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AN INVESTIGATION OF HYDROGEN STRATIFICATION AND ITS APPLICATION FOR THE ASSESSMENT OF CONTAINMENT FAILURE MODES FOR A BWR MARK III CONTAINMENT DURING CORE MELTDOWN ACCIDENTS*

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INTRODUCTION

The BNL staff have performed an extensive assessment of potential failure modes for core meltdown accidents in a Boiling Water Reactor (BWR) with a Mark III containment (refer to Figure 1). The particular Mark III containment under consideration did not initially include provision for any system to control H_2 burning, so that H_2 phenomena were found to be dominant contributors to containment failure. However, all Mark III containments will now have provisions for the control of H_2 burning, which will influence our current assessment of H_2 phenomena.

During core meltdown accidents, hydrogen may accumulate inside the reactor containment building as a result of zircaloy-steam and steel-steam reactions, radiolytic decomposition of water, corrosion of zinc-based paints and coatings, and the interaction of molten materials (from the damaged reactor core) with concrete in the region below the reactor vessel. For such accidents, it is essential to determine potential containment failure modes in order to predict the flow paths of fission products released from the damaged core. The suppression pool of a Mark III containment will effectively scrub any aerosol fission products passing through the pool and thus significantly reduce the off-site consequences of core meltdown accidents. Hence, the integrity of the drywell is important to ensuring that all of the fission products released from the damaged fuel actually pass through the pool. Hydrogen detonation initiated within the wetwell region may fail the drywell wall integrity. Drywell wall failure will cause the fission products to bypass the suppression pool with a corresponding increased release to the environment. Therefore, it is essential to assess the probability of drywell wall failure as well as that of the containment itself.

The flammability and detonability limits of a hydrogen-air mixture are mainly determined by its volumetric concentration. The local concentration of hydrogen within the Mark III containment building varies with the position of the source, the generation rate, generation period, geometric configurations, and mixing and transport processes. This paper examines the hydrogen concentration distribution within the Mark III containment and determines the probability of the various hydrogen burning phenomena that may occur during a postulated core meltdown accident.

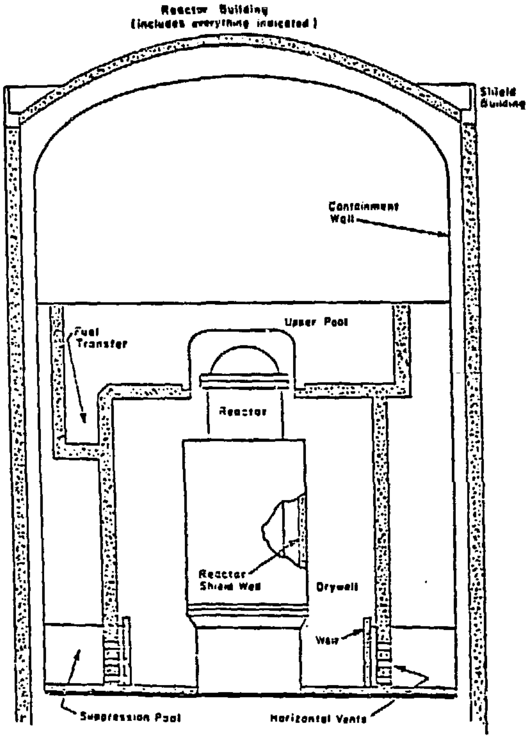

Figure 1 Typical Mark III Containment Buildings.

HYDROGEN DISTRIBUTION IN REACTOR CONTAINMENT BUILDINGS

During degraded core accidents, the mixing and transport processes involving air, steam and hydrogen within containment are influenced by buoyant force, pressure gradient force, containment geometry and forced convection induced by ventilation and spray systems. Generally, to deal with these mixing and transport phenomena, the following factors should be considered:

1. advective momentum
2. turbulent momentum
3. buoyant force
4. shear force

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5. pressure gradient force
6. thermal diffusion
7. turbulent diffusion
8. advective heat transfer
9. condensation rates and latent heat release
10. heat transfer to the walls.

Few experimental investigations of hydrogen mixing and transport have been conducted that are directly applicable to degraded core accidents. Nevertheless, analytic methods may be employed to estimate the evolution of local hydrogen concentrations. These hydrogen concentrations have been estimated analytically as described in the following section.

Theoretical Analysis

Within the BWR Mark III containment, the wetwell region combined with the dome region can be analytically considered to consist of several cells or subcompartments [shown in Figure 1 (Cumming)(1)]. The total height of the containment building is about 150 ft, which corresponds to a characteristic Rayleigh Number of 10^{12} to 10^{15}. This extremely high Rayleigh Number implies a strong turbulent mixing within the containment atmosphere. Hence, in each of the analytically coupled cells, the hydrogen is assumed to be completely mixed with air. The horizontal distance between the walls for each cell is always much larger than the boundary layer thickness, outside of which the shear force can be neglected. For the core meltdown accidents under consideration there will be no ventilation and spray systems available to induce forced convective flows. Therefore, the hydrogen mixing and transport processes are dominated by buoyant forces and pressure gradient forces. An adiabatic containment building is assumed.

The theoretical approach is less complicated than other existing methods (such as RALOC (Cumming),(1) COBRA (Buxton),(2) etc.). Nevertheless, the results derived through this method agree well with those obtained from more complicated and costly computational schemes.

Code Description

At this stage of development only hydrogen mixed with dry air is considered in the code. In each subdivided compartment, complete mixing of hydrogen and air is assumed. The horizontal distance between walls is always much larger than the boundary layer thickness. The shearing force along the walls is neglected. The heat loss to the walls is also neglected. Although the magnitude of conductive heat transfer is also negligible, it is included in this code.

When the hydrogen is released into a subcompartment of the containment building, the hydrogen is assumed to mix with the air completely in any given time step. This added hydrogen will change the concentration, pressure, and enthalpy of the subcompartment. The pressure difference and density difference will drive the hydrogen-air mixture into other compartments. Horizontal flows are ignored due to the immediate mixing assumption. Upward and downward flows across each interface between subcompartments are considered. At the end of each time step, the transporting process will stop and the pressure of a compartment are both larger than the compartment above it, only one direction flow (i.e., expansion) will be considered. For each subcompartment, the time step required for the entering gases traveling through the whole subcompartment may be different. The computational time step is determined as the minimum of these time steps. This time step is also checked and adjusted to assure that the pressure of the receiver compartment is not larger than the donor compartment unless the receiver compartment is the hydrogen source compartment (the hydrogen source compartment is assigned to the lowest compartment).

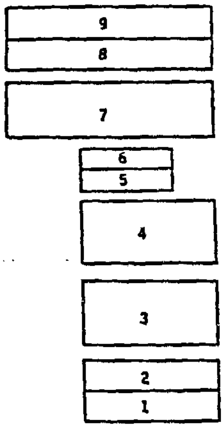
At the interface between two compartments, except for the expansion situation, the upward acceleration is assumed to be equal to the downward acceleration. Downward expansion only occurs when the bottom boundary temperature is lower than the atmospheric temperature within the containment and before the hydrogen is released. Upward expansion only occurs when the donor compartment temperature is lower than the receiver compartment, and the pressure and density of the donor compartment are both larger than the pressure and the density of the receiver compartment.

Calculation Results

The nine-cell nodalization model shown in Figure 2 was used to represent the wetwell compartment. This nine-cell model is similar to the RALOC five-zone model for the Grand Gulf containment building used in Reference (3). Compartments 1, 2, 3, and 4 represent the wetwell volume, which is located above the suppression pool and below the level of the floor of the upper water pool. Compartments 5 and 6 represent the annular region below the level of the top of the upper pool. Compartments 7, 8, and 9 represent the dome region. Two-directional flows are considered when they pass through the interfaces. The difference between these two models is that this code assumed instantaneous hydrogen-air mixing within each cell. Thus, no horizontal transport of hydrogen is considered. The total volumes for both models is identical. The postulated hydrogen injection rate is 50 lb/min and the air injection rate is 350 lb/min over a period of 1800 seconds at 140°F. The results of the present calculations can be compared with RALOC calculation (Thurgood)(3) as shown in Figure 3. The codes predict similar hydrogen distribution patterns during the hydrogen release.

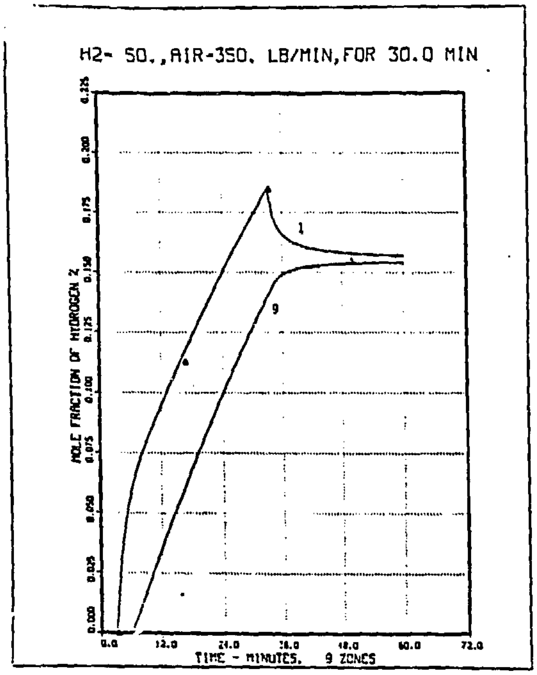
APPLICATION

Hydrogen combustion phenomena are determined by the volumetric concentration of H_2-air mixture and the availability of ignition sources. For a given H_2-air gaseous mixture, when the hydrogen volumetric concentration exceeds 4% and the oxygen volumetric concentration exceeds 5%, a deflagration will occur if an ignition source is available. The detonability limits of a hydrogen-air mixture is not as



Compartment Number	Compartment Volume ft^3	Compartment Height ft
1	56652	12.467
2	76583	12.467
3	152319	24.934
4	159898	24.934
5	53276	11.975
6	49483	11.155
7	338208	27.231
8	249675	20.669
9	249675	20.669

Figure 2



1 - first cell
9 - ninth cell
Δ - SNL/RALOC results of ninth cell

Figure 3

well-defined as the flammability limits. Based on the "induction time" criterion applied in Reference [4], this paper conservatively assumed that when the hydrogen volumetric concentration exceeds 17% and the oxygen concentration exceeds 8%, a detonation is considered possible provided a strong ignition source is available. The most likely ignition sources are electric equipment within the various subcompartments of the containment building. The lower portion of wetwell contains electrically driven equipment, which could initiate combustion phenomena. When the detonation is initiated, thermal pressure loads may reach 250 psia and last for tens of milliseconds. In addition, detonation waves can be enhanced by reflecting between the containment and drywell walls or focused during propagation. By comparing the peak loads against the ultimate capacity of the drywell structures, it has been determined that a detonation could fail the drywell wall.

A *transient event* initiated by a loss of off-site power and diesel failure was selected for analysis using this H_2 concentration model. Operating procedures require that safety relief valves be partially opened in the time frame beyond 26 minutes and then fully opened beyond 32 minutes. Hydrogen and steam generated in the reactor vessel will be released via the safety relief lines into the suppression pool. Noncondensible gases such as hydrogen will leave the suppression pool and enter the wetwell atmosphere. The computer code described in Section 2.2 was employed to predict the distribution and concentration of hydrogen within the wetwell compartment for this accident sequence. The wetwell compartment was subdivided into nine cells. The volumetric hydrogen concentration of each cell was used to determine the probability of a hydrogen deflagration or detonation.

For this accident sequence an ignition source was assumed to be available only after restoration of power. Before the reactor vessel failure, the reaction of 39% of the zirconium cladding in the reactor vessel would result in approximately 1330 pounds of hydrogen being generated and eventually released into the wetwell compartment. Hydrogen distribution corresponding to this H_2 generation is shown in Figure 4 using the nine-cell nodalization model. The calculation results show that for the first 60 minutes, no global detonations are possible. Sixty-six percent of the time a global deflagration was possible, 26% of the time a local deflagration was possible, while 8% of the time a local detonation was possible. If power is not restored prior to reactor vessel failure core/concrete interactions could result in additional hydrogen being generated and released into the wetwell compartment. It was determined that

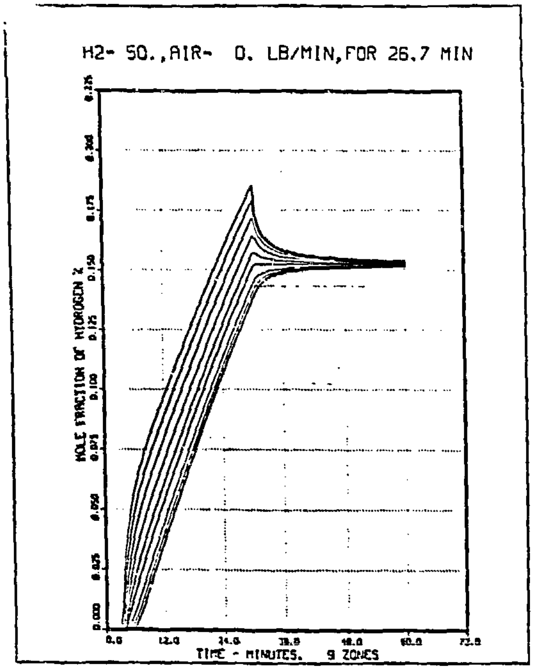


Figure 4

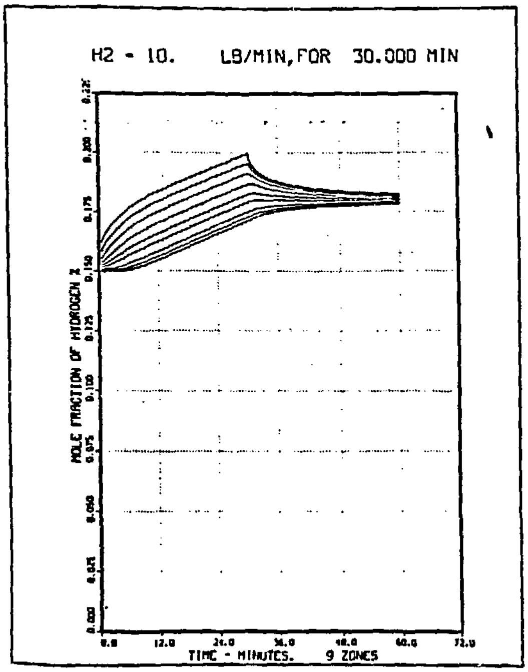


Figure 5

adding hydrogen to the wetwell atmosphere at 10 lb/min for 30 minutes (which is typical of H_2 generation during core/concrete interactions), the hydrogen distribution within each cell is higher than 17 volume percent as shown in Figure 5. Restoration of power during this period may thus result in a global detonation.

SUMMARY

The computer code described in Section 2.2 has been used to evaluate H_2 distribution in a Mark III containment as a function of time. This can be used together with an assessment of peak loads during various H_2 phenomena and a knowledge of the structural capability of the Mark III containment to determine containment building failure modes.

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