Entropy-dominated dissipation in sapphire shock-compressed up to 400 GPa (4 Mbar)

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Abstract. Sapphire (single-crystal Al₂O₃) is an Earth material and a window in shock experiments. Pressure at the core-mantle boundary is ~130 GPa. Sapphire becomes opaque at 100-GPa shock pressures, which precludes measuring temperature with thermal radiance. Ruby is sapphire with a few 0.1% Cr. We have measured wave profiles of sapphire crystals with seven crystallographic orientations at shock pressures of 16, 23 and 86 GPa. At 23 GPa plastic-shock rise times are 1-300 ns, depend sensitively on the direction of shock propagation, and are totally contrary to conventional expectations. Long rise times are probably caused by strong inter-atomic interactions. Our wave profiles and published experiments and theory imply sapphire disorders without significant shock heating up to ~400 GPa, above which Al₂O₃ is amorphous and must heat. The characteristic shape of shock compression curves of many Earth materials at 100 GPa pressures is probably caused by a combination of entropy and temperature. Optimal shock windows are probably m- and s-cut crystals. Implications for the ruby scale, shock synthesis, and the ~$6B National Ignition Facility (NIF) are discussed.

1. Introduction
Sapphire is one of the most widely used, widely studied, and arguably one of the least understood materials under shock compression, particularly shock-induced optical effects in the plastic range from 15 to ~150 GPa and the question of why Hugoniot and diamond-anvil-cell (DAC) pressure-volume (P-V) data are nearly coincident up to 100 GPa pressures, as is the case for many strong materials. In 1970 Barker and Hollenbach found that 15 GPa is the maximum stress at which a c-cut sapphire crystal can be used as a window in a Velocity Interferometer for a Surface of Any Reflector (VISAR). The cause was “shock-induced luminescence and/or loss of transparency” [1]. Metallic fluid hydrogen has been synthesized at 140 GPa by a shock wave reverberating in liquid H₂ contained between two transparent c-cut sapphire crystals [2,3]. The reverberating shock causes sapphire to become opaque, which precludes measurement of temperature T from thermal spectra emitted from the dense fluid. For this reason temperatures in those experiments were calculated.
To try to understand and control the nature of shock-induced defects in sapphire and to see if there is a direction of shock propagation in the hexagonal crystal structure that remains more transparent to higher pressures than $c$-cut sapphire, we have measured temporal profiles of shock waves propagating in seven different directions in the sapphire lattice [4]. At 23 GPa, rise times, or temporal widths, of the plastic-wave shock fronts range from 1 to 300 ns! These wave shapes are not only contrary to conventional expectations, but even to our imagination as to what conceivably might be measured. Because these waves are difficult to understand by themselves, we have also taken into consideration other experiments and recent theoretical calculations [5-8] to gain understanding of this unusual system. Remarkably, while shocked materials are generally considered to be at high temperatures, we discovered that strong sapphire is probably not shock-heated significantly until about 400 GPa. Starting from lowest pressures shocked sapphire disorders continuously via mechanical failure of its strong lattice up to 100 GPa pressures, followed by incomplete transitions to several new phases up to about 400 GPa, at which sapphire is probably amorphous. Dissipative shock energy below ~400 GPa is absorbed primarily in entropy of disorder. Further dissipation at higher shock pressures must then heat amorphous $\text{Al}_2\text{O}_3$, which in turn causes rapid increase in thermal pressure with density. The fact that sapphire is so strong causes the pressure of the transition from primarily entropic dissipation to the addition of significant shock heating to occur at such high pressures that the two effects are resolved experimentally and readily identified. This is the first time to our knowledge that effects of entropic and thermal dissipation have been resolved in shock flows [9].

To arrive at this conclusion it was necessary to consider our wave profile measurements in the context of previous sapphire work above ~10 GPa. Hugoniots [10] of $c$-cut [0001], $a$-cut [11-20], and $n$-cut [11-23] sapphire crystals [11] and of polycrystalline alumina [12] were measured up to ~40 GPa with a rotating-mirror camera. The $a$ axis is in the basal plane, the $c$ axis is perpendicular to the basal plane, and the $n$ axis makes an angle of 61° with the $c$ axis. Above the Hugoniot elastic limits (HELs ~15 GPa), the Hugoniots of these three crystal orientations and of alumina are essentially coincident, which was attributed to substantial loss of shear strength caused by heterogeneous lattice damage (entropy) [11]. The calculated temperature rise of alumina at a shock stress of 30 GPa is small, only ~100 K [12]. Those data were analyzed assuming ideal elastic-plastic flow, though the rotating-mirror technique is weakly sensitive to time dependences of shock waves.

Shock-compressed $n$-cut sapphire starts to lose its transparency at shock stresses in the range 100 to 130 GPa [13]. Between 16 and 85 GPa, optical spectra emitted from shocked sapphire are gray-body-like with an effective temperature of 5600 ± 500 K and an emissivity that increases up to 0.08 at 85 GPa [14]. While those measured temperatures are high, little thermal energy is deposited in bulk because of small emissivities. Those heterogeneous temperatures are larger by an order of magnitude than estimated thermodynamically [12]. Kondo interpreted his spectra as thermal emission from heterogeneous hot spots whose areal density increases with shock stress. Hare et al took fast-framing photographs of $c$-, $a$-, and $r$-cuts [1-102] as shocks traversed those crystals. The $r$ direction makes an angle of 58° with the $c$ axis. They observed heterogeneous hot spots suggested by Kondo and found that their areal density depends on pressure and crystal orientation [15]. Local hot spots are caused by local disorder (entropy). Microstructures of sapphire recovered from high shock pressures were investigated for plastic flow and fracture. Recovered samples indicated that plastic deformation via slip and twinning is sensitive to the direction of shock propagation in the lattice and is largest for shocks travelling in the $r$ direction relative to the $n$ and $c$ directions. At 24 GPa the volume fractions of twins are 0.18, 0.14, and 0.07 for shock propagation in the $r$, $n$, and $c$ directions, respectively [16].

The few shock-wave profiles that have been measured for sapphire have elastic-precursor decays and plastic waves with long rise times (~100 ns) at tens of GPa [17-20]. The cause of those long rise times was not explained and has been a major unanswered question about the nature of shock propagation in strong materials. The shock response of quartz is similar to that of sapphire [19].
Hugoniot data from 20 to 340 GPa have been measured [5,6]. The fit to those Hugoniot data is linear over the entire pressure range: \( u_s = C + S u_p \), where \( u_s \) is shock velocity, \( u_p \) is particle velocity, \( C = 0.874 \text{ cm/}\mu\text{sec} \), and slope \( S = 0.957 \). Virtually all single-phase materials have \( S > 1 \). Slope \( S < 1.0 \) implies a phase transition in virtually all materials in which it has been observed. Thus, those Hugoniot data suggest a continuous phase transition in sapphire from 20 to 340 GPa. Sapphire Hugoniot data also show scatter in the HEL near 30 GPa and a phase transition at 79 GPa [21]. A laser has been used to measure sapphire Hugoniot data from 1.1 to 1.9 TPa (19 Mbar) [7]. Those laser data demonstrate the onset of significant thermal pressures and temperatures above 400 GPa.

To summarize, very few time-resolved VISAR profiles of sapphire crystals have been measured in the plastic regime and those time histories are yet to be explained. Hugoniot data to 340 GPa is anomalous because it implies a continuous solid phase transition from 20 to 340 GPa! Calculated shock temperatures are low, \( \sim 1000 \text{ K} \) at 100 GPa. Optical transparency is heterogeneous, which is indicative of disorder/entropy, up to a shock pressure of 85 GPa and anisotropic, which is caused by the non-cubic crystal structure. Transparency up to 45 GPa correlates with plastic deformation mechanisms of slip and twinning. Only a few directions of shock propagation in the hcp lattice have been investigated: along \( c, a, r \) and \( n \) directions and \( n \) and \( r \) are almost coincident.

In this paper we show results only for \( c \)-cut and \( r \)-cut single crystals, which are sufficient to show that these wave profiles are quite unusual and to draw conclusions about the relative importance of entropic and thermal dissipation. These results suggest the likely reason why Hugoniots of strong materials are virtually coincident with their cold compression curves below \( \sim 50 \text{ GPa} \) and why Earth materials have rapid upturns in shock pressure with compression around \( \sim 100 \text{ GPa} \) [22].

### 2. Experiment

We have measured wave profiles for two thicknesses of seven sapphire crystal orientations at pressures of 16, 23, and 86 GPa, which are (i) near the HEL, (ii) in the two-wave regime above the HEL, and (iii) just below the pressure at which the plastic wave overdrives the elastic wave. Two thicknesses were used to determine steadiness of wave shapes. Shock waves were generated by impact of a 2.0 mm-thick Al impactor plate at velocity \( u_I \) onto the front surface of a 2.0 mm-thick Al base plate. Impactor plates were accelerated with high explosives at the Institute of Problems of Chemical Physics and were designed to preclude spall [23]. Impact velocities \( u_I \) were \( 1.2 \pm 0.03, 1.8 \pm 0.05, \) and \( 5.2 \pm 0.1 \text{ km/s} \), which produce peak stresses in sapphire of 16, 23, and 86 GPa. The Al base plate was backed by a sapphire disk, which was backed by a LiF disk. An Al foil 7 microns thick separated the sapphire from the LiF. The laser beam of a VISAR was incident on axis on the rear surface of the target assembly. The 1-mm diameter beam passed through the transparent LiF disk and reflected off the Al foil at the sapphire/LiF interface. In this way velocity histories of sapphire/LiF interfaces were measured. Sapphire disks, obtained from Princeton Scientific Corporation, were 2.4 and 5.1 mm thick and 22 and 50 mm in diameter, respectively, thinner than used previously [1,11].

### 3. Results

Two sample thicknesses of several orientations showed that wave shapes were nearly steady with run distance, as shown in Figure 1, for \( r \)-cuts shocked to 23 GPa. Profiles of \( r \)-cuts are smoother with time than those of \( c \)-cuts because the \( r \) direction has substantially more plastic deformation than along the \( c \) direction. The elastic wave rises quickly (~ns) to a relatively steady amplitude, as a conventional HEL. The rise time of the plastic wave is \( \sim 100 \text{ ns} \). For \( r \)-cuts, HEL’s (peak elastic stresses) were 13, 13, and 19 GPa for incident peak stresses of 16, 23, and 86 GPa, respectively.

Figure 2 shows wave profiles of 5.0 mm-thick \( c \)-cuts at three incident peak stresses. Fracture is significant in \( c \)-cuts, which causes profiles to be much more “noisy” in time than for \( r \)-cuts. For this reason profiles in Fig. 2 are averages of two or three experiments. Averages are smoother than...
individual profiles. Fracture will be discussed in a future publication. At 16 GPa the elastic shock is sharp and steady for 300 ns, followed by slow decay. The corresponding elastic wave of r-cut at 16 GPa (not shown) starts to relax within 40 ns of reaching its maximum, suggesting elastic strength in the r direction is lower than for c-cut. At 23 GPa the elastic wave of c-cut rises in a few ns and within a few ns starts to relax. The rise time of the second wave is ~300 ns. At an incident stress of 86 GPa, the elastic precursor first relaxes for ~50 ns, followed by a plastic shock with a rise time of ~10 ns. Figure 2 suggests that above ~90 GPa only a single sharp (rise time<ns) plastic shock propagates. For c-cuts, HEL’s were 16, 18, and 24 GPa for initial stresses of 16, 23, and 86 GPa, respectively.

**Figure 1.** Wave profiles at sapphire/LiF interfaces after travelling through 2.4 and two 5.1-mm-thick r-cut sapphire disks and releasing into LiF. Incident shock stress into sapphire is 23 GPa achieved by impact of Al on Al at 1.8 km/s.

**Figure 2.** Wave profiles at sapphire/LiF interfaces after travelling through 5.0-mm-thick c-cut sapphire disks into LiF. Incident shock stresses into sapphire are 16, 23 and 86 GPa, achieved by impacts of Al onto Al at 1.2, 1.8, and 5.2 km/s. Profiles for 1.2 and 1.8 km/s are averages of 2 and 3 experiments, respectively. Profile for 5.2 km/s is average of two experiments with two different velocity-per-fringe VISAR constants.
4. Discussion. Rise times of plastic shock fronts in sapphire are systematically long, ranging from 80 to 300 ns in six of the seven crystallographic orientations investigated [4]. A rise time of a plastic shock front of ~100 ns is 5 orders of magnitude greater than shock rise times of compressible fluids, ~1 ps in fluid Ar [24], for example. The long rise times are telling us that ~100 ns is required to break and/or reorient ~eV bonds to reach maximum compression. The eV bonds strongly resist compression, unlike a soft Vander Waals fluid. In shock-compressed liquid Ar the well depth for pair interactions is ~0.01 eV, 100 times smaller than ~eV bond strengths in Al₂O₃. At 50 GPa liquid Ar is shock-compressed 2.2 fold in density ρ to 14,000 K, and dissipative thermal energy is ~90% of shock energy [25]. At 50 GPa sapphire is shock-compressed 1.1 fold in density to ~500 K, and dissipative thermal energy is only a few % of shock energy. These differences are huge and imply that the long rise times of shock waves in strong sapphire at tens of GPa are caused by the high strength of inter-atomic interactions in an ordered three-dimensional lattice. Above 50 GPa and 15,000 K, shock energy in fluid Ar is absorbed internally by thermal activation of electrons into a conduction band.

In contrast, shock-compressed sapphire is probably not in thermal equilibrium. Calculated shock temperatures, assuming uniform deposition of shock energy, are only ~1000 K at 100 GPa [12], Hugoniot data [5,6] and the 300-K isotherm of ruby (sapphire plus a few 0.1% of Cr) measured in a DAC [26] are nearly coincident up to 100 GPa pressures, and the calculated 0-K isotherm up to 400 GPa [8] is virtually coincident with Hugoniot measurements up to 340 GPa [5,6]. Because of the relatively low temperatures and thermal pressures, strong (~eV) inter-atomic interaction energies, and short experimental lifetimes, sapphire shocked up to 90 GPa is probably not in thermal equilibrium. A non-equilibrium process expected to produce all these phenomena is bond breaking and/or reorientation that occurs continuously and statistically on a ~100 ns time scale. Shock temperatures are kept low from lowest shock pressures by absorption of an ~eV of mechanical energy to break and/or reorient each bond. Such a material is expected to strongly resist compression because correlated motions of large networks of strongly interacting atoms would have to compress as units, resulting in less compression that takes more time to achieve relative to a compressible liquid. Energy absorbed mechanically is not available to heat the shocked sapphire, nor is this energy available to achieve thermal equilibrium. Rather, this mechanical process damages the lattice, producing entropy.

Figure 3. Solid curves are calculated pressure versus compression at 0-K of sapphire [8]. Four sapphire phases are calculated along 0-K isotherm. Horizontal dashed gray lines indicate calculated pressures of phase transitions. Dots are measured Hugoniot points [5,6].
The solid curves in Figure 3 are the four phases that comprise the calculated 0-K isotherm of sapphire up to ~400 GPa [8]. Dots are Hugoniot data measured by McQueen [5] and by Erskine [6]. Theory and experiment are virtually coincident up to ~400 GPa, which implies thermal pressures (and thus shock temperatures) are small compared to pressures on the 0-K isotherm. There are three oxide phases in the range of the fit obtained from those Hugoniot experiments. Given the short ~100 ns experimental lifetimes, it is unlikely that shocked sapphire can anneal into those well-ordered crystalline phases during the experimental lifetimes. The good agreement between theory at 0 K and Hugoniot data implies that sapphire is deforming plastically while changing its short-range order to the predicted structures. From Fig. 3 the onset of phase transitions probably commences near 90 GPa, the pressure of the first phase transition, which is just above the upper limit of our wave-profile measurements and the approximate pressure at which the elastic wave is overdriven by the plastic one.

Phase transitions at 0 K from corundum to $\text{Rh}_2\text{O}_3(\text{II})$-type at ~90 GPa and then to $\text{CaIrO}_3$-type at ~130 GPa have been predicted theoretically [27, 28]. Onsets under shock of opacity at ~100 to 130 GPa [13] and decrease in electrical resistivity at 130 GPa [29] correlate with the corundum to $\text{Rh}_2\text{O}_3(\text{II})$-type and $\text{Rh}_2\text{O}_3(\text{II})$ to $\text{CaIrO}_3$-type phase transitions predicted theoretically. In addition to those two transitions, Umemoto and Wentzcovitch [8] predict a transition from $\text{CaIrO}_3$-type to $\text{U}_2\text{S}_3$-type at 380 GPa. Their calculated pressure-density curves for corundum, $\text{Rh}_2\text{O}_3(\text{II})$-type, $\text{CaIrO}_3$-type, and $\text{U}_2\text{S}_3$-type are plotted in Fig. 3.

In a DAC, compression of corundum at 300 K produces only disordered corundum at high pressures. Only with laser heating and thermal quenching at high pressures were $\text{Rh}_2\text{O}_3(\text{II})$-type synthesized at 103 GPa and $\text{CaIrO}_3$-type synthesized from 130 to 200 GPa at 300 K [30, 31]. X-ray spectra of laser-heated and quenched samples consist of broad individual diffraction peaks superimposed on a significant broad background, indicative of disordered structures with short-range order. Since experimental lifetimes of DAC experiments are probably a factor of ~$10^8$ slower than shock experiments and since compressed and laser-heated corundum transitions to phases that are not well ordered at 100 GPa pressures, it is reasonable to assume that $\text{Al}_2\text{O}_3$ is highly disordered and continually evolves in the much faster shock experiments, in which a phase transition has yet to be observed at 100 GPa pressures on the Hugoniot. Entropy in shock-compressed sapphire is substantial at 100 GPa pressures.

As shock pressure increases up to 340 GPa the corundum phase probably undergoes increasing lattice damage up to ~100-130 GPa. At higher shock pressures sapphire probably transforms continuously to a disordered $\text{CaIrO}_3$-type structure. This continuous transition is probably a frustrated evolution of short-range order toward, but never reaching, the long-range order of the equilibrium $\text{CaIrO}_3$-type phase. Evolution of lattice damage and short-range order under increasing shock compression has associated entropy generation, which increases with shock pressure. Such a continuous phase transition is a likely explanation of why slope S<1.0 over this entire pressure range and why shocked sapphire goes opaque above ~100 GPa. This is the first time to our knowledge that a calculated 0-K isotherm without thermal corrections is so close to the measured Hugoniot over such an enormous range of pressure.

At sufficiently high pressures, shock compression is expected to completely disorder sapphire to an amorphous state, which would maximize lattice entropy. At still higher shock pressures, dissipation would have to go primarily into temperature and thus thermal pressure. The pressure of this crossover can be estimated with laser-driven Hugoniot data up to 1.9 TPa in Figure 4. Above 400 GPa, shock pressure increases dramatically with density, which is probably caused by the onset of thermal dissipation and increasing thermal pressure. From Fig. 3, 400 GPa is just above the calculated pressure of the $\text{CaIrO}_3$-type to $\text{U}_2\text{S}_3$-type transition, the highest-pressure transition predicted on the 0-K isotherm. The authors of [7] suggest that because temperatures are tens of 10,000 K when the slope of
shock pressure with density increases dramatically, sapphire probably melts on the Hugoniot at ~500 GPa, above which liquid Al$_2$O$_3$ is a semiconductor with a mobility gap of ~2 eV.

Figure 4. Measured Hugoniot data of sapphire from 1.1 to 1.9 TPa (19 Mbar) [7]. Data to 340 GPa [5,6] are in mutual agreement and virtually coincident with calculated 0-K isotherm (Fig. 3). Dashed curve is extrapolation of fit to Hugoniot data below 340 GPa. Data points at 1.1 to 1.9 TPa show onset of significant thermal pressure above 400 GPa [7].

4. Implications of this work

Because of the high strength of sapphire, bonds exist to very high shock pressures and, thus, so too does entropy production. For oxides with less strength than sapphire this clear separation of entropic and thermal contributions to dissipation energy has not been recognized previously. At lower shock pressures, say ~100 GPa, in materials with lower strength, entropic and thermal dissipation both occur and effects of the two are not resolved clearly with thermal pressure, as in Fig. 4 at ~400 GPa. This is probably why many oxides have increases in slope of shock pressure with compression at ~100 GPa pressures [22]. In the case of Gd$_3$Ga$_5$O$_{12}$ (GGG), for example, the 300-K isotherm measured in a DAC [32] is nearly coincident with the measured Hugoniot [33] up to ~70 GPa, above which GGG becomes amorphous in a DAC [32]. At a shock pressure of 120 GPa and ~5000 K, GGG probably undergoes a transition to a semiconducting liquid with a mobility gap of 3.1 eV, similar to Al$_2$O$_3$ [7].

Ruby, sapphire with about 0.5% Cr, is expected to behave similarly to pure sapphire. Ruby fluorescence depends on local order of sapphire around Cr atoms. Thus, the ruby fluorescence line is expected to broaden and decrease in magnitude until it loses meaning as a pressure calibrant at some very high pressure. Based on sapphire disorder in a DAC [30,31], the ruby scale calibrated versus shock-wave reduced isotherms can probably be used reliably up to ~150 GPa, the present limit of its calibration [34-36]. In the 150 GPa range the ruby line shape is expected to become increasing more sensitive to the size and positioning of ruby chips used in a given experiment.

Our measured shock-wave profiles at 23 GPa [4] indicate that shock compression of sapphire is essentially ideal elastic-plastic in the $m$ and $s$ directions and farthest from ideal elastic-plastic in the $c$ direction. Based on these observations it is probable that $m$- and $c$-cut sapphire crystals remain the most transparent to highest pressures under plastic shock compression and $c$-cuts are not as good as windows at highest pressures. However, experiments to verify this idea need to be performed.
For the same reason, synthesis of novel materials by shock compression of single crystals might be an important new area of scientific research with potentially broad technological applications. Synthesis probably varies between relatively well-ordered phases produced by first-order phase transitions and amorphous phases, depending on direction of shock propagation. In sapphire, for example, shock propagation in the $m$ and $s$ directions might easily induce first-order phase transitions by slip. Back transformation of shock-induced first-order phase transitions might be impeded by shock-induced defects. On the other hand, shock propagation in the $c$ direction might induce amorphous material, which is irreversible on release of pressure.

The National Ignition Facility (NIF) is designed to produce optimal fusion energy by Inertial Confinement Fusion (ICF). It has been under construction at Lawrence Livermore National Laboratory (LLNL) since 1996 and is expected to cost ~$6B. Our sapphire results have pointed out the need for experiments on solids in order to produce optimal fusion energy. The main impediment to fusion energy production was published in 1972 [37] and is discussed in more detail elsewhere [38]. Optimal production, or “Success” is defined here to be generation of sufficiently large quantities of fusion energy so that NIF could be a new commercial source of non-carbonaceous energy, a national need in the U.S. ICF is the process of dynamically compressing deuterium-tritium (DT) fuel to enormous densities $p$ and temperatures $T$ so that the fusion reaction rate is large. DT-fusion cross sections are very large at keV energies, at which fusion reaction rate is proportional to $p^2T^4$. Thus, unwanted cooling or decrease in density of the degenerate, fluid DT fuel can cause a very large decrease in fusion reaction rate, commonly known as poisoning fusion.

ICF is driven by a series of spherically converging shock waves induced by the pulsed NIF laser. Shock waves are generated by ablation of the outer spherical surface of the solid shell containing the DT fuel ball. Typical first-shocks will be several 100 GPa (Mbar) in likely capsule materials of polycrystalline diamond or nanocrystalline Be. Diamond melts on its Hugoniot at 700 to 1000 GPa [39,40]. Thus, diamond will likely be in the solid phase with strength in such implosions. The biggest impediment to success [37] is mixing shell material into the DT fuel, so that its temperature $T$ would be lowered, which would lower the fusion reaction rate sufficiently to poison fusion. In this case $T$ would be lowered by absorption of thermal energy to ionize atoms injected from the solid shell. Thermal energy is produced by dynamic compression of DT.

Shell material can be mixed into the fuel by Raleigh-Taylor (R-T) and Richtmyer-Meshkov (R-M) instabilities at the interface between the solid spherical shell and DT fuel ball, as well as by surface ejecta of mass from the shell into the DT when the 100 GPa shock in the shell breaks into the DT fuel. As a shock wave propagates through a strong shell material, heterogeneous defects can be generated, as observed in sapphire, which would imprint small imperfections on the interface between shell and DT. These imperfections could act as nucleation sites for R-T growth under subsequent high accelerations, so that eventually shell material is mixed into the fuel. Since shock pressures in the shell have initial magnitudes of several 100 GPa, it is quite likely that material on the inner surface of the shell will simply be ejected directly into the DT fuel, poisoning the fusion process.

Recently, Celliers et al [41] of LLNL reported measurements with a new two-dimensional imaging VISAR over an 800-micron field of view. This technique is sensitive to mode wavelengths on shock breakout from a surface ranging from 2.5 to 100 micron, sufficiently large to poison fusion when amplified by high accelerations. This new diagnostic now makes it possible to survey a wide variety of materials to find optimal shell materials. Optimal shell materials have to be identified by experiment. Optimal materials cannot be identified with computer simulations, the approach of the last few decades, because properties and responses of potential shell materials are unknown at 100 GPa shock pressures. Implosion of an ICF shell requires a material that is sufficiently strong to resist R-T growth and sufficiently weak to generate few in situ nucleation sites for R-T growth. Shell
materials must be strong enough not to eject debris from its inner surface on breakout of a few 100 GPa shock. Given the cost on a giant laser and the fact that 100 GPa pressures can be achieved in strong materials with a two-stage gun, which is orders of magnitude less expensive than a giant laser, it is logical to survey likely materials with a two-stage gun. Potential materials, single crystals and polycrystalline, should be investigated to identify optimal ones. One question, for example, is what is the highest pressure in a material that produces zero surface ejecta on breakout of a 200 GPa shock?

5. Conclusion

The high strength of sapphire enables bonds to persist to very high pressures (~400 GPa) and, thus, enables resolution of a lower shock-pressure regime in which entropy of lattice disorder dominates shock dissipation and a higher shock-pressure regime in which thermal dissipation becomes dominant over and above the saturated entropic contribution to shock dissipation. As a result, the nature of shock flows in strong materials differs systematically and substantially from that in Vander Waals fluids in which dissipation is overwhelmingly thermal at all shock pressures. Sapphire is a unique material in which continual shock-induced lattice damage below ~100 GPa and continual plastic compression and evolution of short range order in a huge range of shock pressure with four successive equilibrium phases causes entropy to preferentially “soak up” shock energy up to 400 GPa, which maintains shock temperatures low via mechanical absorption of shock energy in a system far from thermal equilibrium. This is the first time to our knowledge that contributions of entropy and temperature to shock dissipation energy have been resolved experimentally.

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6. References

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A Hugoniot curve is obtained by single-shock compressions to different pressures.

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