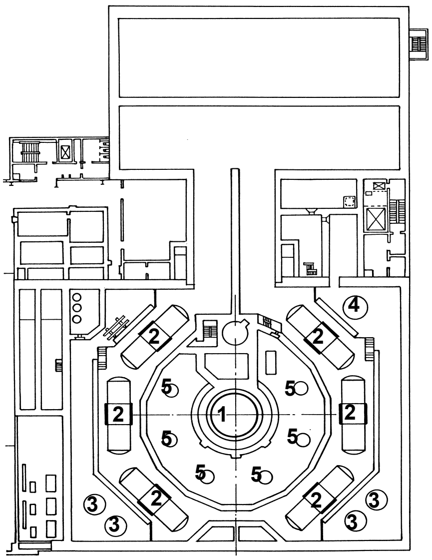

1 Reactor vessel
2 Steam generators
3 Accumulators
4 Pressurizer
5 Main circulating pumps

Fig. 1 Plan View of The Containment at 10.5 m Level

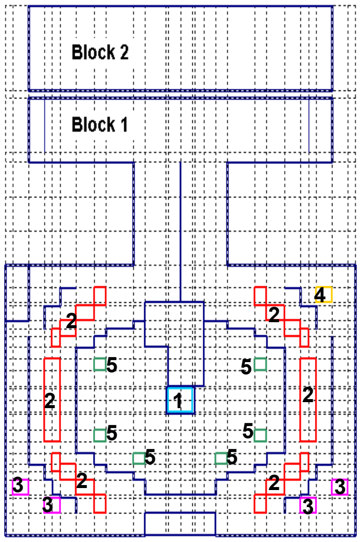

Fig. 2 Plan View of the Containment at 10.5 m Level with the Applied Mesh

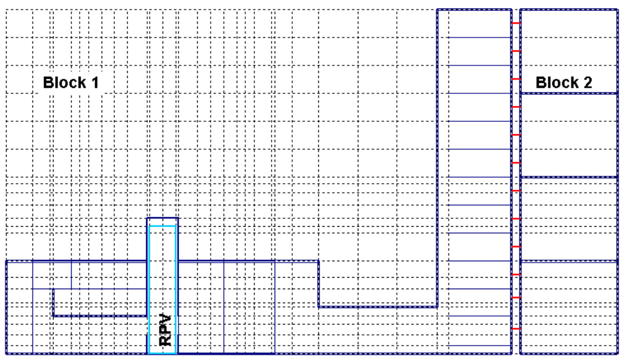

Fig. 3 Cross-sectional View of the Containment with the Applied Mesh

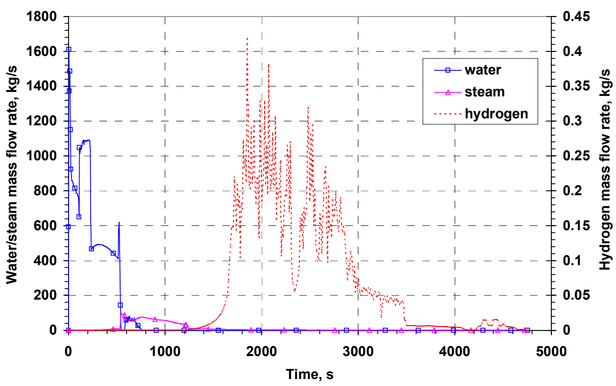

Fig. 4 Discharge Source To The Containment

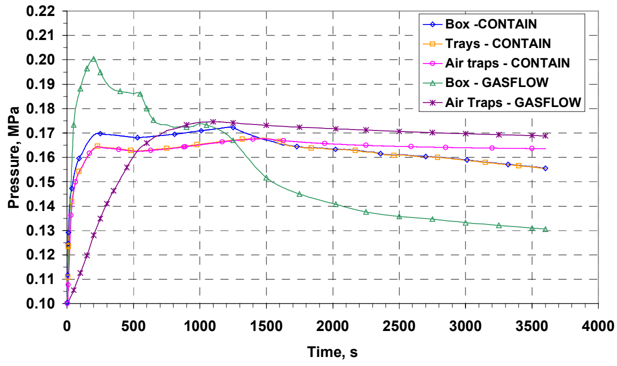

Fig. 5 Containment Pressure

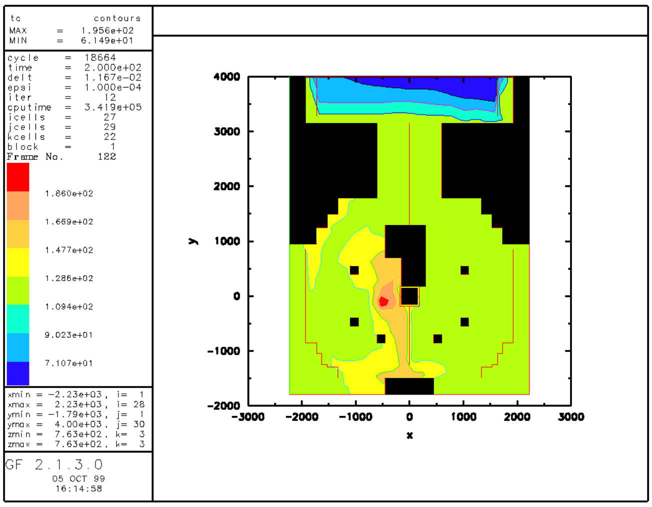

Fig. 6 Temperature Contour Plot, Elev.:7.6 m, Time: 200 s

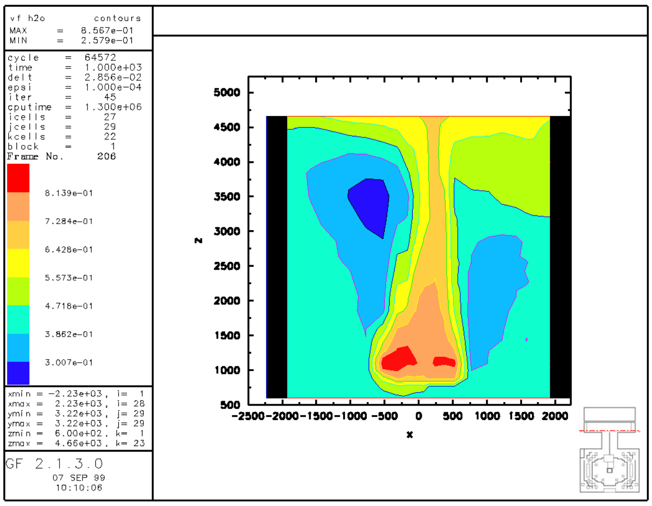

Fig. 7 Steam Concentration Contour Plot, Vertical Cut, Time=1000 s

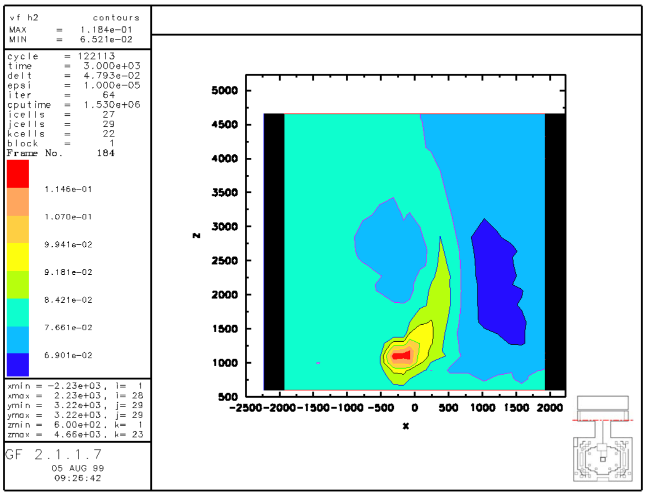

Fig. 8 Hydrogen Contour Plot, Vertical Cut, Time = 3000 s

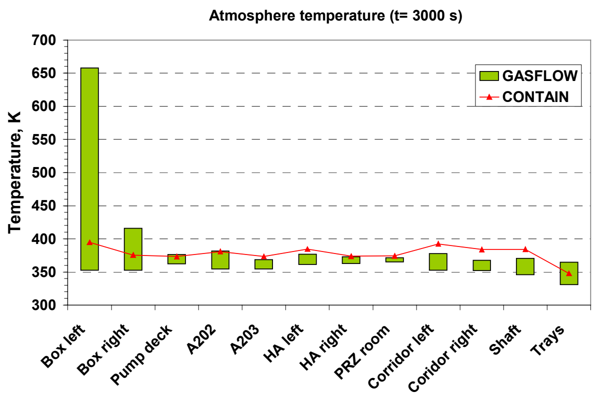

Fig. 9 Atmosphere Temperature

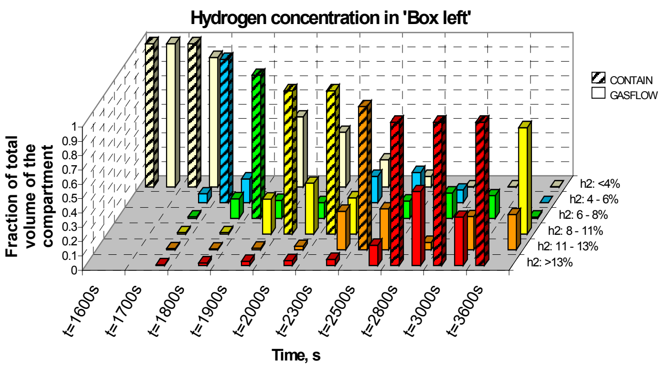

Fig. 10 Hydrogen Concentrations in the Left Side of the SG Box

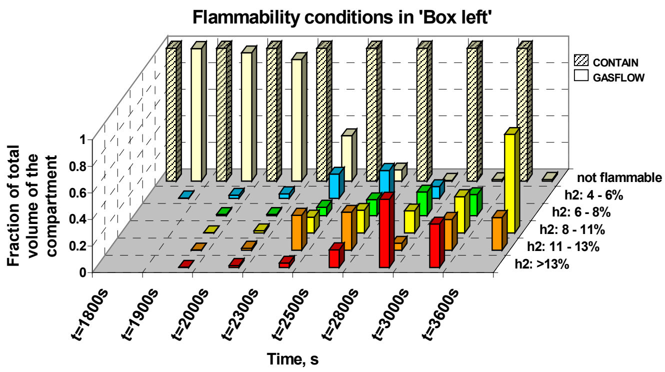

Fig. 11 Flammability Conditions in the Left Side of the SG Box