

Figure 2-25 Model of the Konvoi cavity and compartments

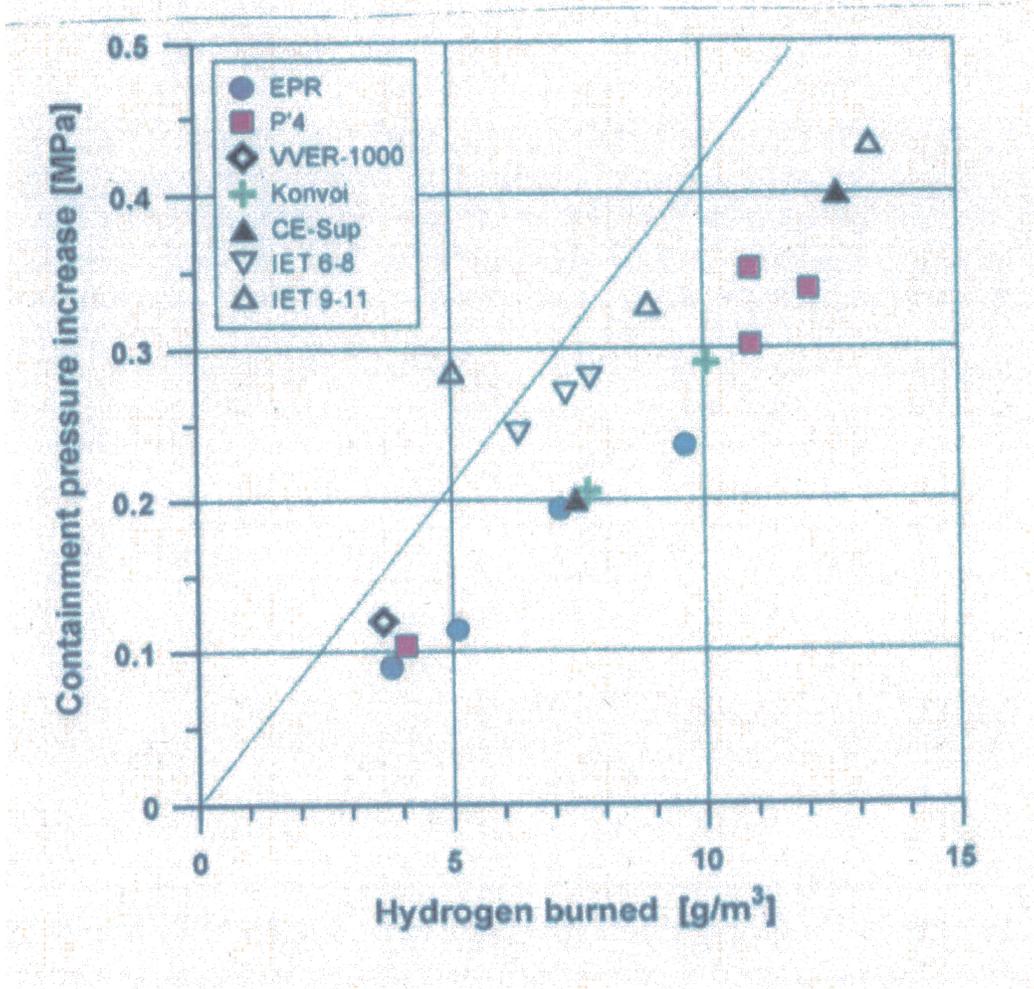


Figure 2-26 Measured containment peak pressure rise over amount of burnt hydrogen per containment volume; the line represents the theoretical pressure increase by thermal energy of hydrogen combustion without heat loss to structure

3.0 REVIEW ON METHODOLOGY OF DCH ANALYSIS

DCH has been extensively studied in the past 2 decades and a number of modeling approaches were proposed and tested. These include the CLCH model (Reference 35) and the TCE model (Reference 36), which were used for assessments of DCH risks for all nuclear plants in the US. Features of these models are described as follows.

3.1 CLCH Model

The key argument of this model is that the heat transfer between the melt and the gas is limited by the amount of blow-down gases that have intimate (coherent) contact with the melt. Once the melt particles are trapped and deposited in the subcompartment, the heat transfer between the melt and the containment atmosphere becomes negligible, and the major energy addition into the atmosphere is through the combustion of the so-called pre-existing hydrogen.

3.1.1 Assumptions

A number of assumptions were made in this model, which are summarized below:

- a) When the vessel is breached under high pressure, the melt is ejected first followed by the high speed steam and H₂ jet. The flow pattern within the reactor cavity (PWR) or pedestal (BWR) is a recirculation flow, which induces a strong interaction between the gas and the melt. The melt is entrained by the jet into small particles. Heat transfer between the gas and melt allow them to reach thermal equilibrium quickly. In the mean time, chemical reactions between the two cause depletion of the steam constituent and increase of the hydrogen constituent.
- b) Once the multiple phases of steam, gas and corium particles flow through the inclined junction, or so-called chute, between the cavity and subcompartment, the gas flow is significantly slowed down because the volume of the subcompartment is much larger than the cavity. The flow speed is expected to be less than the threshold speed to levitate the particles, and most of the corium particles carried by the flow, except those with very small diameters, are deposited in the subcompartment. Once they are deposited, their ability to transfer significant amount of heat and be oxidized is assumed minimal compared to the finely particulate state.
- c) Hydrogen generated during DCH is assumed from Zr, Cr, and Steel oxidation, where Zr and Cr are considered as highly reactive metals, while steel is the less reactive metal. The rates of Zr and Cr oxidation are only limited by the amount of reactant steam. Chemical equilibrium is assumed between the steel, steam, and hydrogen reactants. Pre-existing hydrogen in the containment is assumed to combust when the temperature in the containment reaches the auto-ignition temperature.

3.1.2 Equations of Pressure and Temperature Increases

An implication in the assumptions is that significant heat transfer occurs only in the time frame when the blow-down gas speed is large enough to disperse and levitate the particles. The time is denoted

as the coherent time τ_m . For the blow-down gas, adiabatic expansion is assumed, and the blow-down gas pressure, mass flow rate, and temperature are given by assuming an ideal gas, so that

$$\frac{P_{s,v}}{P_{sO,v}} = \left[1 + \frac{\gamma-1}{2} \Gamma \frac{t}{\tau_s} \right]^{2\gamma/(1-\gamma)} \quad (3-1)$$

$$\dot{m}_{s,b} = \eta A_b \rho_{sO,v} a_{sO} \Gamma \left(1 + \frac{\gamma-1}{2} \Gamma \frac{t}{\tau_s} \right)^{(\gamma+1)/(1-\gamma)} \quad (3-2)$$

$$T_{s,v} = T_{sO,v} \left(\frac{P_{s,v}}{P_{sO,v}} \right)^{(\gamma-1)/\gamma} \quad (3-3)$$

where γ is the ratio of specific heat of C_p/C_v of the gases, A_b is the break area, η is the discharge coefficient, $P_{sO,v}$, $T_{sO,v}$ and $\rho_{sO,v}$ are the pressure, temperature and gas density in the RCS before the blow-down, a_{sO} and Γ are related to the ratio γ and the temperature $T_{sO,v}$. The characteristic depressurization time τ_s is given by

$$\tau_s = \frac{V_v}{\eta A_b a_{sO}} \quad (3-4)$$

where V_v is the volume of the RCS. As stated before, thermal and chemical equilibriums are assumed between the blow-down gases and the corium particles during the coherent time of τ_m . A simple energy balance between the blow-down gases and the corium particles lead to an equation for the temperature of the hot gas and corium mixture:

$$T_{s,c} = \frac{\dot{m}_m C_{p,m} T_m + \dot{m}_{s,b} C_{p,s} T_{s,v} + \Delta H_{r,Zr} \dot{m}_m (\omega_{Zr}) + \Delta H_{r,Fe} \dot{m}_m (\omega_{Fe}) r_{Fe}}{\dot{m}_m C_{p,m} + \dot{m}_{s,b} C_{p,s}} \quad (3-5)$$

where $\dot{m}_m = m_{mO} / \tau_m$ is the entrainment rate in the cavity, m_{mO} is the total mass of corium ejected from the vessel, $C_{p,m}$ and $C_{p,s}$ are the specific heat of the melt and the gas, ω_{Zr} and ω_{Fe} are the mass fractions of Zr+Cr and steel in the melt, $\Delta H_{r,Zr}$ and $\Delta H_{r,Fe}$ are the reaction heat per mass when Zr+Cr and steel are oxidized. As assumed, Zr and Cr are assumed highly reactive and a complete oxidation of these metals is expected, while iron is less reactive, and partial oxidation is considered when chemical equilibrium is reached between the reactants of steel, steam, and hydrogen. The factor r_{Fe} is the constant which account for partial oxidation, which is evaluated based on the chemical equilibrium constant of the iron oxidation equation.

When the hot gas enters the open space in the containment, it mixes with the bulk atmosphere in the containment and elevates the temperature and pressure in the containment. The gas temperature in the containment is thus given in the following formulation by considering an energy balance in the entire containment:

$$\left(m_s C_{v,s} + m_a C_{v,a}\right) \frac{dT_a}{dt} = \dot{m}_s C_{p,s} T_{s,c} - \dot{m}_s C_{v,s} T_a, \text{ for } t \leq \tau_m, \quad (3-6)$$

$$T_{a,f} = \frac{m_{s,v}(\tau_m) C_{v,s} T_{s,v}(\tau_m) + m_{s,a}(\tau_m) C_{v,s} T_a(\tau_m) + m_a C_{v,a} T_a(\tau_m) + \Delta H_{H_2} m_{H_2}}{m_{sO} C_{v,s} + m_a C_{v,a}}, \text{ for } t > \tau_m \quad (3-7)$$

where T_a is the containment bulk temperature, m_s is the mass of blow-down gases, and $\Delta H_{H_2} m_{H_2}$ represents the energy addition due to H_2 combustion. Finally, the pressure in the containment is given by the ideal gas law as

$$P_{a,f} = \left(\frac{m_{sO,v}}{V_v + V_a} R_s + \frac{m_a}{V_v + V_a} R_a \right) T_{a,f} \quad (3-8)$$

3.1.3 Considerations of Iron Chemical Reaction and Pre-existing H_2 Combustion

Steel in the melt ejected from the reactor vessel can be oxidized by the blow-down steam to generate hydrogen. The oxidation is limited by the chemical equilibrium among the reactants of iron, FeO, hydrogen, and steam. If the rate of iron consumption is denoted by \dot{r} , the chemical equilibrium is expressed by a temperature-dependent equilibrium coefficient of K, as

$$K = \frac{\dot{r}(\dot{M}_{H_2} + \dot{r})}{(\dot{M}_m \chi_{Fe} - \dot{r})(\dot{M}_s - \dot{r})} \quad (3-9)$$

where \dot{M}_{H_2} includes the blow-down rate of hydrogen which is originally in the RCS and the rate generated by oxidation of Zr and Cr. The rate of iron consumption can be easily solved from the above equation, and applied to Eq. (3-5).

Besides the oxidation during the blow-down phase, more hydrogen can be generated through oxidation of steel, when 1) certain amount of steel can be trapped in the cavity, therefore subject to oxidation following the dispersion of the main body of the melt; 2) certain amount of steel can be expelled to the open space of the containment, subject to the oxidation in the space. The additional hydrogen generated by these two mechanisms are referred to as the hydrogen sources of "captured" and "dispersed". A lower limit of total hydrogen in the containment can be made if the additional hydrogen generation is considered for only the "captured" iron oxidation; while an upper limit can be made if both the "captured" and "dispersed" iron oxidations are considered.

Combustion of the hydrogen in the containment is assumed only when the containment atmosphere temperature is above the auto-ignition temperature, which is estimated around 850 K to 1070 K, and the hydrogen concentration is above the lean flammability limit of about 5%. Once the hydrogen is considered flammable, its reaction heat is added into the term in Eq. (3-7).

3.1.4 Comparison with Experiments

The CLCH model was compared with the IET series of experiments done in SNL (Sandia National Laboratory) and ANL (Argonne National Laboratory). Figure 3-1 and Figure 3-2 show the comparisons between the model and SNL IET series of experiments, where the curved lines are predictions of the model and the flat lines are experiment data. Figure 3-1 is based on the lower limit of hydrogen generation due to steel oxidation, while Figure 3-2 is based on the upper limit. The data, as shown, is between the lower and upper limit predictions of steel oxidation. Figure 3-3 shows the comparison between the model and ANL IET series of experiments, which is based on the upper limit of hydrogen generation. The model slightly over-predicts the pressure increase compared to the experiments. This is probably because the ANL IET experiments were using a much smaller scale facility, and heat loss to the wall has a larger impact on the measured pressure rise. In general, the CLCH results are reasonable compared to the experiments in the range of the characteristic time ratio of τ_m/τ_s .