Vapor Explosions

A vapor explosion is defined as the explosive growth of a vapor bubble(s) within a liquid due to the presence of a large, nearby heat source. As described in section (Ng), explosive growth only occurs under a set of particular conditions when the growth is not limited by thermal or heat transfer effects but only by the inertia of the surrounding liquid that is accelerated outward during the bubble(s) growth. The possibility and danger of a vapor explosion is pertinent in a number of different technological circumstances. Cavitation at normal pressures is an example of a vapor explosion caused by depressurization of a liquid (Brennen 1995). Vapor explosions also occur when one, highly volatile liquid mixes with another at a higher initial temperature. An important context in which vapor explosions of this kind have been studied is in analyses of hypothetical nuclear reactor accidents in which molten nuclear reactor fuel (usually uranium dioxide) escapes into the surrounding reactor coolant (usually water or liquid metal). The danger is the possibility that the resulting vapor explosion could result in a breach of the reactor containment system. Another context in which vapor explosions have been studied occurs when liquid natural gas (or methane) is spilled into water at normal temperatures (Burgess *et al.* 1972) (this is a particular issue in LNG transportation accidents). Yet another important example is in phreatic volcanic eruptions in which molten lava penetrates a trapped water volume (see below).

In other circumstances the thermal boundary layer at the interface of the bubble(s) inhibits the supply to the interface of the necessary latent heat of vaporization. This is what happens when water is boiled on the stove at normal pressures and this effect radically slows the rate of vaporization and the rate of bubble growth as described in section (Ngg), in effect eliminating the explosion. Such thermally-inhibited growth is manifest in many technological contexts, for example in the growth of bubbles in the liquid hydrogen pumps of liquid propelled rocket engines (Brennen 1994). Thermally-inhibited growth tends to occur when the liquid/vapor is at higher saturation pressures and temperatures, whereas non-thermally-inhibited growth tends to occur closer to the triple point of the liquid/vapor.

Other factors that can effect whether explosive growth or thermally-inhibited growth occurs are the conditions at the interface. If the thermal boundary layer is disrupted by instability or by substantial turbulence in the flow then the rate of vaporization will substantially increase and explosive growth will occur or be re-established. Indeed in a cloud of bubbles the growth itself can cause sufficient disruption to eliminate the thermal inhibition. The vapor explosion would then be self-perpetuating. However, at the kinds of normal operating temperatures for the water coolant in a LWR (Light Water Reactor) or the sodium coolant in an LMFBR (Liquid Metal Fast Breeder Reactor), all bubble growth (in the absence of other effects as described in the following section) would be strongly thermally inhibited and highly unlikely to cause a self-perpetuating vapor explosion. To the authors knowledge no such event has been identified in any nuclear reactor for power generation (see Fauske and Koyama 2002).

A fuel coolant interaction (FCI) event is a modified vapor explosion in which a second material (a hot liquid or solid) is brought into close proximity to the vaporizing liquid interface and provides the supply of latent heat of vaporization that generates vapor bubble growth. It belongs to a class of vaporization phenomena caused by the mixing of a very hot liquid or solid with a volatile liquid that then experiences vaporization as a result of the heat transfer from the injected material. Of course, the result may be either relatively benign thermally inhibited vapor bubble growth or it may be explosive, non-thermally-inhibited growth. Both have been observed in a wide range of different technological and natural contexts, the latter often being described as an energetic fuel/coolant explosion. Examples of such energetic explosions have been observed as a result of the injection of molten lava into water (Colgate and Sigurgeirsson 1973) or of molten metal into water (Long 1957). The key to energetic fuel/coolant explosions is the very rapid transfer of heat that requires substantial surface area of the injected liquid (or solid): fragmentation of the hot liquid (or solid) can provide this necessary surface area. The studies by Witte *et al.* (1973) and their review of prior research showed that such energetic explosions always appear to be associated with fragmentation of the injected hot material. Research suggests that an energetic fuel/coolant interaction consists of three phases: (1) an initial mixing phase in which the fuel and coolant are separated by a vapor film (2) breakdown of the vapor film leading to greater heat transfer and vaporization rates and (3) an explosive or energetic phase in which the fluid motions promote even greater heat transfer and vaporization. In this last phase the explosive behavior appears to propagate through the fuel/coolant mixture like a shock wave. Examples of reviews of the wide range of experiments on fuel/coolant interactions can be found in Witte *et al.* (1970) and Board and Caldarola (1977) among others. However, none of the experiments and analyses on sodium and uranium dioxide showed any significant energetic interaction and most of the experts agree that energetic fuel/coolant interactions will not occur in liquid sodium LMFBRs (Fauske 1977, Board and Caldarola 1977, Dickerman *et al.* 1976).

Among the most dramatic examples of a vapor explosions are *phreatic* volcanic eruptions such as the 2014 eruption of Mount Ontake, Japan or the 2019 eruption of White Island, New Zealand. These are sudden but short-lived, explosive eruptions that are particularly dangerous due to their unpredictability and their violence; both the events listed above led to significant loss of life. It is believed that they are caused by the sudden injection of molten subterranean lava into trapped pockets of water. The explosion is violent enough to shatter solid rock, excavate craters and eject rock fragments and ash out to hundreds of meters from the vent. Eruptions in New Zealand are known to have blasted material out to over three kilometers from the vent. Maeda *et al.* (2017) published seismic evidence of a crack at a depth of $1100m$ that immediately preceeded the Mount Ontake eruption.