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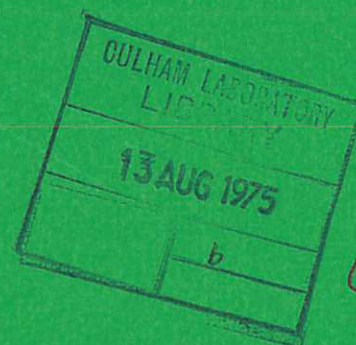
SELF-TRIGGERING OF SMALL-SCALE FUEL-COOLANT INTERACTIONS

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by

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ABSTRACT

Over 300 small-scale experiments have been performed to investigate the interaction that sometimes occurs when hot liquid metal is poured into a container of water. In these experiments molten tin was used. The violence of each interaction was classified by measuring the ratio of the mass of comminuted tin to the original mass of tin, and the effect of varying the initial tin and water temperatures, T_f and T_c respectively, was investigated. In $T_f - T_c$ space there exists a zone, the temperature interaction zone (TIZ), outside of which interactions do not occur without external triggering. The time between the tin entering the water, and the start of the interaction was also measured as a function of T_f and T_c. A qualitative explanation of some of these results is proposed.

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1. INTRODUCTION

Violent interactions resulting from the sudden contact of a cold vapor-isable liquid and a hot liquid have caused considerable damage and injury to personnel in several industries. Anderson and Armstrong (1972) and Witte et al (1970) give resumés of several incidents. These violent interactions are called alternatively thermal explosions, vapour explosions or fuel-coolant interactions (FCIs), and are known to take place under specific conditions between a wide variety of fuels (the hot liquid) and coolants (the cold liquid). It is generally accepted that chemical reactions cannot be the energy source for FCIs because analysis of the debris has not revealed the presence of signi-ficant quantities of chemical reaction products. The energy for the inter-action is therefore derived solely from the excess heat in the fuel and is transferred on a millisecond timescale with rapid vaporization of the coolant, and the formation of finely divided débris.

There is a very wide range of parameters which may influence an FCI. These include the physical properties associated with fuel and coolant (eg. specific heat, thermal conductivity, interfacial surface tension, melting point, viscosity, density, etc.), the initial fuel and coolant temperatures, the quantities of fuel and coolant involved, the effect of solid or gaseous nucleation sites in either fuel or coolant, the ambient pressure and the way in which the two phases are brought into contact. This last point is of particular interest. Experiments have been performed in which fuel and coolant have been brought together in a variety of ways, eg. high velocity impact between the two phases, dropping, injecting or pouring one phase into the other, and it could be that two fundamentally different mechanisms are involved depending upon whether the hot phase is surrounded by the cold, as in the experiments below, or vice versa.

In an attempt to understand FCIs many experiments have been performed using a variety of materials and contact modes. However, not all of these have been done in a systematic way with the careful control of the parameters listed above. We have performed a series of experiments in which the detailed effect of initial coolant and fuel temperatures is investigated. Early experiments by G M McCracken (1973) showed that FCIs were very sensitive to initial conditions and that great care was required in order to obtain reproducible results. This point is amplified in §2. §3 contains the experimental results. Some of the interactions were filmed at 5000 frames per second and a description of a typical event is given in §4. A qualitative

explanation of some of the results is given in §5.

2. EXPERIMENTAL PROCEDURE

The apparatus is illustrated by the block diagram of Figure 1 and consists essentially of a small silica crucible (volume 3 cm^3) pivoted above a container of boiled distilled water.

In early experiments the crucible was heated by Calor gas with the metal surface arranged to be in the reducing part of the flame to prevent oxidation. Later experiments employed a resistively heated crucible, power being supplied by the a.c. mains via a transformer. To minimise oxidation a slow current of helium gas was passed over the surface throughout the heating time which was kept as short as practicable. The gas was introduced at the centre of a stainless steel cap, which loosely fitted over the crucible, and was then allowed to escape at the sides (see Figure 2). Metal temperatures from 250° C to 1000° C (± 10° C), were monitored by a chromel-alumonel thermocouple and milli-voltmeter. Figure 2 shows how the thermocouple was introduced through the cover gas inlet tube and illustrates the crucible assembly.

Each metal sample was heated to the required temperature which was then stabilised by adjusting the heating current. The crucible cap and thermo-couple were removed and the crucible was tipped by a small electric motor actuated usually by the event switch of a high-speed camera, which closed when the camera had reached the required speed. In a few early experiments the crucible was tipped by hand. The molten metal then fell through 30 mm, the smallest practical distance, into water 170 mm deep contained in a tank 150 mm square. Calculations show that the metal cools a negligible amount during the fall to the water surface. In order to obtain reproducible results, care was taken to keep the distilled water as clean as possible, and dissolved gases were removed prior to each experiment by boiling for three minutes. The water was then allowed to cool to about 2° C above the required tempera-ture before the metal was heated and dropped.

3 mm above the water surface the molten metal intersected a light beam which was provided for convenience by a 0.5 mW He-Ne laser. This produced a voltage pulse from a phototransistor detector circuit to trigger a Tektronix type 503 oscilloscope. A Kistler 603 B pressure transducer was mounted flush with the inside of the tank wall 30 mm from the base and was coupled, via a Kistler 5001 charge amplifier, either to the vertical deflection plates of the oscilloscope (triggered as described) or, in later experiments, to a Datalab 905 transient recorder, to monitor the pressure pulses associated with the explosions. In early experiments a crystal microphone was employed just

outside the tank wall to record the sound of the explosions.

The base and two walls of the water tank were made of stainless steel while the other two walls were clear perspex so that selected events could also be recorded on 16 mm film with the use of a Hycam high-speed ciné camera, operated at 5000 frames per second. Illumination from the rear of the tank was provided by 3 x 1 kW tungsten-halogen strip lamps placed behind a diffuse screen, and the tipping motor was triggered by the camera as described above.

After each experiment the water was replaced with freshly boiled and cooled water, and the metal débris collected and dried under an infra-red lamp for further examination.

3. EXPERIMENTAL RESULTS

In this section we describe the results of about 300 experiments in which 12 gram samples of molten tin were dropped into boiled distilled water. The principal parameters varied in these experiments were T_f and T_c, the initial fuel and coolant temperatures. The violence of each interaction was quantified by the percentage disintegration, PD, defined as the ratio of the mass of comminuted fuel to the original mass of fuel. To measure the PD the débris resulting from each interaction was dried and the comminuted débris and the remnant weighed separately. The comminuted fraction of the fuel consists of the small fines and the coke like spongy material which is highly porous. As Figure 4 indicates this is qualitatively quite different from the remnant of smoother lumps which have not taken part in an FCI.

PD has proved to be a good guide to the strength or violence of an interaction until PDs of 100% are approached at which point two experiments may each fully disperse the metal but one may sound more violent and produce much finer debris. Ideally the strength of an interaction should be classi-fied according to the pressure-time history or by the particle size distribution function but neither of these measurements is as readily obtained as the PD, particularly when large numbers of experiments are to be analysed. In some experiments pressure traces were recorded but these were used primarily to measure dwell times, t_D, defined as the time between the metal just entering the water (ie. breaking the light beam) and the initiation of the interaction.

These experiments have revealed the existence of a 'temperature interaction zone' (TIZ) in T_f - T_c space within which FCIs can occur with varying degrees of violence. The zone is clearly shown in Figure 3 where each experiment is marked with a cross or a circle to indicate respectively no interaction (zero PD) or an interaction (a few % to 100% PD). Recent experiments suggest

that the position of the left-hand vertical zone boundary is fixed by the mass of fuel used and moves to the right as the mass is decreased. However, these latter results are preliminary and will not be discussed further here. All experiments with metallic fuels indicate that a necessary criterion for an FCI is that the fuel be molten and thus the left-hand boundary is limited by the melting point of the fuel. [Nevertheless, solid-liquid explosive interactions are possible as has been shown by Bradfield (1966) who observed interactions between graphite and water. Graphite has a high porosity and it may be that the physical mechanism involved is different from that responsible for metallic FCIs.] In practice, with clean water, interactions have not been observed for T_f below 300° C. One experiment in which 12 grams of tin at 700° C was dropped on to the surface of ice at 0° C failed to produce an interaction. The metal drop broke-up on contact and solidified. In these experiments therefore the horizontal boundary is apparently fixed by the coolant melting point. The sloping boundary determines the fuel and coolant cut-off temperatures. We are unable to say whether or not this boundary may be linearly extrapolated to form a triangluar temperature interaction zone since the tin temperature cannot be raised further with the existing apparatus.

Just inside the vertical boundary PDs are very low and the interaction is an extremely mild event that cannot by any stretch of the imagination be called an explosion. Nevertheless some interaction has taken place and the débris, as illustrated in Figure 4, is quite different from that just outside the zone. The most violent explosions take place inside but close to the sloping boundary where explosions from 12 gram samples of tin have, on several occasions, broken glass vessels. The change in the nature of the débris as the temperature interaction zone is crossed is shown in Figure 4.

We now indicate the way in which dwell times and PD vary within the TIZ. Figures 5 and 6 show the variation of PD with increasing coolant temperature at fixed fuel temperatures of 500°C and 600°C respectively. In general the PD increases with increasing coolant temperature reaching 100% as the coolant cut-off temperature is approached. At the cut-off temperature, reported previously by Brauer et al (1968) and Board et al (1972), the PD falls suddenly to zero. The cut-off temperature was found to be just as sharp for all values of initial fuel temperature and decreases in value as T_f is increased. The experimental points above the cut-off temperature can, of course, only be plotted once, but they were repeated several times with the same results. The occurrence of FCIs just below the cut-off temperature has an 'on-off' nature indicating the presence of incipient instability. As Figure 6 shows, for that system with coolant above 60° C, the PD was either

100% or zero with no intermediate values.

Figure 5 illustrates the increased scatter in PD that was the result of gas flame heating. The metal surface was not as clean as for the points presented in Figure 6 for which resistive heating with a helium cover gas was used.

Similarly if T_c is fixed and T_f increased, the PD increases from zero near the fuel melting point, to 100%, but as T_f is increased still further the PD falls suddenly to zero at the fuel cut-off temperature, (Figure 7). It also appears unlikely that PDs greater than 20% will be obtained for fuel temperatures lower than 400°C.

Dwell times measured from film and from pressure records are shown in Figures 8 and 9 plotted respectively as functions of initial coolant and fuel temperatures. t_D increases with coolant temperature (Figure 8) and rises very rapidly as the cut-off temperature is approached. A similar trend is shown in Figure 9 but here the fuel cut-off temperature ($\sim$ 2000°C by extrapolation of Figure 3) has not been approached. In Figure 10 the reciprocal of the dwell time is plotted against T_c. This shows that t_D is proportional to the reciprocal of T_c. In Figure 11, log t_D is plotted against log T_f where T_f is in degrees centigrade, and this curve is reasonably linear over the range covered.

4. DESCRIPTION OF AN INTERACTION

High-speed cine film of a typical interaction shows that after entering the water, the metal drop alters shape, particularly at the front which tends to flatten. Some air, entrained on entry, breaks away and rises to the water surface. After a short time, 10-200 msec depending on the initial fuel and coolant temperatures, the interaction starts and proceeds as a series of cycles at intervals of a few msecs. Each cycle consists of an explosion resulting in a vapour bubble which expands and disperses the adjacent fuel. The bubble collapses and is followed by a more violent explosion and the growth of a larger bubble. This cycle is repeated three or four times after which all the fuel has been dispersed and the interaction is complete.

A model based on these observations and similar films has been proposed independently by several authors, [Roberts (1972), Potter and Jakeman (1972 a & b), Board et al (1972), Buchanan and Dullforce (1973), Buchanan (1974)]. This model assumes that on initial contact a thin vapour layer of coolant forms and

separates the liquid fuel and coolant. Some time later this layer is perturbed by some 'trigger mechanism' and a local increase in heat transfer occurs which results in the formation of a coolant vapour bubble. This bubble expands into the subcooled coolant where the vapour condenses and the bubble then collapses. The adjacent fuel/coolant interface means that the collapse cannot be spherically symmetric and the results of Benjamin and Ellis (1966) and Plesset and Chapman (1971) indicate that a high velocity jet of liquid coolant is formed directed towards the fuel surface. The jet enters the fuel where it disintegrates and vaporises, thus forming another high pressure bubble which expands and allows the whole process to be repeated until all the available fuel has been used.

It should be noted that the trigger mechanism, which results in the formation of the initial bubble, occurs only once; nevertheless, as we shall see below, many of the experimental results may be explained in terms of it. Buchanan (1974) has given a mathematical description of the cyclic part of the model but this will not concern us further here.

A different explanation, discussed by several authors [Katz and Sliepcevich (1971), Katz (1972), Enger et al (1972) and Yang (1973)], involves the super-heating of the coolant beyond its normal boiling point with explosive vapour formation when the homogeneous nucleation temperature, T_h, [Döring (1937)], is reached. This explanation is based on experiments with liquified natural gas, LNG, (the coolant) and water (the fuel). Fauske (1973 a & b) has modified this model, and, assuming intimate contact between the two phases, predicts an interaction when the interface temperature, T_I, exceeds the spontaneous nuclea-tion temperature, T_s. The latter temperature depends on the nature and density of nucleation sites and can have any value between T_h and T_{sat}, the saturation temperature. If $T_I < T_s$ on initial contact, T_s may be reached by heating the coolant slowly in the absence of nucleation sites, or very quickly if nucleation sites are present.

We do not believe that this model can account for all FCIs. Firstly, to transfer sufficient energy from fuel to coolant within the observed timescale of the explosion, an extremely large contact area between fuel and coolant is required. Witte et al (1970) have shown that, in the case of metal/water explosions, heat transfer rates three orders of magnitude greater than those which occur during normal boiling processes are required. This result implies that the contact area must increase by a factor of 10^3. Roberts (1971), by considering the heat diffusion problem in the fuel, has also shown that an area increase of order 10^3 is needed. These results may overestimate the area increase required, but there seems little doubt that an increase of 10^2 is necessary. In the case of LNG/water explosions it is just conceivable that

LNG spreads horizontally by a sufficient amount to give large area enhance-
ment, but for metal/water interactions we observe no spreading. Secondly,
superheating models do not explain the observed cut-off coolant temperature
above which no interaction occurs. On the basis of the superheating model it
should be possible to produce interactions at any coolant temperature including
the saturation temperature. However, our experiments show that molten tin
does not interact with water above a certain temperature.

5. DISCUSSION

The first stage of the cyclic model is regarded solely as a means of
triggering the interaction by supplying the initial perturbation to collapse
the vapour layer and cause the growth of the first coolant vapour bubble
adjacent to the fuel surface. With the exception of the film evidence most of
the experimental results can be discussed in terms of this stage.

There are several ways in which triggering may be accomplished. Two examples
are the sudden application of a pressure pulse to the interface [Board et al
(1972)] and from the shock wave associated with high velocity contact of the
two phases [Guest et al (1973)]. An additional trigger mechanism, little under-
stood, is that associated with the approach and contact of the fuel with the
coolant container base [Long (1957)]. In the latter case the nature of the
solid surface plays an important role in determining whether or not an FCI
occurs.

The self-initiation observed in the present experiments could be provided
by the onset of transition boiling as the fuel cools. Witte et al (1970) have
summarised the violent boiling theory of FCIs which asserts that if the fuel
enters the transition boiling regime (see Figure 12) then violent boiling tears
the fuel apart and causes an FCI. However, we do not think that the onset of
transition boiling is the complete cause, rather it provides circumstances under
which the interaction can develop. This view is also expressed by Board et al(1972).
We now discuss how the boiling curve can be used to explain in a qualitative
way the results of the present experiments.

Suppose the initial temperature of the fuel, T_f, is such that the heat
transfer is by film boiling (Figure 12). In this region the heat flux is
almost proportional to T, the fuel surface temperature [Peterson and Zaalouk,
(1971)]. The time required for the fuel surface to cool to a temperature T_t is
given by (see appendix)

$$\frac{T_t + f_o/a}{T_f + fo/a} = \exp\left\{a^2\sigma^2 t/k^2\right\} \operatorname{erfc}\left\{\frac{a\sigma\sqrt{t}}{k}\right\} \tag{1}$$

We suppose that T_t is the temperature of the surface when the interaction starts and that T_t is not a function of T_f. σ^2 is the thermal diffusivity of the fuel, k the thermal conductivity of the fuel, and f_o and a are constants such that the heat flux from the fuel surface is $f_o + aT$ corresponding to a film boiling. $(-f_o)$ lies in the range $\sim 10^6 - 10^7$ W/m^2 [Duffey et al (1972)]; but we have been unable to find consistent estimates for a. The quantity f_o/a is the temperature T_o at which the linear function $Q_1 \equiv f_o + aT$ becomes zero. The equation (1) relating the initial fuel temperature $\tilde{T}_f$ and a theoretical dwell time $\tilde{t}_D$ may be re-written as

$$T_f = T_o + (T_t - T_o)/\mathcal{M}(\tau) \qquad \qquad \cdots (2)$$

where $\tau = a\frac{\sigma}{k}\sqrt{\tilde{t}_D}$ and $\mathcal{M}(\tau)$ is the modified Mills ratio $\exp(\tau^2)$ erfc τ (see for example Kendall and Stuart, 1953). For tin $\sigma/k = 1.326 \times 10^{-4}$ in SI units.

This theoretical dwell time $\tilde{t}_D$ is related to the observed dwell time t_D by

$$t_D = \tilde{t}_D + t_L \qquad \qquad \cdots (3)$$

where t_L is a time lag. This additional time lag is to be expected since t_D includes the period in air during which the tin drop falls after it cuts the laser beam until the instant it breaks the surface of the coolant. This period must be ~ 4 ms as the drop enters the water at ~ 75 cm/sec. The time lag t_L also includes the inevitable small delay between the instant when the vapour film becomes unstable and the instant when this is observable on a macroscopic level. In what follows the corrected experimental dwell time is taken to be $(\tilde{t}_D - 4)$ millisecs.

The initiation temperature T_t is, we believe, closely related to the Leidenfrost temperature T_L, which is the temperature minimum for the boiling heat flux, separating the regimes of film boiling and transition boiling (see Figure 12). The Leidenfrost temperature is a function of geometry and the degree of subcooling, but values of the order of 400° C are typical. Certainly since we do observe FCIs the initiation temperature T_t, must be greater than the melting point of tin, 232° C. The function $\mathcal{M}(\tau)$ is a monotonically decreasing function of τ with $\mathcal{M}(0) = 1$ and $\mathcal{M}(\infty) = 0$. From equation (2) for the theoretical dwell time $\tilde{t}_D$ to increase with fuel temperature (as is observed), it is necessary that $T_t > T_o$ strictly.

Now for large τ, T_f is given asymptotically by

$$T_f - T_t = (T_t - T_o) \left(\sqrt{\pi}\, \tau \left[1 + \frac{1}{2\tau^2} + \ldots \right] - 1 \right) \qquad (4)$$

Moreover with $\tau \ggg 1$, this reduces to

$$T_f - T_t = (T_t - T_o) \sqrt{\pi}\, \tau$$

$$= a\sqrt{\pi}\,(T_t - T_o)\,\frac{\sigma}{k}\,\sqrt{\tilde{\tau}_D} \quad . \tag{5}$$

The condition $\tau \gg 1$ is equivalent to

$$\sqrt{\tilde{t}_D} \gg \frac{k}{a\sigma} = \frac{10^4}{(1.326)a} \tag{6}$$

Figure 13 shows the curve $\tilde{t}_D \propto (T_f - T_t)^2$, from equation (5) when $T_t = 700^{\circ}K$ and $a.(T_t - T_o) = 6 \times 10^6$. This choice, out of several orders of magnitude examined for T_t and $a(T_t - T_o)$, provides the best agreement between equation (5) and the experimental curve for large dwell times. It is an extremely good fit for $\tilde{t}_D > 80ms$ which implies from equation (6) that $a > 10^5$. Hence $T_t - T_o < 60$, and $-f_o \gtrsim 6 \times 10^7$, which as we mentioned above is of the same order as values measured in related systems.

Figure 13 also shows curves computed from equation (2) with $T_t \sim 700^{\circ}K$, $a(T_t - T_o) \sim 6 \times 10^6$ and $T_t - T_o$ taking the value indicated. These curves are sensitively dependent on T_t and $a.(T_t - T_o)$ but rather insensitive to the choice of $T_t - T_o$. Thus the dwell time increases as the square of the excess of the fuel temperature above an 'interaction temperature' T_t, found to be $\sim 700^{\circ}K$.

We observe then that the simple linear flux model used above provides excellent agreement with the experiments for large dwell times, but is not satisfactory for small dwell times. However this is to be expected since, as Figure 12 indicates, a non-linear flux temperature relation appears more appropriate close to the Leidenfrost point. (A non-linear flux model does not have a straight forward analytic solution and requires substantial computing). The deviation between the experimental and linear-flux dwell times clearly has the correct sign for small dwell times.

There is, therefore, some evidence that the automatic triggering in these experiments is a result of the fuel surface cooling to some 'triggering temperature', perhaps the Leidenfrost temperature, at which temperature the vapour is sufficiently perturbed to initiate the interaction. However, to quantitively test this idea and the foregoing theory much more accurate values of f_o and a are required. These values are not available to us.

In equation (1), f_o, a and T_t are all functions of T_c [see for example, Walford (1969), Farahat (1972), and Duffey et al (1972)]. Correlation analysis indicates that f_o and T_t, if it is the Leidenfrost point, are

linearly dependent on T_c, but the dependence of a on T_c is not known. Therefore, equation (1) cannot be tested against Figure 10.

The coolant cut-off temperature can be explained in two ways. As the subcooling is decreased (T_c increased) the boiling curve moves to the left and the maximum (critical or burn-out) heat flux is lowered [Farahat (1972)]. The dwell time also increases with T_c as we have seen. Hence, either (a) at and above the cut-off temperature perturbations are not sufficiently large to precipitate an interaction, or (b) by the time the perturbations are large enough the fuel surface has solidified thus preventing an interaction.

The second explanation has been suggested by a number of previous authors; Witte et al (1970) implicitly attribute it to Swift (1965). A necessary condition for this explanation to be correct is that, when the interaction does occur, the fuel surface temperature at the moment of triggering is greater than the melting temperature of the fuel.

Experiments by Board et al (1972) have shown that an interaction can be precipitated above the coolant cut-off temperature if the system is disturbed by a pressure pulse propagated several seconds after the initial contact of fuel and coolant. The likely explanation is that the pulse collapses the vapour layer surrounding the fuel, thus supplying the perturbation required to start the interaction. It is not clear whether or not the fuel surface had sufficient time to solidify in these experiments, but if it had solidified it would support (a) above and refute (b).

6. CONCLUSIONS

A large number of experiments have been performed and classified according to their percentage disintegration. The principal result is the identification of a temperature interaction zone in $T_f - T_c$ space within which FCIs automatically occur. If systems can be operated outside the temperature interaction zone, the likelihood of an FCI is diminished. The dwell time has also been measured as a function of T_f and T_c.

In these experiments interactions occur automatically as the fuel cools and before the bottom of the coolant container is reached (which occurs after about 300 msecs). As far as we know the outside of the temperature interaction zone is stable only to automatic or self-triggering on a millisecond timescale. It is however, possible to trigger an interaction outside the TIZ by some other method (eg by the application of a pressure pulse). On a few occasions an interaction has occurred a few seconds after contact with the container base.

If the triggering can be explained in terms of the boiling curve, then any parameter which affects the location of the boiling curve should affect the interaction. As we have seen, the degree of subcooling is one such parameter. It is possible that any parameter which affects the boiling curve in a similar manner results in a cut-off value of that parameter above or below which the interaction does not occur. The ambient pressure is another parameter which affects the location of the boiling curve. As the pressure is increased the boiling curve moves to the left and the maximum is raised; further increase in the pressure results in the decrease of the maximum as the curve continues to move to the left [Chichelli and Bonilla (1945), Farber and Scorah (1948), Hesse (1973)]. Therefore, there ought to exist a threshold in the ambient pressure above which the interaction does not automatically proceed. Of course even above the threshold, a pressure _pulse_ could still trigger the interaction.

A large proportion of the arguments advanced in §5 depend on the boiling curve. Nearly all boiling curves are determined under quasi-static conditions and for a solid-liquid interface, but an FCI is a transient effect involving a liquid-liquid interface, and often occurs in the presence of a fluid velocity field. The determination of the boiling curve under these conditions will be necessary before any quantitative comparison can be made. Walford (1969), Witte and Henningson (1969), and Stevens and Witte (1973), have made some progress in this direction by studying heat transfer from solid spheres moving through a coolant.

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APPENDIX

Consider the equation

$$\frac{\partial T}{\partial t} = \sigma^2 \frac{\partial^2 T}{\partial x^2}$$

in the region $[0, \infty]$, with the initial condition $T = T_f$ and the boundary condition

$$- k \frac{\partial T}{\partial x} = - f_o - a T \quad \text{at} \quad x = 0 .$$

This problem is that of one-dimensional heat transfer with the heat flux at the end proportional to the temperature of the end. It therefore corresponds to cooling by film boiling. Carslaw and Jaeger (1959) have solved this problem with $f_o = 0$, and their solution is easily modified to this case. The modified solution is:

$$T = - \frac{f_o}{a} + \left(T_f + \frac{f_o}{a} \right) \text{erf} \left(\frac{x}{2\sigma\sqrt{t}} \right)$$
$$+ \left(T_f + \frac{f_o}{a} \right) \exp \left(\frac{a}{k}x + \frac{a^2\sigma^2 t}{k^2} \right) \text{erfc} \left(\frac{x}{2\sigma\sqrt{t}} + \frac{a\sigma\sqrt{t}}{k} \right)$$

Thus the temperature T_t at the end $x = 0$ is

$$T_t = - \frac{f_o}{a} + \left(T_f + \frac{f_o}{a} \right) \exp \left(\frac{a^2\sigma^2 t}{k^2} \right) \text{erfc} \left(\frac{a\sigma\sqrt{t}}{k} \right)$$

This is equation (1) and gives implicitly the time for the surface to cool from T_f to T_t. The fuel of course is not a semi-infinite line, but this approximation is valid if the thermal diffusion length is much less than the radius of the spherical blob of fuel. This condition holds for all the times involved here.

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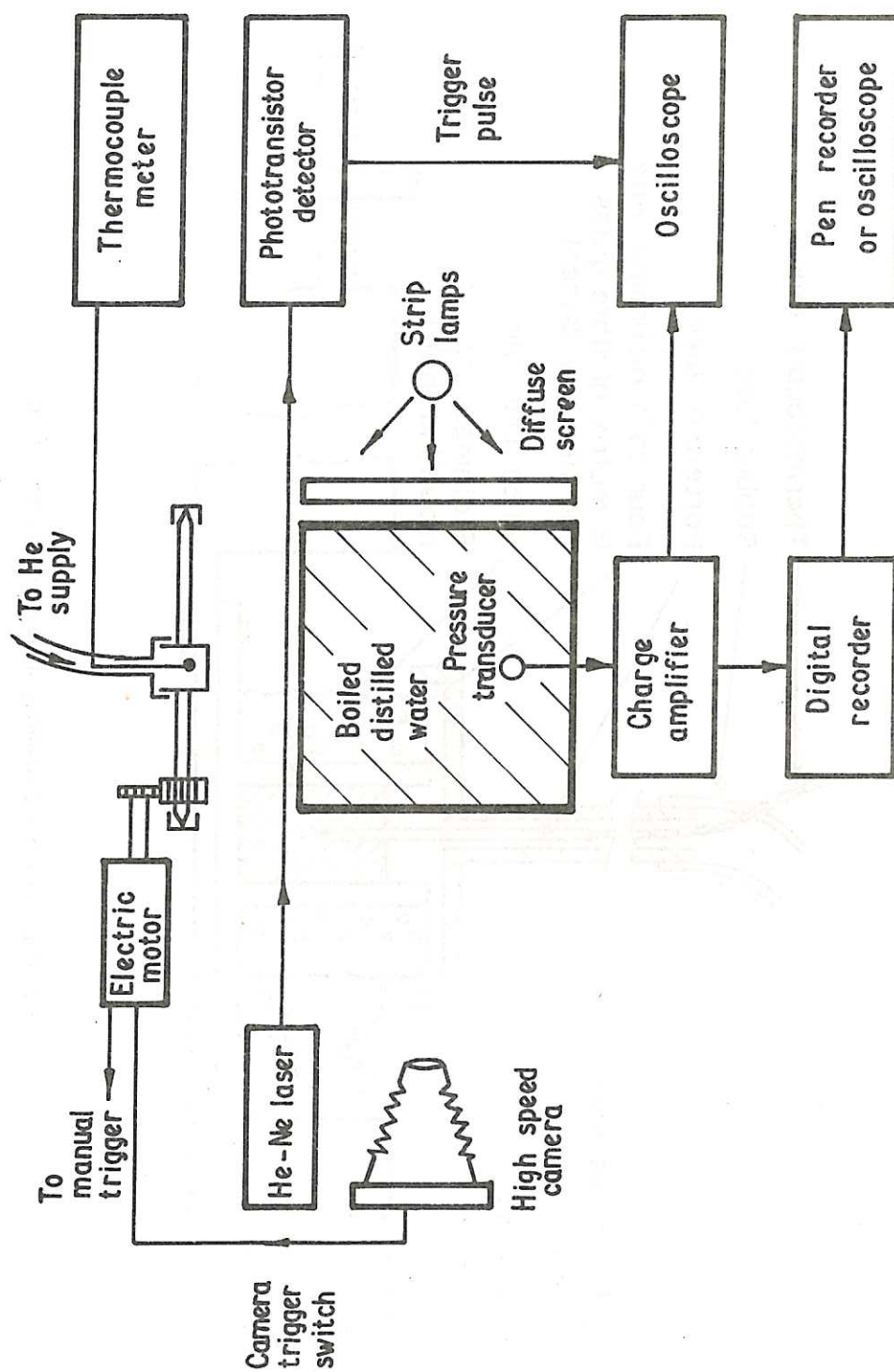
Fig.1 Experimental arrangement

Thermocouple leads

Rubber tube

Porcelain tube

Four coils nichrome wire
in matrix of fibre glass
and fire clay cement

Silica crucible

Stainless steel
mounting bar

Stainless steel
cap

Heating coil
leads
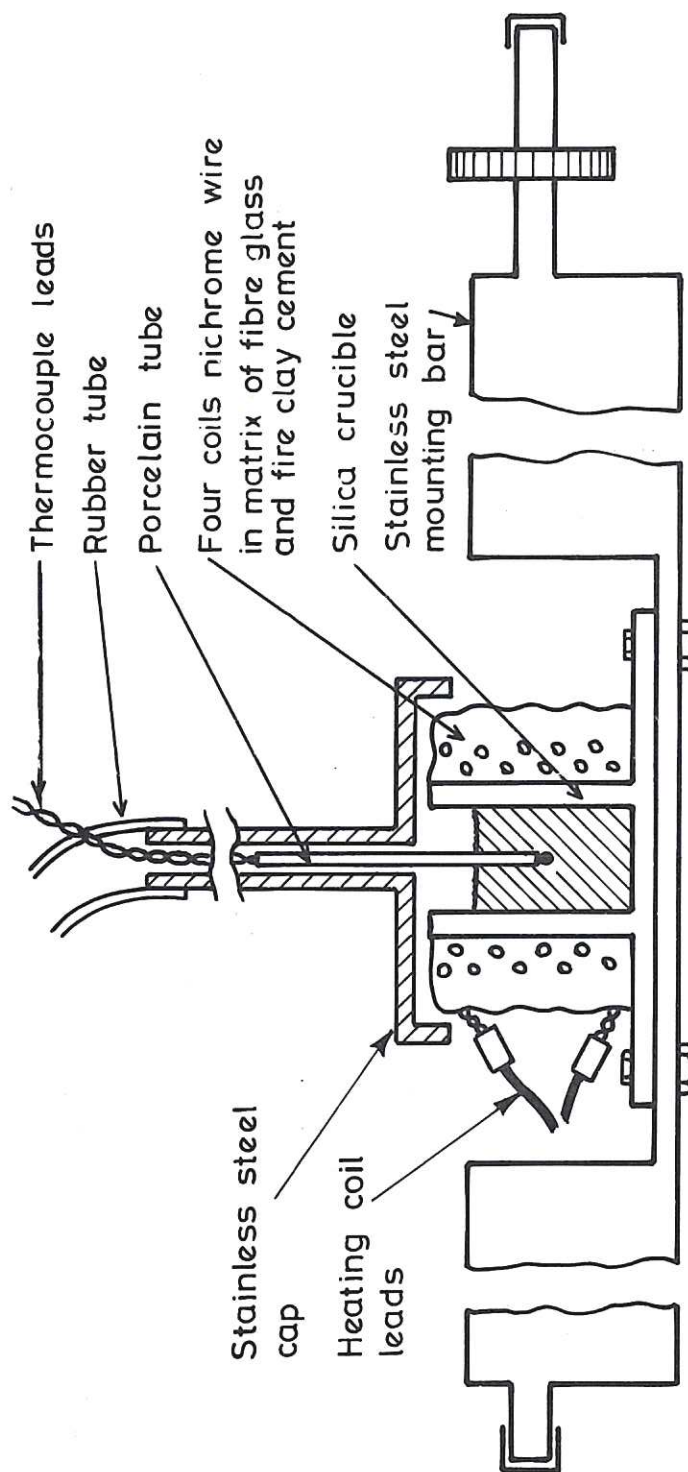
Fig.2   Construction and mounting of crucible and cover gas cap

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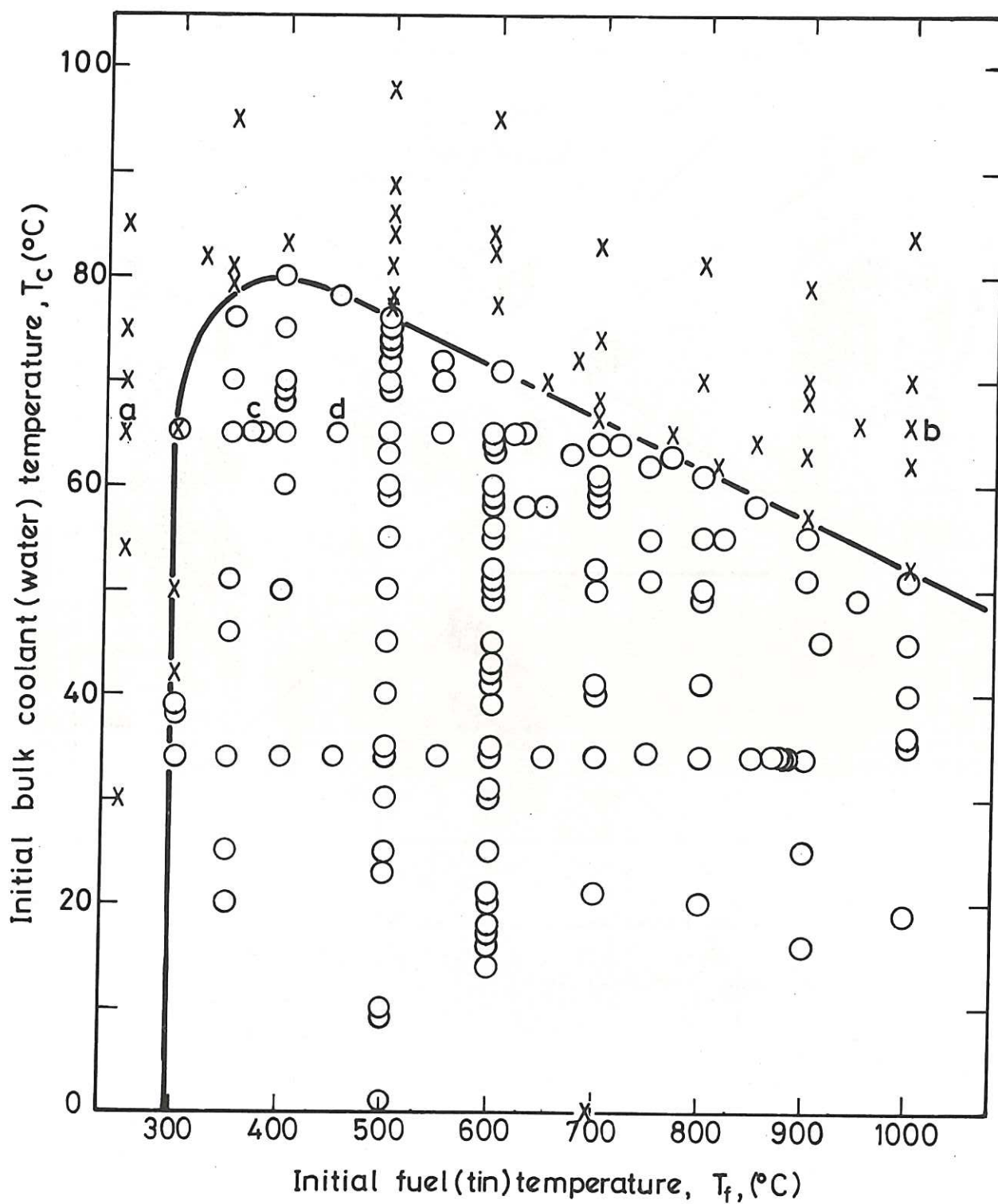
Fig.3 Temperature interaction zone for 12 grams of tin dropped through 3 cm into boiled distilled water.
o indicates an interaction   x indicates no interaction
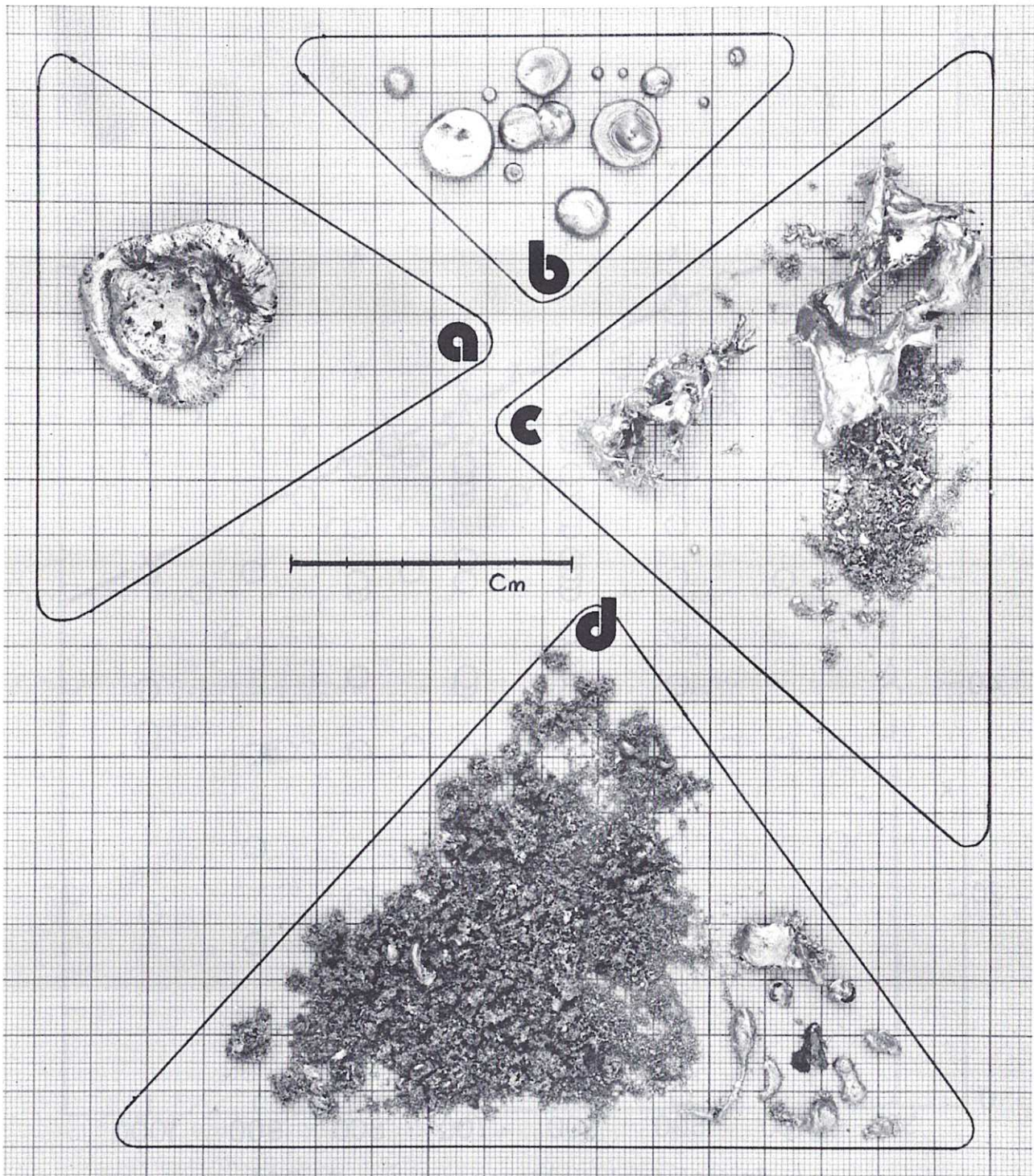
Fig.4   Sequence of pictures of debris as the interaction zone is crossed at a fixed coolant temperature of 65°C.
The positions of these points are also indicated on Figs. 3 and 7.   Initial fuel temperatures are: a, 250°C,
b, 1000°C, c, 370°C, d, 450°C.

Fig.5 Variation of PD with coolant temperature for $T_f = 500°C$. Tin heated by Calor gas flame.
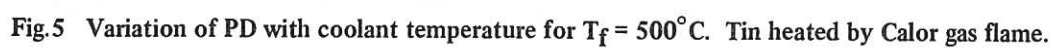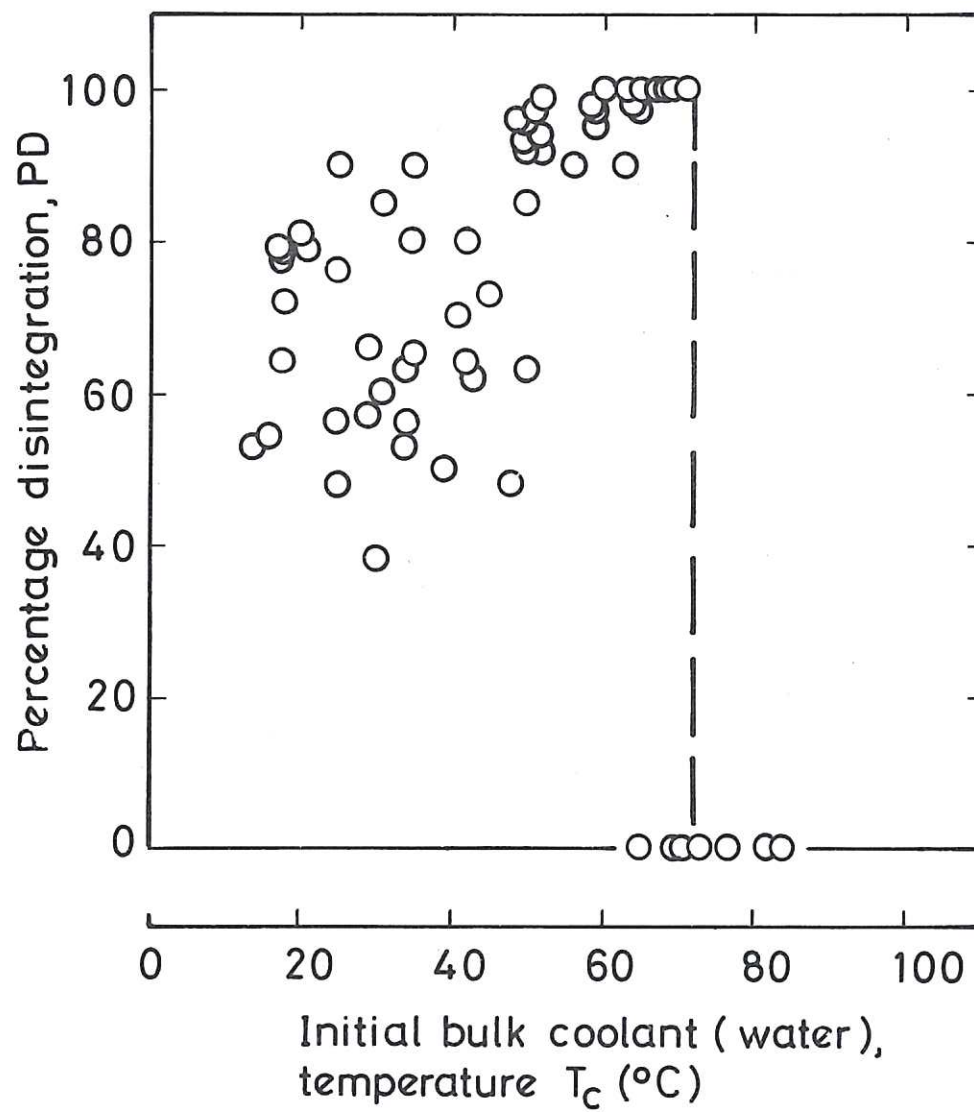
Fig.6 Variation of PD with coolant temperature for $T_f = 600°C$. Tin heated electrically under helium cover gas.
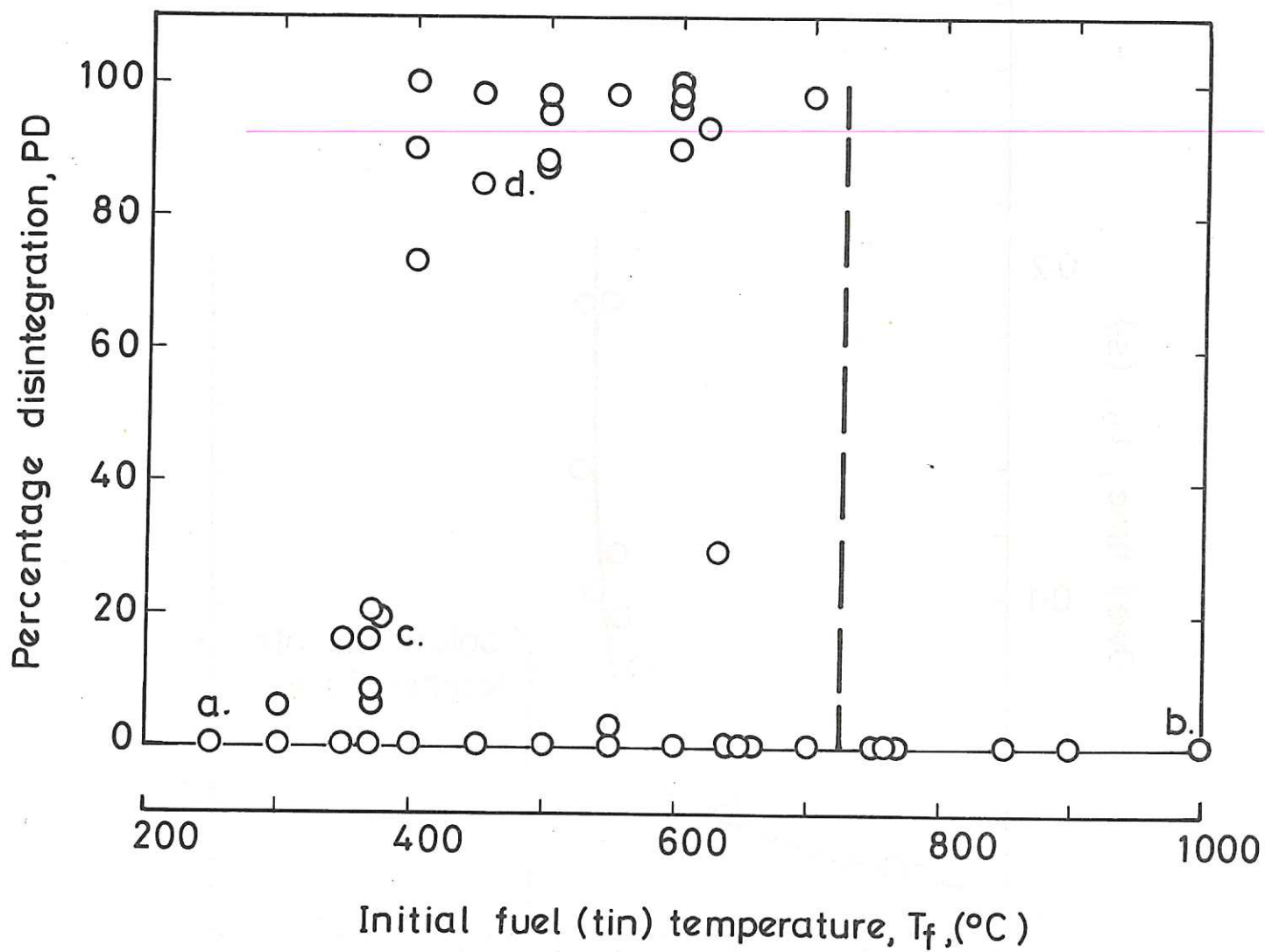
Fig.7   Variation of PD with fuel temperature for $T_c = 65°C$.   The dotted vertical line is the position of the cut-off temperature given by Fig.3 for $T_c = 65°C$.
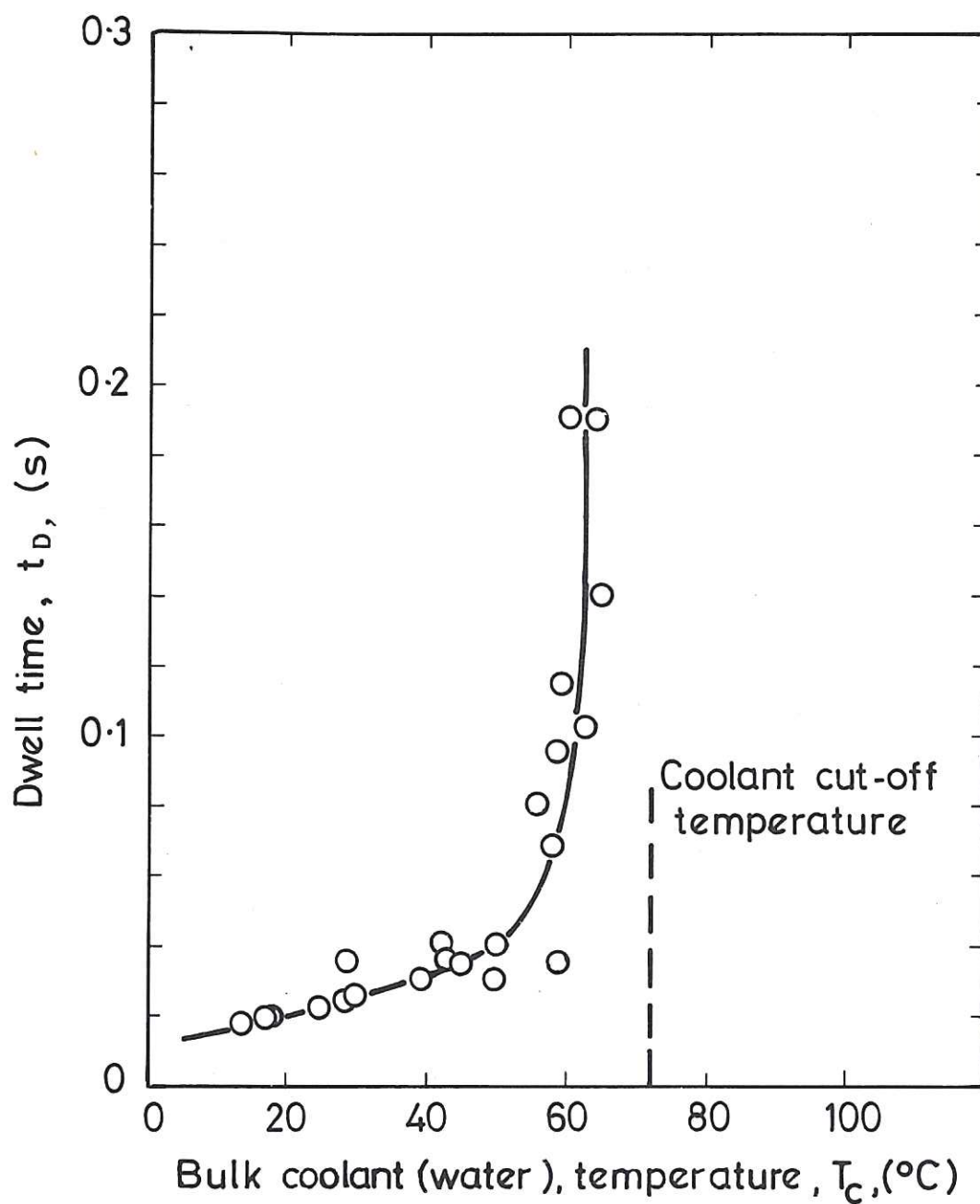
Fig.8 Measured dwell times as a function of coolant temperature for $T_f = 600°C$.
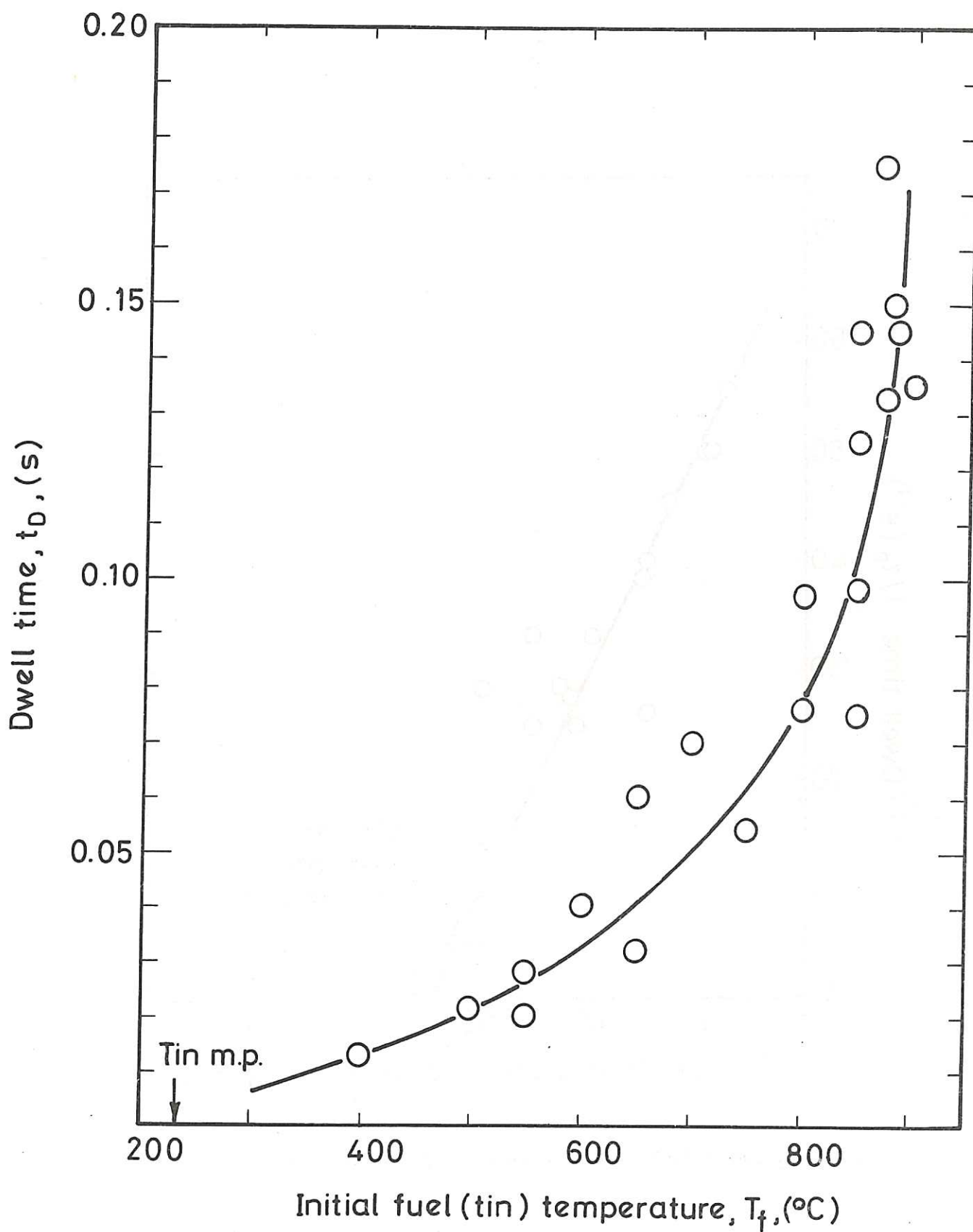
Fig.9 Measured dwell times as a function of fuel temperature for $T_c = 34°C$.
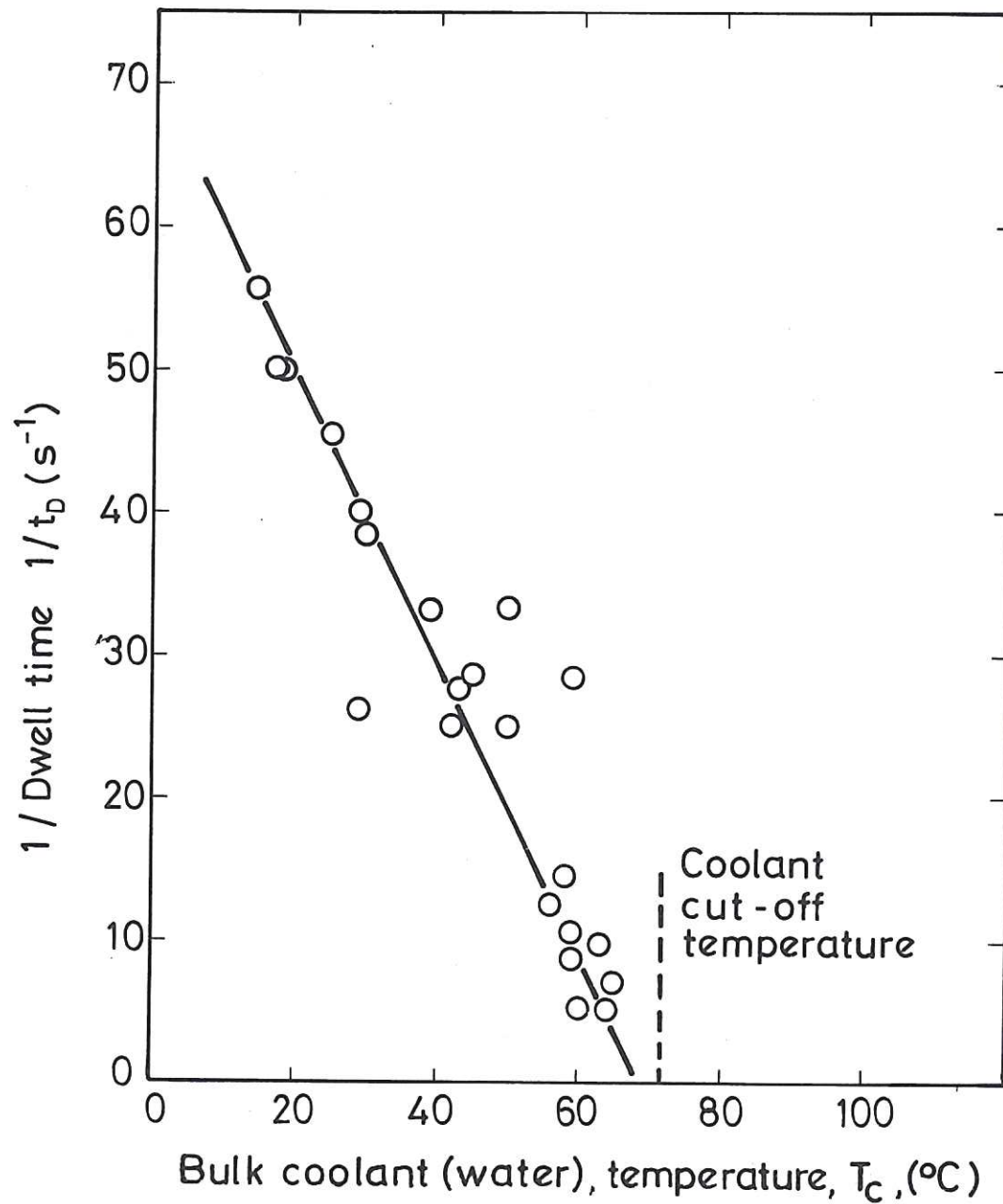
Fig.10 $1/t_D$ against T_c for $T_f = 600°C$. At least squares fit gives $1/t_D = 68.83 - 0.974\ T_c$.
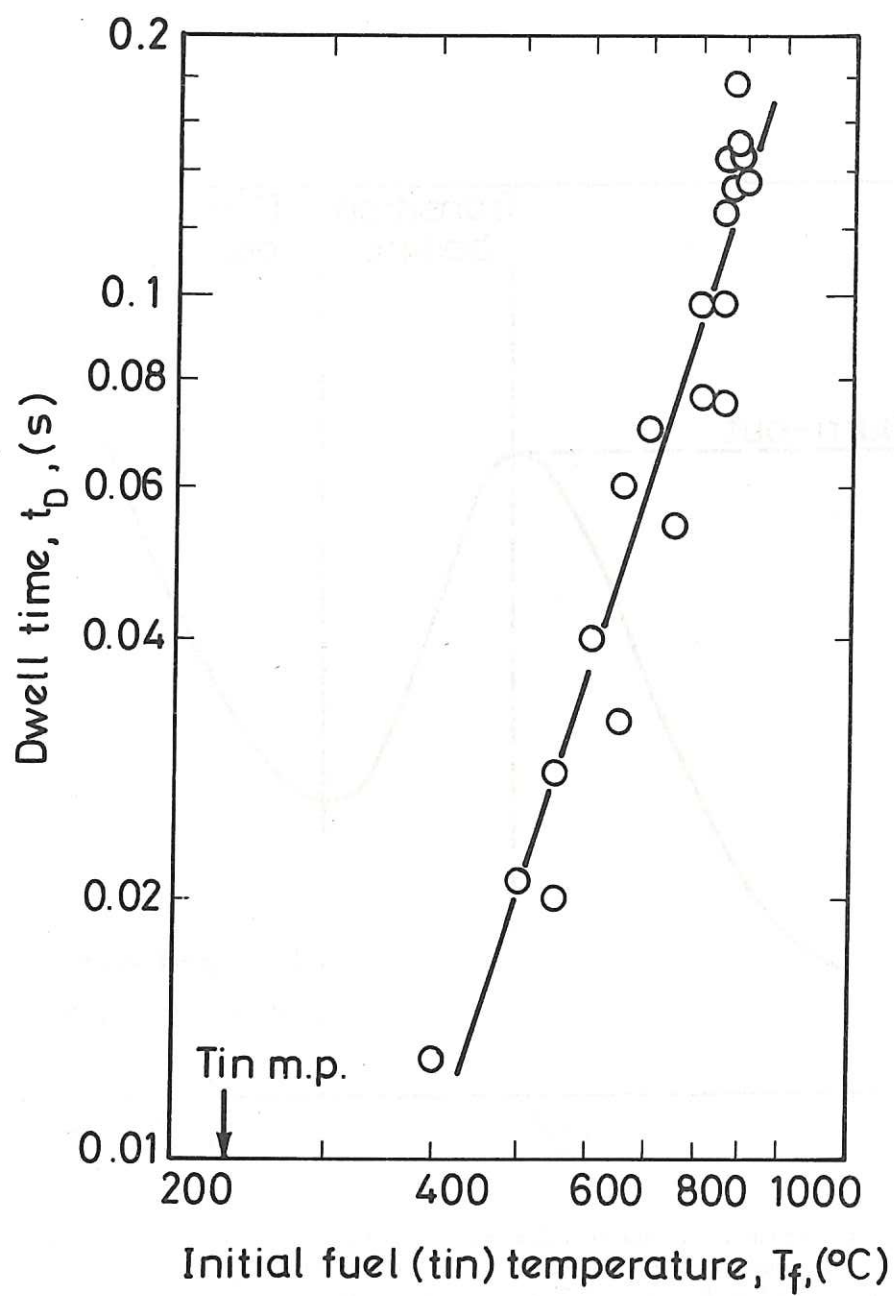
Fig.11 log t_D against log T_f for $T_c = 34°C$.
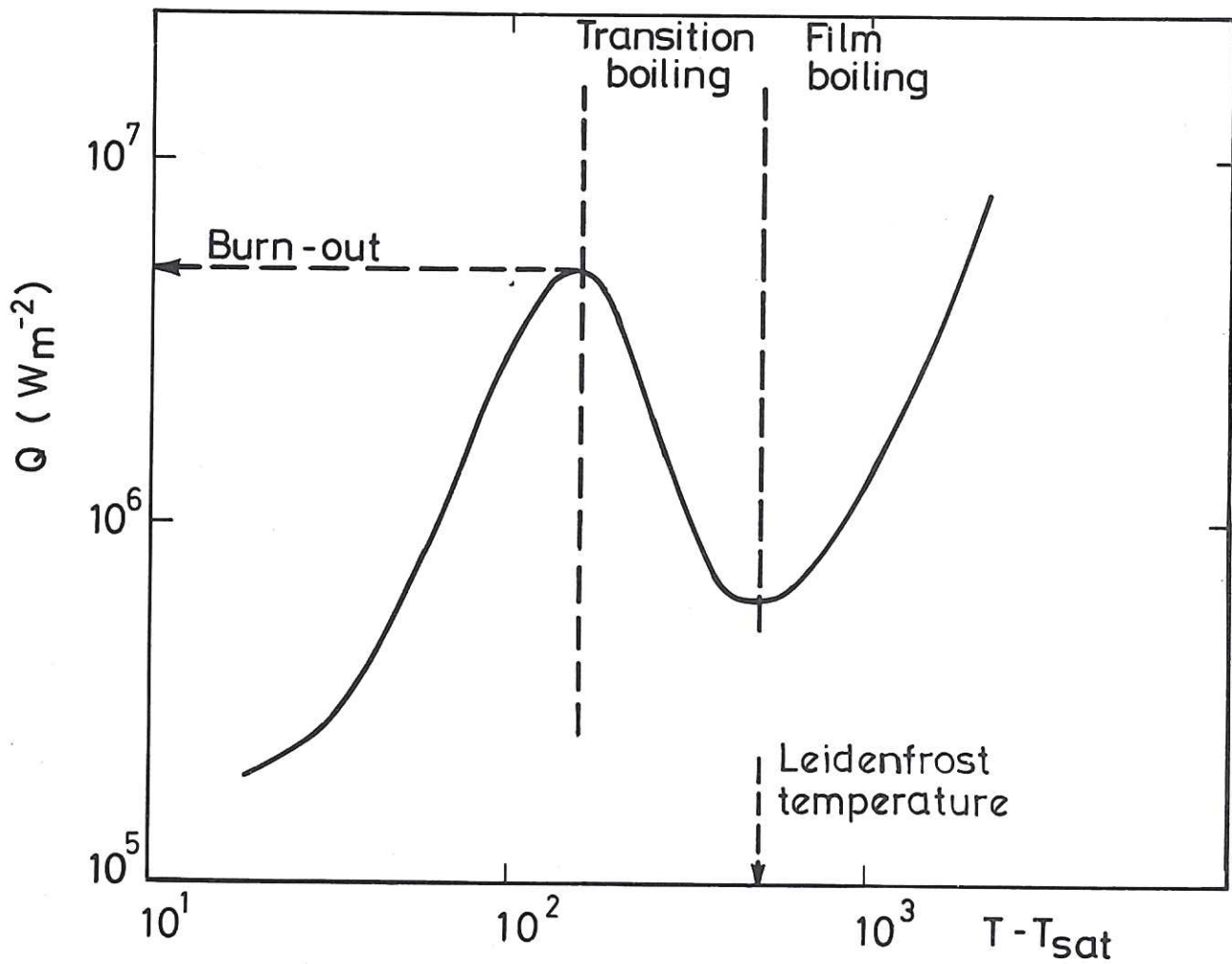
Fig.12   A typical boiling curve. Q is the heat flux and $T-T_{sat}$ the difference between the heating surface temperature and the coolant saturation temperature.   The subcooling is $T_{sub} = T_{sat} - T_c$ where T_c is the coolant temperature.   As T_{sub} is decreased (T_c increased) the transition and film boiling regimes move to the left and the burn-out heat flux is lowered.

Dwell Time $\tilde{t}_D$ (milliseconds)

T_f (°K)
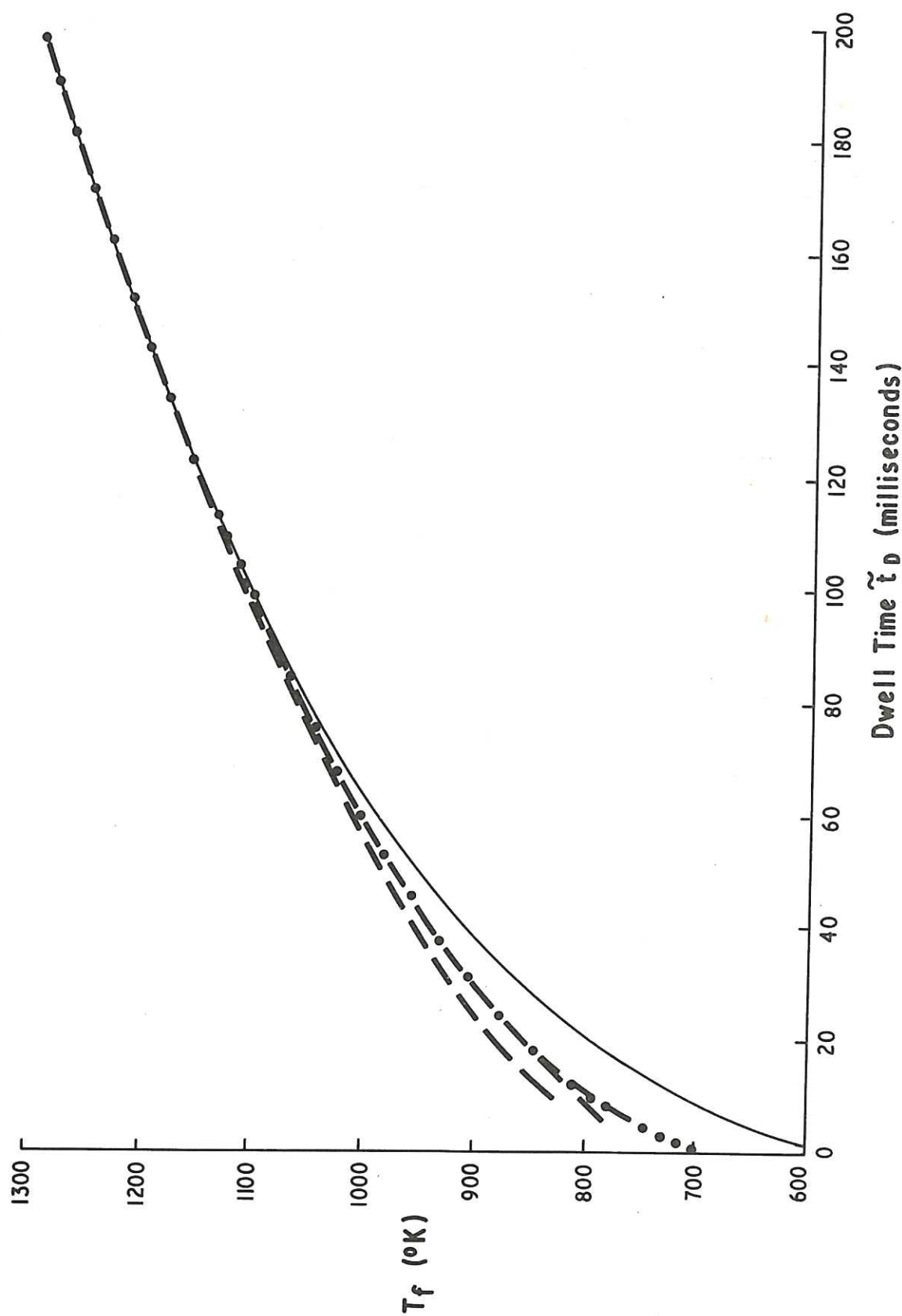
Fig.13 The dwell time $\tilde{t}_D$ as a function of fuel temperature T_f for $T_c = 34°C$. The experimental curve (see Fig.9) is represented by ————. The asymptotic $\sqrt{t_D}$ curve from equation (5) with $T_t = 700$, and a. $(T_t - t_o) = 6 \times 10^6$ is represented by ············ The theoretical curves from equation (2) with $T_t - T_o = 10$, 120 and 200°K for the three curves shown are represented by —————.

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