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**FUEL-COOLANT INTERACTION IN A SHOCK TUBE WITH INITIALLY-ESTABLISHED FILM BOILING**

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**MASTER**

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ABSTRACT

A new mode of thermal interaction has been employed, in which liquid metal is melted in a crucible within a shock tube; the coolant level is raised to overflow the crucible and establish subcooled film boiling with known bulk metal temperature; and a pressure shock is then initiated.

With water and lead-tin alloy an initial splash of metal may be obtained after the vapor film has collapsed, due primarily to thermal interaction, followed by a successive cycle of bubble growth and collapse. To obtain large interactions, the interfacial contact temperature must exceed the spontaneous nucleation temperature of the coolant. Other cutoff behavior is observed with respect to the initial system pressure and temperatures and with the shock pressure and rise time. Experiments with butanol and lead-tin alloy show only relatively mild interactions. Qualitative explanations are proposed for the different behaviors of the two liquids.

1.0 INTRODUCTION

Studies of fuel-coolant interactions have been carried out in the free-contacting (or dropping) mode, in which fuel is poured into coolant<sup>1-5</sup>, or vice versa; injection mode, in which a jet of coolant or fuel is injected into a pool of the other liquid<sup>6</sup>; and in the shock tube mode, in which a coolant column is allowed to impact upon the molten fuel surface<sup>7-9</sup>. While valuable information has been obtained, the first two modes suffer from the disadvantage of uncertain fuel temperature at the instant of triggering the interaction, resulting from the inability to trigger the interaction at will. The third mode, while providing rapid triggering, does not provide for initial contacting between the liquids prior to triggering the interaction, which is characteristic of all large-scale explosions. Large-scale corium-water experiments have been recently carried out with initial film boiling, triggered by a bridge wire or explosive device<sup>10</sup>; however, the strength of the triggering pressure pulse is not well-known. In the present work a different mode of contacting is described, in which liquid metal is melted in a crucible within a shock tube; the coolant level is raised to overflow the crucible and establish subcooled film boiling; and a pressure shock wave is then initiated by rupturing a diaphragm in the driver section.

## 1.1 Previous Work

Several reviews of the vapor explosion literature have been presented earlier<sup>11,12,13</sup>. Hence, only the facts that are of immediate interest will be briefly described here.

In dropping experiments with molten tin and water, it was found that interactions with pressure peaks of  $\sim 10$  bars occurred when the temperatures of the fuel and the coolant lay within a particular range, called the temperature interaction zone (TIZ) by Reynolds, et al.<sup>1</sup>. The cut-off line at an initial tin temperature of  $\sim 300^\circ\text{C}$  could be associated with the freezing of the tin or with the interfacial contact temperature being equal to the spontaneous nucleation temperature of water ( $240\text{-}260^\circ\text{C}$ )<sup>14</sup>. However, additional studies with Freon-water and Gerobend-water<sup>13</sup> have clearly established that the lower cut-off temperature is associated with spontaneous nucleation<sup>15</sup> (Fig. 1). The diagonal cut-off is associated with the stability of the vapor film surrounding the tin droplets with no external triggers. Board, et al.<sup>16,17</sup> conducted several experiments with molten tin and water with various triggers.

With initially coarsely-premixed coolant and fuel, the collapse of the vapor films in some small region may act as a local trigger for fine-scale mixing, which allows escalation to a propagating shock wave. However, a more common mode of interaction is a cyclic mode in which liquid-liquid contact results in vapor nucleation and bubble growth, followed by contraction and further mixing, after which the cycle repeats. This is also the pattern observed in the present experiments, as well as in tin-water experiments with various triggers<sup>16,17</sup>. In both cases the key initiating step, as well as an important elementary step in the cyclic process, consists of collapse of the vapor region.

The destabilization of film boiling on a heated nickel tube due to arrival of a pressure shock was studied experimentally and theoretically by Inoue, et al.<sup>18,19</sup>. Collapse times of the order of 0.1 ms were calculated for Freon 113, which was consistent with observations at 5000 frames/sec. An important observation was that the envelope of peak heat fluxes exhibits a maximum at a calculated interfacial contact temperature well above the critical temperature. This is attributed to the balance between the increased driving force for heat transfer and the increased vapor film stability as the surface temperature is increased. These peak heat fluxes are sensitive to the pressure rise time and the mass of vapor film (and hence to the initial pressure). Free dropping experiments with Freon and oil<sup>20</sup>, as well as shock tube experiments with Wood's metal and water or butanol<sup>7</sup>, have shown that interactions will cease if the initial pressure is above 2 bars.

## 2.0 EQUIPMENT AND PROCEDURE

### 2.1 Shock Tube

The shock tube is basically that described previously<sup>18</sup>, (Fig. 2), consisting of a vertical test section separated from the driver section by a thin mylar membrane. The test section contained an electrically-heated stainless steel crucible, 22 mm diameter x 13 mm, filled up to the rim with 42 g of lead-tin solder.

The initial metal temperature, measured at steady state prior to raising the coolant level, was controlled within  $\pm 2^\circ\text{C}$ . However, the time lag between the liquid overflowing the crucible and the shock passing the crucible was  $\sim 1.5$  s. About 400 experimental runs were performed with reagent-grade n-butyl alcohol and distilled water as coolants and 60/40 lead-tin alloy (m.p.  $187^\circ\text{C}$ ) as the liquid metal (fuel).

With water the parameter ranges were:

1. The pressure of the driver section,  $P_2$ : 1-10.2 bars.
2. The rise time of the shock,  $\tau$ : 38  $\mu\text{s}$ , 0.3 ms, 1.2 ms, 2.9 ms, 0.1 s and 0.5 s.
3. The pressure of the test section,  $P_1$ : 0.33-3.5 bars.
4. The temperature of the fuel,  $T_h$ : up to  $550^\circ\text{C}$ .
5. The temperature of the water,  $T_c$ :  $40$ - $99^\circ\text{C}$ .

With butanol the following test parameters were used:  $\tau = 38 \mu\text{s}$ ;  $T_c = 45^\circ\text{C}$ ;  $P_1 = 0.33, 1$  and  $2.3$  bars.  $P_2$  and  $T_h$  were varied in the same range as with water.

## 3.0 EXPERIMENTAL RESULTS

The choice of butanol and water was governed by previous shock tube results<sup>25,26</sup> in which several coolants (Freon 11, Freon 22, n-butanol, water) were impacted upon the surface of several hot liquids (silicone oil, Wood's metal, mineral oil), and significant thermal interactions were found only with Wood's metal/water, and to a lesser extent Wood's metal/butanol.

The fragmentation resulting from various pressures of the driver and test sections ( $P_2$  and  $P_1$ ) are summarized in Table 1. We define the strength of the thermal interaction in terms of  $E$ , the fraction fragmented: small  $E < 0.25$ ; medium  $0.25 < E < 0.6$ ; large  $0.6 < E < 1$ .

Table 1: Fragmentation with Butanol.  $T_h \sim 320-380^\circ\text{C}$ 

Series	A	B	C	D	E
$P_2$ , bars	3.75	5.1	6.5	6.5	6.5
$P_1$ , bars	1	1	1	0.33	1.7
$P_2/P_1$	3.75	5.1	6.5	19.7	3.83
E, fraction fragmented	0-0.16	0.16-0.33	0.33-0.50	0.5-0.8	0-0.16
Max. $P_{\text{max}}$ , bar	4.7	6	9	15	7

From the table it appears that the fragmentation is a function primarily of the pressure ratio,  $P_2/P_1$ , rather than either the driver pressure or the pressure difference  $\Delta P = P_2 - P_1$ .

The effects of the fuel temperature on the fragmentation and the peak pressures are shown in Fig. 3. In general, medium fragmentation occurs when the hot surface temperature is in the range,  $T < T_h < 265^\circ\text{C}$ . For  $T_h > 290^\circ\text{C}$ , which coincides with the critical temperature<sup>m</sup> of butanol, generally large fragmentation is observed up to  $T_h \sim 385^\circ\text{C}$ . For  $T_h > 385^\circ\text{C}$  medium and sometimes large interactions occur.

For  $T_h > 290^\circ\text{C}$ , the amplitude of the third pressure peak increases with temperature up to  $T_h \sim 370^\circ\text{C}$ , where it exceeds even the first peak amplitude. Increases of  $T_h$  above  $370^\circ\text{C}$  reduce the magnitude of the third peak. When a pressure shock was applied the percentage was much larger than that achieved with butanol under similar conditions, and in many cases most of the metal in the crucible was affected by the interaction. The fragmentation is now considered large when  $E > 0.75$  with most of the metal in the crucible fragmenting into fine debris. The fragmentation is now termed medium when  $E > 0.5$ . Here some metal is left in the crucible and some of the debris is rough, as with butanol. The fragmentation is now termed small when  $E < 0.5$ . Here most of the metal remains in the crucible and the debris fragments are large and rough.

When the water and the metal are both at room temperature the isothermal pressure trace jumps to about  $0.7 P_2$ , followed by strong or mild ringing of the system, depending on  $P_1$ . After about 8-10 ms a strong peak occurs that in some cases exceeds  $P_2$ .

When a thermal interaction occurs the pressure trace is quite different. A series of usually four separated peaks, each one larger than the other, (although sometimes the third peak was larger than the fourth) occurs at the following times after the shock passed: first peak  $t = 1-4$  ms; second peak  $t = 5-11$  ms; third peak  $t = 15-28$  ms and the fourth at  $t = 33-52$  ms. A fifth peak sometimes occurred at high metal temperatures ( $T_h > 380^\circ\text{C}$ ) at  $t > 55$  ms, but it was usually weaker than the third and the fourth peaks.

The pressure dropped slowly after the second and third peaks, and in most cases where large interactions were observed the pressure fell below atmospheric.

The degree of fragmentation as a function of the initial driver and test section pressures,  $P_2$  and  $P_1$ , is shown in Fig. 4. In the pressure range investigated here there is no test section cut-off pressure above which fragmentation does not occur, for any driver pressure investigated. Fig. 4 suggests that the strength of the interaction depends on the pressure ratio,  $P_2/P_1$ , rather than the pressure difference or either pressure alone.  $P_2/P_1 > 3.3$  usually implies large fragmentation for  $T_h \sim 35-45^\circ\text{C}$  and  $\tau \approx 38 \mu\text{s}$ . For  $P_2/P_1$  slightly less than 3.3, and other conditions unchanged, medium interaction usually occurs, becoming milder as the pressure ratio becomes smaller. For  $P_2/P_1 < 2.2$  no interaction occurs.

The effect of the hot metal temperature, at the time the shock has passed, on the peak pressure and fragmentation is shown in Fig. 5 for:  $P_2 = 5.1 \text{ bar}$ ,  $P_1 = 1 \text{ bar}$ ,  $T_c = 35-45^\circ\text{C}$  and  $\tau = 38 \mu\text{s}$ .

The interfacial contact temperature,  $T_I$ , corresponding to  $T_h$  is also shown in the figure. This temperature is calculated from the following equations:

$$T_I = (T_c + \gamma T_h) / (1 + \gamma) \quad (1)$$

where

$$\gamma^2 = (k\rho C)_h / (k\rho C)_c \quad (2)$$

where subscripts h and c refer to the hot and cold liquids, respectively. For water and 60/40 lead-tin alloy,  $\gamma = 5.9$ . Five different regions can be distinguished in Fig. 5:

- A. For  $T_h < T_m$  (melting temperature) no interaction is possible. The first pressure peak is the largest, and usually the only distinct peak.
- B. For  $T_m < T_h < 210^\circ\text{C}$  (where  $T_I \sim T_m$ ) some minor fragmentation may occur.
- C. For  $210 < T_h < 275^\circ\text{C}$  small and medium interaction occurs with maximum pressure peaks of about  $1.5 P_2$ .  $T_h = 275^\circ\text{C}$  corresponds to  $T_I \sim 245^\circ\text{C}$ , which is near the lower limit of the temperature range for spontaneous nucleation of water. Many experimental studies have shown that  $T_{sn}$ , the spontaneous nucleation temperature of water, is less than  $T_{hn}$ , the homogeneous nucleation temperature ( $\sim 305^\circ\text{C}$ ). For water in contact with poorly-wetted surfaces,  $T_{sn} \sim 240^\circ\text{C}$ , and may even be lower<sup>14</sup>.
- D. For  $275^\circ\text{C} < T_h < 350^\circ\text{C}$  ( $T_{sn} < T_I < T_{hn}$ ) large fragmentation is achieved with maximum peak pressures in the range of 20 bars.

- E. For  $T_I > 350^\circ\text{C}$  ( $T_I > T_{I,sn}$ ) large fragmentation is achieved, with maximum peak pressures as high as 35 bars. For the latter two regions, subatmospheric pressures are observed between the interactions. Unlike butanol, there is no region of decreasing pressure peaks with metal temperature for  $T_I \leq 500^\circ\text{C}$ . This agrees with the observations of Inoue and Bankoff<sup>18</sup> that the peak heat transfer, averaged over about 1 ms after collapse of a vapor film around a horizontal heated nickel tube, occurred at a reduced temperature,  $T_r = T_I/T_{I,sn}$ , of about 1.1-1.3, depending on the rise time  $\tau$  of the pressure rise across the shock and the liquid subcooling. For  $T_I > 1.2$  this corresponds to  $T_h > 590^\circ\text{C}$ . With butanol, however, this maximum heat flux should occur at  $T_r = 389^\circ\text{C}$ . Indeed, a maximum in the pressure peaks occurs at  $T_I \sim 370^\circ\text{C}$  ( $T_r = 1.14$ ).

The dotted lines show average pressure curves for the first, second, third, fourth and fifth peaks. It is seen that the first peak is small and does not increase much with metal temperature, indicating largely hydrodynamic collapse pressures. The second peak is somewhat larger, increasing with  $T_h$ , indicating incomplete interaction (small penetration of fuel by coolant). The third and fourth peaks are the large ones, and demonstrate the importance of the interfacial contact temperature. For  $T_I < T_{I,sn}$ , interactions are very minor, in accordance with the Fauske spontaneous nucleation theory. For  $T_I > T_{I,sn}$ , a sharp rise in peak pressures occurs, and for  $T_I > T_{I,sn}$ , the maximum peak pressures are observed. The latter observation may be connected with the fact that coolant comes into contact with nearly pure metal prior to the third and fourth interactions, so that the spontaneous nucleation temperature is maximized.

In addition to  $P_1$ ,  $P_2$  and  $\tau$ , it is found that both water and metal temperatures have a strong effect on the fragmentation. The temperature interaction zones (TIZ) for  $P_2$  of 2.4 and 5.1 bars are shown in Figs. 6 and 7, with  $P_1$  bar and  $\tau = 38 \mu\text{s}$ . The vertical cut-off line is associated with  $T_I \sim T_{I,sn}$  for water, since  $T_I > T_m$ , the melting temperature. On the other hand, a surface oxide layer is observed which hinders initial mixing. The diagonal cut-off line is a function of the pressure shock strength: stronger shocks will shift the line upwards to the right, increasing the interaction zone. This confirms that the diagonal cut-off line is associated with the stability of the vapor film.

The fragmentation achieved with different orifices and different pressures is shown in Fig. 8 for  $T_h = 380-400^\circ\text{C}$  and  $T_c = 35-45^\circ\text{C}$ . For  $\tau < 0.5$  ms the cut-off pressure ratio is  $\sim 2.2$ , independent of  $\tau$ . For  $0.5 < \tau < 3$  ms the cut-off ratio increases slightly with  $\tau$ , while for  $\tau > 3$  ms much stronger shocks are required as  $\tau$  increases.

#### 4.0 DISCUSSION

The explanations given by Board, et al.<sup>16</sup> for their results can be generally applied also to the present geometry. The shock wave provides the initial trigger that collapses the vapor film, and a cycle of bubble growth and collapse provides the mixing and the propagation steps.

#### 4.1 Vapor Collapse

The cyclic escalation process suggested by Ochiai and Bankoff<sup>22</sup> in their "splash" theory focussed on the formation of a high pressure interfacial vapor layer in the region of random liquid-liquid contact. The expansion of this vapor drives a splash jet of hot liquid into coolant, resulting in increased interfacial area and possible escalation. In the present geometry only very minor fragmentation is observed without a shock, when the vapor collapses due to surface cooling. The small tongues of metal obtained in this case indicate that splashes of metal are produced due to the liquid-liquid contacts. However, due to incoherency and rapid freezing, the splashes do not escalate in this confined geometry.

As the vapor layer becomes more stable a stronger pressure shock is required to initiate the interaction. A similar conclusion was drawn by Bankoff, et al.<sup>23</sup> in a study of the stability of Leidenfrost boiling. Inoue, et al.<sup>19</sup> suggested that only partial contacts are made when the vapor collapses. The collapse is effective when the heat transfer between the coolant and the hot surface is dominated by the direct contact, (large contact area) and when the average approach distance is small compared to the largest surface roughnesses, resulting large pressures in the vapor or supercritical fluid. It was also found that owing to the large vapor mass at higher system pressures, the film is stabilized, so that stronger shocks are required for effective collapse. When the system pressure is below ambient, effective collapse can be obtained with weak shocks. The present results are in agreement with these conclusions. Thus, the fact that the fragmentation and the maximum pressure peaks depend on  $P_2$  may be partly attributed to the incomplete initial vapor collapse. Another factor is the oxide layer, which is fractured more readily with stronger shocks.

The effect of the pressure rise time,  $\tau$ , can also be explained by their observations. The effectiveness of the vapor collapse decreases with increasing  $\tau$ . For  $\tau > 0.3$  ms ( $P_2 = 4$ ,  $P_1 = 1$  bar) effective collapse is not obtained with Freon, regardless of  $T_h$ .<sup>1</sup> For water with  $\tau > 3$  ms, strong shocks are required for effective collapse (Fig. 8).

The first interaction is distinguished from subsequent interactions by the fact that there is a coherent oxide layer on the liquid metal surface prior to vapor collapse. This is similar to the situation which obtains with other liquid metals interacting with water, as with aluminum-water, steel-water and tin-water explosive boiling. The impulse due to vapor film collapse must be sufficient to fracture this oxide layer, making line contacts of coolant and underlying hot metal. These line contacts result in local splashes, due to generation of local pressure corresponding to the metal-coolant interfacial contact temperature. The impulse produced can be approximated by

$$I = A t_r (P_v - P_\infty) \quad (3)$$

where  $t_c$  is the line contact residence time,  $(P_v - P_\infty)$  is the resulting pressure difference, and  $A$  is the effective contact area.

The vapor pressure of water is higher than that of butanol, and the ratio of their critical pressures is 5.01. Hence  $P_v$  for water is probably higher than that for butanol with the same initial system and shock parameters, despite the fact that the product  $k\rho C$  is four times larger for water than for butanol, and hence the interfacial temperature with water is considerably lower, for the same metal temperature. As a result larger amounts of metal are expelled out of the crucible with water. This conclusion is in agreement with the present observations and can explain the fact that with water the cut-off pressure ratio,  $P_2/P_1$ , is about 2.2-3.3 while for butanol it is about 6.5.

Since  $P_v$  and  $A$  depend upon the effectiveness of collapse the impulse is smaller as the vapor film becomes more stable for a given trigger. Hence, the cut-off behavior related to system initial pressure and shock strength should be directly related to the magnitude of the impulse in the first interaction. Furthermore, the Jakob number for water is greater than that for butanol, mainly due to the lower molecular weight, and hence vapor density, of water. This implies faster bubble growth and collapse, and hence finer fragmentation.

## NOMENCLATURE

A	-	Contact area
C	-	Specific heat
E	-	Fraction fragmented
I	-	Impulse
k	-	thermal conductivity
P	-	Pressure
$P_1$	-	Initial test section pressure
$P_2$	-	Initial driver section pressure
T	-	Temperature
t	-	Time
$t_r$	-	Contact residence time
$\rho$	-	Density
$\tau$	-	Pressure rise time constant

## SUBSCRIPTS

c	-	Coolant
cr	-	Critical
h	-	Hot
hn	-	Homogeneous nucleation
I	-	Interface
l	-	Liquid
m	-	Melting
sn	-	Spontaneous nucleation
v	-	Vapor
o	-	Initial
1	-	Ahead of the shock front
2	-	Behind the shock front
$\infty$	-	Ambient

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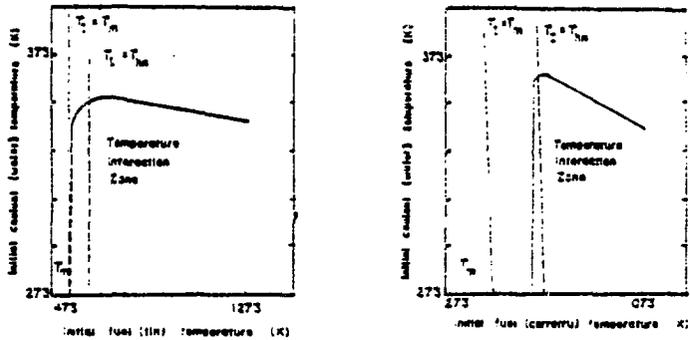


Fig. 1. Spontaneously triggered TIA in different systems (after Dulliford et al. 12).

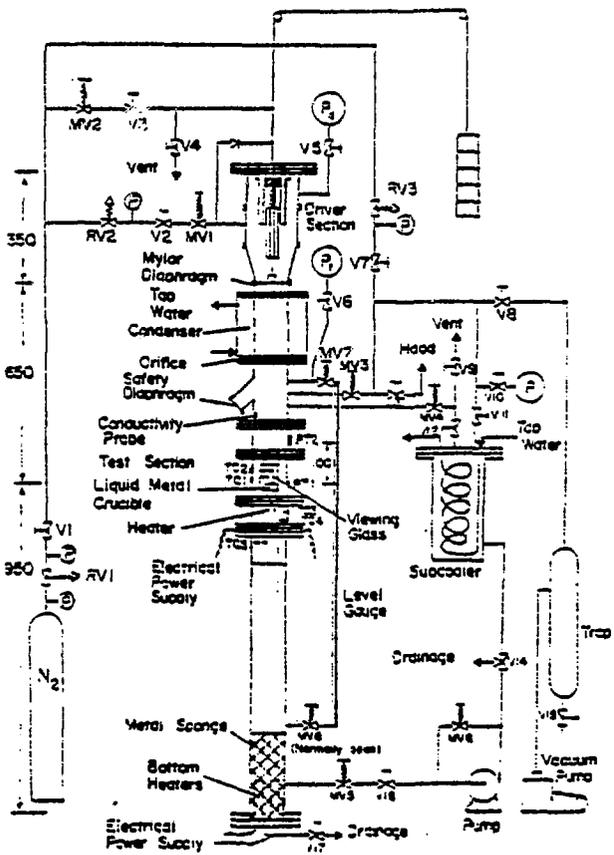
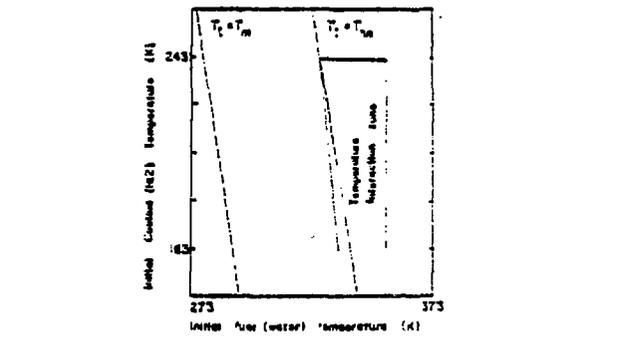


Fig. 2. Schematic description of the apparatus used in the experiments. V1 - magnetic valve, V2 - regulating valve, V3 - manual valve, V4 - magnetic valve, V5 - magnetic valve, V6 - magnetic valve, V7 - regulating valve, V8 - manual valve.

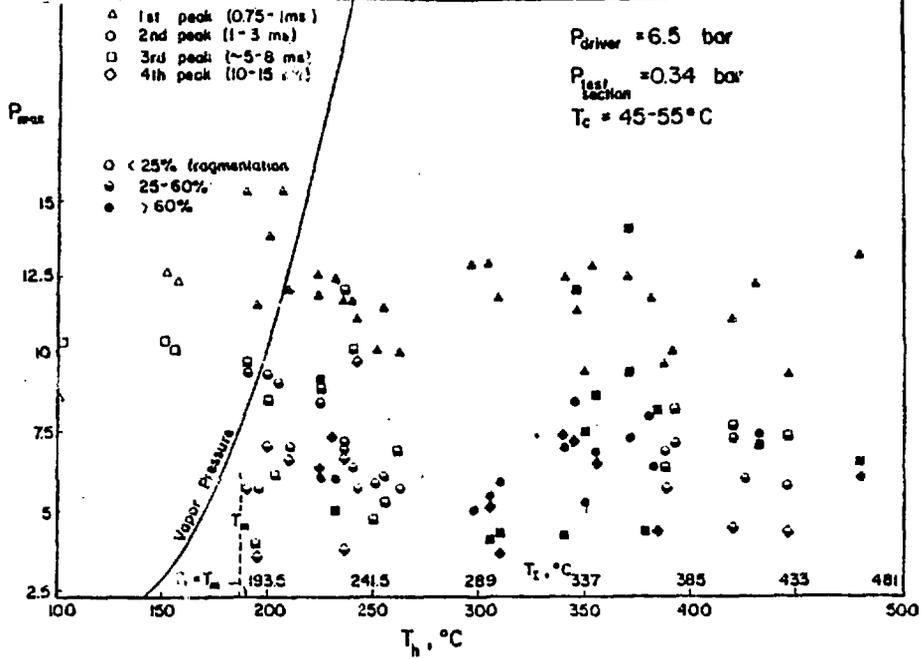


Fig. 3 Effect of the hot metal temperature on the peak pressures and fragmentation with boron. Parameters as for Fig. 4.

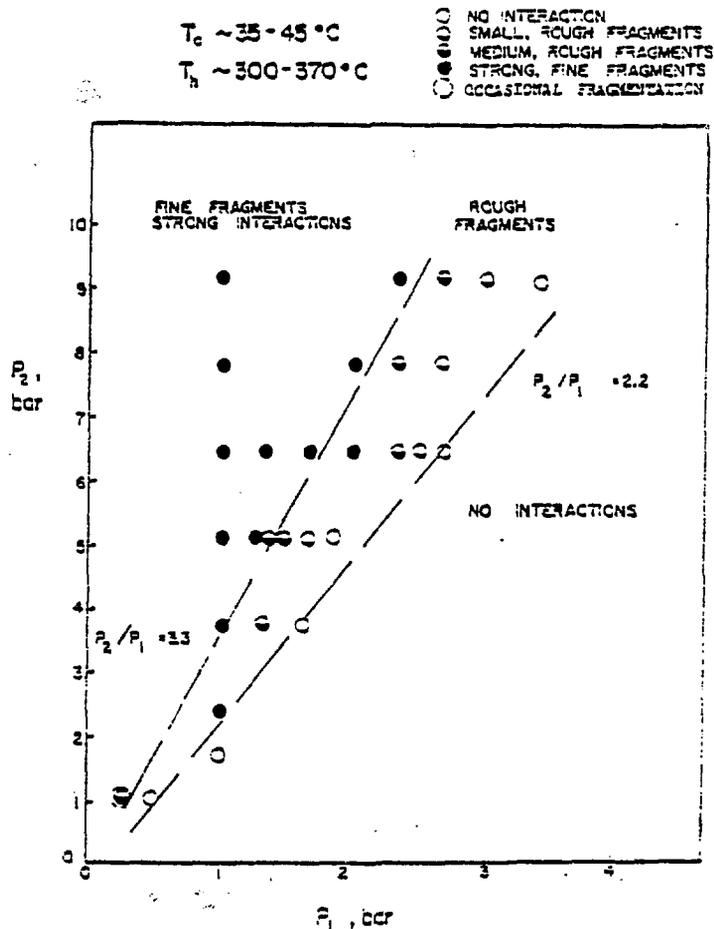


Fig. 4 Fragmentation regions as a function of the initial driver and last section pressures at  $T_c = 45^\circ\text{C}$ .

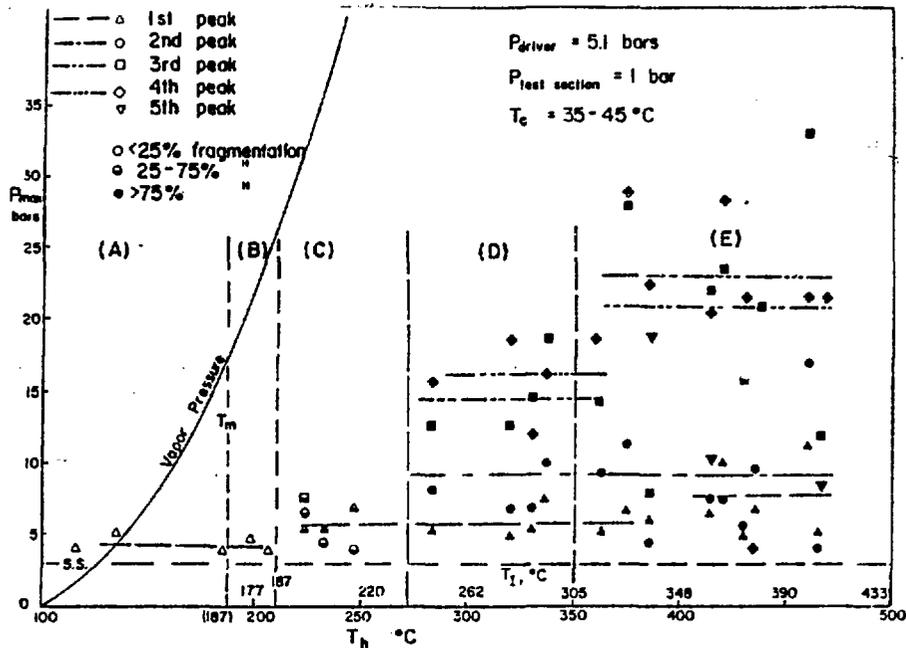


Fig. 5 Effect of the hot metal temperature ( $T_h$ ) on the peak pressure and fragmentation with water.

$P_2 = 5.1$ ,  $P_1 = 1 \text{ bar}$ ;  $T_c = 35-45 \text{ }^\circ\text{C}$ ;  $t = 18 \text{ } \mu\text{s}$ .

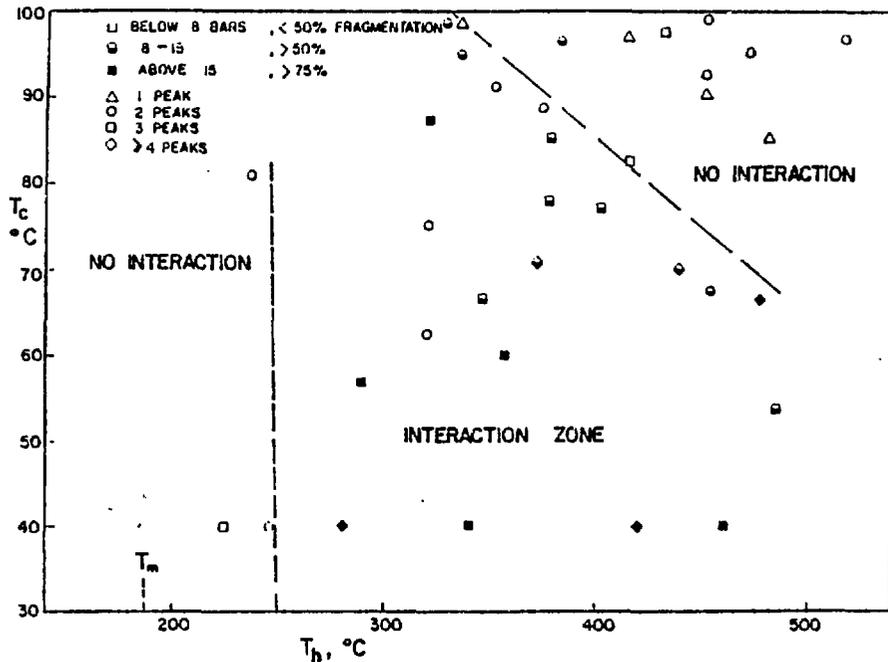


Fig. 6 Temperature interaction zone (TIZ) for water with

$P_2 = 5.1 \text{ bar}$ ,  $P_1 = 1 \text{ bar}$ ;  $t = 18 \text{ } \mu\text{s}$ .

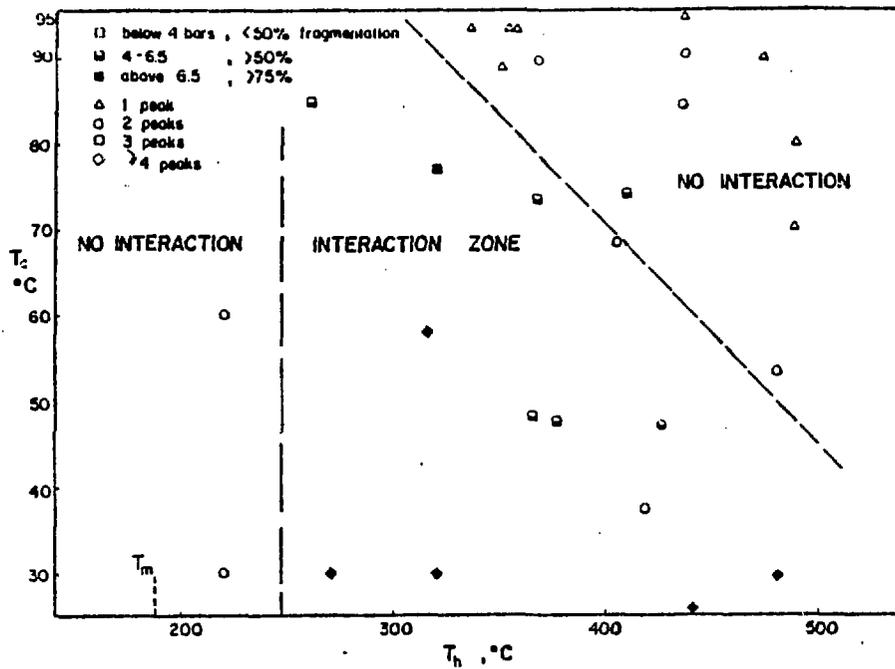


FIG. 7 T2 vs water with  $P_2 = 2.4$  bar,  $P_1 = 1$  bar,  $t = 10$  ms.

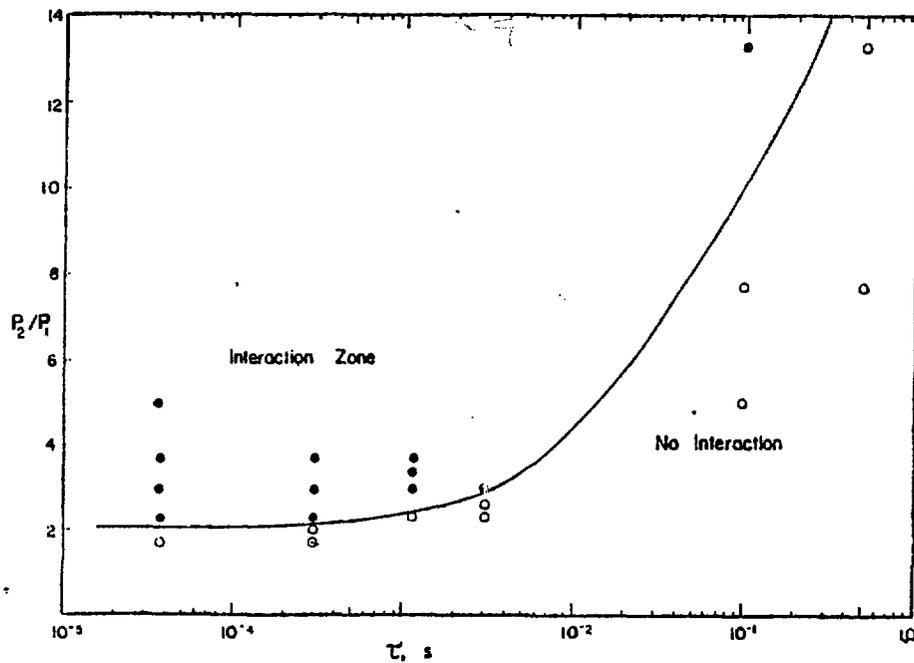


FIG. 8 Effect of the shock rise time on the required retarding pressure ratio.  $T_2 = 40$  °C,  $T_h = 370-450$  °C.