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Fuel-Coolant Interactions in a Shock-tube Geometry

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Abstract

Shock tube experiments with a variety of liquids have been conducted, in which large pressures were obtained for systems of water-Wood's metal, butanol-Wood's metal, and water-molten salt. With water-Wood's metal three separate regions were observed. When the hot liquid temperature was below 210 C (which can be identified as the spontaneous nucleation temperature) no thermal interaction occurred, and the cold liquid column only bounced if vapor was present initially (region A). When the hot liquid temperature was greater than the spontaneous nucleation temperature but the contact interface temperature was less than this value (region B) the low rate of vaporization resulted in bouncing of the liquid column which in turn produced high pressures on the order of the theoretical "water hammer" pressure. Those hydrodynamic pressures are larger than the vapor pressure corresponding to the bulk temperature of the hot liquid and larger than the maximum pressure which may be generated from single phase pressurization. The third region observed when the hot liquid temperature was above the spontaneous nucleation temperature upon contact (region C) resulted in fast production of vapor and impulses larger than the theoretical impulse for stopping the liquid column. The mechanism for producing the high pressures in region C is a combination of hydrodynamic impact and thermal interaction. Since pressures produced in region C are also on the order of impact pressures, the only indication for thermal interaction is a considerable increase in the resulting impulse of pressure pulses with short rise time (<1.0 msec).

When the initial pressure in the system was increased (by means of a thicker diaphragm), the bouncing behavior was suppressed. This was evident from the reduced number of bounces (if any at all), the low relative pressures and impulses, the temperature history and the shape of pressure pulses. Experiments conducted with Freons and oils (mineral and silicone), which did not result in any explosive type of interaction, also fall in a high pressure category and are in agreement with pouring experiments.

As was shown here, the hydrodynamic effects may be very significant in any shock tube analyses, especially when multiple interactions are observed. However, this was not the case in Wright's experiments in which no bouncing was observed and the pressures generated on the first impact were much higher than the theoretical impact pressure. From mixing and heat transfer considerations it is shown that a limited amount of hot liquid can transfer its energy to the cold liquid during the intermixing stage and produce the observed pressures.

INTRODUCTION

The contact of two liquid materials, one of which is at a temperature substantially above the boiling point of the other, can lead to vaporization on a time scale consistent with large shock wave formation. This well-known phenomenon, which is sometimes called a "vapor explosion", is characterized by sudden fragmentation of molten materials, fast energy conversion, and a subsequent shock wave. One method of producing intimate, liquid-liquid contact (which is known to be a necessary condition for vapor explosion) is a shock tube configuration.

The first set of experiments in a shock tube geometry was conducted by Wright et al.⁽¹⁾ using water impacting on molten aluminum. The interactions resulted in very high pressures which occurred on the first impact with very short rise time (80 μ s). (Figure 1). It is most probable that the pressure generated in these experiments was not due to hydrodynamic impact in view of the low driving pressure and impact experiments on solid aluminum. It was found that a rapid chemical reaction between the impacting water and less than 1% of the molten aluminum would have released sufficient energy and hydrogen to generate the pressure pulse shown in Figure 1. To provide some insight into the role of chemical interactions, an experiment was conducted in which water was impacted upon molten silver, which is essentially inert, at 1130 C. The resultant pressure rose to 22.0 MPa in about 0.1 msec before crucible failure, suggesting that thermal processes alone can account for the observed pressure pulses. Unfortunately, the reports give little discussion of the actual experiments and their results, especially the silver experiment, which is the only experiment reported in the literature resulting in large pressure generation with a non-reacting metal.

The same system (water-aluminum) was used by Darby et al.⁽²⁾ and by Guest et al.⁽³⁾ in a similar geometry. The pressures generated were larger than those reported by Wright even though the aluminum temperature was relatively low (720 C). Contrary to Wright's experiments, the interactions exhibited multiple pressure pulses which indicated bouncing of the coolant column, and the maximum interaction pressure occurred always on a subsequent bounce (usually on the second impact) and not on the first impact.

Experiments with lead and water⁽²⁾⁽⁴⁾ produced far less fragmentation and the pressure recorded was barely greater than the theoretical impact pressure. The high speed movies which recorded the lead-water and molten mixture of LiCl + KCl-water system interactions revealed that water was projected upward after a brief mixing period in which a limited depth of the molten material (~ 15 mm) was involved.

Experiments with water-UO₂ powder⁽¹⁾, Na-Al₂O₃⁽⁵⁾⁽⁶⁾, Na-UO₂⁽⁶⁾, and H₂O-steel⁽⁶⁾ resulted in only mild interactions and no strong shock waves were observed.

A simple model was suggested by Board⁽⁷⁾ et al. in which the pressure developed is a result of energy transfer to a nonequilibrium two-phase coolant, expanding against the acoustic loading of the coolant column. Agreement with Wright's experiment was found, but the pressure calculated is very sensitive to the assumed initial distribution of energy between the vapor and liquid phases. This model and the computer codes which are based on it (e.g., Ref. 8) are concerned only with the energy transfer phase and the consequent pressure developed. Goldammer and Kottowski⁽⁶⁾⁽⁹⁾ introduced the hydrodynamic component for describing the interaction pattern, i.e., bouncing behavior, and the pressure magnitudes. This model is based on the assumption that the first pulse is a result of constant volume heating and vaporization proceeds when the resulting wave is reflected from the upper interface and reaches the interaction zone. The vapor sets the column into motion, which is controlled by the vapor pressure at the coolant lower interface, which in turn depends on the heat flux from the hot material, vaporization or

condensation. When the column reenters it is stopped by the hot liquid if condensation is complete, or by a vapor layer. So, the pressure developed is a result of water-hammer pressure or vapor pressure whichever is larger. Good agreement between the theory and experimental results was found concerning the interaction pattern, but the calculated pressures were much larger than the experimental pressures.

To date, all shock tube experiments involve hot liquids, at temperatures well above the boiling point of the cold liquid. In this article we describe some experiments conducted with different pairs of liquids over a large range of hot liquid temperatures, from which we try to evaluate the effects of driving pressures and liquid temperatures on the different mechanisms which generate the high pressures in a shock tube geometry.

Experiments

The experimental apparatus is shown schematically in Figure 2. It consists of three 25.4 mm i.d. stainless steel tubes where the middle section held the cold liquid, and the lower tube contained the hot liquid. A diaphragm, made of Kapton, separated these sections and was ruptured at a specific and repeatable pressure depending on its thickness. The interaction was monitored by three piezo electric pressure transducers (PCB No. 112A05) and three Chromel-Alumel thermocouples located at different elevations. Details on the set up and the experimental procedure are given in References (10) and (11).

Experiments were conducted with the following cold/hot liquid combinations: water/solid surface, water/water, Freon 22/oil (mineral oil or silicon), Freon 22/water, water or n-butanol/Wood's metal, and water/eutectic mixture of LiCl + KCl.

For a given system the primary variables investigated were the initial temperature of the hot liquid and the initial driving pressure. Hydrodynamic and/or thermal interactions, accompanied by bouncing of the liquid column, were observed with water and Wood's metal. In Figure 3 the maximum impulse and maximum pressure obtained in each run are shown for a driving pressure of 0.2 MPa. The theoretical impulse per unit area required to instantaneously stop the water column for this absolute pressure with complete vacuum below the diaphragm is 10.5 KPa·sec and the theoretical water hammer pressure for instantaneous stoppage of the column is 6.20 MPa.

From the impulse graph, it can be seen that up to 210° C ("region A"), the maximum impulse is less than the theoretical one and it always occurs on the first impact. The magnitude of the maximum impulses is similar to the impulse at 90° C and to isothermal water-solid surface runs, suggesting that no additional energy is transferred.

In the temperature range from ~210 to 305° C ("region B") the maximum impulse magnitude is close to the theoretical value based on the initial driving pressure and column displacement. The maximum pressures in each run are higher in this temperature range than the lower temperature range (<210° C) except the abnormally low pressures in three runs around 300° C. The maximum pressure and the maximum impulse of a run never

occurred on the first impact, but rather on the second, third, or fourth bounce. The maximum pressure in some of the runs in this temperature range was higher than the cold liquid vapor pressure corresponding to the hot liquid temperature. A typical result is shown in Figure 4 for $T_h = 220$ C. If the lower bound temperature, $T_h = 210$ C, is identified with the spontaneous nucleation temperature¹², T_{sn} , then region B is in the range of $T_h > T_{sn}$ and $T_I < T_{sn}$ (T_I is the interface temperature upon contact). In this region a low rate of vaporization results in subsequent bounces of the liquid column which may in turn produce high pressures due to hydrodynamic action.

The third temperature range which can be observed occurs for temperatures above $\sim 305^\circ$ C ("region C"). A typical result is shown in Figure 5. In this range the maximum impulse is significantly higher than the theoretical one, and never occurs on the first impact. The same temperature threshold is observed also in the pressure graph. Above 305° C the pressures obtained are high, ~ 7.0 MPa, through the whole temperature range. This region can be identified by the condition of $T_I > T_{sn}$. Here a large amount of vapor is produced which results in large hydrodynamic and thermal effects.

For butanol and Wood's metal, the measured impulses and pressures are of the same order as the respective theoretical hydrodynamic values. (Figure 6). Thus, it is highly suggestive that the pressures generated are a result of water hammer action. An interesting observation regarding the butanol-Wood's metal system is the existence of another region ("region D") when T_I is larger than the thermodynamic critical temperature for butanol (T_{cr}). In this region the pressures are much lower than in region

C and the impulses are somewhat lower. But the most significant difference between regions C and D is the shape of the pulses. In region C the pressure pulses are sharp with short rise time; the pulses in region D are more gradual in growth and decay.

When the driving pressure was increased (by means of a thicker diaphragm) the interactions were suppressed, the number of bounces is reduced to two or three only, and the pressure pulses corresponding to these bounces has a much longer rise time, lower magnitude and impulse than was observed in the low pressure data. Impacting of Freons (Freon-11 and Freon-22) on oils (mineral and silicone), water and mercury which have not produced significant thermal interactions were also suppressed due to the relatively high system pressure, (0.2 MPa) which is consistent with pouring experiments.⁽¹³⁾ As with Freons, the suppression of interactions suggests that the pressure increase eliminates or significantly decreases one of the necessary conditions for explosion. It might be related to the bubble growth process, as is suggested by Henry and McUmbert⁽¹³⁾ and, from another point of view, by Buchanan,⁽¹⁴⁾ or it may affect the mixing process. More experimental data are needed to resolve this question.

A few experiments were conducted with water and a molten eutectic mixture of LiCl + KCl. At low driving pressures (0.2 MPa) all the runs conducted ($T_h = 410$ C and $T_h = 600$ C) resulted in low yield thermal interactions with a 40-50 msec time delay. The pressure pulses observed were relatively low (0.86-1.93 MPa) and sharp (~ 0.2 msec rise time) with a duration of ~ 0.3 msec which is considerably less than the acoustic relief time. An increase in the driving pressure resulted in suppression of thermal interactions, and only relatively low and long pulses were observed.

These results are a good example of a large impulse production on a long time scale ($\sim 30-40$ msec) which does not indicate an explosive thermal interaction. Thus, the fact that an experimental apparatus is ruptured during an experiment does not indicate conclusively the occurrence of vapor explosion. (15)

Hydrodynamic Interaction

In the water-Wood's metal system, the interaction pressure in the lower part of region B is higher than the vapor pressure corresponding to the hot liquid temperature. Since the maximum pressure which can be achieved and sustained when vapor is regarded as the pressure source is the vapor pressure, vaporization cannot be the source for these experimental measurements.

Another mechanism which may result in high pressures, especially in a highly contained system, is "single phase pressurization" (constant volume heating). In this mechanism, temperature change results in coolant expansion which in turn compresses the entire liquid column, if the initial column volume is kept constant during the relief time. This process is described by:

$$\frac{dv}{v} = -\beta_T dP + \alpha_P dT \quad (1)$$

where

$$\beta_T = -\frac{1}{v} \left(\frac{\delta v}{\delta P} \right)_T \quad (2)$$

$$\alpha_P = \frac{1}{v} \left(\frac{\delta v}{\delta T} \right)_P \quad (3)$$

To evaluate the maximum pressure which can be developed by constant volume heating we assume that the hot liquid contraction is negligible compared to the expansion of the coolant. From Equation 1 the coolant column compression is given by:

$$d(L - l_c) = \beta_T (L - l_c) dP \quad (4)$$

where L is the initial column length, and l_c is the length of coolant which has intermixed. If the compression is made in constant volume, i.e., $dL = 0$, the pressure in the liquid can be found from Equations 1 and 4:

$$\Delta P = \frac{\alpha_p l_c}{\beta_T L} \Delta T \quad (5)$$

where $\Delta T = T_{eq} - T_c$, T_{eq} is the equilibrium temperature resulting from intermixing the coolant (l_c) and the hot liquid (l_h) and is given by:

$$T_{eq} = \frac{T_h + \delta T_c}{1 + \delta} \quad (6)$$

where

$$\delta = \frac{\rho_c l_c C_c}{\rho_h l_h C_h} \quad (7)$$

The results of calculating the pressure in the liquid, assuming all the hot liquid interacts ($l_h = 5.0$ cm), $T_c = 20$ C, $\beta_T = 4.8 \cdot 10^{-5}$ bar⁻¹ and $\alpha_p = \alpha_p(T_{eq})$, are shown in Table 1 for different values of l_c at $T_h = 220$ C. It is shown that even assuming all the hot material instantaneously intermixes results in a pressure magnitude at $T_h = 220$ C that

is significantly less than that observed experimentally. Consequently the measured pressures in region B are greater than the maximum possible pressure that could be generated by constant volume heating.

TABLE 1. SINGLE-PHASE PRESSURIZATION OF WATER CONTACTING WOOD'S METAL

T_h C	l_c cm	T_{eq} C	dP MPa
220	0.25	194	0.93
	1.25	135	2.27
	2.5	101	2.5
	5.0	71	2.45
	10	48	2.1
	20	35	1.72
	50	27	1.38
	75	24	1.29
	100	23.5	1.30

So, the large pressures in region B cannot be explained by vapor pressure or single-phase pressurization which suggests that the hydrodynamic component is very important in this region, i.e., the observed pressures are impact pressures due to reentry, a conclusion which is similar to the computer model developed by Goldammer and Kottowski. And indeed, all impulses which produced pressures higher than the vapor pressure have approximately the theoretical hydrodynamic relationship between the pressure and the impulse.

Pulses which produced pressures lower than the vapor pressure acquired larger impulses than theoretically expected from initial hydrodynamic considerations (region C). Those results as well as the composite shape of the pulses in region C suggest that both hydrodynamic and thermal interactions are involved in each pulse at the high temperature runs but it is difficult to differentiate between them. Since the pressures produced are the same order as impact pressures, the only indication for significant thermal interaction is a large increase in the resultant impulse.

Mixing and Heat Transfer Considerations

For rapid heat transfer the hot liquid should be fragmented and dispersed in the coolant as very small droplets. The fragmentation and mixing of the hot liquid in a shock tube geometry is caused by the impact of the coolant resulting in mechanical energy transfer to the hot liquid. The subsequent behavior of the system is determined by the fraction of cold liquid that is vaporized which depends in turn on the amount of energy transferred to the coolant.

In this section, we will show from mixing and heat transfer considerations that the energy stored in the hot liquid in Wright's experiments was sufficient to pressurize the whole column via energy transfer to the cold liquid in contact with the hot surface.

Consider a mixing process in which volume V of hot liquid is intermixed with an equal volume of coolant. Assume that all the kinetic energy of the coolant (E_k) is imparted to the hot liquid as mixing energy (E_m). As discussed by Cho et. al.,⁽¹⁶⁾ in practical situations the mixing

energy is due mainly to the frictional dissipation and other contributions, as surface and kinetic energies, may be ignored. The mixing is assumed to be a one dimensional, one-step process, thus, the maximum mixing energy is given by:

$$(E_m)_{\max} = N_h C_D \pi R_h^2 \left(\frac{1}{2} \rho_c u_m^2 \right) L_m \quad (8)$$

where the mixing zone (L_m) and the number of hot liquid particles (N_h) are:

$$L_m = u_m t_m \quad (9)$$

$$N_h = \frac{V}{\frac{4}{3} \pi R_h^3} \quad (10)$$

where V is the volume of the hot liquid and the coolant which intermixed, given by:

$$V = L_m A \quad (11)$$

The kinetic energy lost by the coolant at any point in time is:

$$E_k = \frac{1}{2} \rho_c L' A u_1^2 \quad (12)$$

where L' is the distance a wave moved through the coolant with sonic velocity (c) during the intermixing period (t_m).

Equating the mixing and kinetic energies, assuming that $u_m = u_1$, we get that the particles radius is

$$R_h = \frac{3}{4} C_D \frac{u_1^2}{c} t_m \quad (13)$$

Note that by considering a one-step mixing process and by assuming that $u_m = u_i$, we evaluated the maximum mixing energy. The upper bound of mixing, or inter-dispersion, may be found from the minimum mixing energy given by: (16)

$$(E_m)_{\min} = 1.81 C_D \rho_c V \left(\frac{L}{t_m}\right)^2 \left[1 - \left(\frac{R_h}{L_m}\right)^2\right] \ln \frac{L}{R_h} \quad (14)$$

Equating the kinetic and the mixing energy, assuming $u_m = u_i$ we get:

$$\left[1 - \left(\frac{R_h}{L_m}\right)^2\right] \ln \frac{L}{R_h} = 0.277 \frac{c}{C_D u_i} \quad (15)$$

The experiments of Reference 1 provide a well defined system for evaluating the extent of mixing since the reported pressurization occurred on the first impact. For this particular experiment we assume that $C_D = 50$ (a typical value for equal volume systems), $t_m = 0.4$ msec, which as shown in Figure 1 is the approximate time from first impact to the maximum pressure recorded and $u_i = 2.3$ m/sec as calculated from the operational method described in Reference 1, i.e., the acceleration of a 0.91 m long column of water with a 100 kPa driving pressure over a length of 2.5 cm. These conditions yield a mixing length of 0.92 mm and aluminum particle sizes of 53 μ m for the maximum mixing energy and 25 μ m for the minimum mixing energy. It should also be noted that an impact velocity of 2.3 m/sec and equal volume mixing produce velocities for the two liquids of 4.6 m/sec and in opposite direction. This gives a relative velocity of 9.2 m/sec and with a Weber number of 12 as a breakup criterion, this relative velocity produces an aluminum particle size of 50 μ m radius. This is close to the values

obtained from mixing considerations. Both of these particle sizes are small compared to the thermal penetration in aluminum which can be estimated from

$$a = \sqrt{\alpha t}$$

For aluminum this is approximately 200 μm in the time specified above, and in fact the thermal penetration for water is 8.4 μm . Consequently, the energy transfer can be assumed to be essentially complete in 0.4 msec. This then enables one to calculate the pressurization resulting from such mixing.

In Reference 1 the aluminum-water shock tube results are represented as the maximum measured pressure as a function of the initial aluminum temperature. The pressure generated at the interface imparts a velocity to the liquid column as given by

$$u = \frac{\Delta P}{\rho_c c} \quad (17)$$

At the time the wave reaches the transducer, the displacement resulting from this motion is

$$\Delta V = \frac{u L_o A}{c} = \frac{\Delta P L_o A}{\rho_c c^2} \quad (18)$$

which is also equal to

$$\Delta V = \rho_c L_m (v_f + x v_{fg} - v_{fo}) \quad (19)$$

Therefore,

$$x = \left[\frac{\Delta P L_o}{\rho_c c^2 L_m} - (v_f - v_{fo}) \right] / v_{fg} \quad (20)$$

where the equilibrium energy equation can be written as

$$h_{fF} - h_{fo} + x h_{fg} = \frac{\rho_h}{\rho_c} [C_h (T_{ho} - T_{hF}) + \gamma] \quad (21)$$

Since the equilibrium steam-water properties are functions of pressure only, Equation 21 can be solved by trial and error once the initial aluminum temperature is specified. The results from this calculation are compared to the experimental data in Figure 7, and it is seen that the above model is in good agreement with the maximum values observed in the shock tube experiment. As the aluminum temperature approaches 1000° C, the equilibrium water temperature becomes supercritical and Equation 21 yields very high pressures. A detailed knowledge of supercritical properties would be required to improve the calculation.

Two additional points must be made with regard to the reported pressures. First, an intimate mixing of about 1 mm each of water and aluminum is required to provide the observed pressure events. Obviously, when the aluminum is initially solid this cannot occur which explains the uniqueness of the aluminum melting point in Figure 7. Secondly, a similar experiment was conducted with molten silver at 1130 C and a peak pressure of approximately 22 MPa was recorded. Assuming the same impact velocity and interaction time for the silver experiment as used for the aluminum results, Equation 21 predicts a slightly supercritical pressure (22.1 MPa) for the molten silver tests. Therefore, the analysis also demonstrates excellent agreement with this result as well.

Equation 21 can be used to approximate the pressure decay of the interaction zone if Equation 20 is expressed in terms of time

$$x = \left[\frac{\Delta P t}{\rho_c^2 c L_m} - (v_f - v_{fo}) \right] / v_{fg} \quad (22)$$

This prediction, which assumes a constant pressure in the interaction zone, is compared to the measured pressure trace in Figure 1 and there is close agreement between the predicted interaction zone pressure and the transducer recording. It must be remembered that when the rarefaction wave returns from the free surface and the second compression wave begins to travel up the column, the column velocity is now three times the initial velocity.

Conclusions

- (1) Hydrodynamic and/or thermal interactions, accompanied by bouncing of the liquid column, were observed with water and Wood's metal. The lower temperature threshold for those interactions is $T_h \approx 210$ C which may be identified with the spontaneous nucleation temperature, T_{sn} . When temperatures were in the range of $T_h > T_{sn}$ and $T_I < T_{sn}$, pressures generated were higher than the vapor pressure or the maximum pressure which may be generated from single phase pressurization. Thus, the hydrodynamic action is controlling the process in this temperature range.

- (2) Large pressures and impulses are observed when $T_I > T_{sn}$.
The mechanism for producing the high pressures is a combination of hydrodynamic impact and vapor production.
- (3) For butanol the measured impulses and pressures are of the same order as the respective theoretical hydrodynamic values.
Thus it is highly suggestive that the pressures generated are a result of water hammer action.
- (4) Impaction of Freons (Freon-11 and Freon-22) on oils (mineral and silicone), water, and mercury have not produced significant thermal interactions which may be due to the high system pressure.
- (5) Interactions are suppressed at elevated initial driving pressures which is similar to the behavior observed in pouring experiments. It indicates that a necessary step is eliminated by pressure increase, related to bubble growth or mixing.
- (6) Relatively long and low pressures may be developed from slow vapor production which results in large impulses.
Thus, a damage occurrence does not indicate conclusively a thermal explosion.
- (7) Wright's experimental results, which occurred on the first impact, are completely consistent with the mixing arguments and can be explained by thermal interactions alone.
- (8) To analyze shock tube data one should regard carefully the hydrodynamic effects which may be very significant, especially when multiple interactions are observed.

NOMENCLATURE

A	Shock-Tube cross-section
C	Specific heat
C_D	Drag coefficient
c	Sound velocity
E_k	Kinetic energy
E_m	Mixing energy
h_{fF}	Final liquid enthalpy
h_{fo}	Initial liquid enthalpy
h_{fg}	Latent heat of vaporization
L	Cold liquid column length
L'	Distance of travelling wave
L_o	Distance from reaction zone to transducer
l	Length of liquid
N	Number of particles
P	Pressure
R	Radius
T	Temperature
T_{cr}	Critical temperature
T_{eq}	Equilibrium temperature
T_{ho}	Initial hot liquid temperature
T_{hF}	Final temperature of hot material
T_I	Interface temperature

T_{sn} Spontaneous nucleation temperature
 t Time
 u Velocity
 V Volume
 v Specific volume
 v_f Liquid specific volume at equilibrium
 v_{fg} Difference between vapor and liquid specific volumes
 v_{fo} Initial liquid specific volume
 x Mass quality
 z Thermal penetration distance

Greek

α Thermal diffusivity
 α_p Thermal expansion coefficient
 β_T Compressibility
 δ Parameter
 γ Heat of fusion
 ρ Density

Subscripts

c Cold
 h Hot
 i Impact
 m Mixing

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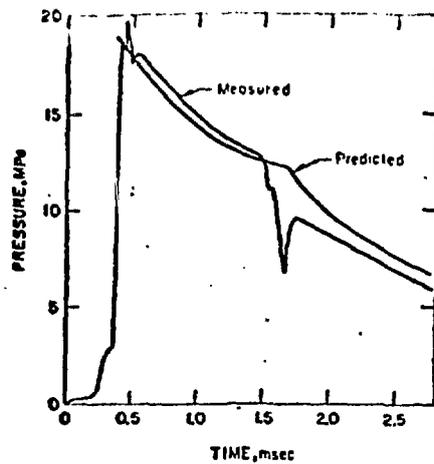


FIGURE 1. PREDICTED AND MEASURED PRESSURE PULSE FROM WATER IMPACT ON 950° C ALUMINUM

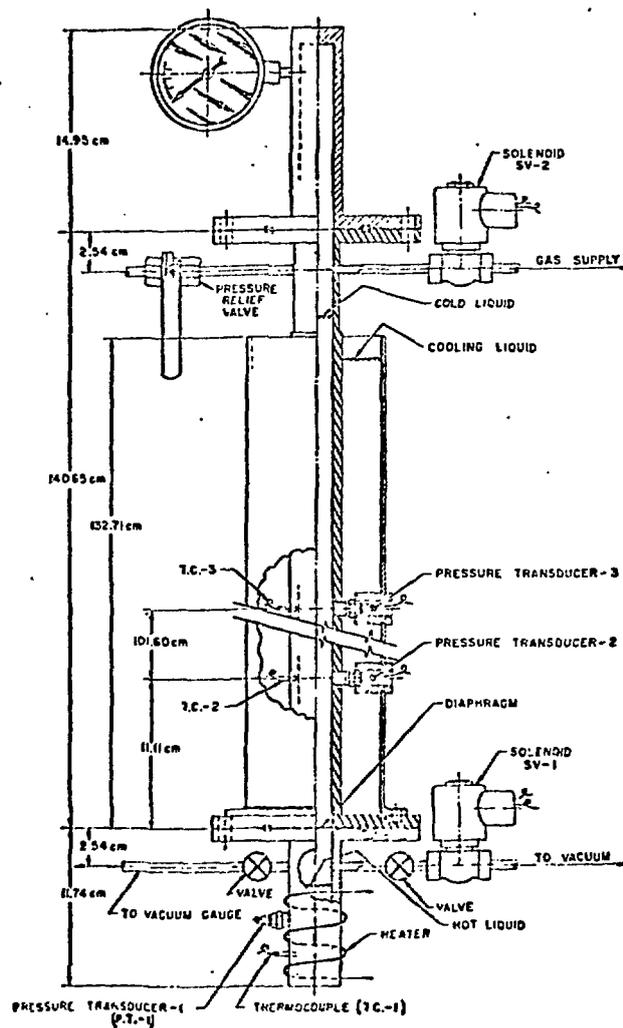


FIGURE 2. LIQUID-LIQUID SHOCK TUBE

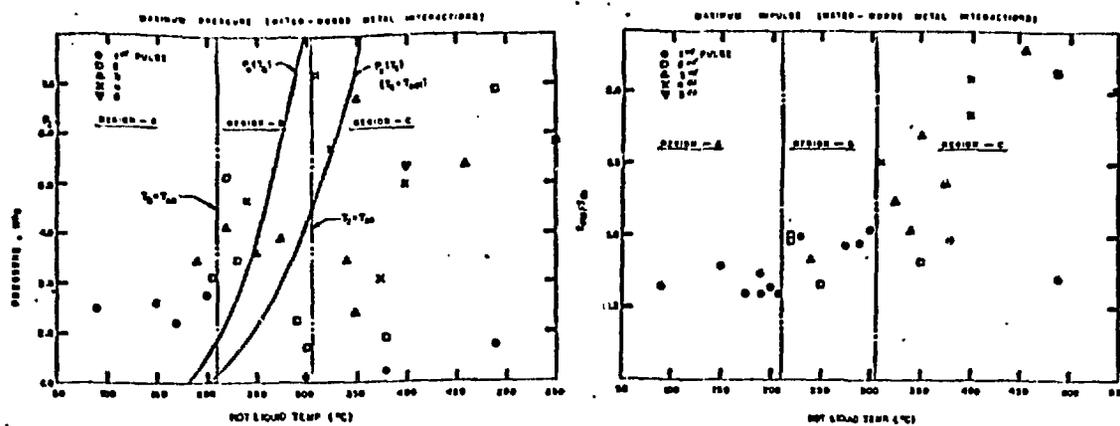


FIGURE 3. MAXIMUM PRESSURE AND MAXIMUM IMPULSE OF WATER-WOOD'S METAL INTERACTIONS

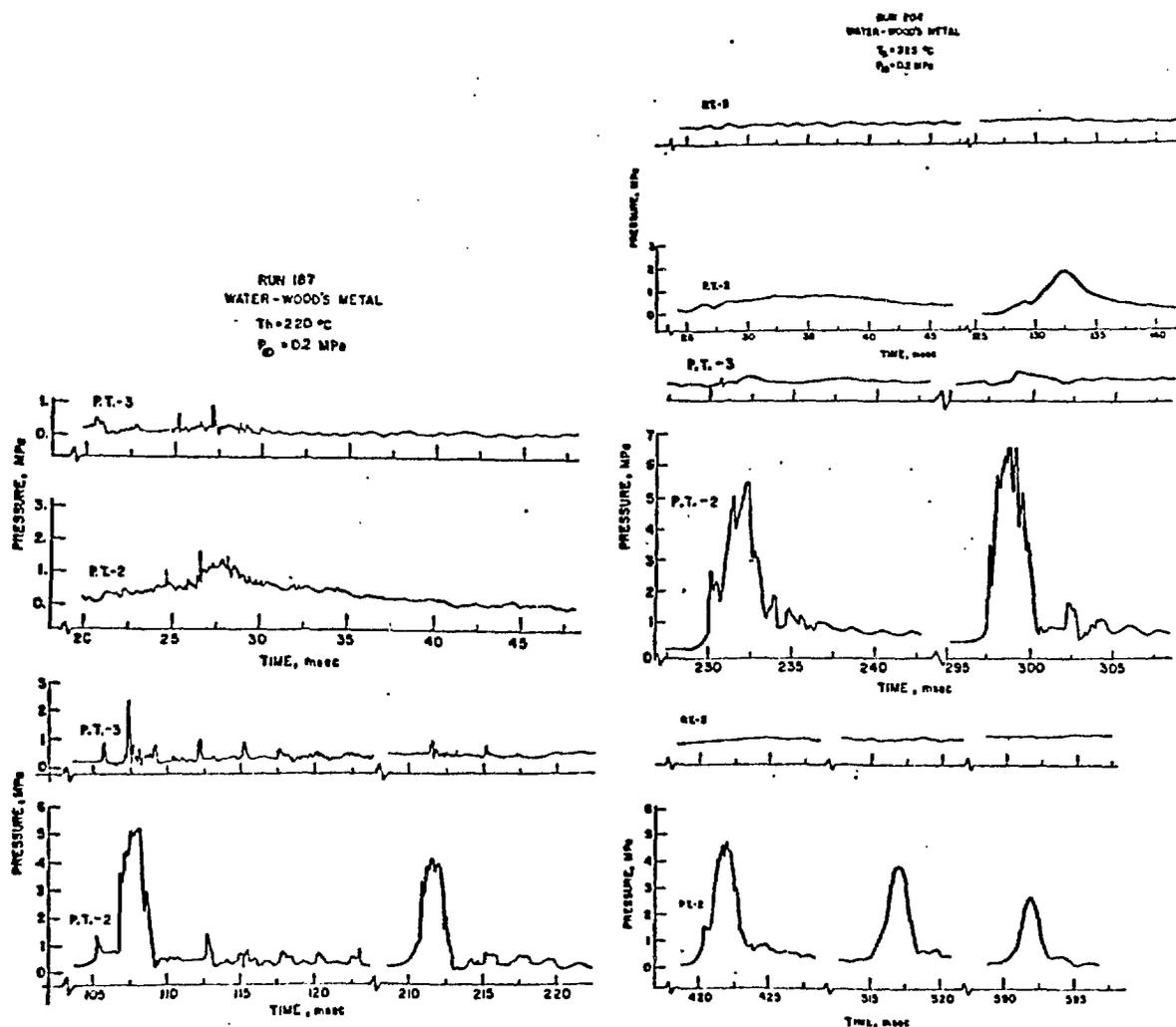


FIGURE 4. WATER-WOOD'S METAL INTERACTION IN REGION B

FIGURE 5. WATER-WOOD'S METAL INTERACTION IN REGION C

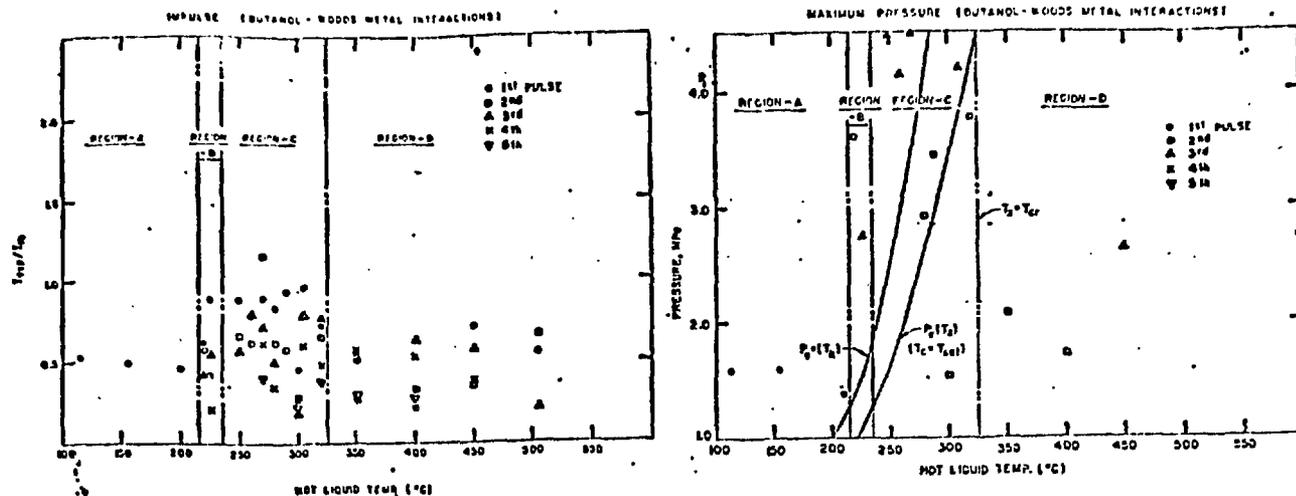


FIGURE 6. MAXIMUM PRESSURE AND IMPULSE OF BUTANOL-WOOD'S METAL INTERACTIONS

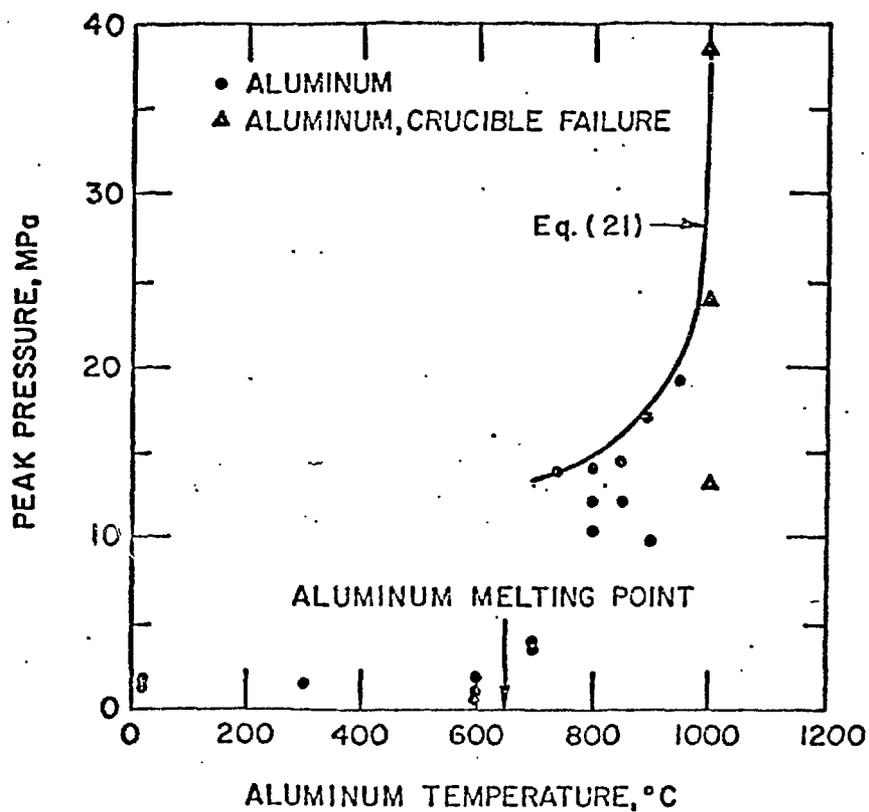


FIGURE 7. TEMPERATURE DEPENDENCE OF THE PEAK PRESSURE FROM WATER IMPACT UPON ALUMINUM