12 mm. The result is shown in Table 2 as shot No. H267. The input and output measurement agreed to within 1 per cent and the shock profile showed no dispersion in time. Thus, on the basis of this measurement the 60° orientation samples can be considered as exhibiting pure longitudinal wave propagation without detectable error in measurements or calculations.

### (b) *High pressure experiments*

Analysis of the explosively-driven shock profile measurements requires a number of additional assumptions due to the reflection of the shocks from the free surface of the samples and the subsequent interaction of the reflected elastic wave with the slower moving high pressure wave. The arrival of the shock waves at the free-surface causes a complete reflection of the incident wave back into the bulk of the sample. If this reflection occurs symmetrically, the resulting free surface velocity is twice the incident particle velocity. This free-surface velocity assumption has been applied to compute the incident particle velocity from the measured free surface velocity. The interaction of this reflected elastic wave with the high pressure wave causes a detectable effect on the data analysis.

The high pressure wave is perturbed before it arrives at the measuring station; thus, the principal problem is to deduce the unperturbed second wave shock velocity from the measurements at the free surface. This interaction is a more important problem than that experienced in experiments on metals because of the possibility of the irreversible loss of shear strength at high pressures. A detailed and graphical description of the problem is given by Ahrens *et al.*[28] and is discussed for the similar situation in quartz by Wackerle [24] and Fowles [25].

Following Wackerle [24] the second wave propagation velocity, $U_2$, is calculated from the relation:

$$U_2 = \bar{U}_2\left[1 - \frac{\Delta t}{t_1}\left\{\frac{(U_3 - 2u_1)(U_1 - 2u_1)t_2 - U_1^2 t_1}{U_1(U_3 - 2u_1)t_2 + U_1^2 t_1}\right\}\right] \tag{11}$$

where $\bar{U}_2$ is the nominal shock velocity taken as the original thickness, $l$, divided by the arrival time, $t_2$, of the second wave at the free surface, $\Delta t$ is the difference in arrival times between the first and second waves, $t_1$ is the arrival time of the first wave, the $u$'s are the particle velocities of the various waves as indicated by the subscripts, $U_3$ is the shock velocity of the reflected elastic wave after interaction with the second wave, and $U_1$ is the shock velocity of the first wave.

In the stress range just above the HEL the calculated value of $U_2$ is sensitive to the choice of a value for $U_3$ which is not measured in the experiment. However, even though $U_2$ cannot always be calculated unequivocally the uncertainty in $U_3$ is not sufficient to change any conclusions and only in the experiments 178-66, 357-67 and 192-64 does it affect the $U_2$ values significantly. In the data shown in Table 2 the value of $U_3$ is chosen to be $U_1 + 2u_1$, in accordance with the view that the material can be elastically reduced to zero stress and subsequently restressed to support the same HEL value. This assumption was found to lead to no inconsistencies among the data and among comparisons to other investigators data.

In order to examine the possibility of non-steady material response accompanying the transition from elastic compression to inelastic compression, experiments were conducted at three sample thicknesses and for four different explosive driving pressures. Although no unequivocal evidence of stress relaxation was observed behind the elastic wave, the amplitude of the elastic wave, HEL, summarized in Table 3 shows both a thickness dependence and a driving pressure dependence which is characteristic of non-steady behavior of the elastic wave. It is probable that small stress relaxation could occur and not be detected by the displacement-time measurements which are inherently

*Table* 3. *Hugoniot elastic limits of sapphire*

| Driver | 0° orientation | 90° orientation | 60° orientation |
|---|---|---|---|
| Sample thickness | | | |
| Baratol | | | |
| 13 mm | — | — | 120 |
| 11 mm | 165* | 155 | — |
| 6 mm | 140 | — | — |
| TNT | | | |
| 13 mm | 140 | — | — |
| 11 mm | — | 135 | — |
| 6 mm | 150 | — | — |
| Comp B | | | |
| 13 mm | — | — | — |
| 11 mm | 150 | — | 165* |
| 6 mm | 170 | — | — |
| 9404 | | | |
| 13 mm | 195 | — | 130 |
| 11 mm | — | 180 | — |
| 6 mm | 210 | — | — |

*mean value of two experiments.

limited by poor resolution of rapid changes in velocity.

The values observed range from 120 to 210 kbar. Thus sapphire exhibits the largest HEL value ever observed for any material. There is considerable scatter in the HEL data. Examination of similar sapphire samples in polarized light indicated considerable internal strain in many samples and it appears that the scatter in HEL values results from the extent of the internal strain in the samples.

## 5. DISCUSSION

Because of the very large HEL values, the shock compression response for sapphire is well suited for use in studying the effects of large anisotropic compressions on solids. From the data in the elastic range, values for several third order elastic constants will be computed at substantially larger compressions than previously employed. From the data in the high pressure region above the HEL the shear stress configuration will be determined and conclusions drawn concerning the effect of shear on compressional behavior of solids. Finally, the HEL values themselves will be analyzed to provide a basis for predicting the conditions under which large values of HEL are observed. As indicated in the introduction the present understanding of these questions for solids other than the metals is inadequate even though these questions are important to our determinations of high pressure equations of state, physical property measurements under shock compressions, and a general theory of plasticity of solids.

This section will first compare the data in the elastic range to extrapolations of ultrasonic measurements of elastic constants. Following this, the high pressure data above the HEL will be examined for evidence of shear stress components and compared to the amplitudes of the HEL and to values for other solids.

### (a) *Elastic range data*

The compressions achieved in the elastic range are an order of magnitude larger than those achieved in the recent ultrasonic measurements of Gieske and Barsch[36].