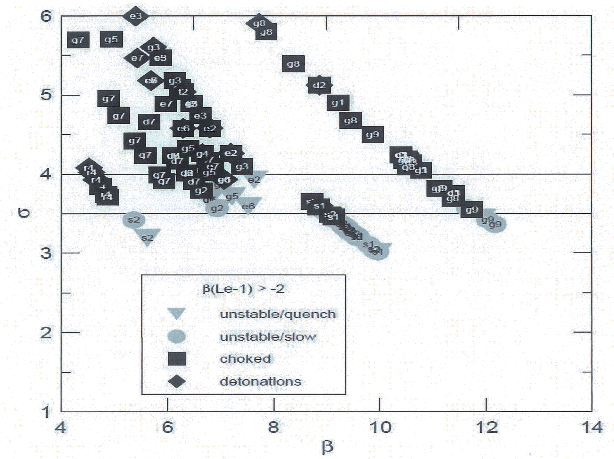


**Figure 2-21 Combustion regime as function of expansion ratio σ and Zeldovich number β for hydrogen-rich (including stoichiometric) mixtures (i.e., β(Le-1) >-2). [Reference 6]**

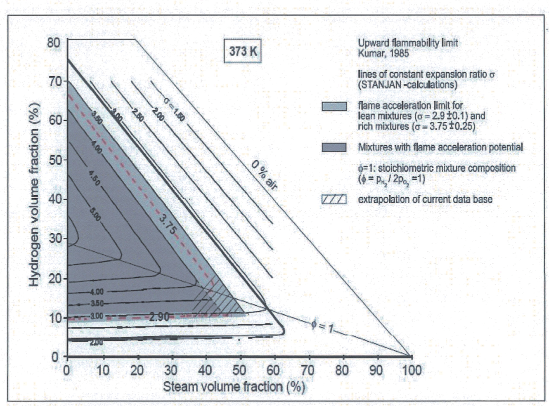


**Figure 2-22 Expansion ratio and flame acceleration limits of hydrogen-air-steam mixtures at 373 K [Reference 6]**

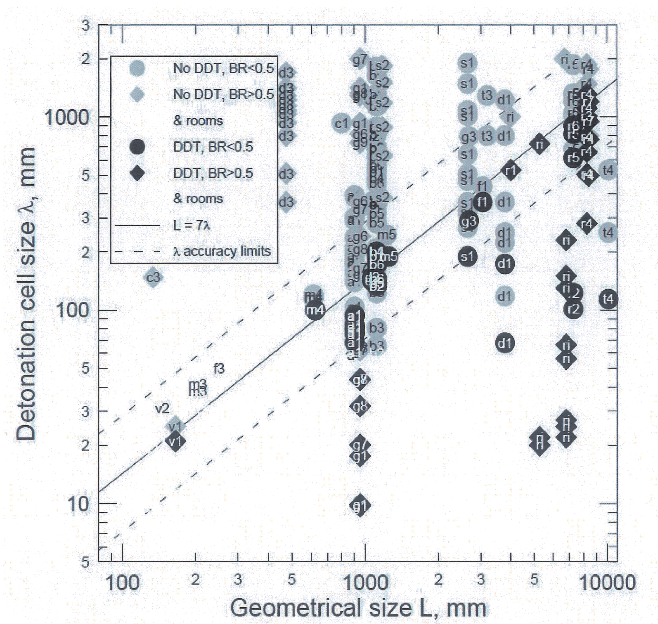


**Figure 2-23 L/λ correlation for onset of detonations [Reference 6]**

## 2.10 Hydrogen Mixing and Distribution

The ability to predict hydrogen concentrations in the containment is crucial to the prediction of the occurrence of combustion and its consequences. Distribution of hydrogen concentrations depend on gas mixing rates which depend on a number of mechanisms, (1) jet entrainment (entrainment of surrounding gases by high momentum jet from a pipe break), (2) inter-compartmental flow (driven by pressure differences among compartments), (3) forced flow (induced by containment fans or sprays), (4) natural convection (induced by density differences and steam condensation), and (5) diffusion (molecular process). The time scales for the above mixing mechanisms range, in increasing order, from less than seconds for jet entrainment to days for diffusion.

### 2.10.1 Experiments

Several experimental programs were aimed at understanding the behavior of hydrogen mixing in a containment during a LOCA. The major programs were, in order of increasing test facility volume, (1) the Containment Systems Test Facility (CSTF) experiments (876 $m^3$) in the U.S. during the early 1980s (Bloom et al., 1983), (2) the NUPEC's hydrogen mixing and distribution tests (1300 $m^3$) in Japan during the early 1990s [Reference 41], and the Heiss Dampf Reaktor (HDR) program (11,000 $m^3$) in Germany during the late 1980s [Reference 68,69, 70, 72]. In all these experiments, helium was used as a simulant gas instead of hydrogen for safety reasons. As for the geometry of the test facility (Figure 2-24), the CSTF simulated the highly simplified PWR ice condenser containment. The NUPEC facility simulated the large dry PWR containment with delicate internal structures typical of the Japanese and U.S. design. The HDR facility simulated the highly compartmentalized containment with a large dome. Among these facilities, the size of the HDR containment in terms of free volume (10000 $m^3$) is the largest.

Up-scaling the experimental results to the actual scale is another challenge faced by engineers in all fields [Reference 21, 43].

What we have learned so far from small and relatively large scale experiments is that homogeneous mixing within the source compartment can be expected if the jet entrainment dominates the mixing. This occurs when the injection rates are high such that the characteristic Froude number is high. When the injection rates are low the buoyant plumes form instead of jets. Vertical stratification develops such that the region above the injection point is relatively well mixed and the region below the injection point remains unmixed for a much longer (diffusion) time scale. Natural convection alone can provide good mixing after termination of the jet. Forced air recirculation can increase mixing significantly.

### 2.10.2 Code Prediction

Information obtained from the experimental programs is utilized for identifying various mixing processes as well as for guiding the construction and validation of mathematical models to be used in the computer codes. Only through the use of computational models, can experimental results be applied to the actual containment scale and realistic accident conditions.

Fast-running lumped-parameter codes have limits in their ability to predict hydrogen concentrations. The lumped-parameter approach, which has been the backbone of accident analysis codes (such as MAAP4, CONTAIN, MELCOR, RALOC, and HECTR) since their inception, is based on a small number (say, in the range of 4 to 10 for a containment) of nodes (or volumes) interconnected by flow junctions. The momentum equations for the flow network are solved. No momentum is treated within the nodes. Quantities (such as temperature, pressure, and gas compositions) within the nodes are assumed to be uniformly mixed. Hence, intrinsically, the lumped-parameter codes cannot predict stratification of gases within the nodes, and the rate of mixing among nodes depends on the flow rate through junctions.

A limited number of code validations against HDR (Reference 22, 37) and NUPEC tests [Reference 40, 58, 60, 61] were organized by OECD/NEA as international standard problems ISP-29 and ISP-35, respectively. We learned from these exercises that the lumped-parameter codes do a reasonable job of predicting mixing when the processes are dominated by either high momentum jet, inter-compartmental flow, or forced flow, but not so good with the stratified conditions controlled by natural convection. In analyzing NUPEC test M-7-1 which was well mixed throughout the facility due to water sprays, all participating codes had difficulty in matching, to a reasonable degree, the helium concentrations in the lowest compartment and in the dead-end compartments that were not greatly affected by global mixing due to sprays. This is also the major failure of the lumped-parameter codes in predicting the gas concentrations in the HDR test E11.2 where gases below the injection compartment remained relatively unmixed resulting in global stratification.

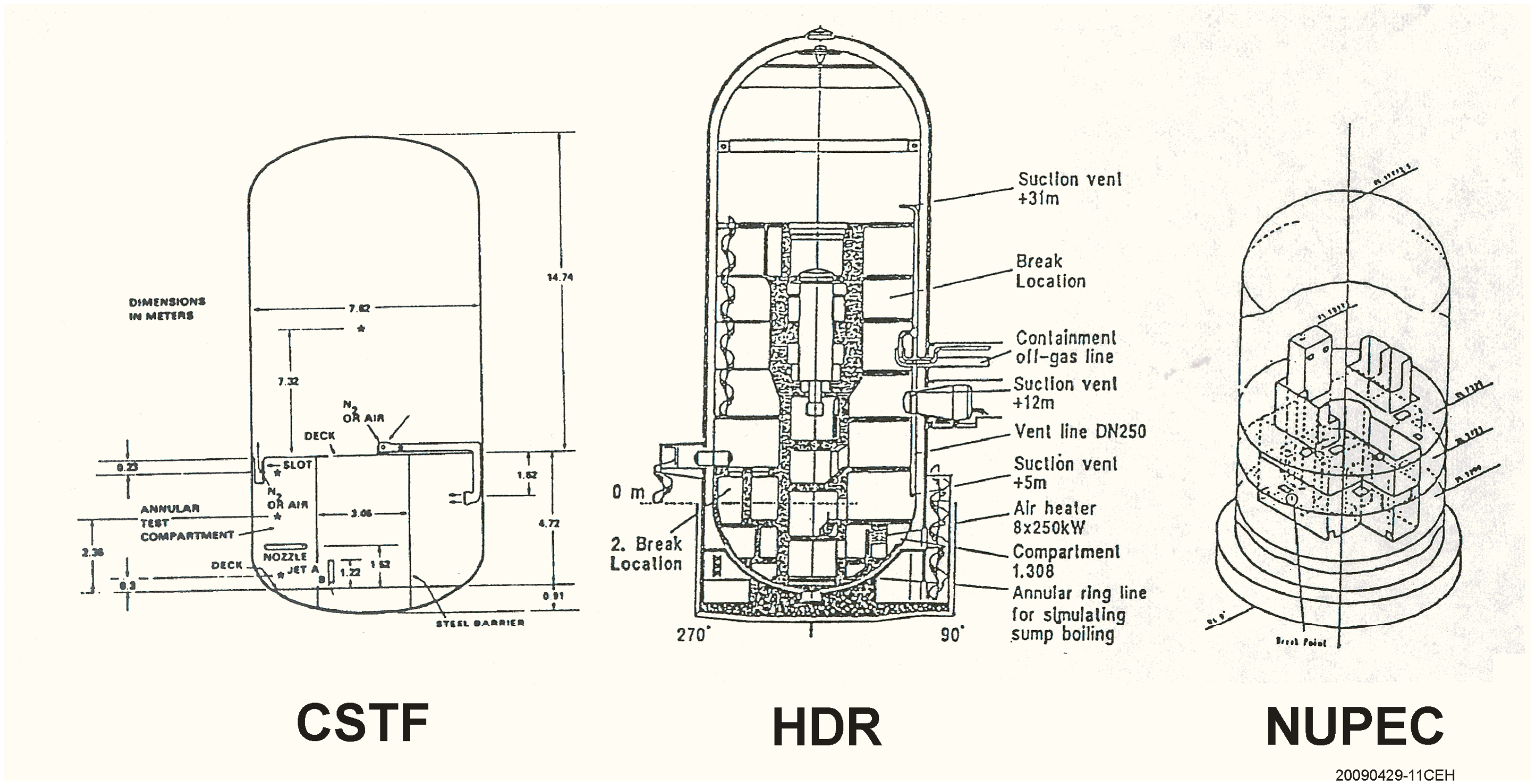


Figure 2-24 Hydrogen distribution and mixing tests

### 2.10.3 Subnode Physics Model in MAAP4

To overcome the deficiency in coping with stratified conditions in the lumped parameter code, the subnodal phenomena must be considered. In the MAAP4 code, the so called "subnode physics" model was developed to account for stratification. The subnode physics model determines the condition required for flow stagnation in the node in question (based on pressure equilibrium with its horizontally connected node). The required condition is that the penetration depth (within the node in question) of the lighter gas entering from the node above through a vertically oriented junction, or of the heavier gas entering from the node below exceeds the distance required to clear the nearest horizontally oriented junction, then the junction is shut off to any buoyancy-driven flow. The model, hence, does not always allow buoyancy-driven flow through the vertically-oriented junction. The rate of gas mixing among various nodes can be then properly predicted.

The results of MAAP4 calculations of the HDR Test E11.2 with and without the subnode physics model are compared in Figure 2-25, Figure 2-26, and Figure 2-27 (Reference 17). Figure 2-25 shows an excellent improvement in the calculated gas temperature at 0 m elevation from a maximum error of ~36 K to about 6 K. Figure 2-26 and Figure 2-27 also show a very good improvement in the calculated gas concentration in the upper dome and at the 10 m elevation. It can be noted that the trend of the test data, which is incorrectly predicted without the subnode physics model, is correctly predicted by the addition of the subnode model.

The subnode physics model offers no guarantee of success to applications involving more complex flow networks than considered for the HDR test. This is an area that has not been thoroughly investigated.

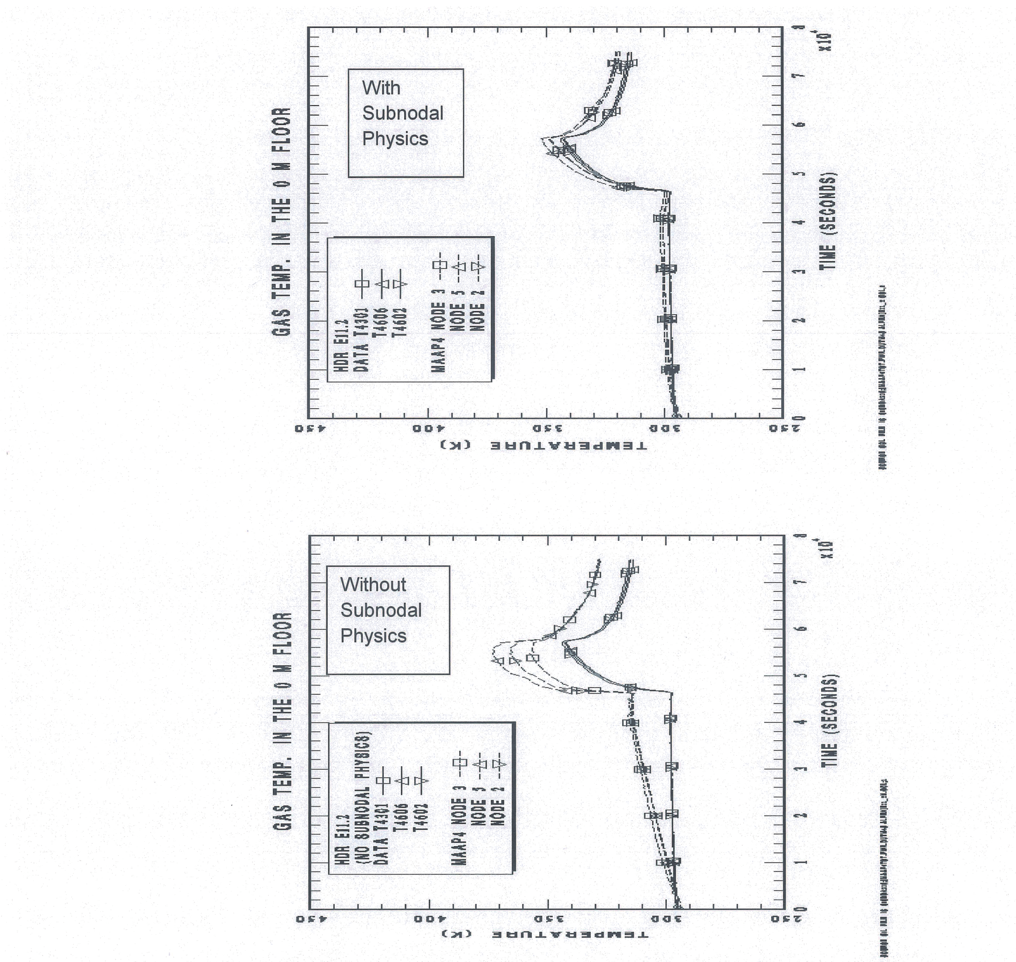


**Figure 2-25 Gas temperatures at 0 m floor; comparison of MAAP4 results to HDR Test E11.2 data**

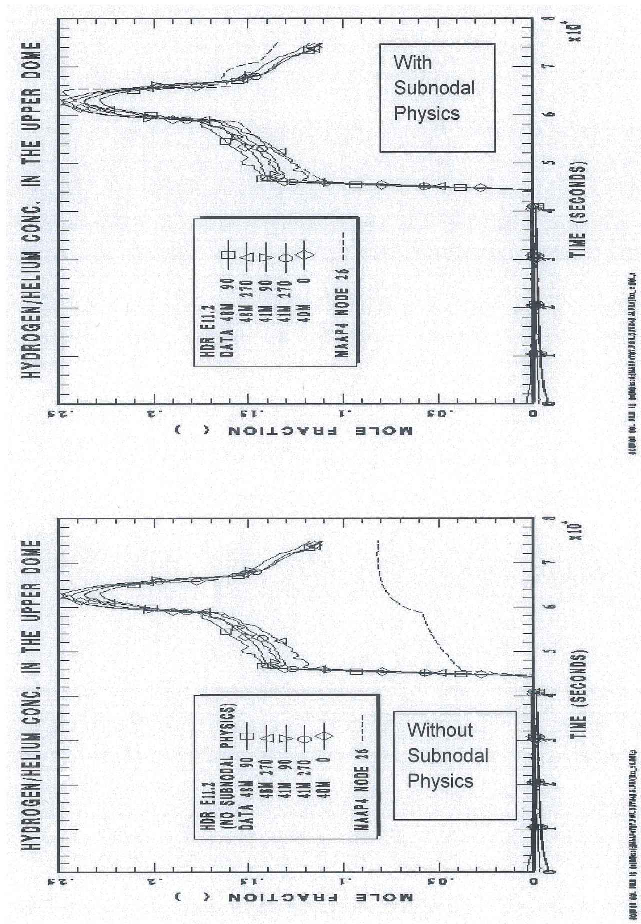


**Figure 2-26 Hydrogen/helium concentration in the upper dome; comparison of MAAP4 results to HDR Test E11.2 data**

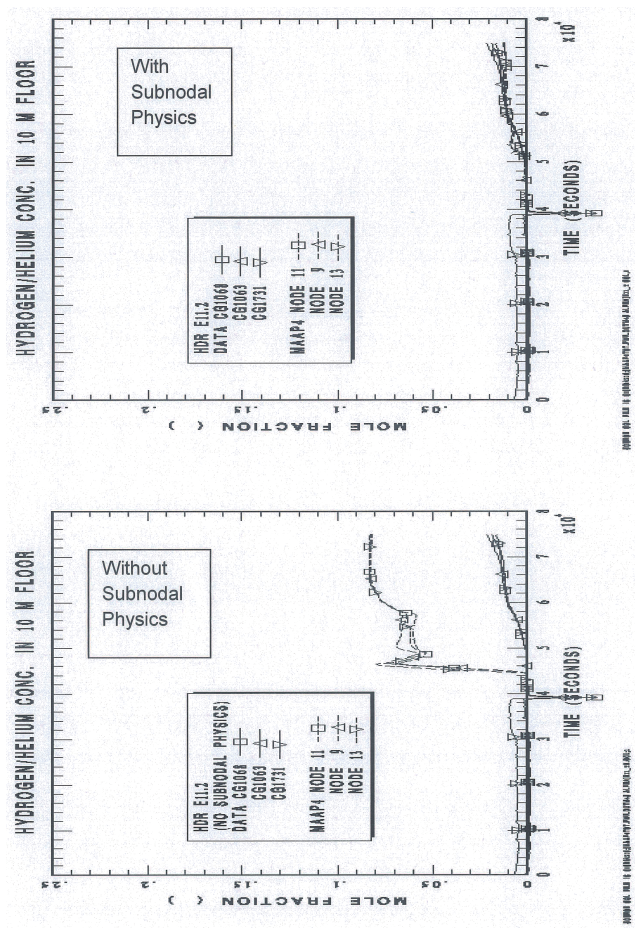


**Figure 2-27 Hydrogen/helium concentration at 10 m floor; comparison of MAAP4 results to HDR Test E11.2 data**