

TABLE VI. Summary of results.

	Benzene	Carbon disulfide	Carbon tetrachloride		Liquid nitrogen	
Lower segment						
C (km/sec)	1.50 ± 0.10	1.18 ± 0.22	1.11 ± 0.08	1.17 ± 0.17	1.19 ± 0.06	1.12 ± 0.50
S	1.67 ± 0.04	1.67 ± 0.14	1.67 ± 0.05	1.72 ± 0.06	1.56 ± 0.03	1.68 ± 0.11
T (km/sec) ⁻¹	...	...	...	-0.06 ± 0.01	...	-0.04 ± 0.02
U_s limits (km/sec)	2.70-5.83	2.40-3.50	2.30-4.70	2.30-8.26	2.58-5.60	2.58-8.92
Middle segment			...	...	...	...
C (km/sec)	4.64 ± 0.99	constant				
S	0.46 ± 0.10	shock				
T (km/sec) ⁻¹	...	velocity				
U_s limits (km/sec)	5.83-6.26	interval				
Upper segment				...		...
C (km/sec)	1.37 ± 0.17	1.11 ± 0.07	1.87 ± 0.14		1.85 ± 0.38	
S	1.39 ± 0.03	1.35 ± 0.02	1.32 ± 0.03		1.32 ± 0.08	
T (km/sec) ⁻¹	...	...	...		...	
U_s limits (km/sec)	6.26-9.00	3.50-8.20	4.70-8.26		5.60-8.92	
Average initial temperature (°K)	293	293	293	293	75	75
Average initial density (g/cc)	0.879	1.264	1.594	1.594	0.820	0.820
Sound speed (km/sec)	1.31	1.16	0.93	0.93	0.88	0.88
Transition pressure (kbar)	133 ± 5	62 ± 4	164 ± 5	...	135 ± 3	...

U_s-U_p plane. An adjustment of the potential parameters ($n=6.4$, $r^*=6.60$ Å, and $T^*=327^\circ\text{K}$) would probably bring the two curves into better agreement.

E. Liquid Nitrogen

The Hugoniot data are presented in Table IV and in Figs. 10 and 11. The data reported by the Russian investigators¹⁰ are also included in the U_s-U_p plot. Since the initial temperature of the 2024 dural standard was the same as the liquid nitrogen, the equation of state of the 2024 dural had to be adjusted to 75°K , resulting in the equation,

$$U_s = 5.387 + 1.335U_p \quad (14)$$

with $\rho_0(75^\circ\text{K}) = 2.820$ g/cc and the Grüneisen ratio $\Gamma_0 = 2.0$.

The experimental assemblies were constructed and measured at room temperature. Distances and setbacks of pin contactors have been adjusted to allow for the thermal contraction to 75°K . The values listed in Table IV for the shock velocities reflect this adjustment.

Two straight lines fit the U_s-U_p data with a change in slope occurring at about $U_s = 5.60$ and $U_p = 2.90$ km/sec. The lower line fits

$$U_s = 1.19 \pm 0.06 + (1.56 \pm 0.03)U_p \quad (15)$$

and the upper line fits

$$U_s = 1.85 \pm 0.38 + (1.32 \pm 0.08)U_p \quad (16)$$

A smooth curve also provides a good fit of the data

and is described by a quadratic in U_p ,

$$U_p = 1.12 \pm 0.50 + (1.68 \pm 0.11)U_p - (0.04 \pm 0.02)U_p^2.$$

(17)

The present data agree reasonably well with the Russian results.

The intercept with the U_s axis defined by Eq. (15) is higher by nearly 35% than the reported sound speed³⁴ of 0.88 km/sec. This leads to the possibility of a transition occurring below 19 kbar, the lowest pressure used in this study.

The $P-V/V_0$ plot of Fig. 11 shows two concave upward curves with a cusp at 135 kbar. There is considerable scatter of the points, especially at the higher pressures. A temperature associated with 135-kbar pressure was calculated to be 3400°K . If a transition occurs at this pressure, the Hugoniot could cross into the solid phase below 19 kbar and then at 135 kbar recross the fusion line and remain in the solid-liquid mixed-phase region.

Liquid nitrogen shock Hugoniots have been calculated^{35,36} using a Lennard-Jones and Devonshire and a modified Buckingham (exp-6) intermolecular potential which agree well with the experimental Hugoniot between 20 and 170 kbar. The calculations were performed with a computer code developed by Fickett of this laboratory. The code is based on the cell model and assumes: The pair potentials are additive; each cell has 12 nearest neighbors; there is one molecule per cell. The 12 nearest neighbors are uniformly smeared over a spherical surface whose radius cor-

responds to the nearest-neighbor distance. The calculated Hugoniot which agree with the experimental Hugoniot have the following potential forms:

$$\text{LJD } \Phi(r) = [kT^*/(n-6)] [6(r/r^*)^{-n} - n(r/r^*)^{-6}], \quad (18)$$

$$\text{exp-6 } \Phi(r) = [kT^*/(\alpha-6)] \times \{6 \exp[\alpha(1-r/r^*)] - \alpha(r/r^*)^{-6}\}, \quad (19)$$

where r^* is the position of the potential minimum, T^* is the temperature equivalent of the energy of the potential minimum at $r=r^*$, r is the intermolecular distance, k is Boltzmann's constant, n is the repulsion term for the LJD form, and α is the steepness parameter for the exp-6 form. Table V is a list of the values for these "constants" from which the Hugoniot were calculated. Also included for comparison are the values used by others. Figure 12 shows the calculated and experimental Hugoniot. The most recent calculations²² are by Salzman, Collings, and Pings. These agree with the experimental Hugoniot and the parameters used except for the value of n in the repulsion term. A comparison of the parameters for the exp-6 potential used in this study with Fickett's values indicated close agreement. No significance was placed on the separation of the experimental and calculated Hugoniot curves about 170 kbar. The calculated Hugoniot indicates a stiffer material than observed.

IV. SUMMARY

Table VI summarizes the equation of state parameters obtained for each liquid and indicates the appropriate range, standard deviations, and initial conditions. The benzene and carbon disulfide $U_s - U_p$ data are represented by a linear relationship while the carbon tetrachloride and liquid nitrogen data are represented equally well by a linear relationship or by a quadratic in U_p . A transition occurs in benzene and carbon disulfide with the possibility of a mixed phase region existing between the low and high pressure phases. The evidence for the occurrence of a transition in carbon tetrachloride and liquid nitrogen is not as strong as for the other two liquids. Considering Table VI, the values for the slope of the lower and upper line segments for each liquid are very similar.

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