Phase Explosion

When a liquid is heated slowly, this heating process is shown in Figure 1 [Xu 2002] as bimodal through heterogeneous boiling with vapour bubbles formed below the surface at nucleation sites. The binode line represents equilibrium between the surface temperature T and the vapour saturation pressure Ps which is calculated from the Clausius–Clapeyron equation.
A nucleation site may consist of a dust in the liquid in which gas or vapour is trapped, or a foreign gas bubble existing in the liquid.
However, if the heat rate is fast enough, the liquid may become superheated; the liquid temperature can exceed the boiling temperature. If the temperature continues to increase, the spinode line (see Fig.1) is reached and the liquid becomes unstable and catastrophically relaxes to a liquid-vapour mixture.

Atomization due to pressurised release of superheated liquid, is termed flash boiling atomization. This is a type of atomization that can occur when a vessel containing a pressurized liquid is ruptured. Such event can be extremely hazardous because a superheated liquid is in a metastable state. As early as the 16th-Century boiler explosions occurred principally in shipping. In the United States at around 1910 there was an average of 2-boiler explosions each day.

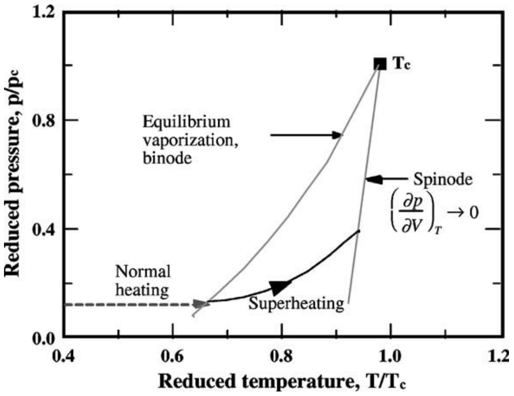

Figure 1 : Normal heating & superheating

Once in the metastable region a liquid not need to reach the spinode line to change in a liquid-vapour mixture [Christensen 2003]. A process which will prevent a liquid from reaching the spinode line is called homogeneous nucleation. It consists of the spontaneous creation of vapour nuclei within the liquid, without the aid of pre-existing nucleation sites. Spontaneous nucleation prevents significant superheating during slow heating processes. The rate of spontaneous nucleation is given by [1]:

$$J = N\left(\frac{3\sigma}{\pi m}\right)^{1/2} \exp\left(\frac{-W_{\mathrm{cr}}}{k_{\mathrm{B}}T}\right) \qquad [1]$$

In order to reduce free energy, smaller embryos than the critical size will collapse, while those larger will grow and are considered as nuclei.

Using relation [1] it can be shown that the rate of nucleation is small for temperatures less than 0.9*Tc*. It has been reported [Xu 2002] that the frequency of spontaneous nucleation is approximately 0.1 s-1 cm-3 for temperatures near 0.89*Tc*. *But when the temperature exceeds 0.9Tc, Phase Explosion (PhE) occurs as demonstrated with laser and electric discharges.*

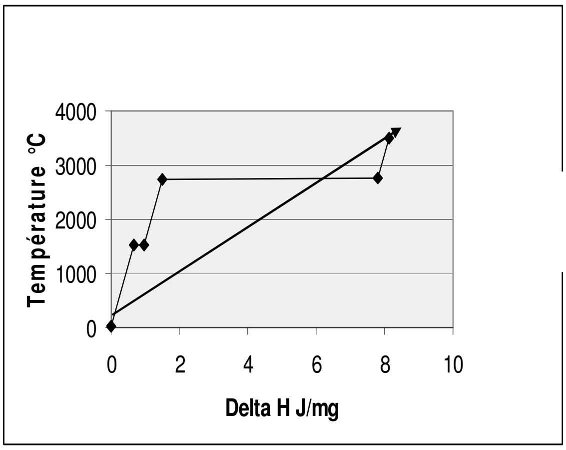

Figure 2 : Iron Enthalpic Diagram

PhE in Laser / metals interactions:

In recent years laser ablation due to rapid pulsed heating has been the subject of a considerable amount of research.
Researchers in this field are generally interested in the mechanisms of ablation, the production and transport of vapour, liquid droplet formation and ejection, and material properties near the thermodynamic critical point.

The nanosecond lasers can deploy a great power to the metal surface. As a result, as shown by the arrow for instance, on the iron enthalpic Figure 2, the surface temperature raises sharply leading to a direct sublimation of surface layer, with explosive emanation of steam and fine droplets. The liquefaction step is skipped.

There are a large number of experimental evidence (Martynyuk 1974; Davies 1993; Miotello 1995; Mele 1997; Kelly 1996; Yoo 2000; Bulgakova 2001; Lu 2002) of PhE in nano second laser ablations which lead to a sudden increase in the rate of removal and ejection of great quantities of droplets.

When a laser pulse of high intensity hit the surface, the temperature rises rapidly to be close to the critical temperature (T = 0.8-0.9 Tc). Homogeneous nucleation occurs near this temperature. Once the bubbles have reached a critical radius rc, they explode in a steam and droplets mixture. The critical radius is calculated [Yoo 2000] as:

$$r_c = 2\sigma / (P_{sat}(T_l) \exp\{v_l[P_l - P_{sat}(T_l)] / RT_l\} - P_l) \qquad [2]$$

According to Eq. [1] the spontaneous nucleation rate increases exponentially with temperature. During pulsed laser heating, the amount of nuclei generated by spontaneous nucleation is negligible at temperatures lower than 0.9Tc. **At a temperature of about 0.9Tc, a significant number of nuclei can be formed. Still using equation 1, the spontaneous nucleation frequency increases dramatically to 10^{21} s-1 cm-3 for temperatures near *0.91Tc*. Hence, explosive phase change occurs, which turns the liquid into a mixture of liquid and vapour. *This is the Phase Explosion*.**

PhE violence is also illustrated by the Figure 3, extracted from Pakhomov 2003.

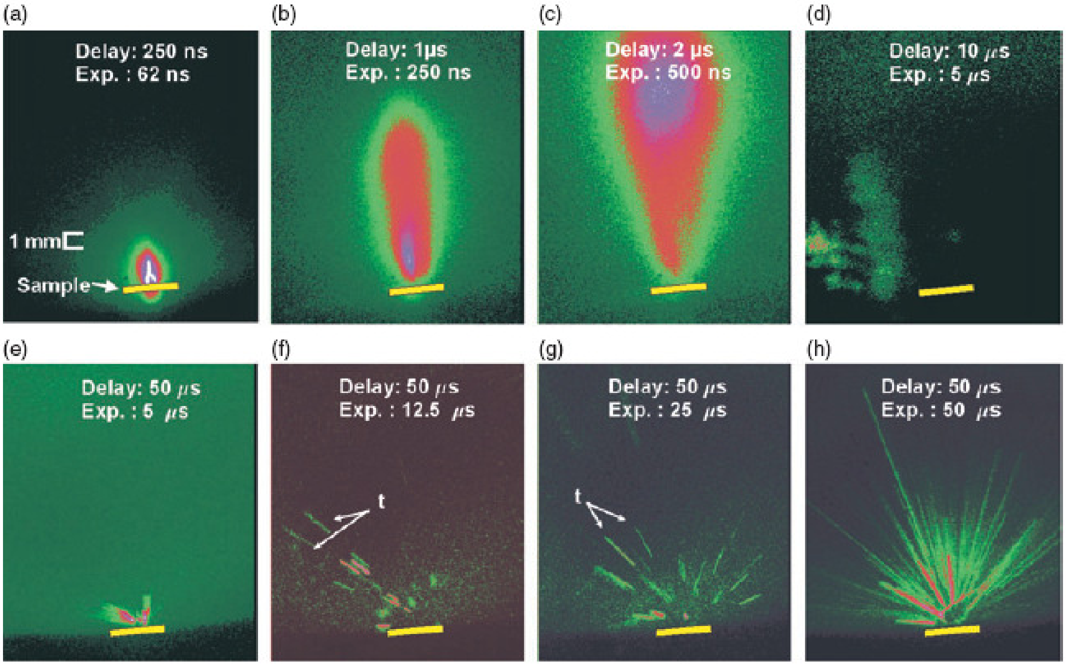

Figure 3. ICCD-images of ablated lead target, delay and exposure times as indicated (see text for details).

(Projected oxide by metal surface sublimation in a restraint cone).

PhE in water: KJoule pulsed electric discharge experiences in water:

With a Marx electric machine, KJoule of electrical energy are brutally discharged in a metallic hollow ellipsoid (0.5 l) submerged in water, as shown in Figure 4. The correct electrodes gauge was sought by successive approximations, around 6.5 mm.

On figure 4, the "voltage" curve recorded in the oscilloscope is the voltage curve at the 50KV power supply terminal. The measured intensity is the true dampened oscillation, with a rise time of 1µ S and a length of 50 µ S for 20 oscillations.

Two things are interesting to notice, during strong electric shock:

+ in KJoule high voltage and micro-second pulsed electric discharge in water, the huge power does not form a huge single steam bubble, but a PhE cloud of tiny bubbles (fig 4), which ultimately explodes violently.

+ if there is no big bubble, why this liquid projection (fig.5) when then the output is top headed up? There are not big bubbles burst but refraction of the shock wave at the water/air interface.

***Fig 4 :Left: issuance of a PhE small bubbles front, in KJ electric discharge*. Right: Voltage and Intensity variations**

The PhE which is a dramatic increase in nucleation frequency, portrays the catastrophic change of any metastable liquid to a liquid-vapour mixture.

The PhE properties find application in improving fuel injection in diesel and gasoline motors.

NOMENCLATURE

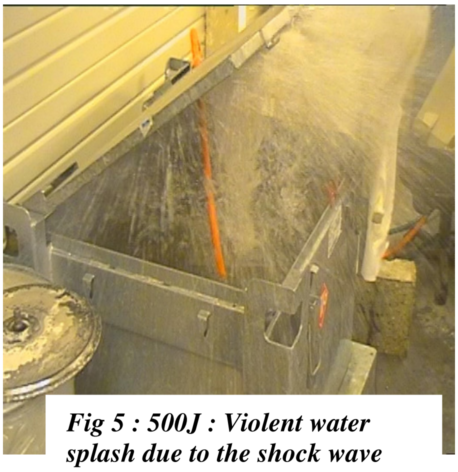

Fig 5 : 500J : Violent water splash due to the shock wave refraction

J: rate of spontaneous nucleation

N: number of liquid molecules per unit volume

Psat (Tl): pressure saturation at Tl,

P_c: Critical pressure

PhE: Phase Explosion

Tc: Critical temperature

P_l, v_l, T_l respectively pressure, volume, temperature of the overheated liquid,

R: gas universal constant

W_{cr}: the energy needed to form critical vapour nuclei at temperature T

k_B: Boltzmann Constant

m: molecular mass

r_c: Critical bubble radius

σ: surface tension

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