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THE INFLUENCE OF SOLID BOUNDARIES IN INHIBITING SPONTANEOUSLY TRIGGERED, SMALL-SCALE FUEL COOLANT INTERACTIONS

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THE INFLUENCE OF SOLID BOUNDARIES IN INHIBITING SPONTANEOUSLY TRIGGERED, SMALL-SCALE FUEL COOLANT INTERACTIONS

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ABSTRACT

The nature of the coolant container base plays an important role in the triggering of large scale vapour explosions producing interactions by entrapment, in for example copper and aluminium dropped into water, which would not have occurred by spontaneous triggering. Similar base triggered interactions have been observed in small-scale tin/water drop experiments but the event was rare.

The most important effect of the base in the small-scale work appears to be to inhibit interactions which would otherwise have occured spontaneously. In shallow coolant, cut-off temperatures are shown to be a function of coolant depth, approaching the Stevens/Witte thin-to-thick vapour film transition temperature in the limit of zero depth. In deep coolant, cut-off temperatures approach a limiting maximum value given by the position of the sloping boundary of the tin/water temperature interaction zone. The results may be explained if a base suppression mechanism is postulated to inhibit those interactions with normal dwell times greater than the sum of the fall time to the base and a waiting time required for the base to take effect. Estimates of the waiting time have been derived from the experimental data and shown to be a linear function of the reciprocal of the coolant temperature.

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1 INTRODUCTION

Since the work of Long (1957) in which 50 kg quantities of molten aluminium were dropped into water it has been recognised that the nature of the base of the containment vessel plays an important role in the triggering of large scale vapour explosions. For industrial purposes it was possible to identify surface treatments which minimised the likelihood of explosions occurring, but despite continued efforts there is no real understanding of the processes involved.

In small-scale experiments the base can have a similar effect (Dullforce 1978). Interactions between molten tin and water have been observed to be triggered on the base with coolant above the cut-off temperature normally associated with spontaneous triggering. These interactions were rare and were not themselves considered spontaneous, but, as with some large-scale experiments (Fry & Robinson 1979), due to a different triggering mechanism, possibly involving entrapment of the coolant between metal and base with subsequent superheating.

Spontaneous triggering is widely believed to be due to the destabilisation of a vapour film surrounding the molten metal as it cools through film and into transition boiling, and the cut-off temperature has been related to the establishment of the thick film boiling regime (Reynolds et al 1976) identified from the quenching of hot metal spheres by Stevens and Witte (1973). This correlation is, however, not entirely satisfactory particularly when extrapolated to high metal temperatures.

In this paper experiments are reported which show that in small-scale tin/water drop experiments the most important effect of the base is, not to trigger interactions by entrapment, but to inhibit interactions which would otherwise have occurred spontaneously. In shallow coolant cut-off temperatures are shown to be a function of coolant depth, approaching the Stevens/Witte transition temperatures only in the limit of zero depth. In deep coolant cut-off temperatures approach a limiting maximum value given by the position of the sloping boundary of the tin/water temperature interaction zone (TIZ) (Dullforce et al 1976). The results may be explained if a base suppression mechanism is postulated to inhibit those interactions with normal dwell times greater than the sum of the fall time to the base and a waiting time required for the base to take effect.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus and procedure used was similar to that described in detail elsewhere (Dullforce et al 1976). Minor changes were made and only a brief description is therefore included here for the sake of completeness.

12 g samples of tin were raised to the required initial temperature in an electrically heated fused silica crucible. To prevent oxidation during the heating time the crucible top was closed with a loosely fitting lid through which inert gas was continually flushed. Beneath the crucible was a container of distilled water previously boiled to remove dissolved air. When the water had cooled to within a few degrees of that required the metal sample was heated and dropped.

After each experiment the debris was removed from the tank, dried under an infra-red lamp, and the container filled with freshly prepared water. The extent of each interaction was determined by the percentage disintegration, PD, defined as the ratio by mass of the finely fragmented tin (sub-millimetre) to the mass of the initial sample.

Three new series of experiments are reported below. In the first, coolant was contained in a rectangular perspex tank 157 x 142 x 100 mm deep. An inverted shallow conical shaped false steel base was placed in the tank on supports of various heights to alter the effective depth of the coolant between 20 and 95 mm. The dish shape also insured that the metal sample remained as a single drop at the centre of the base. The drop height through air to the water surface was 20 - 30 mm.

A second series of experiments investigated the effect of very deep coolant in a 150 x 140 x 600 mm deep mild steel tank with perspex windows.

The third series used the 600 mm deep tank and a similar tank 180 mm deep both with a flat steel base. Drop height was varied up to 910 mm.

3 EXPERIMENTAL RESULTS

The small-scale spontaneous triggering of molten metal drops and some refrigerants falling in oil and water are probably the most investigated of all contact modes. Interactions occur within the bulk coolant, without external influence and usually before the container base is approached. For some systems it has been shown that spontaneous interactions can only occur within well defined regions in fuel temperature/coolant temperature space called temperature interaction zones (TIZ). Spontaneous interactions do not occur outside the zones although externally supplied perturbations to the system, such as base triggering or applied pressure pulses (Board et al 1972) can produce an interaction.

TIZs, which are well documented for several systems (Dullforce 1978) are characterised by a boundary corresponding to the onset of interactions at low fuel and coolant temperatures, and a cut-off condition defined by a boundary at high temperatures. We shall briefly recall the details of the tin/water system of interest in this paper and which is shown, without the detailed experimental points in figure 1. This diagram will be called the 'normal' TIZ for tin/water interactions and was derived by dropping 12 g samples of molten tin through 30 mm of air into 4000 cm^3 of water contained in a tank 180 mm deep with a flat steel base.

3(i) Characteristics of the 'normal' tin/water TIZ

The tin/water TIZ has straight line boundaries which we can call for convenience the vertical, horizontal and sloping boundaries. The horizontal boundary is simply fixed by the coolant freezing point and the vertical boundary by the interface temperature condition $T_I = T_{hom}$ discussed elsewhere (Dullforce 1978), the general validity of which has not been demonstrated for other trigger modes. The sloping boundary, also called the upper or coolant cut-off boundary, is more difficult to understand but has been explained in terms of the Stevens/Witte thin-to-thick vapour film transition (Reynolds et al 1976). The transition line is shown in fig 1, dotted in the region of extrapolation.

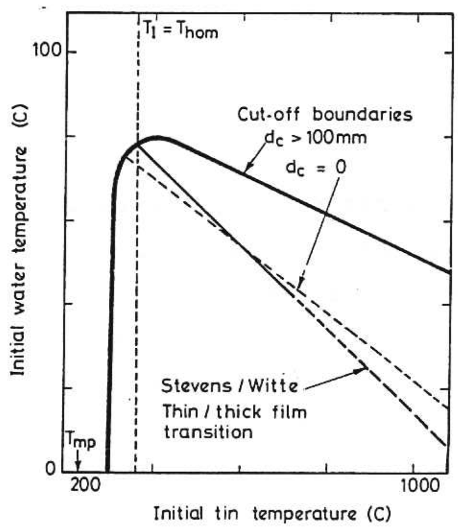

Fig.1 The 'normal' tin/water TIZ

At any fixed value of fuel temperature, T_f, the sloping boundary gives a value for the coolant cut-off temperature which will be called the normal cut-off temperature, T_{nco}, and which is given by the empirical equation:

$$(T_f - T_{sat}) = 19T_{sat} - 20T_{nco} \approx 20(T_{sat} - T_{nco}) \quad ....(1)$$

which may be compared with that for the Stevens/Witte (S/W) line for which:

$$(T_f - T_{sat}) = 10.5\,T_{sat} - 10\,T_c \approx 10(T_{sat} - T_c) \quad ....(2)$$

where T_c and T_{sat} are the coolant temperature and saturation temperature respectively. Only at low values of fuel temperature do the lines approach closely, to within 5^o, while at high fuel temperatures they become widely different.

Interactions occurred after a dwell time, t_D, defined as the time between initial contact of the tin with the water and the start of the interaction. Dwell times were measured from high speed cine films and pressure histories and have been shown to increase with both metal and coolant temperature. Figure 2(a) shows a plot of t_D against the reciprocal of T_f for a fixed coolant temperature of 34 °C. A similar plot against $1/T_c$ for a fixed tin temperature of 600 °C is shown in figure 2(b). Both plots show an abrupt change in gradient at the Stevens/Witte transition temperature, corresponding to a dwell time of 35 ms.

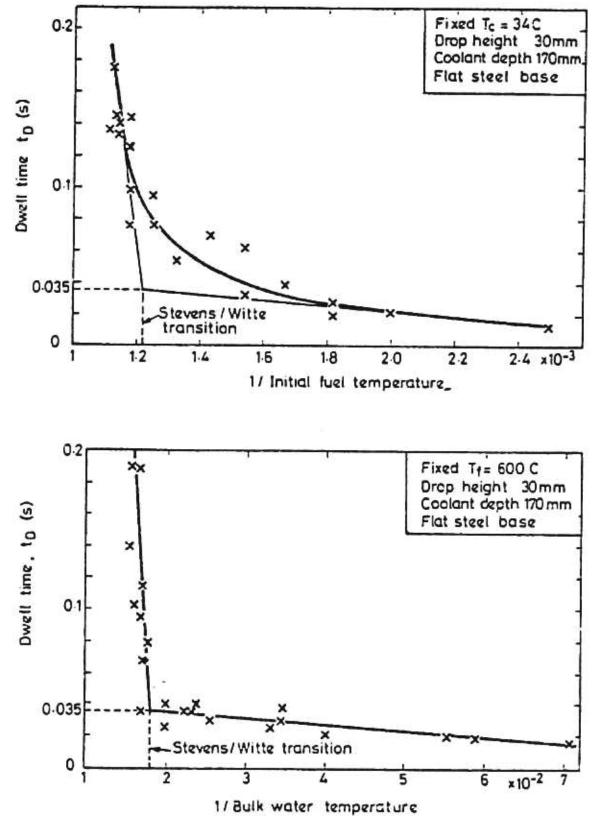

Fig.2 The variation of dwell time with fuel and coolant temperature

The penetration distance below the water surface as a function of time depends on the initial impact velocity, v_i, as shown in figure 3. Distance-time curves are shown for three drops with drop heights, d_h, of (a) 910 mm, (b) 300 mm and (c) 30 mm. The calculated values of v_i are 4.23 ms^{-1}, 2.32 ms^{-1} (cf measured 2.27) and 0.77 ms^{-1} respectively. Terminal velocity was measured as 0.76 ms^{-1} for curves (b) and (c) [which were 12 g drops] and is not much greater for curve (a) a 44 g drop for which a deep container was used. Only part of this curve is given in figure 3.

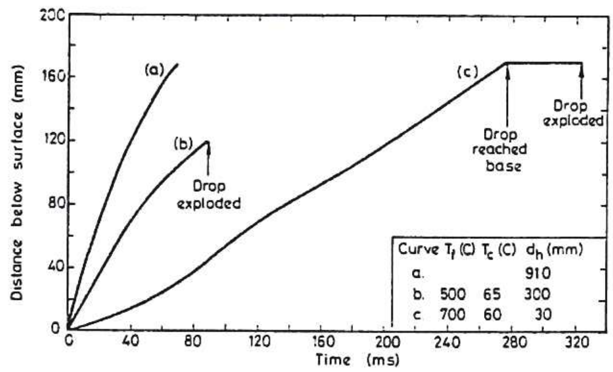

Fig.3 Penetration distance below water surface for tin drops as a function of drop height and time

For d_h = 30 mm there was an initial slowing down of the drop just below the water surface, which corresponds to the flattening of the leading edge on entry and the subsequent change in drag coefficient, but terminal velocity was essentially regained after about 120 ms. This particular drop reached the tank base in 280 ms and an interaction occured about 40 ms later. The initial drop was seen to spread on reaching the base into a flat pancake, possibly trapping coolant and vapour beneath it and preventing direct contact. The vaporization of this coolant could account for the slight swelling and lifting of the pancake just before triggering occured at a point on the edge. The interaction travelled across the pancake at about 20 ms^{-1}.

3(ii) The suppression of base triggered interactions

With a flat bottomed coolant tank interactions occurred occasionally at high coolant or fuel temperatures outside the sloping boundary and several seconds after initial contact of the liquids, a very much longer time than that normally associated with spontaneous triggering. 12 g tin drops falling in water at terminal velocity are marginally stable and split into several smaller drops on impact with the base (see figure 4). It was noticed that the long dwell time interactions occurred when these small droplets ran together at the sides or corners of the coolant tank and coalesced.

Initially it was thought that coalescence entrapped coolant within the fuel leading to superheating and its subsequent rapid vaporisation. With a flat bottomed tank there was no guarantee that coalescence would always occur. It was encouraged by putting a false shallow conical shaped base into the tank (apex angle $\sim 170^{\circ}$) which ensured that the drops ran together at the base centre. About 20 experiments were then repeated outside the sloping boundary. Surprisingly, no interactions were observed, and the base was used in subsequent experiments with no further interactions beyond the sloping boundary. Sample debris beyond cut-off with the shaped base is shown in figure 4(b).

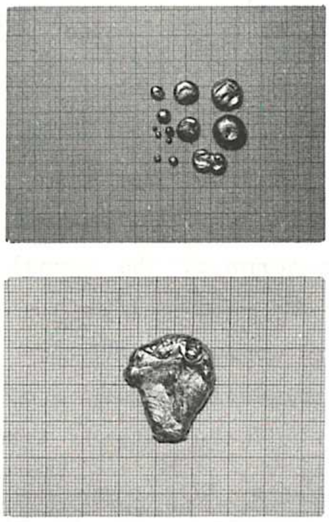

Fig.4 Sample debris outside the sloping boundary with (a) flat base, (b) shaped base

It would appear from these results that base triggering is not caused by coalescence but is the result of trapping coolant between the molten tin and the container base and walls. Furthermore, the sharp geometry of the tank edges and corners was required in order to trigger in this way. In some large-scale experiments, eg copper/water (Page & Boxley 1979), interaction is only achieved by base triggering but, in the present experiments, it was a rare occurrence.

3(iii) The effect of decreasing coolant depth

Figure 5 shows the result of decreasing coolant depth on cut-off temperatures for tin initially at 500 °C and 700 °C. The effect is clearly restricted to shallow pools less than about 100 mm deep for which the cut-off temperature falls linearly with decreasing coolant depth, d_c. That depth above which the normal cut-off temperature is attained is labelled the normal cut-off depth, d_{nco}, and appears to be slightly dependent on fuel temperature. d_{nco} is 95 mm and 110 mm at 500 °C and 700 °C respectively.

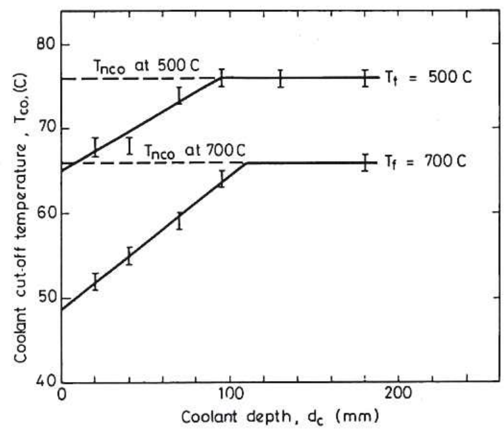

Fig.5 Cut-off temperature as a function of coolant depth and tin temperature

The data of figure 5 for depths up to d_{nco} is presented again in figure 6 in terms of the normalised parameters $(T_{sat} - T_{nco})/(T_{sat} - T_{co})$, the ratio of coolant subcooling at the normal cut-off temperature to that at the reduced cut-off temperature, and $(d_{nco} - d_c)/d_{nco}$, the ratio of the depression of the coolant depth below the normal cut-off depth to the normal cut-off depth. Both sets of data fall on a common straight line. As d_c approaches d_{nco} the normalised depth approaches zero and the normalised cut-off temperature approaches unity. As d_c is reduced to zero on the other hand the normalised depth approaches unity and the normalised cut-off temperature approaches the finite value of 0.65.

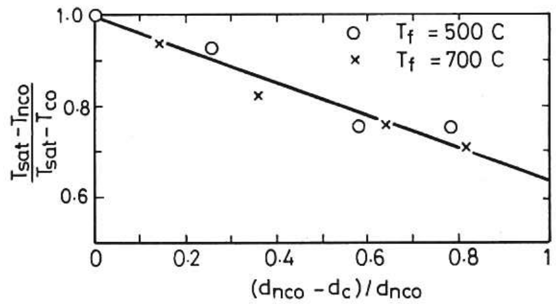

Fig.6 Non-dimensional plot of cut-off temperature against coolant depth

The finite value of the intercept on the temperature axis of figure 6 reflects the non-zero values for T_{co} at zero depth suggested by extrapolation in figure 5. Further, the single intercept value enables a limiting minimum value of cut-off temperature to be found for any fuel temperature from the equation:

$$(T_{sat} - T_{nco}) = 0.65(T_{sat} - T_{co}) \qquad \ldots\ldots\ldots\ldots.(3)$$

The result is a straight line on the TIZ, shown in figure 1, which then represents the maximum possible depression of the sloping boundary. This line corresponds very closely to the Stevens/Witte thin-to-thick film transition line.

3(iv) The effect of increasing coolant depth

18 experiments were performed in a 600 mm deep tank with an initial tin temperature of 550 °C and drop height of 30 mm. The coolant cut-off temperature was found to be 76 °C (± 1 °C) which is not significantly higher than the 74 °C (± 1 °C) taken from the TIZ for which coolant depth was 180 mm.

3(v) The effect of increasing drop height

The influence on T_{co} of the speed of the drops in the water was investigated by adjusting the drop height between 30 mm and 910 mm. There was no measureable change for a drop height of 300 mm with d_c = 170 mm and fuel temperatures of 550 °C and 900 °C. With d_c = 470 mm and T_f = 550 °C drop height was increased to 600 mm and 910 mm which resulted in a decrease in T_{co} as shown in figure 7. The highest PDs were observed close to T_{co} but decreased with increasing drop height. At 910 mm for example no PD exceeded 45% while 100% was common at 30 mm and 300 mm.

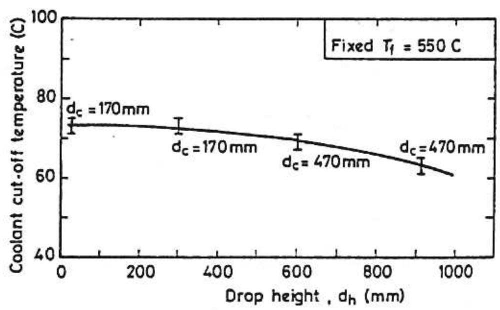

Fig.7 Variation of cut-off temperature with drop height for T_f = 550 °C

4 INTERPRETATION OF THE RESULTS

In shallow containers the coolant cut-off temperature is a function of coolant depth, increasing as the depth is increased. Since there is no evidence that the presence of the base can effect the spontaneous triggering of drops in the bulk coolant, contact with the base must determine the value of T_{co}, and we are led to postulate that if the normal dwell time, a function of T_c, is greater than the fall time to the base spontaneous interactions are inhibited by some base suppression mechanism.

Whatever the nature of this mechanism, the base will require time, which we shall call the waiting time, t_w, in which to take effect, and we then assume that interactions may take place after reaching the base but before the waiting time has expired. It t_f is the drop fall time to the base conditions for spontaneous triggering may be summarised as follows:

$t_f > t_D$	spontaneous triggering in bulk coolant
$(t_f + t_w) > t_D > t_f$	spontaneous triggering on base possible
$t_D > (t_f + t_w)$	spontaneous triggering prohibited

Estimates of the waiting time have been made from the experimental data and are shown in table 1 for a fixed fuel temperature of 600 °C (the only value of T_f for which we have measurements of t_D as a function of T_c). At fixed values of coolant depth up to 100 mm the relationship of figure 6 has been used to predict the reduced cut-off temperatures taking a value for d_{nco} of 103 mm (midway between those for 500 °C and 700 °C). Mean dwell times are tabulated from figure 2(b) and fall times from curve (c) of figure 3. Figure 8 shows how the waiting times decrease linearly with $1/T_{co}$.

Approaching the limit of zero coolant depth the fall time is zero and the waiting time would be equal to the measured dwell time, in this case 35 ms. The corresponding coolant temperature is about 53 °C. Below this dwell times are generally less than t_w and interactions should occur. Above 53 °C dwell times are greater than t_w and interactions should be prohibited.

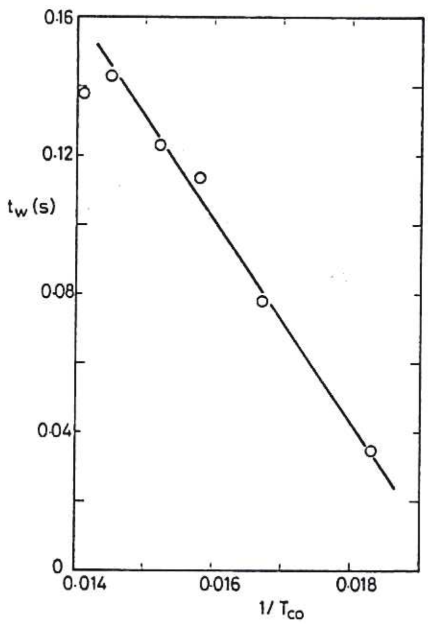

Fig.8 Estimated waiting time as a function of coolant temperature

Interactions with longer dwell times are observed, however, if the coolant depth is increased. A longer t_D corresponds to higher coolant temperature and higher values of t_w and, therefore, the position of the sloping boundary becomes dependent on coolant depth, moving up as d_c is increased. As we move further into the thick film regime, however, t_D increases very rapidly and the dwell time curves become almost vertical. Very deep containers are then required for any change in cut-off temperature to be observed. The position of the sloping boundary in practice then becomes essentially independent of coolant depth as shown by the flattening of the curves of figure 5.

Table 1 Estimates of waiting time from dwell and fall time data

d_c (mm)	$\frac{d_{nco} - d_c}{d_{nco}}$	$\frac{T_{sat} - T_{nco}}{T_{sat} - T_{co}}$	T_{co} (^oC)	t_D (ms)	t_f (ms)	$t_w = t_D - t_f$ (ms)
0	1.000	0.65	55	35	0	35
20	0.806	0.718	60	130	52	78
40	0.612	0.786	63	190	82	108
60	0.417	0.854	66	230	107	123
80	0.223	0.922	69	280	137	143
100	0.029	1.000	71	310	172	138

For a fixed coolant depth the cut-off temperature will be altered by any parameter which influences either the fall time or the waiting time. The fall time is shown in figure 3 to be strongly dependent on entry velocity, decreasing as v_i increases, and this leads to lower allowed values of t_D and the lowering of the cut-off temperature shown in figure 7.

t_w depends on the details of the base suppression mechanism about which we may only speculate. Direct contact with the base may rapidly cool the tin so that when the normal dwell time has expired insufficient thermal energy is available to support the interaction. Alternatively the trigger mechanism itself may be inhibited by suppression of the instability at the coolant/vapour interface responsible for vapour collapse. For either mechanism we postulate that direct contact is necessary and a major contribution to t_w comes from the time after reaching the base required to achieve this. Large drops for instance spread on impact with a flat base and interactions can occur during this spreading as described in section 3(i). In the absence of a trigger spreading proceeds until break-up into the very small drops of figure 4(a). Since there is no evidence from almost 100 films of tin drop experiments that spontaneous triggering occurs after break-up we conclude that the sphericity of small drops facilitates the escape of trapped coolant and vapour and leads quickly to direct contact.

5 CONCLUSIONS

(i) Coolant cut-off temperature and hence the position of the sloping boundary of the tin/water TIZ is a function of coolant depth up to $\sim$ 100 mm. Above 100 mm the sloping boundary is essentially independent of depth and its position is given by that of the 'normal' TIZ.

(ii) The lowest values of cut-off temperature and hence the maximum depression of the sloping boundary corresponds to the limit of zero coolant depth, in which position it lies very close to the Stevens/Witte thin-to-thick vapour film transition line.

(iii) Further evidence of the relevance of the Stevens/Witte line to these experiments is indicated by the dwell time measurements which increase rapidly in the thick film region.

(iv) It is postulated that in tin/water small drop experiments contact with the container base before the normal dwell time has expired inhibits the spontaneous triggering of vapour explosions.

(v) The base suppression mechanism has not been identified. The finite time, t_w, for it to take effect was derived from the dwell and fall time data and was shown to be linearly dependent on the reciprocal of coolant temperature.

(vi) Spontaneously triggered interactions occur in bulk coolant if $t_D < t_f$, on the base if $t_D < (t_f + t_w)$ and are inhibited if $t_D > (t_f + t_w)$.

(vii) Parameters which effect t_f or t_w, such as the speed of fall of the drop through the coolant, can alter the cut-off temperatures. Thus increasing drop height lowers T_{co}.

(viii) This behaviour of the base for small-scale experiments is in contrast to large scale copper/water and possibly aluminium/water experiments where contact with the base appears essential if interactions are to occur. Triggering in this case is assumed not to be spontaneous (ie due to vapour blanket collapse) but caused by coolant entrapment and superheating. This mechanism we refer to as base triggering.

(ix) Base triggering in small drop experiments was observed but was a rare event and could be inhibited by using a base that prevented tin drops running into sharp edges and corners where trapping might occur.

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