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Performance Report

Our current research has mainly concentrated on investigation of the thermal-hydraulic behavior of liquid metal/water interaction and on investigation of the chemical reactivity of gallium and indium in particular. Low melting point metals (tin, lead, gallium, and indium) were chosen as the initial fuel simulants. Tin and lead are known not to chemically react with water and therefore were suitable for the non-isothermal base experiments.

A total of thirty four[8] experiments was performed as part of this initial test series. In order to be able to visualize the shape of the falling water front which impacts the fuel surface, in five experiments a transparent quartz tube was used instead of metal crucible. The motion of the water surface before the impact was photographed by a high speed camera. Water at room temperature was used as both coolant (water was dyed) and fuel. Unfortunately, the quartz tube could stand only the experiments with driving pressures up to $2.3 bar$. The falling water front showed not to be flat but rather with two-three waves; the source probably due to interfacial instabilities. A limited depth of fuel (i.e., water in the crucible) was involved in the reaction.

The remainder of the experiments was done with a metal crucible and with different driving pressures and initial H_2O and liquid metal temperatures. The experimental parameters were in the following ranges:

- fuel temperature: from $300°C$ to $600°C$,
- water temperature: room temperature and in the range of $60°C - 70°C$,
- driving pressures: from $2.5 bar$ to $12 bar$.

The water column length was $2.765m$. In most of the experiments $12 cm^3$ of fuel was poured into the crucible so that the coolant fall distance was $\sim 0.52m$. In a couple of experiments the crucible was empty and for those the falling distance was $0.547m$. The parameters of the experiments chosen for the discussion and data analysis in this paper are given in table 1.

Our scoping tests have demonstrated that the whole experimental set-up works properly and that the timing of both, Keithley and LeCroy, data acquisition systems is within acceptable limits. From these tests the preliminary

[8]Semi-successful experiments or scoping experiments done in a different set-up are not included in this test series.

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FUEL	Expt. No.	T_f [°C]	T_c [°C]	P_{sys} [10^5Pa]	P_{rc} [10^5Pa]	H_{fall} [m]	P_i [10^5Pa]	P_i^{th} [10^5Pa]
AIR	42	22.9	20.4	10.97	0.0136	0.547	284	390
WATER	39	22.4	20.1	11.98	0.036	0.514	255	390
	18	23.2	22.3	11.354	0.0507	0.551	264	445
TIN	10	314.3	24.1	11.764	0.0052	0.533	274	434
	27	598.8	24.5	11.993	0.0121	0.496	186	374
LEAD	35	586.5	23.7	2.483	0.0129	0.514	118	178
	33	590.1	22.7	11.99	0.0133	0.514	179	382
GALLIUM	38	316.9	22.4	11.63	0.0031	0.515	214	426
	13	607.4	24.8	11.528	0.0187	0.552	269	437
	36	563.9	60.8	10.931	0.0147	0.515	230	393
INDIUM	37	301.6	22.6	11.594	0.0133	0.519	235	384
	14	599.4	24.4	11.671	0.0147	0.551	276	434
	30	600.8	63.2	11.733	0.0133	0.514	199	376

Table 1: Experimental Parameters

information on thermal-hydraulic behavior of the interactions was gathered. Detailed and more complete analysis of all collected data is in progress and it should give more general and firmer conclusions.

The experiments where the water column impacts a rigid bottom of the crucible were conducted to study the hydrodynamic behavior of the water column upon the diaphragm rupture, to check how much the water column actual behavior differs from the theoretical one for the instantaneous elastic impact, and to obtain baseline for the analysis of our isothermal and non-isothermal experiments. The dynamic pressure traces PT0, PT1, and PT4 vs. time for such an experiment, experiment number 42, are given in figures 3, 4, and 5 respectively[9]. The uncertainty in pressure readings is $0.69barg$ for PT0 and PT1, and $0.03barg$ for PT4.

Initially, pressure in the shock-tube above the diaphragm was P_{sys} = $10.97bar$ while the reaction chamber was evacuated to $P_{rc} = 0.0136bar$. As seen on figures, at the moment when diaphragm ruptured (first spike on the PT0 trace) pressure transducers PT1 and PT2 have registered an abrupt pressure decrease (sharp dip). About $49ms$ (t_i) later, water has impacted

[9]For the locations of the pressure transducers, see fig. 4

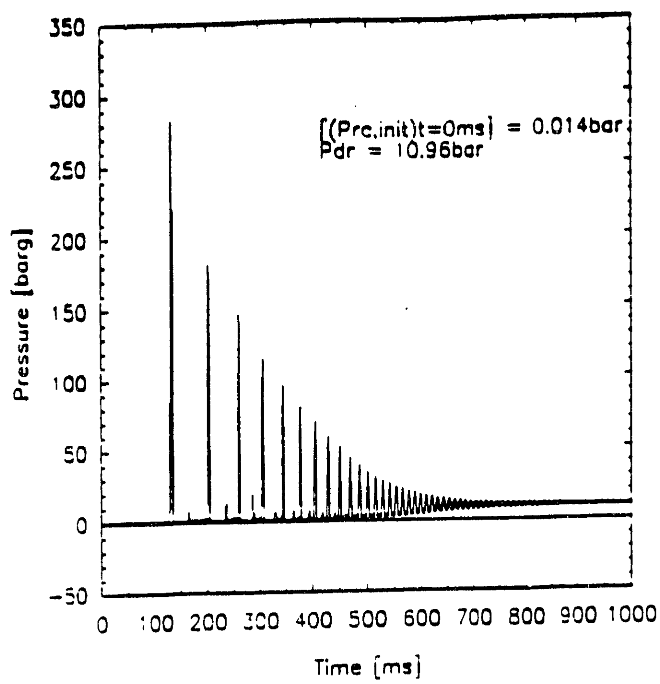

Figure 3: Experiment No.42: Dynamic pressure PT0 vs. time.

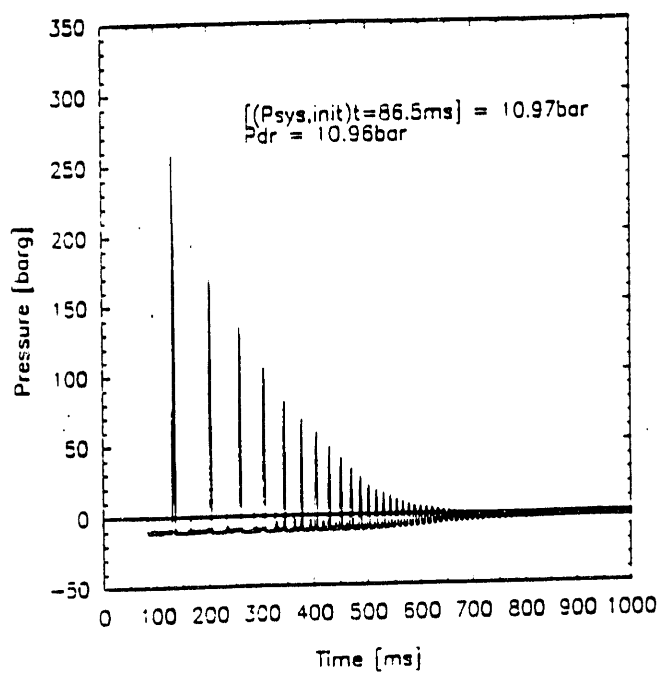

Figure 4: Experiment No.42: Dynamic pressure PT1 vs. time.

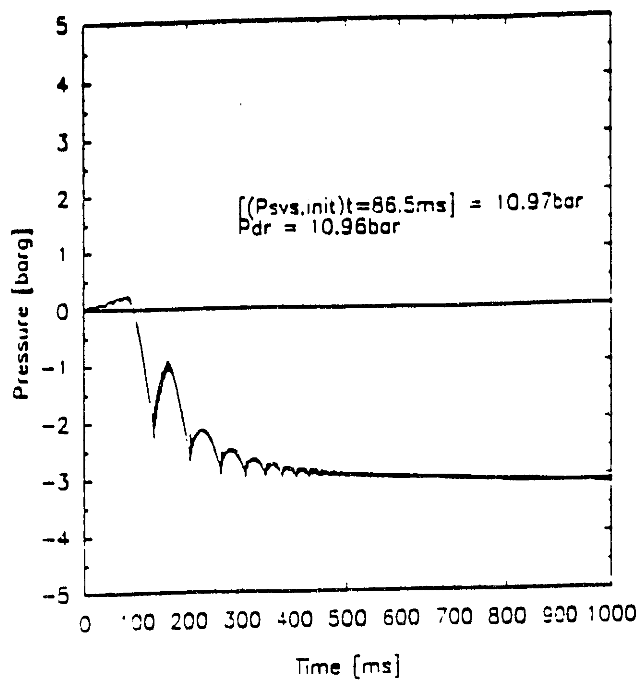

Figure 5: Experiment No.42: Dynamic pressure PT4 vs. time.

the crucible bottom (largest spike on PT0 and PT1 trace, i.e. first dip on PT4 trace). The measured impact pressure, $P_i = 284bar$, is smaller than the theoretical value, $P_i^{th} = 390bar$ (see table 1), for the "water hammer" pressure for an ideal instantaneous impact [10, p72]

$$P_i^{th} = \frac{c_c(P_{sys} - P_{rc})t_i}{L_c} + P_{sys} \tag{1}$$

The discrepancy between P_i and P_i^{th} is due to the precursor jet (smaller spike on PT0 trace right before the main one) and the compression of the remaining air and vapor in the reaction chamber as the water column was approaching the crucible bottom.

At the impact the water column stops, the impact pressure is relieved from the upper water/gas interface, and the water column moves upward (expansion phase). The first pulse is followed by many bounces with progressively lower maximum pressures. Short and sharp pressure pulses seen in PT0 and PT1 represent small precursor jets impacting on a surface and being quickly relieved by the surrounding gas space. The timing of all the pressure spikes for all three pressure traces are in good agreement with each other. They are within the half relief time ($t_a = L_c/c_c = 2ms$) for our shock-tube.

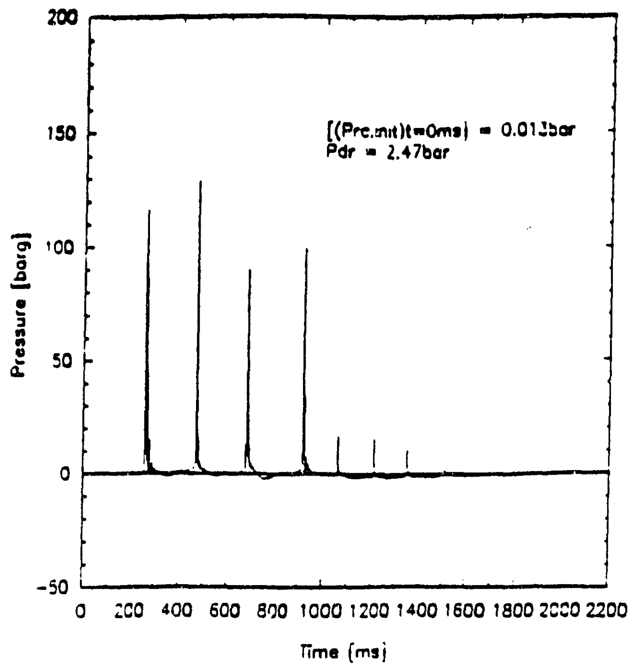

Figure 6: Experiment No.35: Dynamic pressure PT0 vs. time.

The same aforementioned impact characteristics but with smaller pressure amplitudes are present in isothermal experiments where water impacts water.

In the non-isothermal experiments (with molten lead, tin, gallium, and indium as "fuels") the number of pressure pulses is much smaller (between four and eight), their duration is longer, and they are not evenly spaced, indicating some effect from thermal interactions. The water column bouncing stops when the molten metal thermal potential is completely exhausted and all the vapor condensed. As expected, the increase in fuel and water temperature, as well as increase of driving pressure, caused more energetic interactions to occur. In figures 6 and 7 the dynamic pressure traces PT0 vs. time for $P_{dr} = 11.98bar$ and $P_{dr} = 2.47bar$ lead experiments (experiments number 35 and 33), are given respectively. Uncertainty in pressure readings is $0.35barg$ for experiment number 35 and $1.38barg$ for experiment number 33. As seen, pressure pulses have larger amplitudes in experiment with higher driving pressure.

From the measured parameters the initial impact energy and mechanical energy release of the fuel/coolant interaction were calculated. Here, we will present only data calculated for the first spike which, in most cases, is of the largest amplitude and representative of the data trends.

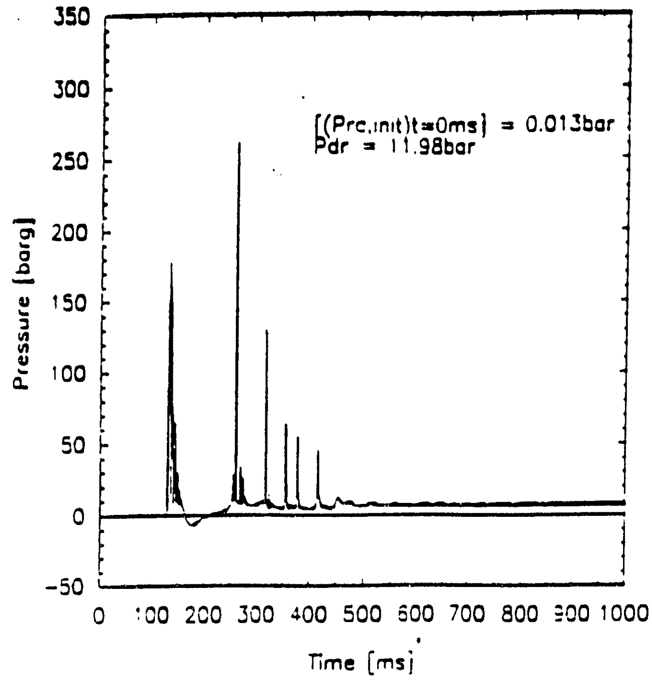

Figure 7: Experiment No.33: Dynamic pressure PT0 vs. time.

The impulse per unit area by the coolant column was obtained by integrating the PT0 pressure trace over the time duration of the first pulse and given in figure 8. It can be seen that tin and lead high temperature thermal interactions have largest impulse values and, therefore, are the most energetic interactions.

The work done during gas expansion, i.e. compression, was calculated using the following formula

$$W_{1-2} = \frac{P_2V_2 - P_1V_1}{1-k} \pm m_c g H_{fall} \tag{2}$$

where gas expansion and compression were assumed to be isentropic processes.

The absolute values of expansion and compression work are plotted in figure 9, while their ratio is given in figure 10. Both plots show that in our experiments water column impact on either rigid or liquid surface is significantly inelastic. Water vapor and non-condensible gas in the reaction chamber cause some instabilities and mixing and, therefore, the ratio of compression and expansion work is reproducibly about 0.5.

In experiments with gallium and indium initially at $\sim 600^oC$ some oxi-

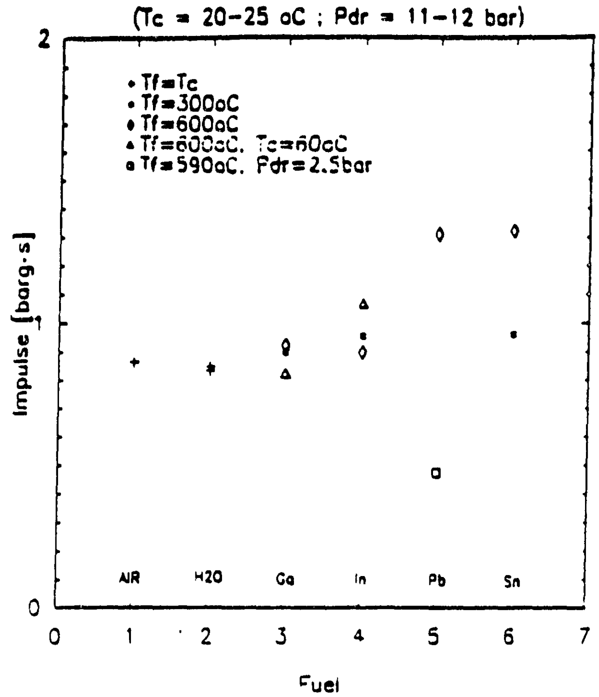

Figure 8: Impulse by coolant column during the first pulse.

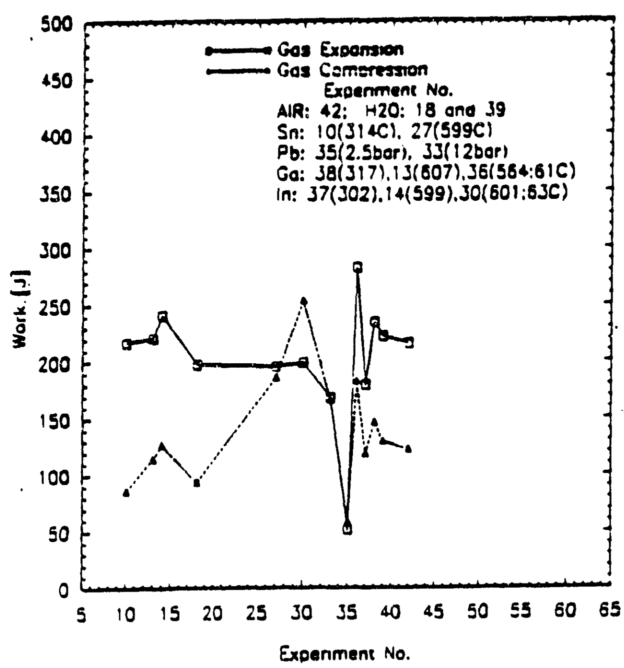

Figure 9: Expansion and compression work for the first pulse.

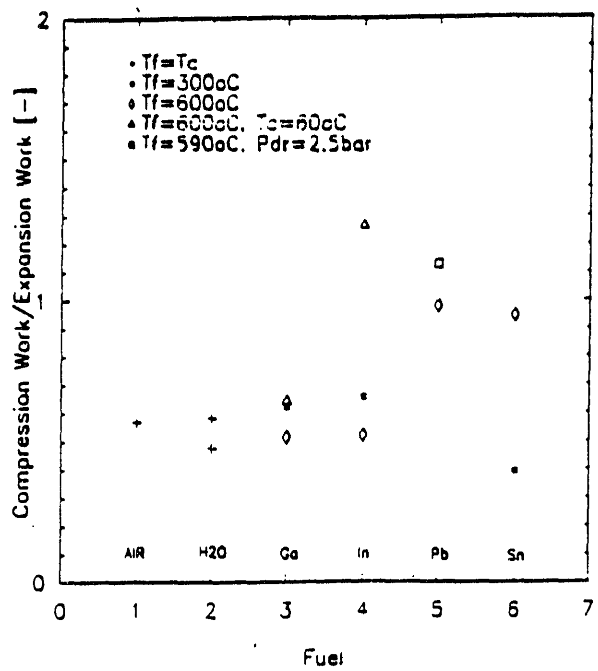

Figure 10: Ratio of compression and expansion work for the first pulse.

dation was observed. After the experiments the darkest parts of the debris were usually found on top of the solidified "fuel" in the crucible. Samples of such "black" debris from experiments number 13, 36, and 30 were chemically analyzed. Chemical analysis has found $94.92^{w}/o$ and $96.14^{w}/o$ of Ga, i.e. $81.95^{w}/o$ of In in samples. The higher oxidation level of indium is, maybe, the explanation of the fact that indium compression/expansion work ratio is the largest of all the values presented in figure 10. But, even if indium has oxidized more than gallium, chemical reactivity of none of the metals was of significant level.

So far there is no available mechanistic model that could be directly used for our data analysis. None of the existing models include mixing and fragmentation[10] upon impact. What is needed for our further data analysis is a physical model that would incorporate the existing Kranert's macroscopic shock-tube model [3] and the effects of mixing and fragmentation in the early stage of liquid metal/H_2O interaction. Therefore, in the final stage of this work the existing models (that cover some aspects of the process in a shock-tube) should be combined, and the resulting model should be used for the analysis of the obtained data.

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