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Design of a New Liquid Cell for Shock Experiments*

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Abstract: Controlled impact methodology has been used on a powdergun to obtain dynamic behavior properties of Tributyl Phosphate (TBP). A novel test methodology is used to provide extremely accurate equation of state data of the liquid. A thin aluminum plate used for confining the liquid also serves as a diagnostic to provide reshock states and subsequent release adiabats from the reshocked state. Polar polymer, polyvinylidene fluoride (PVDF)[1] gauges and velocity interferometer system for any reflector (VISAR) [2] provided redundant and precise data of temporal resolution to five nanoseconds and shock velocity measurements of better than 1%. The design and test methodologies are presented in this paper.

Introduction: A variety of well-established loading and diagnostic tools [3] is available to determine the shock Hugoniot for materials. In particular, these test methodologies can be easily adapted for use with solids, to determine the off-Hugoniot states of materials. Techniques, however, are limited for applications to determine the equation of state and the off-Hugoniot of liquids. Some techniques have been reported to determine the equation of state and/or the optical properties of liquids [4]. What is new in this study is the test methodology to determine the shock Hugoniot states, reshock and release states (from the reshock state) in a single experiment. In these experiments, the transit time between the wave arrival at the PVDF gauge and the velocity interferometer signal at the witness plate is determined to an uncertainty of five nanoseconds. This allows for an extremely accurate estimate of the shock velocity in the TBP liquid, even though one has to correct for the transit time in the aluminum witness plate using the published equation of state (EOS) data for aluminum [5].

Material Description: The liquid studied in these experiments is Tributyl Phosphate (TBP), chemical formula $[C_4H_9O\text{-}]_3PO$, a common industrial solvent and plasticizer. At ambient conditions, TBP has a density of 0.9725 g/cm^3 [6], and an acoustic wave speed velocity--measured in this work to be 1.262 km/s. As with most molecular liquids, TBP tends to react adversely with many types of materials.

Liquid Cell Design and Experimental Technique: The motivation of this program was to provide an accurate experimental database for TBP leading to equation of

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state (E.O.S.) development [7]. Experiments to study material properties of solids under shock loading can routinely be designed to produce well-defined state of stress in a sample [8]. However, translating this technique for studies involving liquids is not as convenient. One must provide fixtures that not only to contain the liquid in an non-atmospheric environment, but also to allow extremely accurate and meaningful information from the experiment while maintaining uniaxial strain conditions.

The technique, used in this study is shown in Figure 1. This experimental design would provide the ability to measure directly two primary material attributes - shock velocity and stress – both of which are necessary for determining material properties under shock loading. In addition, this technique will provide particle velocity information from a witness plate, which can be used to directly infer shock and reshock states within the liquid. In a typical reverberation experiment performed using a solid, the material under study would impact a thin high impedance witness plate while the VISAR would monitor witness plate motion. The witness plate would be of a material that has been well-characterized [5].

The experimental method employed to induce shocked states in the TBP is indicated in Figure 1. A thick projectile plate (aluminum, copper or plexiglass) is accelerated on a powdergun prior to impacting the driver plate of the liquid cell target. Three electrical shorting pins are used to measure the velocity of the projectile at impact. Four similar pins were mounted flush on the impact plane to monitor the planarity of impact. The resulting uncertainty in projectile velocity determination was better than 0.2%, while the measured tilt for these experiments

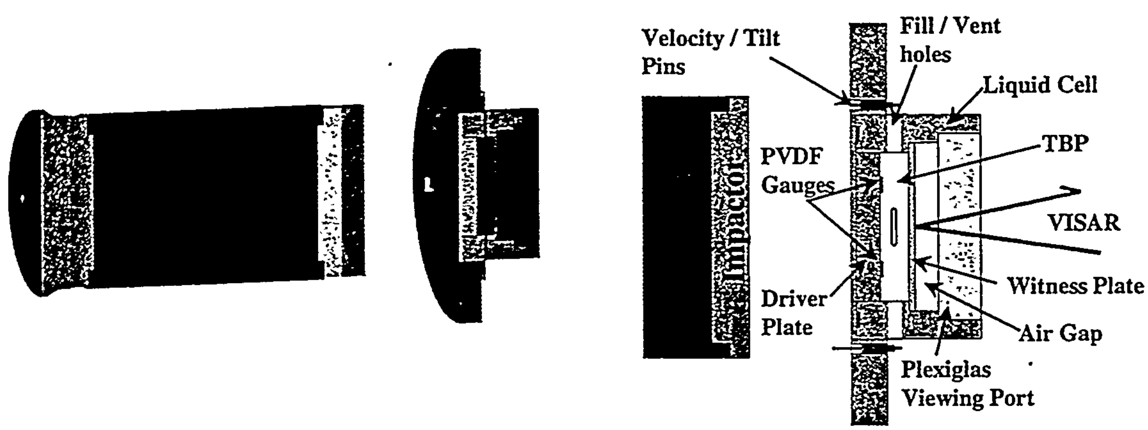

FIGURE 1. Experimental configuration

was less than a milliradian. As indicated in Figure 1, the liquid TBP is contained in a cylindrical 6061-T6 aluminum or an aluminum-coated polymethylmethacrylate (PMMA) container with a thick 6061-T6 driver plate and a thin (0.65mm) 1100 aluminum plate serving as end caps to the liquid can. The gap between the thin (witness) plate and the aluminum-coated PMMA shown in Figure 1, is maintained at atmospheric pressure to prevent any bulging of the thin plate when the entire assembly is placed under vacuum. As indicated in the figure , the liquid is filled in from the fill hole from the bottom, thus allowing the displacement of air through the vent hole on the top, ensuring that there are no air bubbles trapped in the liquid cell during the fill process. As shown in Figure 1, two PVDF gauges are mounted at the aluminum, TBP interface to determine very accurately the arrival times for the input stress pulse into TBP, while a VISAR is used to record the free-surface velocity motion of the aluminum witness plate. In all experiments, and for all diagnostics, low loss coaxial cables and 1 GHz digitizers provide the high-frequency recording capability required to properly interpret the sensor responses.

As stated earlier, TBP tends to react adversely to a variety of materials. Caution was taken to select materials that have shown no indication of reaction with the liquid. Careful scrutiny was taken in selecting materials for the experimental design. Early visual tests suggested no reaction with a (PMMA) disc. PMMA was therefore selected for the cell in the first iteration of design primarily for machining ease. Subsequently, the experimental data indicated anomalies that could not be explained. After further research [9] it was determined that TBP in fact did react with stressed PMMA. In this investigation, PMMA becomes stressed when it is machined to include holes, threads etc.. as part of the design for the liquid cell. The use of multiple and redundant gauge provided highly accurate and reproducible information that led us to conclude that the PMMA could be polymerizing the liquid TBP, resulting in stiffer response. Further studies were repeated using aluminum for the cell design. Experimental results later in this paper will show the difference in the results obtained using the two cell designs.

Diagnostics: In addition to the electrical shorting pins to measure velocity and impact planarity, two PVDF polymer shock sensors, and a velocity interferometer, VISAR, were used to measure the transit time in the TBP liquid to determine the shock velocity with extremely high precision.

PVDF gauge is based on piezoelectric response of meticulously prepared polymeric film, which is typically 25µm in thickness and can provide direct stress-rate versus time with exceptional sensitivity. PVDF gauges offer many unique features for measuring shock compression such as self-powered operation, large stress range, high output signal, and stress dependant output signal. Due to its nanosecond response, PVDF, also provides "time-of-arrival" capability. The stress-rate dependency of the output signal produces very fast loading and unloading pulses lending itself to large amplitude current spikes with durations from one to five nanoseconds.

These responses are measured in the "current mode" to provide both a simple circuit and the most revealing electrical behavior. Careful consideration was taken to insulate the gauges and isolate them from electrical current paths. As previously mentioned, aluminum coated PMMA was used for the cell. During the experiment, it is possible that if TBP were a polar fluid, then electrical charge could build up effecting the gauge performance. The metallic coating allows a path for electrical discharge instead of perturbing the gauge response.

Velocity interferometry, VISAR, is the most commonly used diagnostic at the STAR Facility. The interferometer superposes the doppler-shifted light from the moving surface at two slightly different times, producing a fringe number proportional to the surface velocity. Velocity interferometry, VISAR, is a precision tool for obtaining velocity-vs-time profiles of the motion of the surfaces of shocked experiments. Particle velocity and temporal resolution currently available using the interferometer one percent and 1-2 nanoseconds respectively.

Combining these two methodologies allows you to determine the transit time in TBP very accurately. In addition, you can get an independent estimate of the input stress into the TBP.

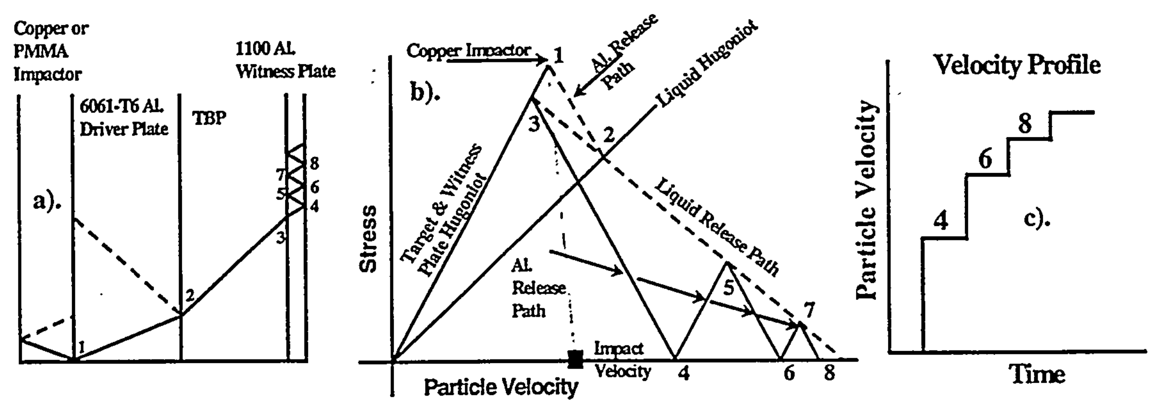

FIGURE 2. Principle of the technique as indicated by the a). X-t and, b). Stress-Particle Velocity Diagram. The anticipated particle velocity history is displayed in c).

Principal of Technique: As indicated in the Lagrangian X-t diagram, and the corresponding P-u diagram in Figure 2a and 2b, upon impact, a shock wave propagates through the aluminum driver plate, referred to as state 1 in Figure 2. When the shock arrives at the TBP interface it will release to a stress state 2 as shown in Figure 2. This will propagate as a shock in the TBP and as a release wave from state 1 to state 2 into the thick driver plate. The two PVDF gauges located at the interface record the arrival of this stress front at the liquid interface. When this stress front arrives at the thin 1100-aluminum witness plate, the liquid will reshock to state 3, and the shock will propagate in the thin witness plate traversing towards the free surface. The estimate of this shock (or reshock in TBP) is easily estimated by the first velocity arrival indicated in free-surface velocity measurement. This is represented by state 4 in Figure 2a and 2b. Subsequent wave reverberations through the witness plate (recorded at states 6, 8, etc..) decompresses the witness plate then recompresses the witness plate to a shocked state that is determined by the current stress on the liquid unloading curve. Thus the acceleration history of the witness plate contains detailed experimental

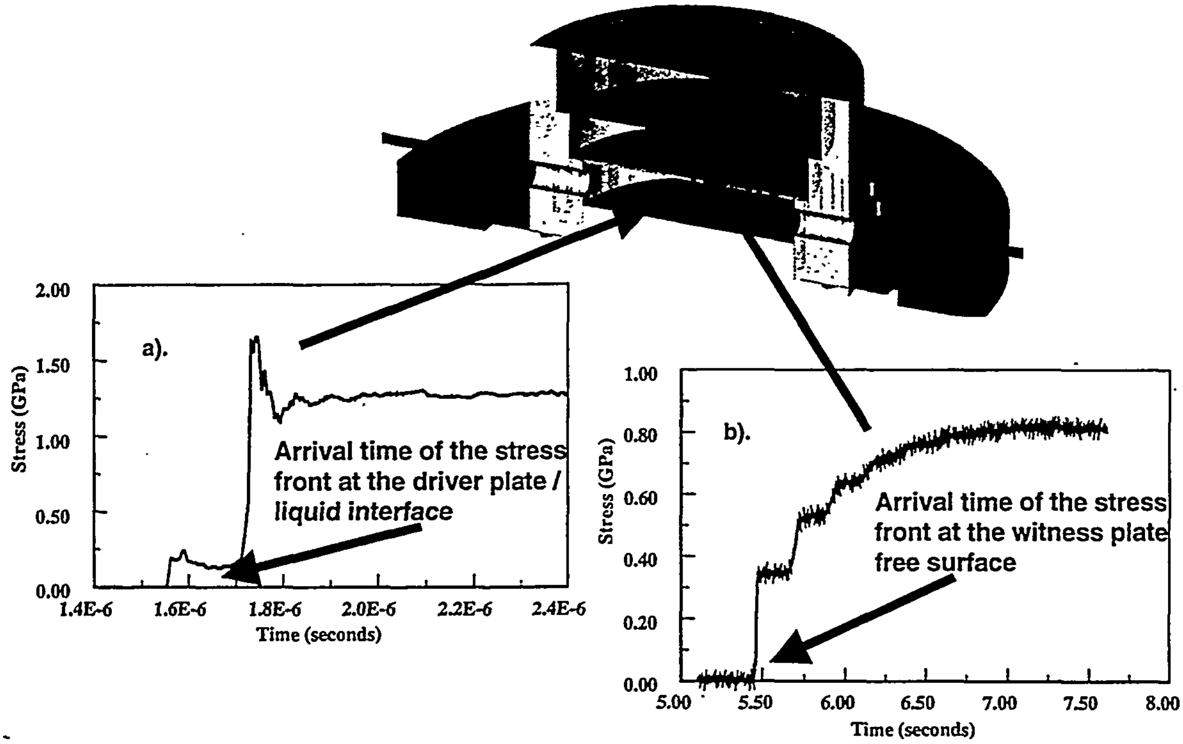

Figure 3. The arrival time of the stress front at the driver plate-liquid interface (a); arrival time of the stress front at the witness plate free surface shown in (b) as detected by the interferometer.

information regarding reshock compression and subsequent release properties of the liquid.

Experimental Results: The determination of shock velocity was resolved from the PVDF and VISAR data. As illustrated in Figure 3, PVDF sensors are located on the rear surface of the driver plate. The gauges are encapsulated in Teflon, which not only isolates the gauge from the liquid, but also provides a uniform 75 μm layer that covers the entire driver plate. The output current pulses have signal risetimes of a few nanoseconds (fig. 4, inset); to record such signals, low inductance current viewing resistors are placed on the leads and the signals are transmitted to 1 GHz digitizers through low-loss coaxial cables with negligible attenuation. The arrival time of the stress front is, however, determined to better than a nanosecond.

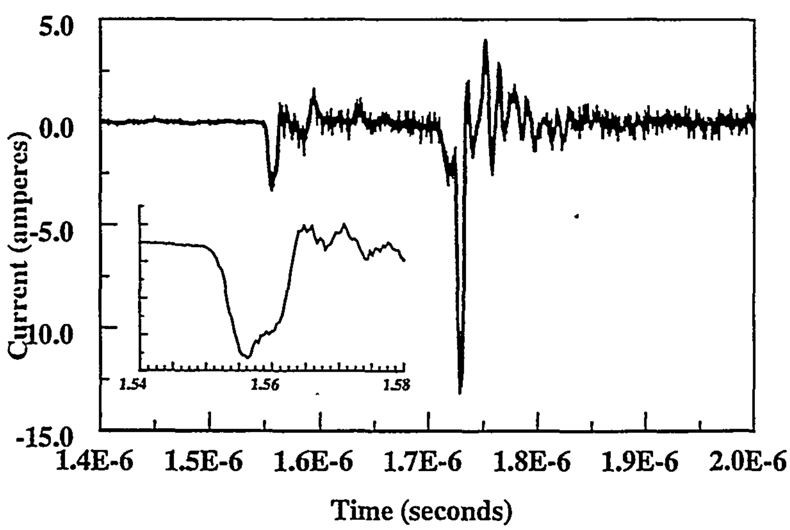

FIGURE 4. Observed current record. Inset: Expanded current view of elastic precursor.

Since the observed current pulse is less than the shock transit times through the film, the current is directly related to the input stress. The reverberation of the PVDF gauge is complex due to the impedance differences between the driver plate (aluminum), the gauge package (Teflon), and the liquid (TBP). Yet the gauge is clearly representing the behavior of the shocked aluminum. The stress level calculated from the PVDF gauge is within 3-5% of the value determined from the VISAR data. This is within the accuracy of reported for PVDF gauge. The fast rising PVDF current pulse provides an extremely accurate "fiducial" for arrival of the shock front at the driver plate-liquid interface. When combined with the VISAR time resolution, of better than three nanoseconds [10], and utilizing the well characterized aluminum properties [5], transit times in the liquid was determined to a temporal resolution of 5 nanosecond. This leads to an accuracy of better than 1% in estimates of shock velocity.

Hugoniot States: In these experiments, the transit time between the wave arrival at the PVDF gauge and the velocity interferometer signal at the witness plate is determined to an uncertainty of 5ns. This allows an extremely accurate estimate of the shock velocity in the TBP liquid, even though one has to correct for the transit time in the aluminum witness plate using the published equation of state (EOS) data for aluminum. The measured shock velocity is listed in Table I. Whenever a two-wave elastic-plastic structure emanates at the driver plate/TBP interface, the shock velocity is calculated using the arrival time of the plastic wave. This is reasonable, as the material non-linearities will cause the precursor wave to be totally overdriven by the faster moving second wave in the TBP. Using impedance matching techniques, the particle velocity in the TBP, u_2, is calculated using the measured shock impedance of the liquid and the estimated path of aluminum from state 1 to state 2 (refer to figure 2). Note, state 2 is the Hugoniot state (σ_H, u_h) for the liquid TBP. The shock velocity versus particle velocity data is shown in Figure 3. The corresponding Hugoniot stress and strain states in the liquid is then obtained using,

$$\sigma_h = \rho_L U_L u_h \quad \text{and} \quad \varepsilon_h = u_h/U_L \qquad (1)$$

where ρ_L, U_L are the initial density and measured shock velocity of TBP respectively, and u_h is the particle velocity in the TBP. These are listed in Table I. Pressure versus particle velocity represented in Figure 6, indicates also that this technique is very accurate. Though the pressure is determined indirectly, the fit for this data appears consistent with the data from the shock-velocity versus particle-velocity data.

Table I. Impact Conditions and Experimental Results. Driver Plate, and Witness plate thickness were nominally 8.0, and 0.7 mm thick respectively.

Shot #	Impactor	I.V. (km/s)	U_L (km/s)	σ_H (GPa)	u_H (km/s)	ε_H (GPa)	Cell Material
TBP-1	Aluminum	0.591	2.784	1.361	0.499	0.179	PMMA
TBP-2	Aluminum	1.379	3.780	4.116	1.111	0.294	PMMA
TBP-3	Aluminum	2.207	4.990	8.296	1.697	0.340	PMMA
TBP-4	Aluminum	0.431	2.325	0.849	0.373	0.160	PMMA
TBP-6	Copper	0.606	2.820	1.983	0.717	0.254	Aluminum
TBP-7	Copper	1.167	3.869	4.959	1.308	0.338	Aluminum
TBP-8	Copper	2.273	5.472	12.760	2.379	0.435	Aluminum
TBP-9	PMMA	0.415	1.662	0.244	0.134	0.090	Aluminum

Figure 6 describes the hugoniot states in the aluminum and PMMA cell. There is a distinct difference that indicates the data from the aluminum-coated PMMA cell is consistently stiffer throughout the range of pressures. It is believed that the adverse reaction of the PMMA cell with TBP resulted in thickening of the liquid and thus resulting with a stiffer response.

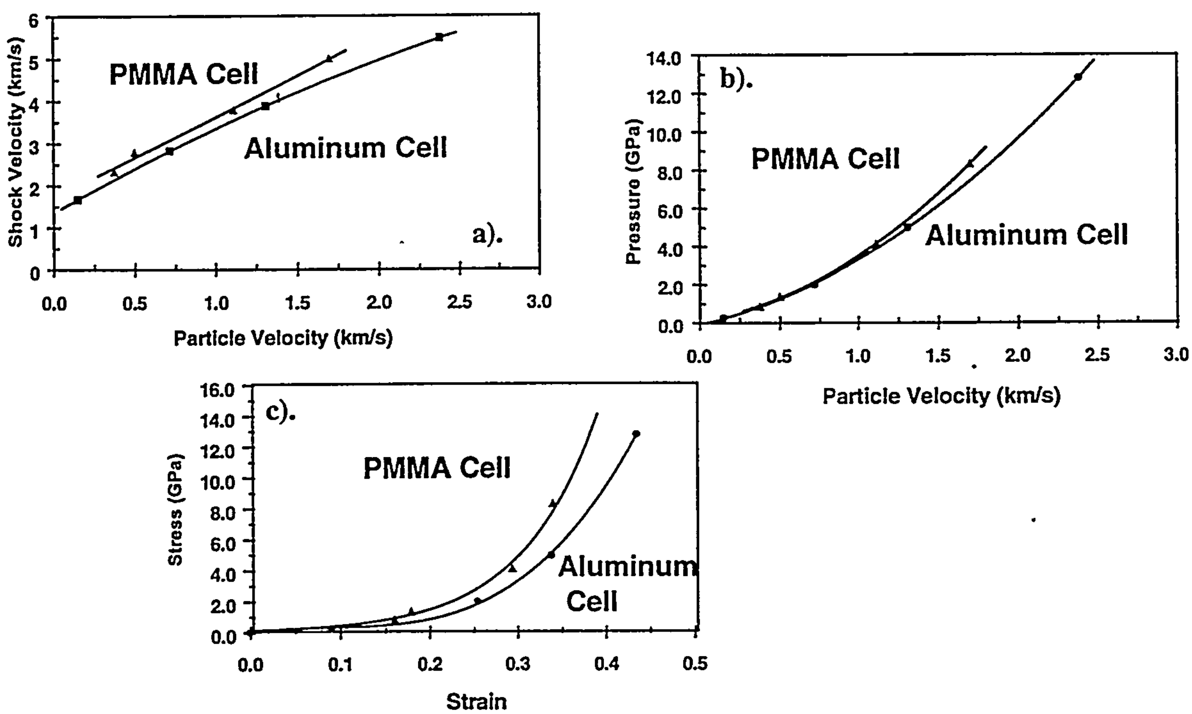

Figure 6. a). Shock Velocity vs Particle Velocity, b). Pressure vs Particle Velocity, c). Stress vs. Strain

Conclusions: We have shown that the new cell design can, with extremely accurate precision, determine material properties from molecular liquids. The cell design and accurate diagnostics can determine shock velocities to within 1%. This accuracy resulted in distinguishing the shock velocity differences in the PMMA and aluminum cells. We believe that this design will work for virtually all types of liquids and can be expanded to studies on gases.

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