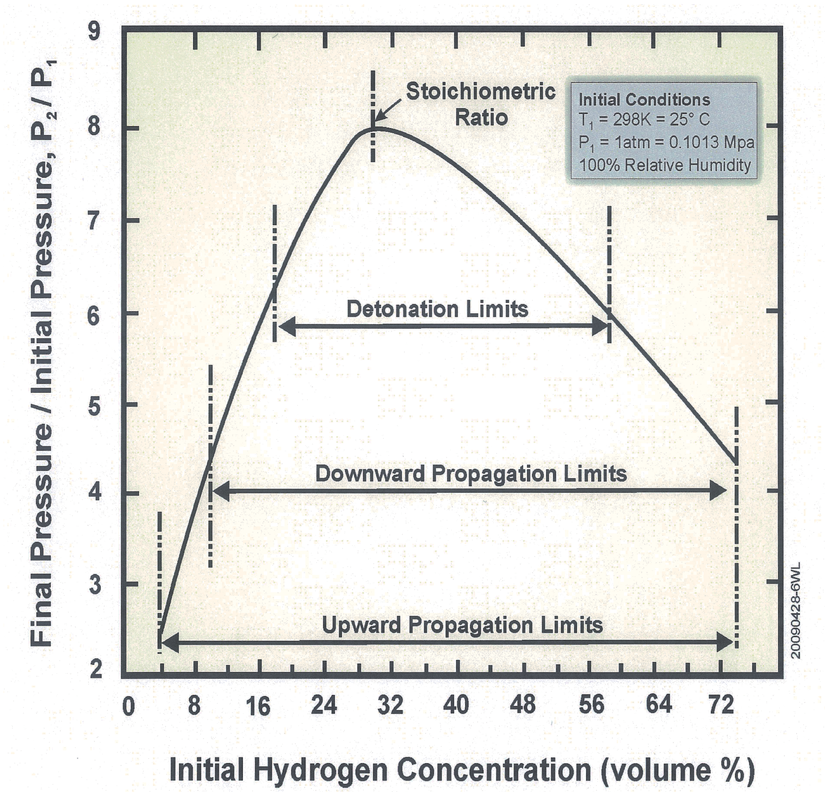

Figure 2-6 Theoretical adiabatic, constant volume combustion pressure ratios of hydrogen-air mixtures [Reference 52]

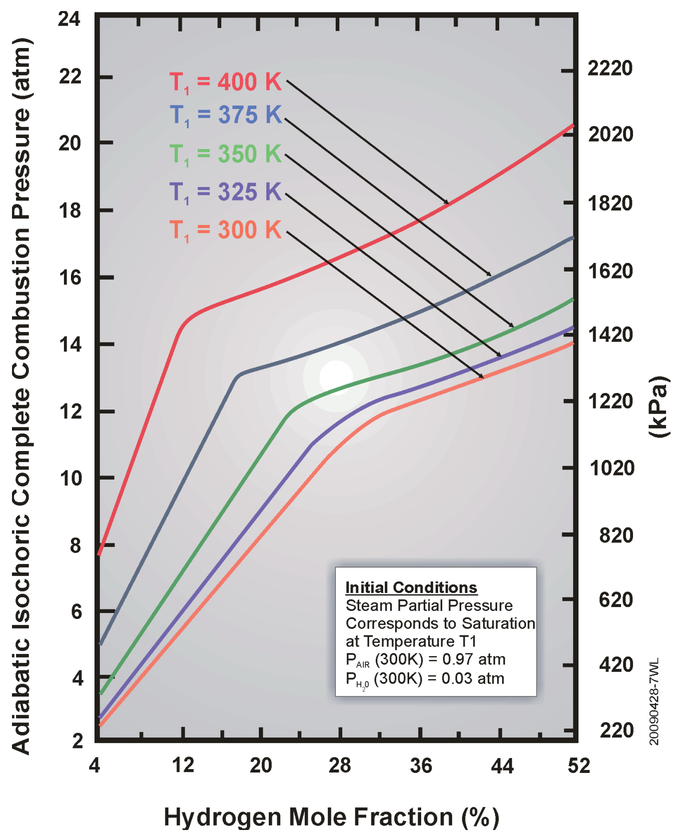

Figure 2-7 AICC pressures for various containment initial conditions [Reference 50]

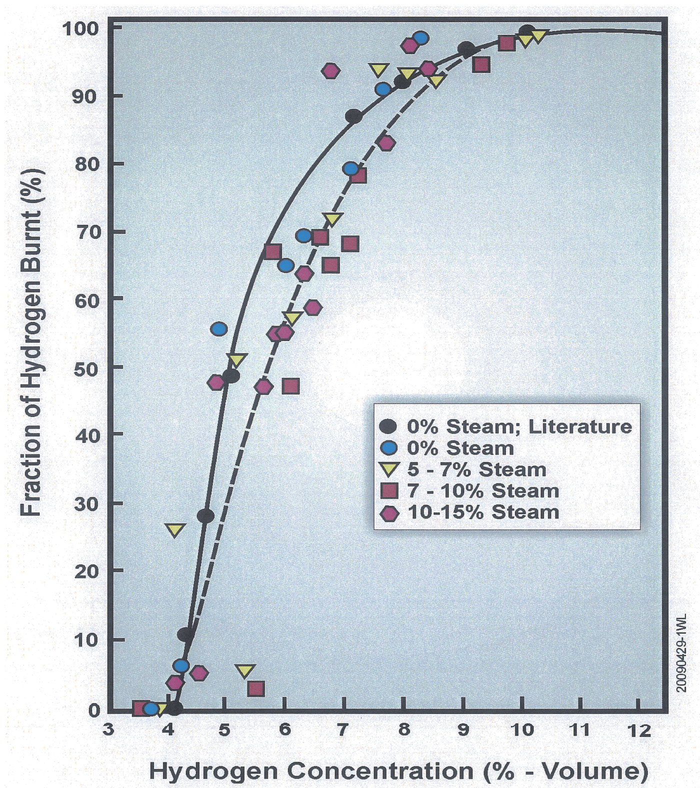

Figure 2-8 Degrees of Combustion in Hydrogen Air Steam Mixtures [Reference 29]

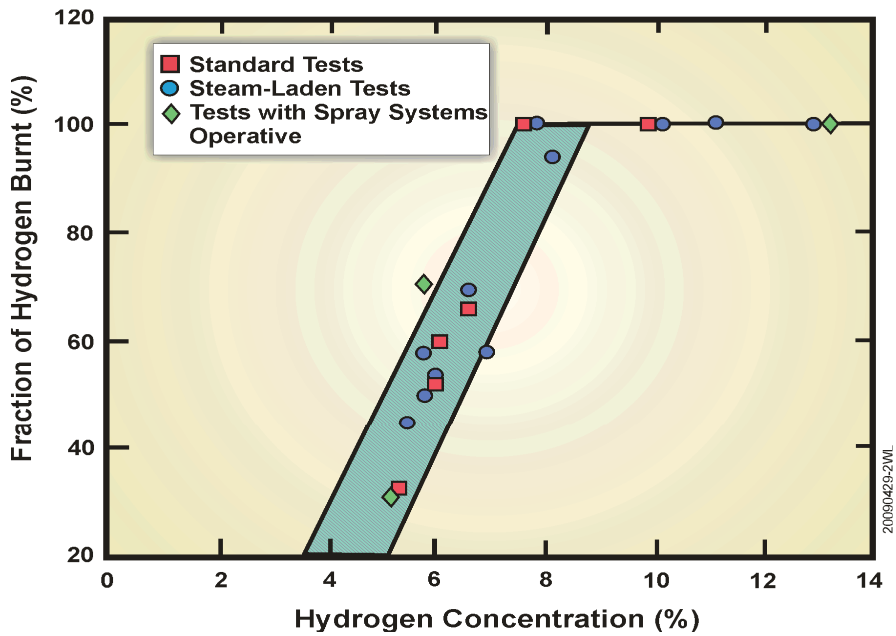

Figure 2-9 Hydrogen concentration during incomplete burning [Reference 44]

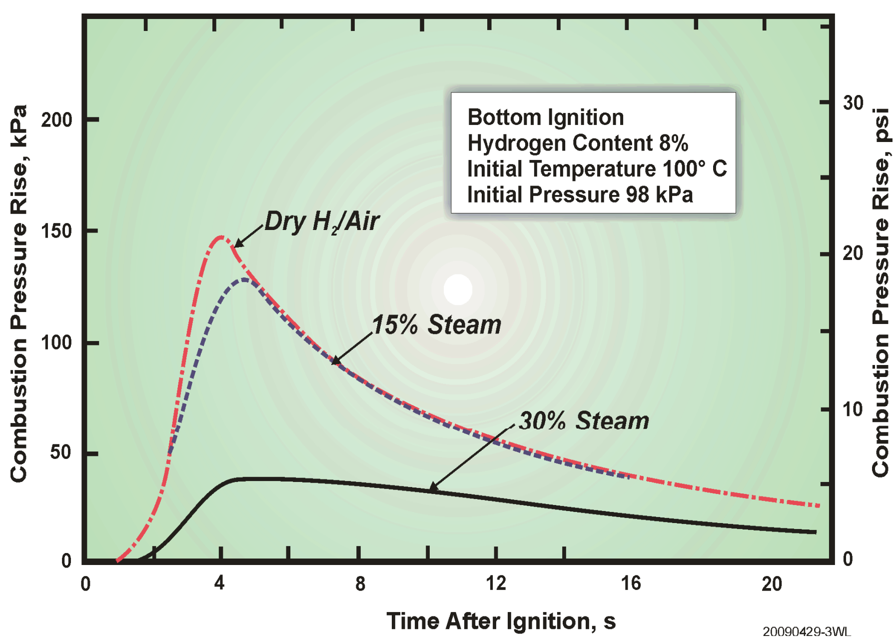

Figure 2-10 Combustion Completeness for Nevada Test Site Premixed Combustion Tests [Reference 44]

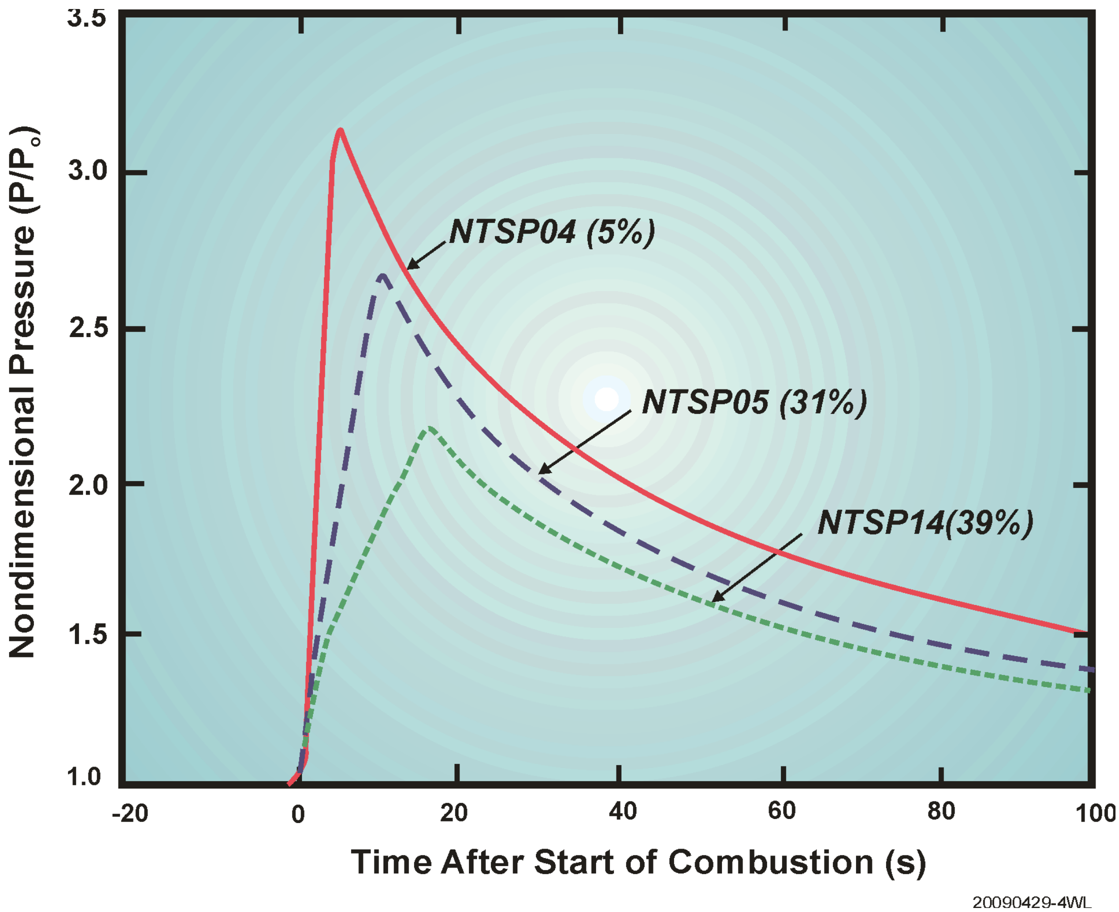

Figure 2-11 Comparative pressure profiles for three 8% (nominal) hydrogen combustion tests having different pre combustion steam concentrations. [Reference 44]

2.5 Flame Acceleration (FA) and Detonation

2.5.1 Deflagrations

Slow deflagrations results in a flame that travels with a speed of approximately 100 m/s or less. This is much slower than the speed of sound. The pressure will be in equilibrium with the containment during the combustion. No dynamic loads are generated. Accelerated deflagrations or accelerated flames travel between ~100 and ~1000 m/s which can be fast enough to generate shock waves and significant dynamic loads [Reference 23]. Flame acceleration is likely to occur in a highly confined region rather than in a partially confined region, and is strongly influenced by the scale of the region and the size, shape, and spacing of obstacles within the region. The obstacles induce turbulence in the flow generated by the expansion of the burned gases. The turbulence widens the flame front area. This improves the transport properties. The result is an increased combustion rate. The positive feedback from the enhanced combustion rate makes the flame accelerate even more [Reference 25, 9].

For multi-compartments interconnected by junctions of relatively small flow area, an ignition in a single compartment could cause accelerated flames in the neighboring compartment due to hot gas expansion and turbulence at the junction [Reference 20]. The prediction of flame acceleration in simple geometries can be achieved by a combustion code that solves the Navier-Stokes equations and incorporates reasonable turbulence-combustion interaction models [Reference 20]. This method requires enormous computing resources even for a system of small scale and simple geometry. An application of a computational fluid dynamics (CFD) based combustion code to real plants with highly complex geometries is impractical at the present time. An attempt to address the issue of accelerated flames in multi-compartments with simple geometry within the framework of a lumped parameter code using MAAP4 was presented by Luangdilok et al. [Reference 30]. However, more development work is needed to extend this approach to a much more complicated geometry of a nuclear plant.

2.5.2 Detonations

Detonation of a hydrogen/oxygen mixture can occur if enough energy is introduced to the system to create initial shock waves. According to Figure 2-3 at least 100 GJ/s is required to detonate an ideal mixture. No such source is present in the reactor containment so this form of detonation can be ruled out from this study report. The only type of detonation that can occur is therefore one that is generated from a deflagration-to-detonation transition.

The hydrogen/oxygen mixture condition can cause detonation. The flame can then accelerate above the speed of sound. The energy released from the combustion sustains a shock wave that further ignites and combusts the hydrogen/air mixture. This leads to a detonation. The phenomenon is usually called deflagration-to-detonation transition (DDT). The energy needed to ignite this form of detonation is equivalent to the energy needed to ignite a slow deflagration. Detonations travel between 1400 and 2200 m/s and may also generate significant dynamic loads [Reference 66]. Figure 2-12 shows the relation between detonation speeds and dynamic pressures for dry air as a function of hydrogen concentrations at 1 atm, 298 K. The degree of occurrence of

DDT depends on a number of parameters. The detonation limits cannot currently be predicted by any principles theory.

Engineering correlations that are used to predict the limits have been developed based on a measurable quantity called the detonation cell width. The detonation cell width represents a characteristic length of a detonation wave that describes the sensitivity of the mixture to detonation. The smaller the detonation cell width is, the easier it is to get the mixture to detonate. The detonation cell width is a very important property for predicting the detonation behavior of the detonable mixture. It is further discussed in Section 2.6.

2.5.3 Deflagration to Detonation Transition (DDT)

Three methods for DDT evaluation have been proposed. The method of Sherman and Berman (1986) which gives the probability of DDT, requires too much qualitative engineering judgment that could be very subjective. The DDT criterion proposed by Peraldi et al. (1986) requires as a prerequisite that for a flame to accelerate to DDT the flame must reach the sonic speed. However, determining whether the flame is sonic or not is not an easy task. The latest method proposed by an expert group is commissioned by OECD/NEA. The group issued the so-called “State-of-the-Art Report on Flame Acceleration and Deflagration-to-Detonation Transition in Nuclear Safety” that set the standard for DDT evaluation at present time [Reference 6].

2.6 Detonation Cell Width

The detonation cell width (λ) is a very important property for predicting the detonation behavior of a mixture [Reference 65, 36, 2]. The smaller the detonation cell size is, the more sensitive a mixture is to detonation. Measured cell widths for mixtures of hydrogen in dry air at 25°C are shown in Figure 2-13. The curve always has a U-shape with a minimum value of λ near stoichiometry (29.7% hydrogen). The cell widths may vary from about 1 cm for 30% H_2 in air to several meters for very lean or rich mixtures. A general way of correlating the detonation cell widths to mixture composition is in terms of equivalence ratio, denoted by ϕ. The equivalence ratio is the ratio of the number of moles of hydrogen divided by the number of moles of air to that quotient at stoichiometry. The equivalence ratio ϕ, the hydrogen mole fraction X_{H_2}, and the steam mole fraction (or other diluent) X_s are related by

$$\phi = SX_{H_2} / (1 - X_{H_2} - X_s) \quad (2\text{-}1)$$

or

$$X_{H_2} = \phi(1 - X_S)/(\phi + S) \quad (2\text{-}2)$$

where S = 2.387. As an example, equivalence ratio for 13% hydrogen in dry air is 0.357. This value is unchanged by addition of steam to the dry mixture because the overall H_2 and O_2 mole fractions decrease in the same proportion.

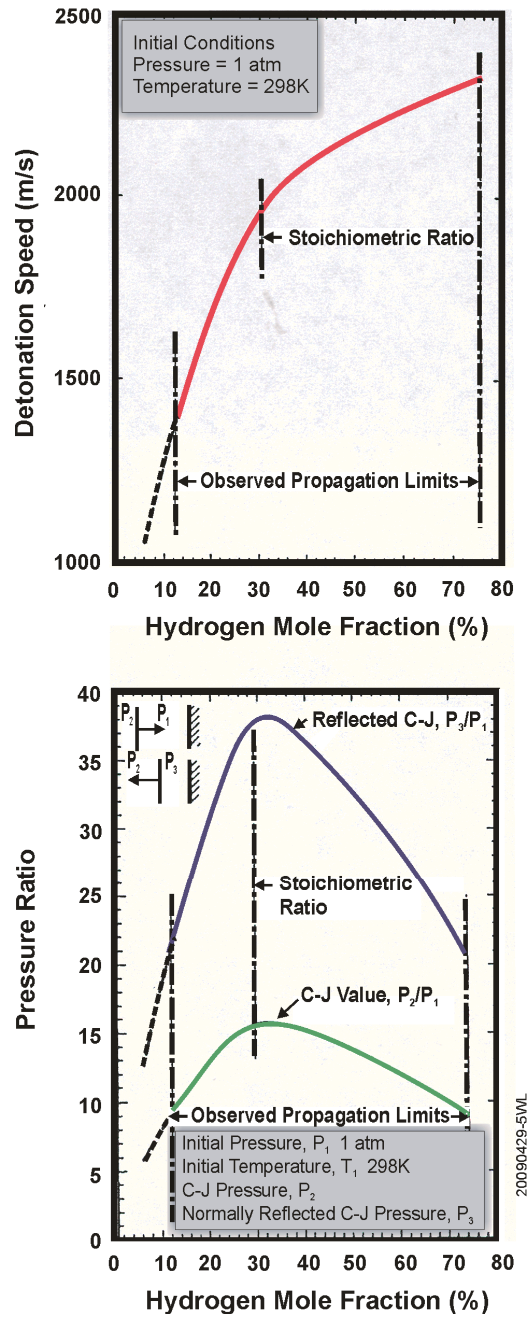

Figure 2-12 Detonation pressure ratios (below) and speed (above) for hydrogen-air mixtures [Reference 66]

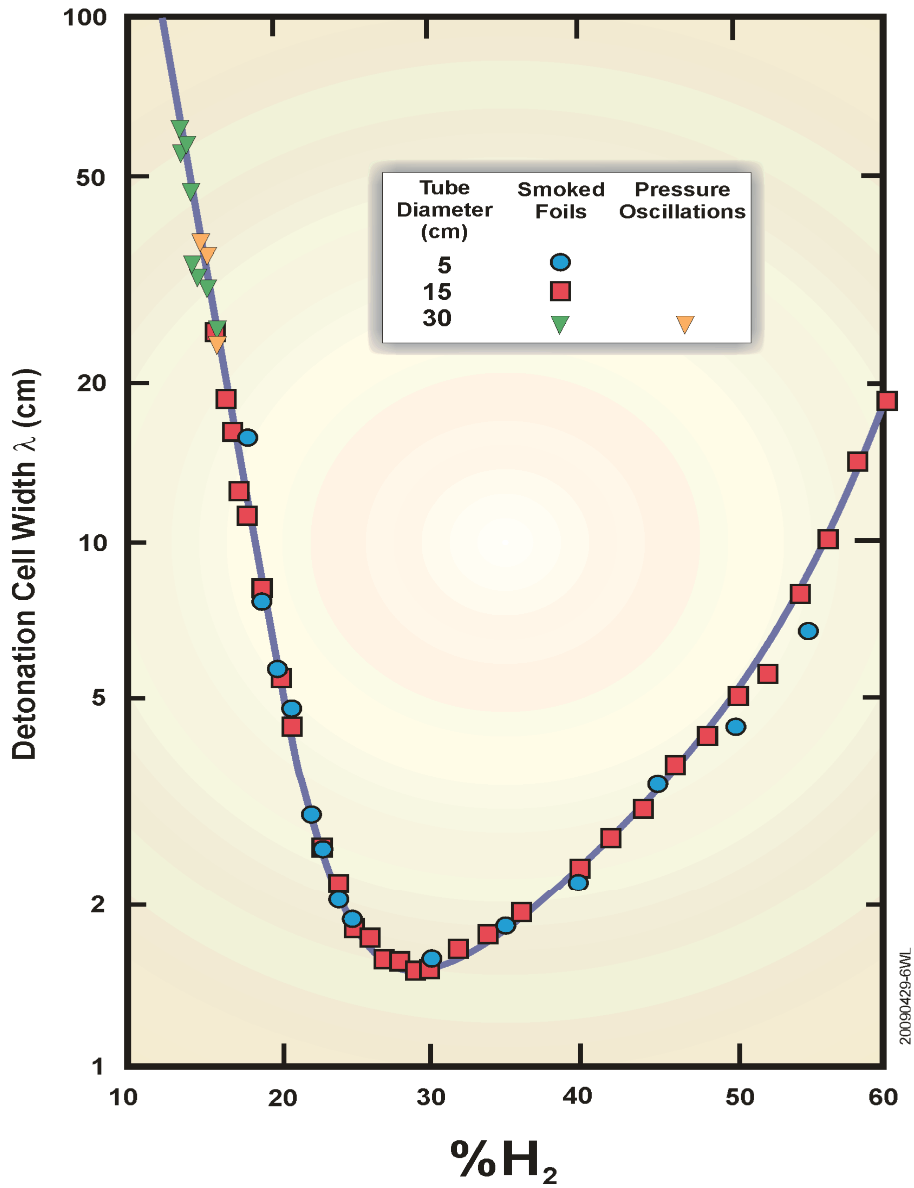

Figure 2-13 Measured values (McGrill, Sandia) of the detonation cell width (λ) as a function of hydrogen concentration [Reference 65]

The detonation cell width increases dramatically with the addition of steam as shown in Figure 2-14 for mixtures at 100°C. Figure 2-14 shows predictions given by a model developed by Shephard (1985). The addition of carbon dioxide to mixtures at 20°C and 1 atm and at 100°C and 1 atm increase the detonation cell width as much, or more than, the addition of steam [Reference 57]. Thus, steam or carbon dioxide as a diluent makes detonation more difficult to achieve. As temperature increases, detonation becomes easier as seen by the decrease in cell width in Figure 2-15. Comparing the two figures, one can clearly see that in this temperature range the steam inerting effect is far more pronounced than the heating effect on detonation cell size.

2.7 Correlations for Deflagration to Detonation Transition

Detonations are most likely to be initiated by a deflagration-to-detonation transition (DDT) in reactor accident scenarios. A mixture may be ignited by an ignition source, then accelerate to choked flow conditions where DDT is possible. The lowest hydrogen concentration for which DDT was observed was 15% (Sherman et al., 1989) at the FLAME facility at Sandia, which is a half-scale model of an ice condenser upper plenum, 2.44 m high, 1.83 m wide, and 30.5 m long. This long rectangular channel can be partially vented on top, and to promote turbulence, obstacles can be placed along the interior. The 15% low limit corresponds to a case with no venting and periodic obstacles every 1.83 m. In a case with no obstacles, 25% hydrogen was required, as shown by Figure 2-16, and for a case with obstacles and 50% venting, 20% hydrogen was required. However, according to the most recent state-of–the-art report, DDT is possible for mixtures at elevated temperatures even at hydrogen slightly higher than 10% [Reference 6].

The scale of the combustible mixtures and enclosure has been observed to be important for DDT. Larger scale appears to promote flame acceleration (a necessary condition for DDT) over a wider range of mixtures. Most experimental data were obtained in small scales which are not directly applicable to reactor scales. Since larger scales promote flame acceleration, most data can be regarded as non-conservative. Efforts to resolve this problem have been made to correlate the occurrence of DDT to the detonation cell width and the smallest dimension of the flow channel. This does not account for the presence of obstacles (such as blockage ratio and spacing) in the flow field. Hence, this type of correlation is not universal, but it is the only guideline available. Peraldi et al. (Reference. 42), based on experiments in circular tubes of up to 30 cm in diameter filled with orifice ring obstacles, proposed that a necessary condition for DDT is that the minimum transverse tube dimension (d) must be sufficiently large to accommodate at least one transverse detonation cell width (λ) characteristic of the mixture of the tube. Quantitatively this can be written as

$$d/\lambda \geq a \qquad (2\text{-}3)$$

where a=1. Some other researchers suggested a more conservative value of $a = \pi$ (Lindstedt and Michels, 1989) for tubes. It is more conservative than that of a=1 because it says that DDT can occur at larger detonation cell width (i.e., less chemically sensitive mixture) for the same tube of diameter d. The important conclusion to draw from this is that a deflagration-to-detonation transition can take place in large scale containments even if the ideal chemical composition of the mixture for detonation does not exist.

Extensive research at Sandia leads to a summary of conditions for detonation propagation of various geometries as shown in Figure 2-17. It is noted that these geometries are still too simplistic for reactor applications.

More recent research as summarized (by Dorofeev) in Breitung et al [Reference 6] suggests a characteristic size L to represent a more complicated geometry such as tubes with obstacles and a system of connected rooms. The necessary condition for DDT is that $L > 7\lambda$. The characteristic size L for channels with obstacles and its changes with blockage ratio is illustrated in Figure 2-18. This is the most current criterion that is based on extensive experimental data and is acceptable for reactor applications. Further discussion on this is provided in section 2.8.

A review of more recent work in the methodology of DDT assessment compiled by an OCED-commissioned expert group [Reference 6] indicates that improvement in the characterizations of the nature of DDT has been achieved to the extent that quantitative prediction is possible, but still subject to large uncertainties. One of the combustion characterizations that were not mentioned in earlier work was the expansion ratio (unburned-to-burned mixture density ratio). It must be greater than the critical expansion ratio for flame acceleration (which is a prerequisite to DDT) to occur. This expansion ratio is a parameter representing the reactivity of the mixture, while the critical expansion ratio can be regarded as a boundary between slow flames and fast flames as shown in Figure 2-19 [Reference 6].