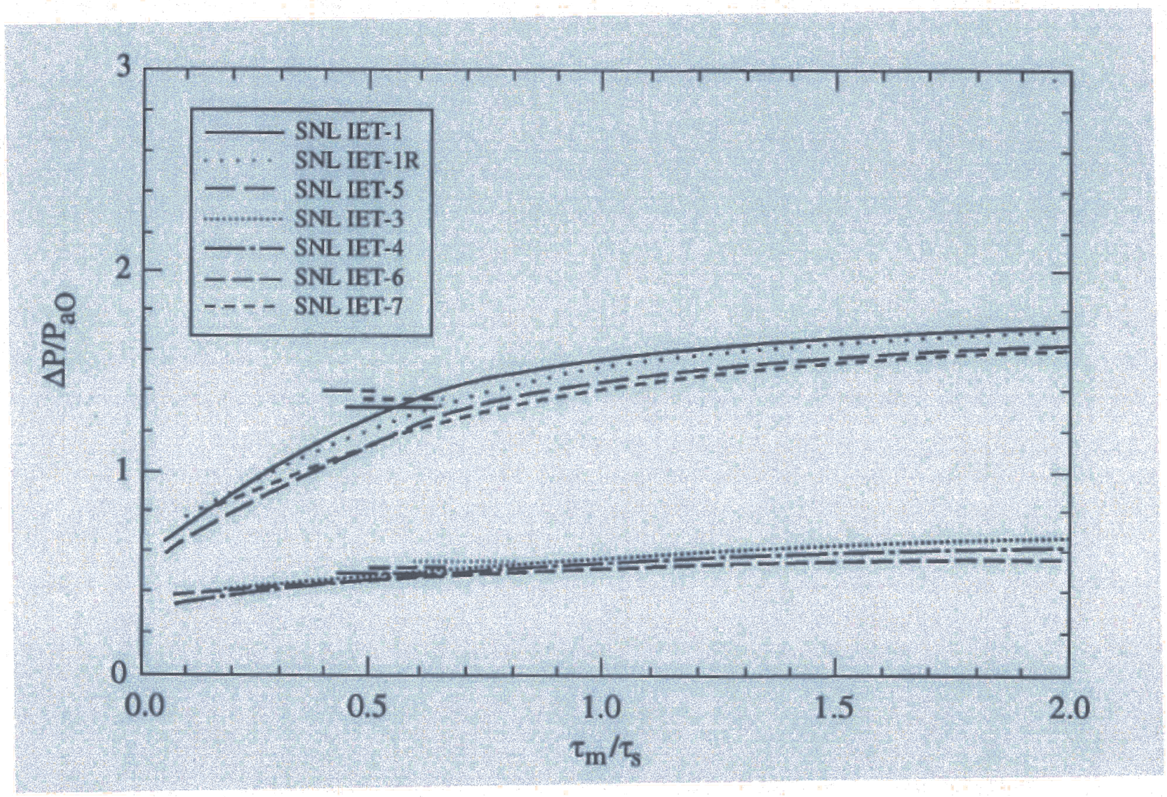

Figure 3-1 Comparisons of pressure increase predicted by CLCH model and the experiment data measured by SNL IET series of experiments. Lower limit of hydrogen generation is assumed for steel oxidation.

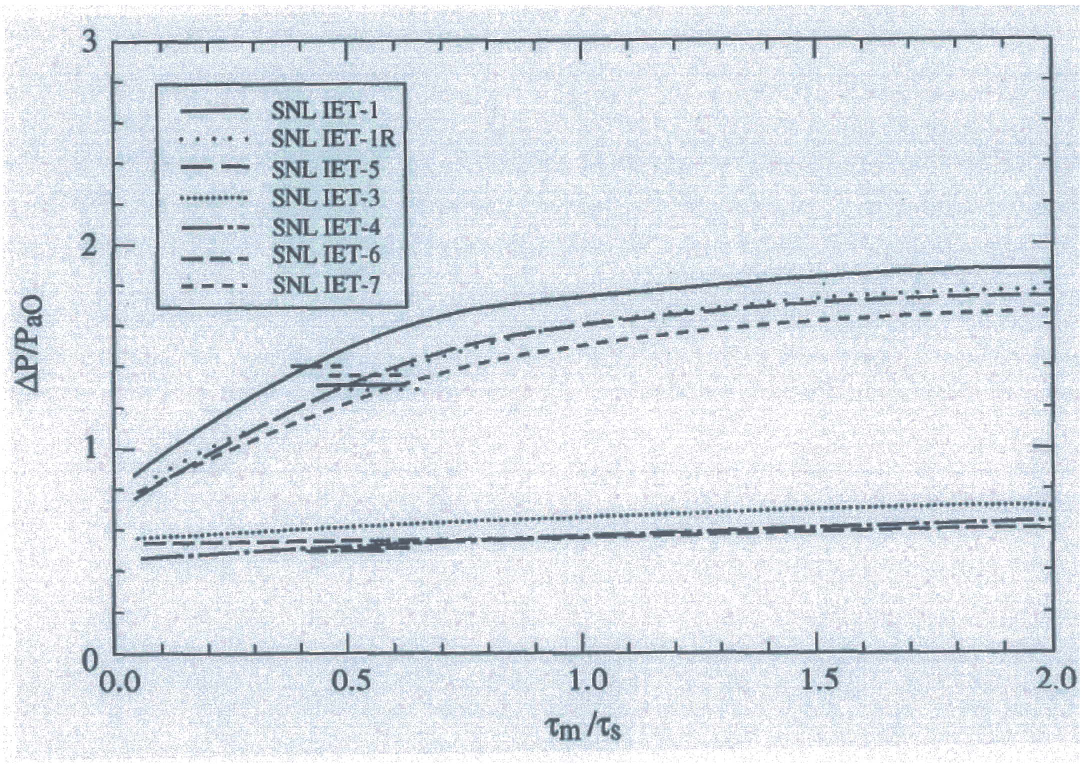

Figure 3-2 Comparisons of pressure increase predicted by CLCH model and the experiment data measured by SNL IET series of experiments. Upper limit of hydrogen generation is assumed for steel oxidation.

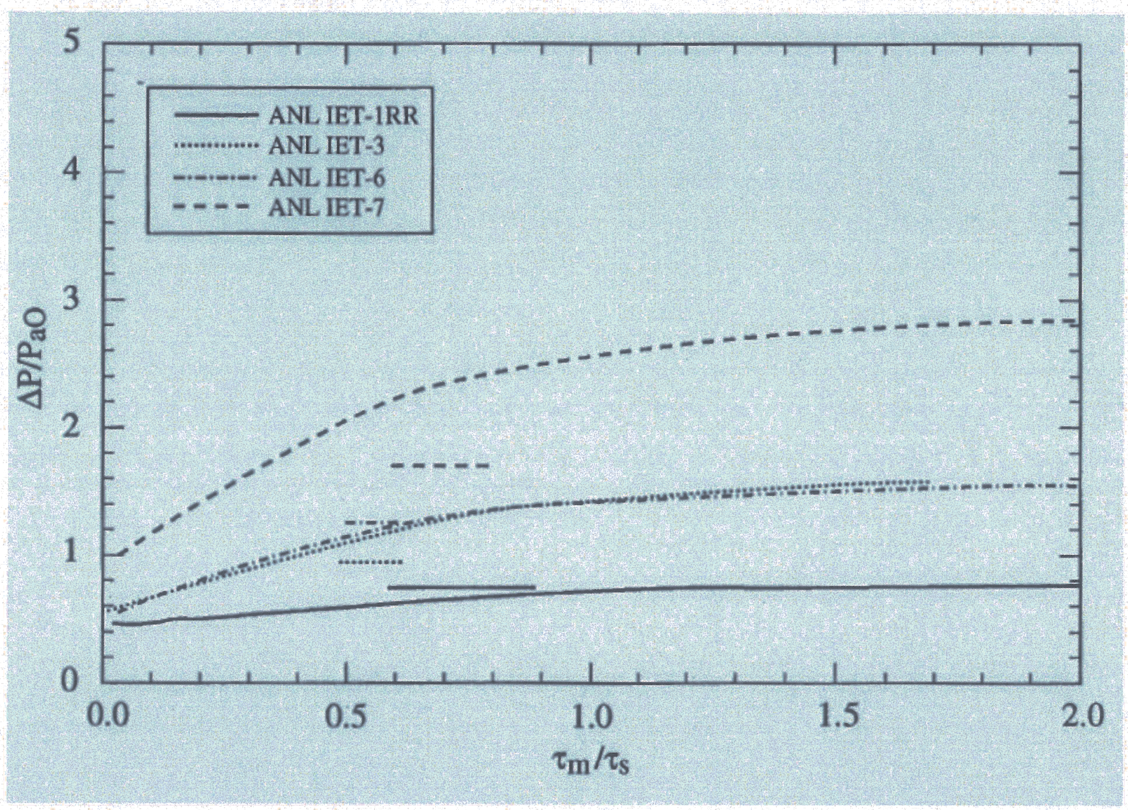

Figure 3-3 Comparisons of pressure increase predicted by CLCH model and the experiment data measured by ANL IET series of experiments. Upper limit of hydrogen generation is assumed for steel oxidation.

3.2 TCE Model

The TCE model is another model used to assess the DCH risk, which is an extension of the SCE model to account for the effect of containment compartmentalization. The major difference between the TCE and CLCH model is that: a) In the TCE model, both the gases in the containment and the gases blowing-down to the RCS exchange energy with the melt particles, while the CLCH model only considers the blow-down gases; b) the TCE model considers the limit to the heat transfer due to trapping of the melt particles in the subcompartment by using two nodes in the containment; c) two modes of combustion of hydrogen are considered in the TCE model: diffusion flame and bulk deflagration, while the CLCH only considers the deflagration when the bulk temperature is above the auto-ignition temperature.

3.2.1 Assumptions

A number of conservative modeling assumptions are made in the SCE and TCE models, and these are listed in the following:

a) The entire containment space can be modeled with two compartments, and each of them receives a fraction of the dispersed corium particles. The subcompartment includes the reactor cavity and surrounding areas such as the corium chamber, ICI chase, and access area; the upper dome includes the remaining open space in the containment. Thermal and chemical equilibrium is reached between the gas space and the dispersed particles in each compartment.

b) The containment atmosphere is adiabatic during the DCH process. The maximum pressure and temperature in the containment are determined by the thermal and chemical reaction heat transfer between the dispersed corium particles and containment gas.

c) The mass of gases in the subcompartment that can reach thermal equilibrium with the corium particles is the maximum between the mass of gases in the sub-compartment prior to the vessel failure and the mass of the gases and steam which is coherent with the dispersal process during the blow-down. The blow-down is assumed to be an isentropic (adiabatic) process. A coherence ratio is defined as the time required for dispersing all the corium in the cavity to the blowdown time. The fraction of the mass of gases and steam coherent with the corium is calculated as a function of the coherence ratio.

d) Hydrogen combustion occurs only in the upper dome compartment. Three sources of the hydrogen are considered: pre-existing hydrogen that is released from the RCS to the containment before vessel failure, the hydrogen released from the RCS as part of the blowdown gases, and the hydrogen generated from metal oxidation during the DCH process.

e) The hydrogen generated from oxidation of Zr, Cr and Al is limited only by the amount of steam coherent with the dispersal process. The hydrogen generated from oxidation

of steel is limited not only by the amount of steam available, but also by the chemical equilibrium between the steel and steam.

f) A diffusion flame is the expected mode of hydrogen combustion in the upper dome compartment. The lowest oxygen mole fraction that can sustain the diffusion flame is determined through the balance of chemical reaction heat and the heat required raising the temperature of entrained air.

3.2.2 Prototype SCE Model

The SCE model assumes that the entire containment volume can be treated as a single control volume. The dispersed debris is assumed to mix completely with the entire containment atmosphere and to remain airborne long enough to enable all thermal and chemical interactions to come to equilibrium.

Based on these assumptions, the maximum pressure rise in the containment resulting from DCH is obtained by combining the energy balance equation and the ideal gas law. That is,

$$\frac{\Delta P}{P^o} = \frac{\Delta U}{U^o} = \frac{\sum \Delta E_i}{U^o\left(1+\psi\right)} \tag{3-10}$$

where ΔP and ΔU are the pressure increase and internal energy increase in the containment gas space, P^o and U^o are the initial pressure and energy. ΔE_i represents the energy input into the containment, and ψ is the ratio of the total heat capacitances in the RCS and in the containment.

The energy input is the sum of the energies due to blow-down gases ΔE_b, melt ΔE_t, metal oxidation ΔE_r, and hydrogen combustion ΔE_{H2}, i.e.,

$$\sum \Delta E_i = \Delta E_b + \Delta E_t + \Delta E_r + \Delta E_{H2} \tag{3-11}$$

In the above equation ΔE_b and ΔE_t are evaluated by assuming that the blow-down gas pressure is reduced to the initial containment pressure and that the melt is cooled to the initial containment temperature. The chemical reaction term ΔE_r is evaluated for the metals in the melt in the order of Zr, Cr, and steel. The blow-down steam is considered as the source of oxidant of the reaction, and it reacts with the most reactive metal, then the less reactive ones, until all the steam is exhausted. The combustion term ΔE_{H2} is evaluated for the hydrogen coming from three sources: pre-existing hydrogen in the containment, hydrogen in the RCS, and hydrogen generated during metal oxidation. The combustion is assumed to be complete when all the oxygen within the containment is exhausted.

Figure 3-4 shows a comparison of the pressure increase predicted by the SCE model with those measured in the experiments. As shown, the SCE model tends to over-predict the pressure increase, mainly because it fails to consider the limitation to the energy exchange when melt particles are trapped in the subcompartment.

3.2.3 Extension from SCE Model with Consideration of Trapping Corium in the Sub-Compartment

In light of the insufficiency of the SCE model, a more sophisticated TCE model was developed to account for the trapping of the melt. As stated in the assumption section, the entire containment was split into a subcompartment and the upper dome.

When the vessel fails, the melt particles can be carried into the two compartments at the same time. The premise of the TCE model is that DCH occurs independently in the subcompartment and in the upper dome. The energy balance in each compartment shows that the individual contributions to the containment energy can be written as the product of the efficiency and the maximum internal energy change based on the SCE model, so the containment pressurization can be written as

$$\frac{\Delta P}{P^o} = \left(\eta_1 + \eta_2\right)\left(\frac{\Delta P}{P^o}\right)_{1C} \tag{3-12}$$

In the above equation, η represents the efficiency, the subscripts 1, 2, and 1C mean the subcompartment, upper dome, and SCE model respectively.

The efficiency of the DCH process in the subcompartment can be derived through an energy balance equation for the subcompartment. Since the hydrogen combustion is assumed to occur in the upper dome, the energy exchange in the subcompartment includes only the terms due to blowing down gas and melt, and metal oxidation. If the fraction of blow-down gases and melt entering the subcompartment is denoted as f_{a1}, the energy addition into the subcompartment is given by

$$\Delta U_1 = \frac{f_{a1}\left(\Delta E_b + \Delta E_t + \Delta E_r\right) - f_{a1} N_d C_d \left(T_1 - T_r\right)}{1 + \psi_1} \tag{3-13}$$

where $f_{a1}N_dC_d$ is the heat capacitance of the melt entering the subcompartment , and T_r is the reference temperature, typically the initial temperature in the containment. The term T_1 is an average temperature of the blowing-down gases coherent with the melt, and the gases pre-existing in the subcompartment. ψ_1 is the ratio of heat capacitance between the melt and the amount of gases available for heat transfer in the subcompartment. Note: the amount of the gases for heat transfer in the TCE model is assumed the maximum between the blowing-down gases coherent with the melt and the pre-existing gas mass in the subcompartment. Therefore, the term ψ_1 can be written as

$$\psi_1 = \frac{f_{a1} N_d C_d}{\max\left[f_{a1} f_{coh} N^0_{RCS}, f_{v1} N^0\right] C_v} \tag{3-14}$$

where f_{coh} is the so-called coherence ratio, f_{v1} is the volumetric fraction of the subcompartment (to the entire volume of the containment), N^0_{RCS} and N^0 are the total moles of gases originally in the

RCS and containment, and C_v is the specific heat (per mole) at the constant volume. If the subcompartment volume is large, the mass of gas pre-existing in the subcompartment will dominate the heat transfer. This is one of the major differences between the TCE model and the CLCH model. With these definitions, the efficiency in the subcompartment is thus formulated by dividing the ΔU_1 by the ΔU in the SCE model, that is

$$\eta_1 = f_{a1}\frac{1+\psi}{1+\psi_1}\left[1-\left(\frac{\Delta E_{H2}}{\sum \Delta E_i}\right)_{1C}\frac{T_1 - T_r}{T_d^0 - T_r}\right] \quad (3\text{-}15)$$

Similar derivation can be made for the efficiency in the upper dome, which is given by the following formulation

$$\eta_2 = \frac{1+\psi}{1+\psi_2}\left[f_{a2} - \left(f_{a2} - f_{burn}\right)\left(\frac{\Delta E_{H2}}{\sum \Delta E_i}\right)_{1C} - f_{a2}\left(\frac{\Delta E_{H2}}{\sum \Delta E_i}\right)_{1C}\frac{T_2 - T_r}{T_d^0 - T_r}\right] \quad (3\text{-}16)$$

One of the key variables in the efficiency formulations is the coherence ratio f_{coh}, which is defined as the fraction of the blow-down gases participating intense heat transfer and oxidation with the melt particles. The coherence ratio is a function of the time ratio R_τ of the entrainment time and the blowing down time. If the blow-down is assumed an adiabatic expansion process, the coherence ratio is given by

$$f_{coh} = 1 - \left(1 + \frac{\gamma - 1}{2} R_\tau\right)^{-2/(\gamma-1)} \quad (3\text{-}17)$$

where γ is the ratio of c_p/c_v of the blowing down gases. The time ratio must be determined through the momentum equation for the corium particles in the cavity. Here the flow regime in the cavity is assumed to be finely dispersed corium particles carried by the high speed gases. If the particle sizes are assumed to be independent with the gas flow speed, and drag on the particles by the gas flow is considered, the time ratio can be written as a function of the geometric and physical parameters of the RCS and the cavity:

$$R_\tau = \frac{\tau_e}{\tau_b} = C_{R_\tau}\, f_d \left(\frac{T_{RCS}^o}{T_d^o}\right)^{1/4}\left(C_{d,h}\,\frac{M_d^o}{M_g^o}\,\frac{A_h\, V_c^{1/3}}{V_{RCS}}\right)^{1/2} \quad (3\text{-}18)$$

where $C_{R\tau}$ is a modeling parameter matching the experimental data, and $C_{d,h}$ is the dragging coefficients of the gas flow, f_d is the dispersal fraction, which is normally very close to 1, T_{RCS}^0 and T_d^0 are the initial temperatures of the RCS and the particles, M_d^0 and M_g^0 are the initial masses of the melt and the gases in the RCS, A_h is the break area of the vessel, V_c and V_{RCS} are the total volumes of the cavity and the RCS.

The second key variable in the TCE model is the term of hydrogen combustion in the equation of

the efficiency η_2. Several hydrogen sources are considered: (1) hydrogen injected into the atmosphere at the time of vessel breach as part of the blow-down gases, (2) hydrogen produced from reactive metals (Zr, Ni, and Cr)-steam reactions with the coherent part of the blowdown gases, (3) hydrogen produced from iron-steam reaction, and (4) pre-existing hydrogen in containment. Similar to the CLCH model, hydrogen from the iron-steam reaction is subject to chemical equilibrium limitation. As the hot jet of steam and hydrogen mixture enters the upper dome, the combustion of the jet flame is considered, which is capable of burning as long as the jet temperature is above the auto-ignition temperature of the jet flame. The jet flame can entrain the pre-existing hydrogen into the burning zone of the flame, so that it contributes to the total hydrogen combustion heat. If the upper dome temperature is higher than the auto-ignition temperature for deflagration, a global combustion is also considered for the energy release.

The TCE model has been compared with experiments extensively. Figure 3-5 shows comparisons of the coherence ratio and hydrogen generation in Zion-like containments between the model prediction and the measured data. Figure 3-6 shows the comparison of the measured and predicted containment pressure increase. TCE model predictions are reasonable compared with the experiments in general.

3.2.4 Probabilistic Framework

Besides phenomenological modeling factors in TCE model, the DCH loads depend on parameters that characterize the system initial conditions; that is, primary system pressure, temperature and composition (i.e., hydrogen mole fraction), melt quantity and composition (zirconium and stainless steel mass fraction), initial containment pressure and composition (hydrogen mole fraction), and geometry (containment volume and the size of the breach). The key component of the framework, therefore, is the casual relation between these parameters and the resulting containment pressure (and temperature) under the influence of the uncertainty in the coherence ratio. Of these parameters, some are fixed, some vary only over a narrow range, and some are so uncertain that they can be approached only in a bounding sense. The following features were considered in coming up with the final choice of a framework in:

(a) Geometry: The specific geometry is fixed for a given plant; however, the basic features are that that is an intermediate compartment between the cavity and the main containment volume and that the lower head fails in a local (rather than global) manner. In addition, the geometry is characterized by the free volume of the containment and the primary system volume.

(b) Containment Conditions: Typically, high-pressure scenarios evolve with significant primary system venting prior to vessel breach; this venting increases the containment pressure to ~ 0.25 MPa with temperatures near saturation. This pressure will be lower if any of the active containment heat removal systems are operational. The containment atmosphere will also contain hydrogen at a concentration of a few mole percent. Pre-existing hydrogen is limited by the quantity of zirconium available to react in the core, and thus there is a constrained relationship between pre-existing hydrogen in the containment and the hydrogen produced by steam/zirconium reactions in the DCH event.

(c) Primary System Conditions: Reasonable consistency between reactor coolant system (RCS) pressure (and temperature) and melt mass and composition is emphasized here.

TCE model predictions indicate that DCH loadings are insensitive to the temperature of the primary system. Pressure can be enveloped rather than predicted. This leaves only the expelled melt parameters in need of quantifications: melt quantity, composition and temperature. These are the variables that drive the DCH process; however, they are highly uncertain. They depend on the complex interactions and the many scenario bifurcations in the core meltdown, relocation, and lower head failure processes, and are hence in need of very careful quantification.

The probabilistic framework can be structured in the manner. The initial melt parameters are to be quantified as independent probability density functions, representing modeling uncertainty in the parameters (variations from stochastic processes are assessed as insignificant relative to modeling uncertainty). These functions are formed into a joint probability density/function for the peak containment pressure. This distribution function is combined with the set of containment fragility curves (probabilistically distributed themselves) to obtain a probability distribution of the containment failure frequency.