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3-Dimensional Analysis of the Steam-Hydrogen Behavior from a Small Break Loss of Coolant Accident in the APR1400 Containment

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Abstract

In order to analyze the hydrogen distribution during a severe accident in the APR1400 containment, GASFLOW II was used. For the APR1400 NPP, a hydrogen mitigation system is considered from the design stage, but a fully time-dependent, three-dimensional analysis has not been performed yet. In this study GASFLOW code II is used for the three-dimensional analysis. The first step to analysis involving hydrogen behavior in a full containment with the GASLOW code is to generate a realistic geometry model, which includes nodalization and modeling of the internal structures such as walls, ceilings and equipment. Geometry modeling of the APR1400 is conducted using GUI program by overlapping the containment cut drawings in a graphical file format on the mesh view. The total number of mesh cells generated is 49,476. And the calculated free volume of the APR1400 containment by GASFLOW is almost the same as the value from the GOTHIC modeling. A hypothetical SB-LOCA scenario beyond design base accident was selected to analyze the hydrogen behavior with the hydrogen mitigation system. The source of hydrogen and steam for the GASFLOW II analysis is obtained from a MAAP calculation. Combustion pressure and temperature load possibilities within the compartments used in the GOTHIC analysis are studied based on the Sigma-Lambda criteria. Finally the effectiveness of HMS installed in the APR1400 containment is evaluated from the point of severe accident management

Key Words : GASFLOW, severe accidents, hydrogen mitigation, PAR and igniter, APR1400, steam condensation, combustion

1. Introduction

In order to analyze hydrogen distribution during a severe accident in the APR1400 containment, GASFLOW II was used. GASFLOW II[1,2] is a finite-volume computer code that solves the time-dependent compressible Navier-Stokes equations with multiple gas species in three-dimensional computational domains.

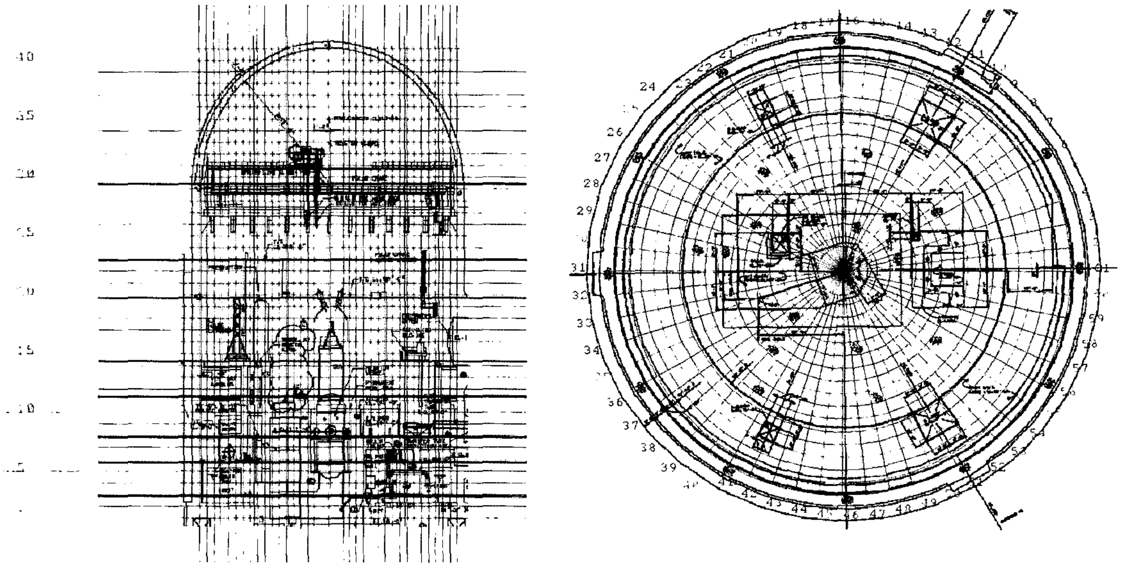
APR1400[3] is the next generation nuclear power plant designed in Korea, which produces 1400 MWe. The current design specifies 26 Passive Autocatalytic Recombiners (PARs) and 10 glow plug type igniters to be installed within the containment for the mitigation of the hazards of hydrogen generated and potentially released into the containment during a severe accident. Fast deflagrations, possibly leading to impulsive pressure loads, which could result from the hydrogen generated involving the active reaction of fuel-cladding and steam in the reactor pressure vessel during a severe accident and released to the containment, could possibly threaten the integrity of the nuclear power plant containment. To evaluate the effectiveness of the Hydrogen Mitigation System (HMS) and analyze the hydrogen transport and mixing behavior within the containment, a lumped-parameter code such as MELCOR[4], MAAP[5], or GOTHIC[6] is usually used. But these lumped-parameter codes have limitations in predicting the three-dimensional behavior of hydrogen transport and mixing within a full containment. In parallel with the lumped-parameter analyses, we intend to examine the three-dimensional effects by performing full containment safety analyses with mechanistic Computational Fluid Dynamics (CFD) codes. For the APR1400, a fully time-dependent, three-dimensional analysis of hydrogen behavior has not been performed yet. In this study, the GASFLOW II code is used for this three-dimensional analysis. This computational fluid dynamics(CFD) code is designed to be a best estimate tool for predicting the transport, mixing and combustion of hydrogen with the possibility of adding other gases for simulating design basis and beyond design basis or severe accidents in nuclear reactor containments. The code can model two-phase effects of condensation and/or vaporization in the fluid mixture regions within the assumptions of the homogeneous equilibrium model(HEM). It also calculates two-phase heat transfer to and from structures by convection and mass diffusion. The reactor safety problems so far have mostly been analyzed in coupled volume approaches by the so called lumped parameter(LP) codes. These LP-codes conserve mass and energy but do not include the momentum balance, which a CFD code like GASFLOW always does. GASFLOW is the only CFD code so far that has been applied to 3D simulations of steam/hydrogen release during severe accident scenarios with quite large problem times in real and complex containment geometries. Recently a radiation model has been implemented in the GASFLOW code which is applicable in arbitrary 3D geometries. The model was validated with the successful analysis of the FZK PASCO tests[7,8]. The code was successfully used for the interpretation of integral containment tests from the German Heisdampfreaktor and the Battelle Model containment[9]. And the validations of local phenomena predictions from the calculation are underway using Thai, TOSQAN and MISTRA tests[10,11]. Some good preliminary results are obtained with GASFLOW code. GASFLOW has been applied for several years on the 3D analysis of steam/hydrogen distributions for various hypothetical scenarios in different reactor containments. The simulations generally included the mitigation effect of passive autocatalytic recombiner(PAR) boxes in the 3D concentration fields of hydrogen and oxygen. The major applications were made for spherical KWU type containments with the analysis of large break loss of coolant accidents[12]. Framatome-ANP applied GASFLOW for the 3D analysis of steam/hydrogen distribution and combustion in a containment model of the European pressurized reactor(EPR) for various hypothetical scenarios beyond the design limit[13]. Recently 3D analysis of steam-hydrogen distributions during a small break loss of coolant severe accident has been performed using GASFLOW for a generic VVER 1000 pressurized water reactor containment[14]. The first step to analysis involving hydrogen behavior in full containments with the GASFLOW II code is to generate a realistic geometry model, which includes nodalization and modeling of the internal structures such as walls, ceilings, and equipment. This three-dimensional geometry modeling for multi-dimensional mechanistic codes requires the attention of many details resulting in intensive efforts concerning man-hours. It often makes the multi-dimensional code analyses difficult for use as a design tool. Recently the Forschungszentrum Karlsruhe (FzK) developed a Graphical User Interface (GUI) system for the GASFLOW II code to make containment geometry modeling much easier and error free[15]. The internal structures of the containment are modeled using the GASFLOW II GUI by overlapping the containment cut drawings in a graphical file format on the mesh view. In this study the GUI is used to model the geometry of the APR1400 containment. The total number of mesh cells generated is 49,476.

A SB-LOCA(Small Break-Loss Of Coolant Accident) scenario was selected to analyze the hydrogen behavior with the HMS. The source of hydrogen and steam for the GASFLOW II analysis is obtained from a MAAP calculation. Hydrogen concentrations in the containment varied with the time, steam behavior such as condensation, which affects the hydrogen flammability, and sensitivity conditions are analyzed. Combustion pressure and temperature load possibilities within the compartments used in the GOTHIC analysis are studied based on the Sigma-Lambda criteria. Finally the effectiveness of the HMS installed in the APR1400 containment is evaluated from the view of severe accident management.

2. Geometry Modeling of APR1400 Containment

2.1. Mesh Definition

The first step to modeling of the containment geometry is preparing the 3-dimensinoal node distribution. The coordinate system which can be used in GASFLOW is a Cartesian or cylindrical type. The basic shape of the APR1400 containment is cylindrical with a dome at the top. Although the primary shield wall and refueling pool look like a cube, the secondary shield wall is also cylindrical. For APR1400 a cylindrical coordinate system is selected to reduce the block-off computational cells and stair-shaped walls. In the radial direction 18 nodes are generated with first node on the axis and the last point at the containment inner wall. To accurately define reactor cavity annulus $i=2$ and $i=3$ nodes are positioned at the correct locations of the reactor vessel outer wall and reactor cavity wall, respectively. The other nodes from $i=4$ to $i=17$ are distributed at equal distances. The nodes in the azimuthal(φ) direction are uniformly distributed to make the geometry modeling easy. The total number of nodes generated is 61 with a 6 degree interval. The axial or z-directional nodes are generated from the reactor cavity floor to the top of the containment dome. 41 nodes are used for the axial direction with a uniform distance. The APR1400 containment is modeled with a single



(a) (b)

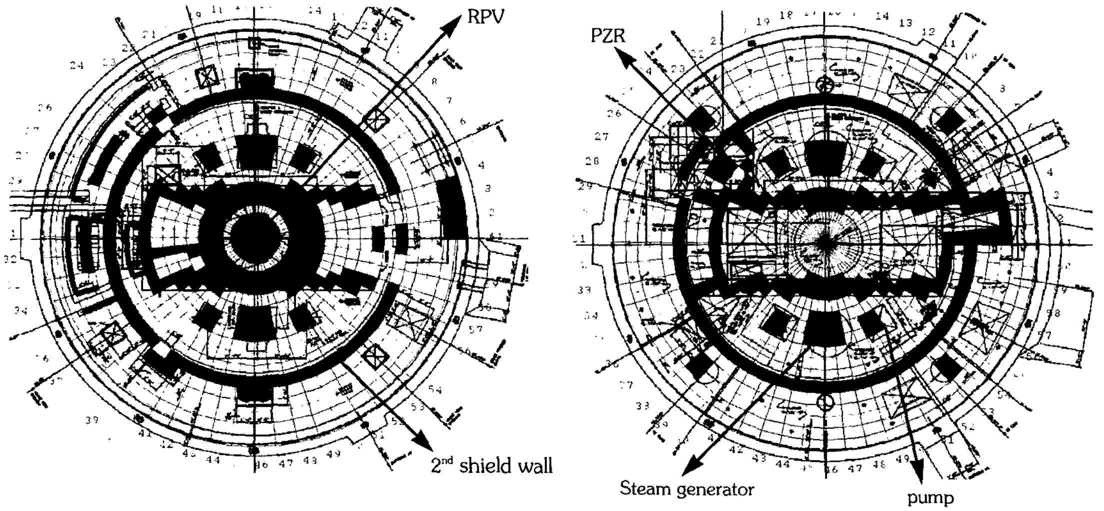
Fig. 1. Generated Cylindrical Mesh Overlapped on the Containment Cut Drawing, (a) vertical cut view, (b) horizontal cut view at elevation 81ft

block grid, and the total number of mesh cells generated is 49,476 including boundary ghost cells. Figure 1 shows the horizontal and vertical meshes with the containment cut drawings overlapped. In figure 1(a) the scaled r-z mesh is overlapped on the vertical cut drawing of Apr1400 containment, and the scaled r-φ mesh with horizontal cut drawing at an elevation of 81ft is shown in figure 1(b).

2.2. Modeling of Internal Structures of APR1400 Containment Using GUI

The inside of a nuclear power plant containment is very complex. It is equipped with RPV, steam generators and pumps, etc. And the containment is compartmentalized into many rooms by concrete walls and floors. In order to model the complicated inside of the containment GUI is used which was developed by FzK. The basic operation is computer mouse clicking to model the internal structures on the graphical window which shows a containment cut drawing with a scaled mesh.

On this graphical window, mesh cells are selected by a computer mouse and defined as structure. GASFLOW has three modelers to model a complex geometry, which are OBSTACLES, WALLS, and HOLES. If the thickness of the internal structure such as a compartment wall is smaller than a mesh space, it is modeled as WALLS in GASFLOW. Figure 2 shows the modeled internal structures at the specified axial location. The green colored mesh cells are modeled as OBSTACLES and WALLS are colored blue at the cell faces. In figure 2(b) the modeled primary and secondary shield walls are shown with main equipments. In the APR1400 containment 26 Passive Autocatalytic Recombiner(PAR) and 10 glow-type igniters are installed for the purpose of hydrogen mitigation. These devices are modeled by the same GUI procedure. The modeled full containment geometry is shown in figure 3. To show the main equipment hidden by concrete walls some part of the modeled geometry is cut



(a) (b)

Fig. 2. Views of Generated Obstacles and Walls (a) at k=7 and (b) at k=13

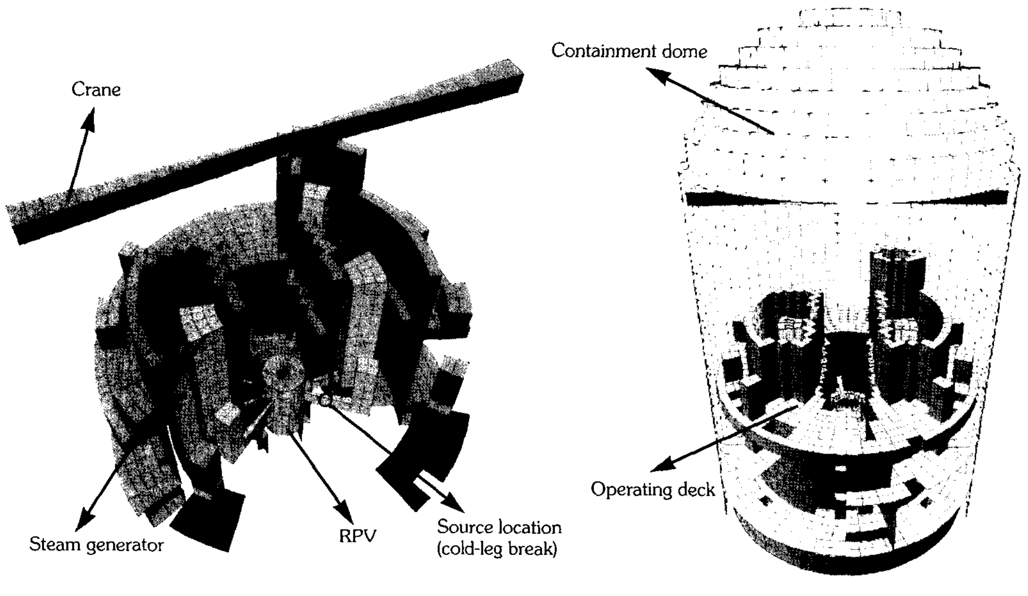


Fig. 3. 3-D Perspective View of APR1400 Containment Modeled for GASFLOW Analysis

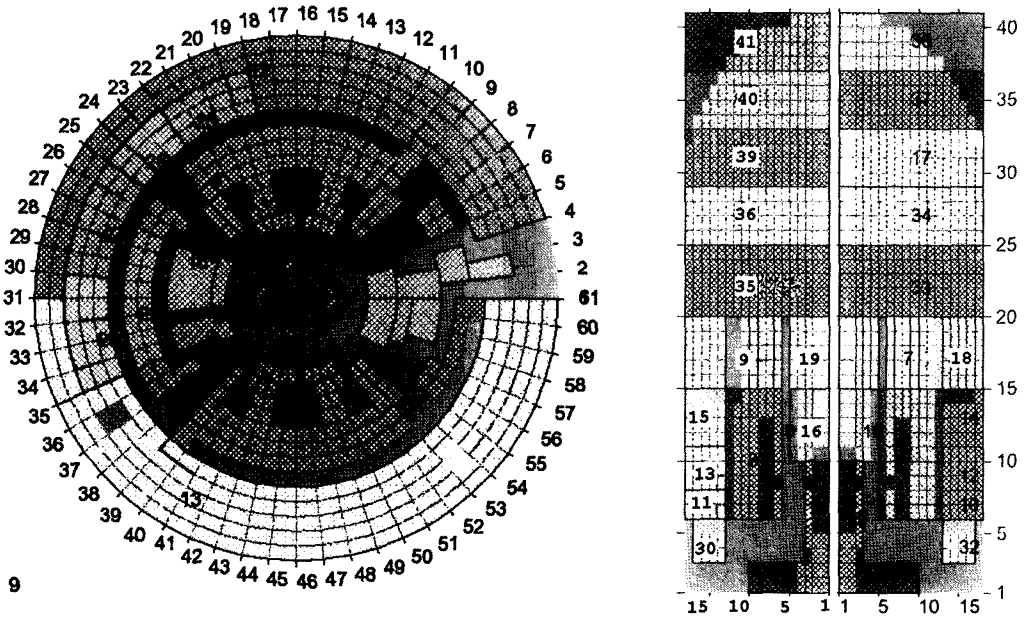
out in the left picture of figure 3.

2.3. Room Definition Using GOTHIC Nodalization

The APR1400 containment is a 80 m high concrete structure from the reactor cavity floor. It includes some compartments partitioned by walls such as the pressurizer room, steam generator room, reactor cavity room, and valve rooms etc. In order to evaluate gas species concentrations and the possibility of flame acceleration in each compartment the computational control volumes modeled in the GOTHIC analysis[16] are imported

Table 1. Free Volumes of the Compartments Defined in APR1400 Containment

	Compartments of APR1400		
No.	Definition	Volume for GOTHIC(m^3)	Volume for GASFLOW(m^3)
1	Reactor cavity	311.50	333.05
2	ICI chase room	110.40	130.83
	...	...	...
6	S/G #2 lower compartment	2,192.81	2,643.6
	...	...	...
38	Containment dome #2(highest)	1,853.33	1,968.5
Total		94,668.36	93,874.49



(a) (b)

Fig. 4. Visualization of the Defined Rooms in 3d GASLOW Mesh, (a) horizontal view at k=9, (b) vertical view at j=11 and 41

into the GASLOW model. In figure 4 the compartments modeled in the GOTHIC analysis are shown. It defines 41 compartments for the APR1400 containment. The dome region is divided into 6 rooms, and the upper containment from the operating deck also has 6 rooms. The free volume in the APR1400 containment is about 94,668m3. Table 1 shows free volumes of some compartment calculated in GASFLOW. Compared to GOTHIC data they are said to be conservative.

3. GASFLOW Analysis of SBLOCA for APR1400 Containment

The selected accident scenario to be calculated by the GASFLOW is a small break loss of coolant accident (SLOCA23)[3]. This sequence was chosen to be most probable from the APR1400

PSA results, and is a representative of transients in which the hydrogen can be released into the steam generator compartments[16]. SLOCA23 is initiated by the loss of coolant from a cold-leg break, and followed by failure of the safety injection system and the inability to aggressively cool-down the secondary side for the shutdown cooling system injection. Initially pressure and temperature of the atmosphere in the containment are 1 bar and 300K respectively. The air contains vaporized water up to 67% relative humidity in the initial conditions. It is stationary before water, steam, and hydrogen blow out from the cold-leg break which act as mass, momentum, and energy sources of the flow field. The source is obtained from the MAAP calculation for the SBLOCA. With the source, GASLOW calculates the distributions of species concentrations and temperature in the containment.

3.1. Source of SBLOCA

MAAP analyzes the in-vessel phenomena after the accident starts, and it calculates the blow down rate of water, steam and hydrogen, which is used as source data for the GASFLOW calculation. Figure 5 gives the water, steam and hydrogen source during 9,000sec of SBLOCA calculated from the MAAP analysis. During the first 4,000sec saturated water and steam are discharged, then steam and hydrogen blow out for the remaining time. The total amount of water, steam and hydrogen discharged into the containment during 9,000sec are 165,319kg, 97,294kg, and 637.6kg, respectively. The temperature of the source term is modeled using the enthalpies varied with the time obtained from the MAAP data. The discharged steam and water in the first 4,000sec are saturated and the saturation temperature is obtained from the steam table using the in-vessel pressure during the accident. After 4,000sec superheated steam is discharged with hydrogen whose temperature is assumed to be the same as steam temperature.

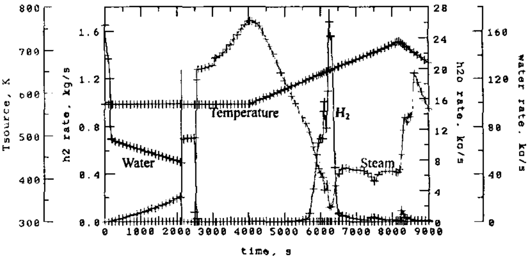


Fig. 5. GASLOW Source Data for APR1400 Containment, Steam, Water, Hydrogen Source and Temperature of SBLOCA from MAAP Analysis

3.2. Results of GASFLOW for SBLOCA

To find out the 3-dimensional flow behavior and hydrogen concentration in the APR1400 containment with PARs in operation a GASFLOW analysis was conducted. In this case it was assumed that the igniters are not operated. The saturated water blowing out from the cold-leg break vaporizes in the isoenergetic process. And this vaporized water spreads into the steam generator room. But because there is a large flow path between two steam generator compartments and the temperature of massively expanded water vapor is not so much high, it spreads around easily. Figure 6 shows the flow structure at t=1,000sec, where the vertical jet flow is found in each steam generator room. Some part of the vaporized water source makes an upward flow and some part spreads into the other steam generator room and goes to the containment dome by buoyancy. The vaporized water is mixed well in the containment atmosphere because of its lower temperature. After the water discharge ended, super heated steam blows out from the cold-leg break. Because the

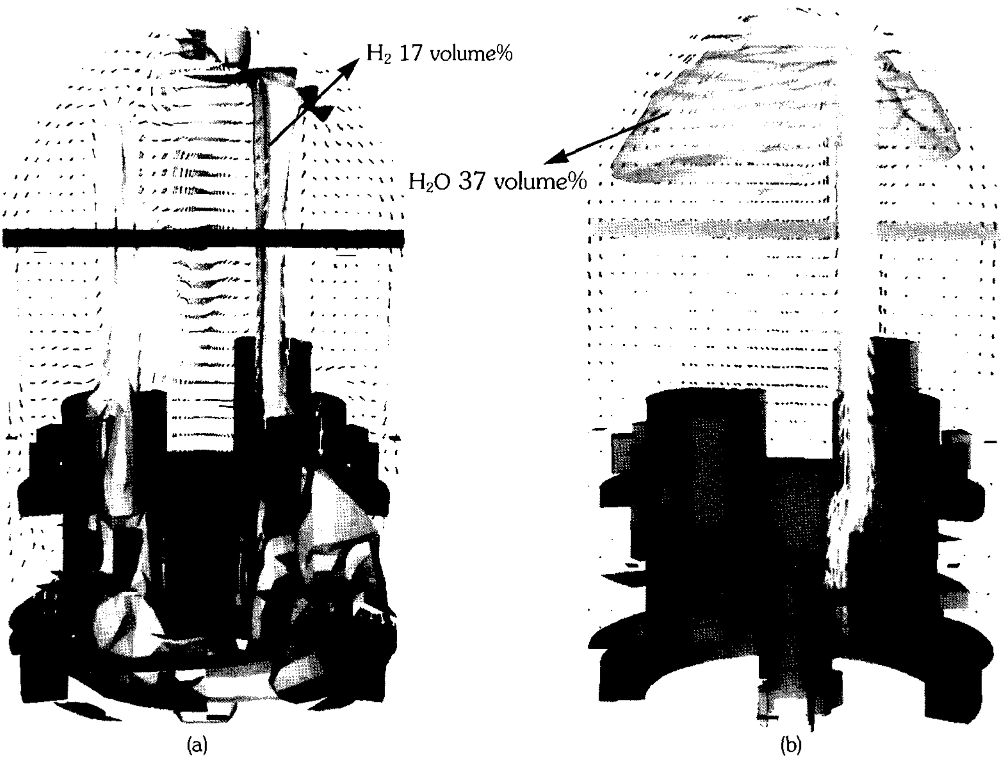


Fig. 6. Flow Behavior in the Containment Shown by Velocity Vectors and Iso-surface of Steam Concentration at (a) t=1,000sec, (b) t=4,000sec

temperature of the jet is very high, buoyancy force is large. And it makes the jet flow upward only. At 4,000sec after the accident was initiated a steam cloud whose concentration is larger than 37 volume% is developed at the dome region. From 6,000sec hydrogen starts to blow out with steam. Because the temperature of this source jet is also high, there is little spreading around it at the discharge location. The upward jet which arrived at the top of the dome expels a steam cloud down to the cylindrical part of the containment. The hydrogen concentration of the jet is around 15 volume%. Figure 8 shows the hydrogen and steam concentrations in the interesting compartments e.g. lower compartment of the steam generator room with the source(room no. 6 in figure 4) and the highest compartment of the containment dome(room no. 38). Though the average concentration of hydrogen at room 6 is below 10 volume%, the maximum concentration is above 60 volume%. Concentration of hydrogen accumulated at the highest dome compartment as shown in figure 7 is above 15 volume%. The abrupt increase of maximum temperature in the lower steam generator compartment is because of the heat release from hydrogen recombination of the PARs installed in the steam generator room. In the case of using PARs only the σ and $D/7\lambda$ criteria exceed 1.0 for a few minutes in the highest compartment of the containment dome, which means there is a possibility of flame acceleration and transition from deflagration to detonation in the compartment.

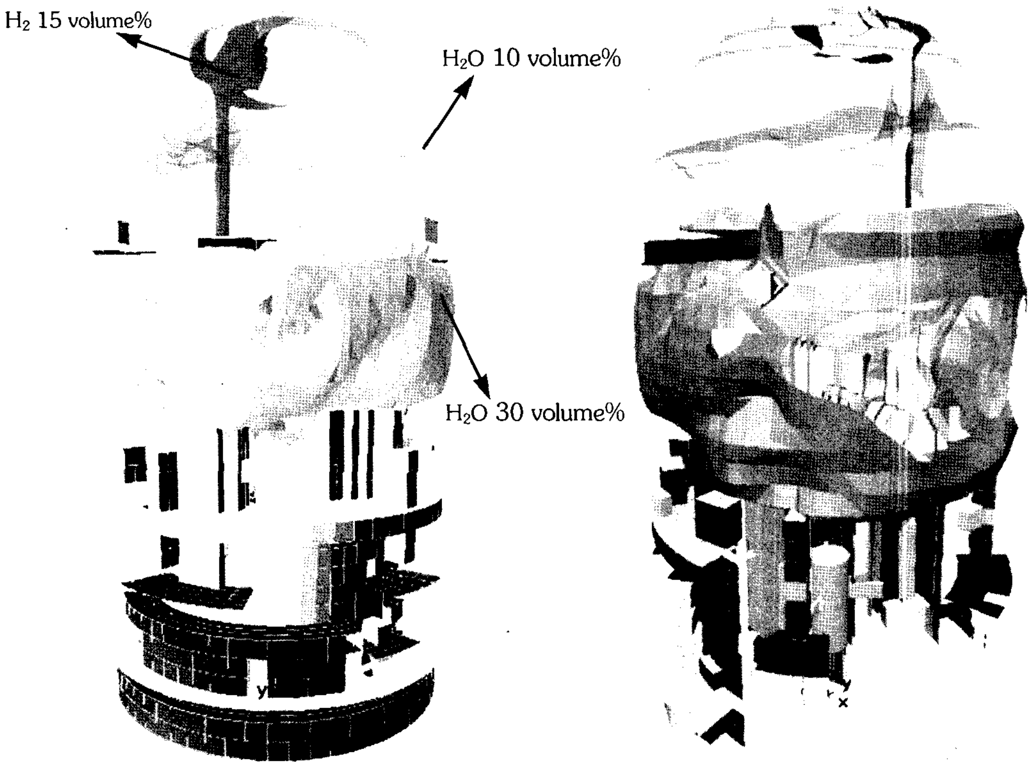
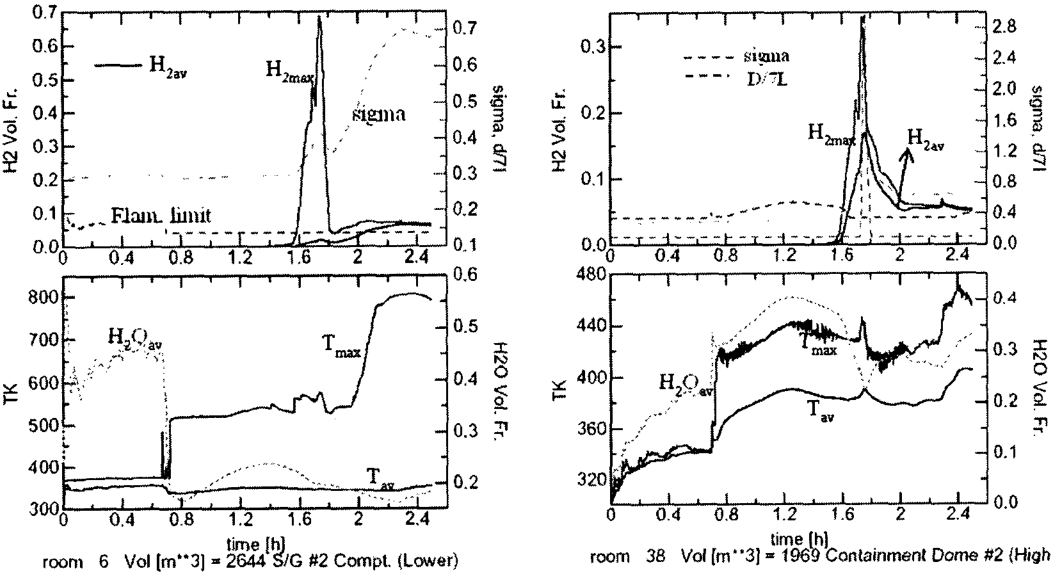
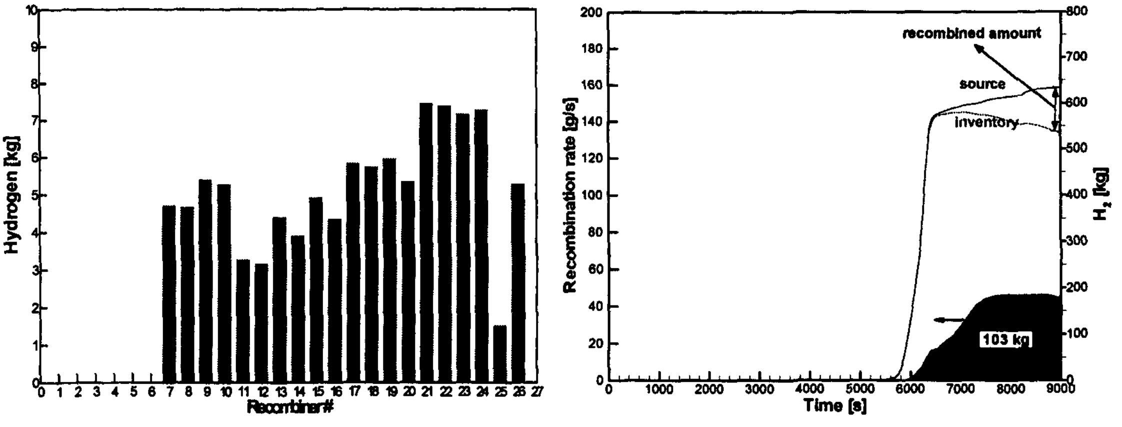


Fig. 7. Steam and Hydrogen Distributions at 6237sec. from GASLOW Analysis of SBLOCA for APR1400 Containment with PARs



(a) (b)

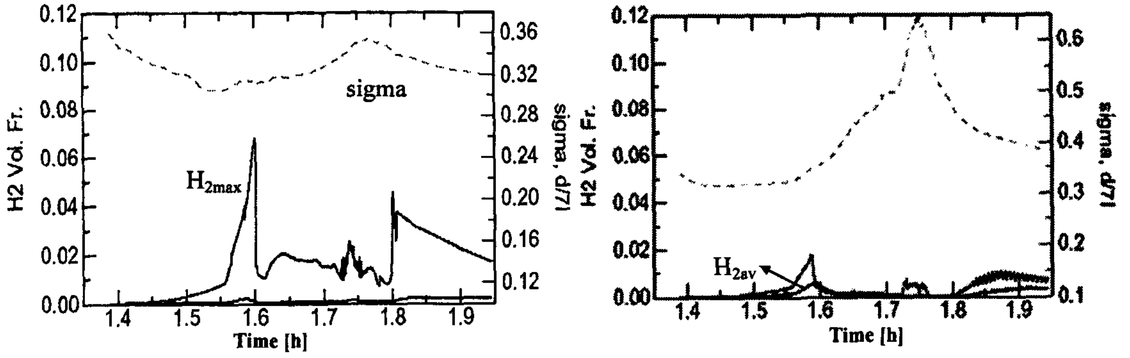
Fig. 8. Hydrogen and Steam Concentrations with Temperature Variation in the (a) lower compartment of steam generator room, (b) highest compartment of containment dome



(a)

(b)

Fig. 9. Hydrogen Recombination of PARs Installed in APR1400, (a) recombined hydrogen mass oof each PAR until 9,000sec., (b) hydrogen source and inventory with PARs' recombination rate



(a)

(b)

Fig. 10. Hydrogen Concentrations in (a) lower compartment of steam generator room, (b) highest compartment of containment dome

The performance of the PARs for the SBLOCA is depicted in figure 8. Usually large-size Siemens recombiner FR90 1-1500 recombines 4 to 5 gram of hydrogen per seconds. For this study all the 26 PARs are chosen as a large size, because their size is not yet defined in the design specification of APR1400. Recombiners numbered 7 to 10 are installed in the two steam generator rooms, and 21 to 24 are installed at the polar crane.

The total amount of recombined hydrogen until 9,000sec is about 103kg, and the inventory which is the amount of hydrogen left in the containment is about 534kg. From the analysis of GASFLOW it is said that the hydrogen released from the cold-leg break forms a strong upward jet flow in the steam generator room and it directly goes to upper dome through the open top of the steam generator room.

The openings in the cylindrical secondary shield wall supplies an entrainment of ambient gas to the jet flow. It is shown that hydrogen is accumulated at the upper dome during the peak release of hydrogen.

APR1400 uses a dual strategy for hydrogen mitigation, which means that passive PARs and active igniters are used. The current design specification of APR1400 has 10 igniters installed in the containment. For the SBLOCA scenario chosen in this study it is thought that igniters can effectively consume the hydrogen released from cold-leg break. Before verifying this postulation the flammability of the hydrogen released at the steam generator room is checked. Figure 8 depicts that the lower compartment of the steam generator room which has a hydrogen source, is in the flammable condition during the peak hydrogen release. GASFLOW calculation was restarted from 5,000sec with the igniters turned on. Figure 10 show the hydrogen concentration in the steam generator room and upper dome compartment. Maximum concentration of hydrogen is around 2 volume% except for a few minutes in the steam generator room. It is said that the hydrogen is effectively reduced by combustion.

Figure 11 is the pressure-time history when PARs with or without igniters are used for SBLOCA. The blow-down of saturated water and steam leads to an increase of the containment pressure up to 1.75 bar. It is shown that steam condensation at concrete walls of the containment reduces the pressure a little. When the igniters are turned on the containment pressure increases rapidly with hydrogen combustion. Its maximum value is around 2.5 bar

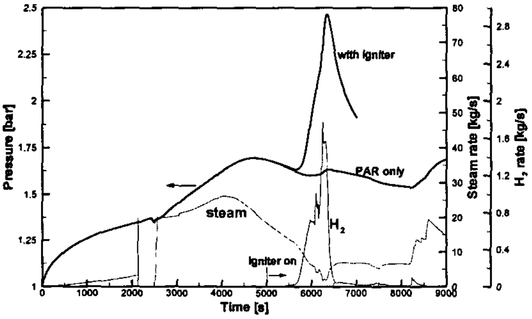


Fig. 11. Pressure Variation in APR1400 Containment for the SBLOCA by GASFLOW Analysis

4. Conclusions

GASFLOW analysis has been conducted for the SBLOCA accident in the APR1400 containment with PARs and(or) igniters. For the SBLOCA selected in this study hydrogen was accumulated in the containment dome region quickly when only PARSs were used. But 1,000sec after the peak hydrogen release it was mixed well in the containment atmosphere, and maximum concentration of hydrogen was reduced to round 7 volume%. When hydrogen starts to blow out, steam inertization was not so sufficient that the hydrogen cloud rapidly reached flammable conditions in which the igniters can be suitably used for the hydrogen mitigation. It was calculated that the glow-type igniters were turned on from t=5,000sec. A standing flame was made around the upper part of the reactor coolant pump by the igniter installed in the steam generator room with a source. The standing flame burnt most of the hydrogen blown-out, and the hydrogen concentration in the containment was below 2 volume%. In this analysis it was shown that the igniters are very effective for the fast hydrogen release in the steam generator room. But in view of the thermal load on the containment and equipment survivability from the standing flame it is necessary to study thermal behaviors with GASFLOW in detail. The computational mesh used in this study is a little coarse compared to previous studies at FzK. It is planned to use fine mesh for the GASFLOW analysis of hydrogen behaviors in the APR1400 containment.

Acknowledgement

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