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MECHANISMS OF VAPOR EXPLOSIONS

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DISCLAIMER

1. Introduction

Currently two principal concepts dominate the fuel-coolant interaction field. One is the Fauske[1] theory of spontaneous nucleation and the other is the Board-Hall[2] theory of thermal detonation waves. Considerable differences of opinion exist with respect to both of these theories, and it is important to determine to what extent these ideas are valid, and, if so, whether they can be reconciled.

The Fauske hypotheses can be summarized as follows: For a large-scale vapor explosion to occur, it is necessary that:

1. The two liquids initially be in the film boiling mode, in order to allow coarse pre-mixing on a global scale.
2. Liquid-liquid contact must be established (triggering event).
3. Spontaneous nucleation must occur upon contact. (This requirement is obviously not necessary if the critical temperature of the cold liquid is exceeded when liquid-liquid contact occurs.)
4. Inertial and/or structural constraints must be sufficient to allow the development of high pressures.

The first two and fourth requirements are now generally accepted, but there has been some controversy over the third requirement. Catton, et al.[3] have observed nucleate boiling on the surface of a tin drop (more properly, on a projection from the drop) in water prior to violent dispersal of the drop. Reynolds, et al.[4] find the lower bound of the tin temperature "window" explosive interaction to correspond to a surface temperature of 250-275°C, which is below the theoretical homogeneous nucleation temperature (~ 300°C) of water. The latter observation is quite consistent with the Fauske theory, since spontaneous nucleation from a tin-water surface would be expected to be in this temperature range. The highest observed superheat for water, attained

under carefully controlled conditions in the absence of a solid surface, is about 280°C. The calculated surface temperature in the Catton experiments was also in the spontaneous nucleation range, although the observation of nucleate boiling prior to violent dispersal raises interesting questions, which will be discussed later.

In fact, the third Fauske requirement can be replaced by the necessity for rapid local pressurization to occur ($\sim 10^{-3}$ - 10^{-4} sec. time constant) in order to sustain a pressure shock. Spontaneous nucleation is a sufficient, but not necessary, condition for rapid pressurization (which is a necessary condition).

There thus appears to be very strong experimental evidence that the Fauske hypotheses are valid.* This is the important question for UO_2-Na interactions, which do not satisfy the first requirement (initial film boiling).**

On the other hand, the later theory by Henry and Fauske[5], which also presupposes spontaneous nucleation, deals with the detailed sequence of events leading to liquid-liquid contact in the so-called "free contacting mode". This is much more speculative, since the time scales are of the order of 10^{-4} - 10^{-5} sec., and direct experimental confirmation is lacking. Alternative theories for the initiation and propagation steps have been given by Ochiai and Bankoff[6], (Buchanan[7], Board et al.[8], Caldarola et al.[9] and Colgate[10]). None of these can be considered to be firmly based at the present time. There is some confusion of the earlier Fauske hypotheses, and the later Henry-Fauske theory for propagation of a vapor explosion. The two

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*A complete review of the experimental evidence and current theories of vapor explosions is given in Chap. 5, "Liquid-Metal Two-Phase Flow and Heat Transfer", by S.G. Bankoff and H.K. Fauske, to be published by Pegamon Press.

**It is conceivable that coarse initial mixing of fuel into sodium might occur in a prompt burst situation on a time scale short enough to prevent rapid boiling. However it is difficult, even in this situation, to visualize a pressure shock wave, in view of the very rapid establishment of liquid-liquid contact during fuel injection.

theories are actually quite distinct, although, of course, they are compatible.

The Board-Hall theory, on the other hand, approaches the problem of vapor explosions from a quite different point of view. No attempt is made to consider the initiation processes. Instead, a fully-developed steady-state detonation wave is hypothesized, and jump balances across the shock are invoked, together with the well-known Chapman-Jouguet condition for a self-supported shock in a homogeneous medium. The support mechamism derives from Taylor instability of the fuel droplets due to the large relative velocities behind the shock. This instability, which is predicted theoretically to be important at Bond numbers $> 10^5$ ($Bo = \frac{\rho_f g r_o^2}{\sigma}$, where ρ_f is the density of the surrounding fluid (Na), r_o is the initial drop radius, and g is the drop acceleration, calculated from a force balance using a drag coefficient, $C_D \sim 2$). Very fast drop breakup times ($\sim 10^{-4}$ s) and very high peak pressures ($\sim 10^4$ bar) are calculated for approximately equal volumes of sodium and UO_2. Although these predictions have since been seriously questioned, the viewpoint of a propagating detonation wave has been useful.

2. Results

2.1 Experimental

Small drops of a volatile liquid (pentane) were allowed to fall onto the surface of a hot, non-volatile liquid (silicone oil or glycerol). The release height, drop diameter and hot liquid temperature were significant variables. The objective was to determine the threshold condition for explosive boiling (spattering), and for vapor-film destabilization (wetting). The results confirmed the existence of a homogeneous nucleation threshold for explosive boiling, with a delay time when the initial contact temperature was less than T_{hn}. The critical Weber number for breakdown of Leidenfrost boiling was correlated in terms of a dimensionless hot liquid temperature, and a dimensionless drop diameter.

2.2 Theoretical

2.2.1 "Splash" Theory of Initiation and Early Propagation[6,11]

Using the above experimental correlations a "splash" theory was constructed for the initiation of a vapor explosion, when the initial contact temperature, $T_{io} \geq T_{hn}$. This depends upon the concept that in film boiling, momentary contacts are made between the hot and cold liquids, resulting in rapid local pressurization. The resulting splash is calculated from potential flow theory, and forms a new region of interfacial contact, depending upon the effective Weber number of the splash. If the new contact is made over a larger area than the original contact, the mixing process is escalated; otherwise, it dies down. The original contact area was assumed to be a random variable, following a log-mean probability density distribution. The exact shapes of the resulting curves of maximum detected pressure vs. hot liquid temperature depend upon the mean and variance, but were in reasonable agreement with oil-Freon free-contacting data due to Henry, et al.

2.2.2 Recalculation of Board-Hall Theory

It was shown that the Board-Hall estimates of the peak shock pressures were

low by an order-of-magnitude in order to sustain a steady-state Chapman-Jouguet wave. The principal reason was the B-H theory assumes a single fuel drop in a very large volume of coolant in estimating the time for velocity equilibration behind the shock, although a dense dispersion is necessary for an efficient explosion. When the finite coolant-fuel mass ratio is taken into account, pressures of $\sim 10^5$ bar are estimated for a coarse UO_2-Na mixture, instead of $\sim 10^4$ bar. It does not seem possible to attain such pressures. Another reason was the failure to take into account the unequal phase velocities in the B-H estimate of the P-V diagram, which leads to qualitatively different results than with single-phase detonations.

2.2.3 Breakup of UO_2 Drops in Sodium

UO_2-Na represents a unique fuel-coolant combination, because of its thermal conductivity ratio. This results in liquid-liquid contact and violent boiling as soon as the two liquids are mixed. It was shown that a UO_2 drop entering a sodium pool is quickly broken up, due to bubble growth and collapse on the surface. The impact of the resulting microjets exceeds the yield strength of the fuel crust by two orders of magnitude, resulting in penetration of the coolant into the fuel and rapid dispersal.

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