Temperature and Density on the Forsterite Liquid-Vapor Phase Boundary

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Abstract The physical processes during planet formation span a large range of pressures and temperatures. Giant impacts, such as the one that formed the Moon, achieve peak pressures of 100s of GPa. The peak shock states generate sufficient entropy such that subsequent decompression to low pressures intersects the liquid-vapor phase boundary. The entire shock-and-release thermodynamic path must be calculated accurately in order to predict the post-impact structures of planetary bodies. Forsterite (MgSiO₃) is a commonly used mineral to represent the mantles of differentiated bodies in hydrocode models of planetary collisions. Here, we performed shock experiments on the Sandia Z Machine to obtain the density and temperature of the liquid branch of the liquid-vapor phase boundary of forsterite. This work is combined with previous work constraining pressure, density, temperature, and entropy of the forsterite principal Hugoniot. We find that the vapor curves in previous forsterite equation of state models used in giant impacts vary substantially from our experimental results, and we compare our results to a recently updated equation of state. We have also found that due to under-predicted entropy production on the principal Hugoniot and elevated temperatures of the liquid vapor phase boundary of these past models, past impact studies may have underestimated vapor production. Furthermore, our results provide experimental support to the idea that giant impacts can transform much of the mantles of rocky planets into supercritical fluids.

Plain Language Summary Collisions onto planets during planet formation can reach extreme pressures and temperatures. Giant impacts, like one that may have made the moon, reach pressures of millions of atmospheres. Decompression from such high pressures causes the material that makes up planets to melt and vaporize. To help predict the post collision structure of planets, we performed laboratory experiments on the mineral forsterite (MgSiO₃) that recreates the extreme conditions of these collisions. We used the Z Machine, a facility at Sandia National Laboratories that can launch projectiles up to 40 km s⁻¹ (almost 90,000 miles per hour), to measure the properties of forsterite once it has decompressed. We find that previous models of forsterite melting and vaporization do not match the experimental results found here. The results provide experimental support that giant impacts yield planets that may have mantles that are partially supercritical fluids, that behave like liquids and gases.

1. Introduction During terrestrial planet formation, impacts were a widespread and fundamental process (Chambers, 2010), the scale of which ranged from small impacts between planetesimals to giant impacts such as the Moon-forming impact. The post-impact structures of a giant impact depend upon the specific parameters of the impact. The equations of state (EOS) of the constituent materials are necessary to enable calculation of the energy deposited by the event and the internal structure, including the amount of melting and vaporization. Previous work has found that energetic, high-angular momentum impacts create synestias (Lock & Stewart, 2017; Lock et al., 2018) and less energetic impacts form a more traditional planet and disk structures (Canup et al., 2013). Understanding the evolution of planetary bodies after a giant impact requires robust EOS models.
Giant impacts between Earth-sized planets can generate pressures and temperatures in excess of 500 GPa and 15,000 K. Subsequent decompression melts and vaporizes significant fractions of the constituent materials. Recent work has shown that vaporizing collisions are relatively common during planet formation in that almost all impacts onto large embryos create vapor (Davies et al., 2020; Kraus et al., 2012, 2015; Stewart & Ahrens, 2005). Wide-ranging EOS models are required that span the extreme conditions achieved during giant impacts as well as the subsequent decompression to the liquid-vapor phase boundary.

Hydrocode simulations of planetary collisions often use forsterite (Mg$_2$SiO$_4$), the Mg end-member of the olivine system, as a proxy for the bulk silicate composition of differentiated bodies. The most commonly used EOS for forsterite, M-ANEOS, is an extension of the Analytic Equations of State (ANEOS) code package (Thompson, 1990; Thompson & Lauson, 1974) which includes molecular vapor species. ANEOS was originally developed for silica in Melosh (2007). ANEOS-based material models require many input parameters that must be constrained by thermodynamic data.

The ANEOS models for forsterite used in previous giant impact studies were developed without experimental constraints for the vapor curve at high pressures and without measurements of the shock response above about 200 GPa. Recently, the shock states for forsterite were measured at pressures from 200 to 950 GPa, to determine the relationships between pressure ($P$), density ($\rho$), temperature ($T$), and specific entropy ($S$) (Davies et al., 2020; Root et al., 2018). Stewart et al. (2020) found substantial differences between previous ANEOS models for forsterite and these new data, and developed improvements to the ANEOS code package to improve the fit to experimental temperatures and entropies.

The liquid-vapor phase boundary is difficult to access experimentally for silicates because they have critical point temperatures that preclude static measurements. Evaporation experiments have determined the triple point for forsterite at 2,163 K and 5.2 Pa (Nagahara et al., 1994), but these experiments do not extend to the critical point. Previous studies determined the thermodynamic states on the liquid-vapor phase boundary of silica (Kraus et al., 2012) and iron (Kraus et al., 2015) and developed a technique to enable measurements of state variables with a dynamic shock-and-release experiment. In this work, we utilize this technique to provide the first experimental constraints on the forsterite liquid-vapor curve near the critical point.

In a planar shock experiment, a flyer plate generates a shock wave that propagates through the sample and compresses it uniaxially. The shock wave is a near discontinuous feature that separates ambient $P$, $\rho$, and energy states from high $P$, high $\rho$, and high energy shocked states. These shock states obey the one-dimensional Rankine-Hugoniot jump conditions derived from conservation of mass, momentum, and energy:

$$\frac{\rho}{\rho_0} = \frac{u_s - u_p}{u_s}$$  \hspace{1cm} (1)

$$P - P_0 = \rho_0 u_s u_p$$  \hspace{1cm} (2)

$$E - E_0 = \frac{1}{2} (P + P_0) \left( \frac{1}{\rho_0} - \frac{1}{\rho} \right)$$  \hspace{1cm} (3)

where the subscript naught indicates the initial condition, $u_s$ is the shock wave velocity, $u_p$ is the particle velocity, $V$ is specific volume, and $E$ is the specific internal energy. The collection of all possible shock states for a single initial condition is a curve known as the Hugoniot. The Hugoniot with initial conditions at standard temperature and pressure conditions (STP) is the principal Hugoniot. An illustration summarizing the thermodynamic paths utilized in our experiments is given in Figure 1. The principal Hugoniot, with example shock state at point A, is shown by the blue line in Figure 1.
Figure 2. Generalized schematic of the flyer plate experiments on the Sandia Z Machine. In each experiment, both the anode and cathode are 1.2 mm thick aluminum flyer plates that impact target panels with several science samples and diagnostic windows. The ability to field up to 14 samples per shot enables multiple types of measurements in a single experiment: Shock and partial release, shock-and-release, and reverse impact experiments.

The decompression path from a shock state provides an opportunity to probe the temperature and density of the liquid-vapor phase boundary. Once the shock wave reaches a free surface, a rarefaction wave propagates back into the shocked sample, decompressing the sample. The rarefaction wave is a pressure wave that propagates at the speed of sound and is assumed to be isentropic in a liquid (dark blue decompression path in Figure 1). The rarefaction also accelerates the decompressing material, where the acceleration depends upon the sound speed. During decompression from a sufficiently strong shock, the isentrope will intersect with the liquid-vapor phase boundary, for example, at point B in Figure 1. To continue decompressing, the sample must begin to vaporize. The phase change also represents a discontinuity in the sound speed, leading to separation of decompression waves above and below the liquid-vapor phase boundary. Material is therefore inertially trapped between the two waves at the density of the liquid-vapor phase boundary. The thermal emission from this liquid layer can also be measured to constrain the temperature of this state (B) on the phase boundary.

The density of the liquid layer at state B in Figure 1 is determined by conducting a reverse impact experiment, where the accelerated liquid flyer plate is the material of interest. In a reverse impact experiment, such as Kraus et al. (2012) and Kraus et al. (2015), a standard window is placed downrange of the sample by a known gap distance. The liquid layer traverses this gap and impacts the window, generating a shock in the trapped material and in the window. The shock that propagates back into the liquid flyer lies on the Hugoniot with initial conditions on the liquid branch of the liquid-vapor phase boundary. The thermal emission from this liquid layer can also be measured to constrain the temperature of this state (B) on the phase boundary.

In this work, we present data obtained through the Z Fundamental Science Program at Sandia National Laboratory’s Z Machine. Our experiments exploit the shock-and-release thermodynamic path to attain temperatures and densities on the liquid branch of the liquid-vapor phase boundary.

2. Experimental Methods

Shock compression experiments were performed at the Sandia Z machine using a magnetic drive generated by an intense current pulse. The large current and field densities generate magnetic pressures up to 650 GPa that can accelerate aluminum flyer plates up to 40 km/s (Lemke et al., 2005). Figure 2 shows a schematic of the experimental configuration. The principal diagnostic in this work was the Velocity Interferometer System for Any Reflector (VISAR) (Barker & Hollenbach, 1972; Barker & Schuler, 1974), which measures flyer plate velocity, shock wave velocity, and transit times. Selected samples also employed a Streaked Visible Spectrometer (SVS) to measure the emission spectrum from the sample, as used in previous experiments (Root et al., 2018). All variables in this work are defined in Table 1, and Hugoniot relations are defined in Table 2.

Two types of experiments were performed for this work that take advantage of the shock-and-release thermodynamic path described in Section 1. The first type of experiment was a reverse impact experiment, where forsterite was shocked and then decompressed across a vacuum gap of
Table 2
Equations for the Principal Hugoniots of Materials Used in This Work

| Material   | Hugoniot equations                                                                 | Reference |
|------------|------------------------------------------------------------------------------------|-----------|
| Forsterite | \( u_s(u_p) = 4.632 + 1.455u_p + (4.291E - 03)u_p^2 - (7.844E - 04)u_p^3 \)         | (1)       |
|            | \( T(u_p) = -183.188u_p + 15.605u_p^2 + 2.785u_p^3 \)                             | (1)       |
|            | \( S(P) = -28691P^{-0.5} + 152.8P^{0.5} - 0.0208P^{1.5} + 3.680 \)               | (2)       |
|            | \( \gamma(P) = \gamma_{\infty} + (0.377 - \gamma_{\infty})\left(\frac{P_0}{P}\right)^{1.705} + 0.657e^{-(P-0.93)^2/0.192^2} \) | (2)       |
| \( \alpha \)-quartz | \( u_s(u_p) = 1.754 + 1.862u_p - (3.364E - 02)u_p^2 + (5.666E - 04)u_p^3 \)       | (3)       |
| TPX        | \( u_s(u_p) = 1.795(\pm 0.018) + 1.357(\pm 0.003)u_p - 0.694(\pm 0.027)u_p^2 \)   | (4)       |

Notes. Errors on the parameters for \( u_s(u_p) \) for TPX are given. Uncertainty for \( \gamma(P) \) of forsterite is 32%. Uncertainty for the others have co-variance matrices included in the supplemental materials in Table D1. The forsterite principal Hugoniot equations have a range of validity from 200 to 950 GPa, and the initial density \( (\rho_0) \) is 3,220 kg/m\(^3\). The forsterite \( \gamma(P) \) function is valid from 2,597 to 6,500 kg/m\(^3\), where \( \gamma_\infty = 2/3 \) and \( \rho_0 = 2,597(\pm 11) \) kg/m\(^3\). The quartz principal Hugoniot \( u_s(u_p) \) equation have a range of validity 40–800 GPa, and the initial density is 2,651 kg/m\(^3\). TPX principal Hugoniot equations have a range of validity up to 985 GPa, and the initial density is 833 kg/m\(^3\). The material-specific \( u_s(u_p) \) equations can be transformed to pressure, specific volume and specific internal energy via the Rankine-Hugoniot conservation equations. References: (1) Root et al. (2018), (2) Davies et al. (2020), (3) Knudson and Desjarlais (2013), (4) Root et al. (2015).

Reverse impact experiments (following shock-and-release) were previously conducted in Kraus et al. (2015) to measure the density of liquid iron on the vapor curve. The theoretical development of the shock-and-release technique to effectively generate a “liquid flyer plate” was presented in Kraus et al. (2012). We used synthetic single-crystal forsterite samples from MolTech GMBH and Princeton Scientific Corp. The forsterite was oriented on the [001] axis, which has an index of refraction of \( n_{001} = 1.651 \). The samples had an initial density of \( \rho_0 = 3.22 \pm 0.01 \) g/cm\(^3\) (Deer et al., 2013).

When the shock reaches the down range free surface of the sample, we measured the time of flight of the uniaxially expanding forsterite across gaps of known thickness to determine the velocity of the liquid flyer plate. The decompressing forsterite then strikes a standard window, and we determined the shock state generated in the window by measuring the shock velocity using VISAR and applying the known material Hugoniot. Multiple gap distances on the same experiment allowed us to constrain the velocity of the uniaxially expanding forsterite, and multiple windows of different impedance (initial density) helped us constrain the density of the liquid layer using standard impedance matching techniques (Sections 2.1 and 3.1).

The second type of experiment was a shock-and-release experiment with a quartz window backed by a forsterite sample. The quartz shock temperatures were calibrated by Hicks et al. (2006); Millot et al. (2015) with reflectivity corrections from Celliers et al. (2010) and were used as a standard reference material to determine the relative luminosity of the unknown mineral sample. Quartz shock velocities were used to calculate the shock temperature by interpolating between existing data and propagating the uncertainties of the calibrated reference and measured shock velocity. The emission spectra of the shocked and released forsterite were measured using the SVS diagnostic. The post-shock emission measurements are described in detail in Section 2.2. Reverse impact and shock-and-release experiments were not performed together because the SVS was commissioned concurrent with this project.

### 2.1. Reverse Impact Experiments

This section describes the reverse impact experiments in detail, providing new illustrations of the main features observed in the raw data and their interpretations. The VISAR system was the primary diagnostic, measuring the velocities of reflecting surfaces and reflecting shock fronts. Additionally and most importantly, VISAR captured time of flight transit measurements using changes in the reflected intensity of light.
on the detector. In these reverse impact experiments, the forsterite samples were only weakly reflecting at the pressures achieved and material traveling within the gap was not measurably reflecting. Time of flight measurements were used when reflecting surfaces could not be measured. An example of raw VISAR data are shown in Figure 3.

Initially, the highly reflective aluminum flyer has a strong signal (large negative value) given its high reflectivity. Upon impact with the forsterite (at time $T_a$), the signal approaches a small value because the forsterite shock front is only weakly reflecting at the pressures achieved (Root et al., 2018). The signal further approaches zero upon free-surface breakout ($T_b$). The voltage drop in the gap represents the vapor stagnating against the TPX window, where the slight decrease in light directly after the increase is a weak shock in the TPX window ($T_c$). The sudden increase in light at time $T_d$ is caused the liquid flyer striking the window and generating a strong shock. The increase in contrast of the VISAR (resolved phase shifted signals) is caused by the strong reflecting shock in the window overtaking the weak shock ($T_e$). The final drop to zero signal is the shock reaching the free surface of the window ($T_f$).

In a reverse impact experiment, the sample is initially impacted by the flyer and shocked to a state on the principal Hugoniot (at time $T_a$). VISAR is used to measure the shock wave velocity directly when the shock is strongly reflecting. If the shock front is weakly reflecting, the shock wave velocity is determined by the transit time through the known sample thickness. The shock Hugoniots for forsterite (Root et al., 2018) and the standard windows: $\alpha$-quartz (Knudson & Desjarlais, 2009, 2013) and TPX (Root et al., 2015), are well-characterized, such that measuring $u_s$ provides $P$ and $\rho$ of the shock state via the Rankine-Hugoniot relations.

When the shock front reaches the downrange free surface (at time $T_b$), it decompresses by a rarefaction wave, which propagates up range back into the shocked sample. The decompression results in an acceleration for which the expansion velocity, $u_{p,exp}$ is given by the Riemann integral (Rice et al., 1958),

$$u_{p,exp} = u_{p,in} = \frac{P_{amb}}{\rho_{in}} \frac{dP}{\sqrt{\rho \left( \frac{\partial P}{\partial V} \right)_S}} = u_{p,in} - \frac{P_{amb}}{\rho_{in}} \frac{V}{c_s} \frac{dP}{\partial t}, \quad (4)$$

where the subscript $S$ in the derivative denotes an isentrope, $u_{p,in}$ is the initial particle velocity given by the Rankine-Hugoniot jump conditions, $P_{in}$ is the pressure of the initial shock state, and $P_{amb}$ is the...
decompressed pressure. As the sample decompresses into the gap, the leading edge decompresses the fastest and accelerates more quickly than up range material. The unloading process requires a decrease in density to satisfy the isentropic decompression path, such that the decompression is limited in time by the expansion velocity. Thus, during decompression, the densities are the lowest at the leading edge of the expanding sample and increase in the up range direction.

Phase decomposition is an important effect to consider in the context of this work. Kraus et al. (2012) considered the time scales of fragmentation, nucleation and growth, and spinodal decomposition for silica decompressing via an isentrope near the critical point. Kraus et al. (2012) suggested that phase separation occurred by nucleation and growth at the phase boundary rather than spinodal decomposition because the timescale of spinodal decomposition is orders of magnitude longer than nucleation and growth. For a forsterite isentrope intersecting the liquid-vapor phase boundary near the critical point, phase separation likely occurs by the same mechanism. Thus, the results reported in this work are asserted to correspond to the liquid-vapor phase boundary, rather than the extended spinodal states. Furthermore, incongruent vaporization must be addressed as compositional separation between the liquid and vapor phases would complicate this work. Iron bearing olivine has been shown to vaporize incongruently in experiments performed by Costa et al. (2017). However, in the absence of iron, forsterite vaporizes congruently under equilibrium conditions, as shown in Nagahara et al. (1994). Thus, when the isentropic decompression path intersects the liquid-vapor phase boundary, forsterite is asserted to vaporize congruently.

Decompression upon shock breakout at the free surface is achieved by a rarefaction fan. Unlike a shock, rarefaction wave spreads out into a fan as it propagates because the sound speed decreases with decreasing pressure. At the liquid-vapor phase boundary, there is an abrupt and large change in the sound speed. As the material decompresses isentropically, the path crosses the liquid-vapor phase boundary. The discontinuity separates the rarefaction wave by splitting the decompression wave. The downrange section of the wave, within the liquid-vapor dome, accelerates more quickly than the up range section, which is still above the liquid-vapor dome. The velocity differential between the waves creates a portion of liquid that is inertially trapped at the liquid-vapor phase boundary at point B in Figure 5 at time \(T_c\). The rarefaction fan is calculated using the method of characteristics in Lagrangian coordinates (e.g., Kraus et al., 2012; Zel’Dovich & Raizer, 2002). Using the revised ANEOS forsterite model from Stewart et al. (2020), the 5,335 J/K/kg release isentrope from a 430 GPa shock is given in Figure 5 and the slope of the associated characteristics are given as

\[
\frac{dh}{dt} \bigg|_{T_c} = \frac{\rho_C}{\rho_0},
\]

Figure 4. Cartoon of the main events in the reverse impact experiment observed in the raw data shown in Figure 3.
where \( h \) is the Lagrangian coordinate and the subscript \( i \) denotes specific characteristic \( ρ \) and \( cs \). The characteristic curves, starting from the free surface at the Lagrangian position 0, define the propagation of the rarefaction wave up range into the sample (Figure 5). Each characteristic curve describes the propagation of disturbances from the free surface based on the density and sound speed, such that higher density and sound speed characteristics propagate faster than lower density and sound speed characteristics. The discontinuity in sound speed at the liquid-vapor phase boundary creates a plateau in density that thickens over time. We refer to the region of material trapped at state B as the liquid layer or “liquid flyer”.

In the gap between the sample and window, the decompressing material expands until it impacts the down range window (at time \( T_d \)). The window is initially impacted by material, which is within the liquid-vapor dome, or the co-existence region of liquid and vapor. The liquid-vapor mixture stagnates against the standard window, causing a small intensity increase in signal return of the VISAR (Figure 3). As the liquid-vapor mixture builds up against the window, the signal intensity increases until the window becomes opaque, indicating a weak shock in the window. The magnitude of this change (if it occurs during the experiment) is entirely dependent upon window material and shock pressure in the forsterite sample. For example, shot Z2792, which had a forsterite shock pressure of \( \sim 330 \) GPa had reverse impact experiments with \( α \)-quartz and TPX windows. The \( α \)-quartz window is not shocked strongly enough by the vapor to become opaque, yet the TPX window does become opaque. Material at the liquid branch of the liquid-vapor phase boundary impacts shortly after, driving a strong shock in the window that quickly becomes reflecting when it overtakes the weak shock (\( T_e \)). Higher density liquid behind the inertially trapped material drives a ramp compression velocity profile at later times.

In a reverse impact experiment, three measurements are paramount. First, the shock state of the sample was measured by impedance matching from shock velocities that were determined by either a reflecting shock measurement or a shock transit time measurement through the sample. For this work, the shock transit time measurement uncertainty was large because the free surface breakout of the shock front was not always clear, although it was typically observable. Second, the liquid flyer velocity of the gap was measured, through a time of flight measurement. Third, the shock state in the window was determined through a direct shock velocity measurement determined by the reflecting shock velocity profile using the VISAR diagnostic and the known principal Hugoniot. Determining the shock state of the window driven by the inertially trapped liquid wall gives \( P \) and \( u_p \) in the liquid layer.

The velocity measurements are presented in Table 3. Interpretation of different events in the VISAR data is aided by hydrocode simulations of each experiment, which is discussed in section Appendix A of Supporting Information. These observed experiment parameters are used in Section 3.1 to calculate the density of the inertially trapped liquid layer.

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**Figure 5.** (a) Release isentrope in green from a 430 GPa shock, similar to the highest reverse impact experiment, in \( ρ-T \) space, starting from the principal Hugoniot (blue) and intersecting the liquid-vapor phase boundary (black) at point B (Figure 1). (b) Characteristics in Lagrangian coordinates, showing the plateau in the density profile that occurs at the intersection of the phase boundary. Higher density characteristics are opaque and opacity decreases with decreasing density.
Table 3

Experimental Measurements From the Reverse Impact Experiments on Forsterite: Impact Velocity of the Aluminum Flyer Plate ($v_i$), Shock Velocities ($u_s$) in the Sample and Window, and the Velocity of the Liquid Flyer Plate ($v_l$)

| Shot #  | Window material | $v_i$ (km/s) | Sam. $u_s$ (km/s) | Win. $u_s$ (km/s) | Gap dist. (μm) | $v_l$ (km/s) |
|--------|-----------------|--------------|-------------------|------------------|---------------|--------------|
| Z2792 N1 | TPX             | 14.68 ± 0.69 | 14.38 ± 0.13      | 15.72 ± 0.1      | 502 ± 10      | 15.30 ± 0.32 |
| Z2792 N4 | α-quartz        | 14.69 ± 0.03 | 14.50 ± 0.19      | 13.62 ± 0.05     | 497 ± 5       | 15.52 ± 0.25 |
| Z2792 S3 | TPX             | 14.69 ± 0.02 | 14.56 ± 0.20      | 15.84 ± 0.05     | 204 ± 4       | 15.45 ± 0.45 |
| Z2792 S6 | TPX             | 14.72 ± 0.03 | 14.79 ± 0.33      | 15.90 ± 0.15     | 800 ± 5       | 15.43 ± 0.19 |
| Z2868 N1 | TPX             | 15.82 ± 0.02 | 15.39 ± 0.14      | 16.40 ± 0.05     | 487 ± 6       | 16.38 ± 0.21 |
| Z2868 N4 | α-quartz        | 15.75 ± 0.01 | 15.50 ± 0.10      | 14.05 ± 0.05     | 489 ± 3       | 16.46 ± 0.25 |
| Z2868 S3 | TPX             | 15.64 ± 0.02 | 15.45 ± 0.15      | 16.60 ± 0.05     | 211 ± 9       | 16.50 ± 0.75 |
| Z2868 S3 | TPX             | 15.62 ± 0.01 | 15.34 ± 0.19      | 16.48 ± 0.02     | 794 ± 6       | 16.37 ± 0.21 |
| Z2879 N1 | TPX             | 12.83 ± 0.01 | 13.57 ± 0.30      | 13.98 ± 0.05     | 499 ± 16      | 12.96 ± 0.43 |
| Z2879 N4 | α-quartz        | 12.87 ± 0.03 | 13.35 ± 0.43      | 12.02 ± 0.02     | 495 ± 7       | 12.91 ± 0.23 |
| Z2879 S2 | α-quartz        | 13.81 ± 0.04 | 14.03 ± 0.16      | 12.71 ± 0.03     | 236 ± 40      | 14.66 ± 2.52 |
| Z2879 S3 | TPX             | 13.77 ± 0.03 | 14.02 ± 0.24      | 14.81 ± 0.03     | 212 ± 9       | 14.82 ± 0.67 |
| Z2879 S5 | α-quartz        | 13.78 ± 0.02 | 13.87 ± 0.22      | 12.81 ± 0.03     | 780 ± 6       | 14.07 ± 0.14 |
| Z3422 S2 | α-quartz        | 17.32 ± 0.01 | 16.34 ± 0.15      | 14.56 ± 0.05     | 506 ± 3       | 17.76 ± 0.15 |
| Z3422 S3 | α-quartz        | 17.34 ± 0.02 | 16.29 ± 0.15      | 14.55 ± 0.06     | 317 ± 7       | 17.86 ± 0.42 |
| Z3422 S5 | TPX             | 17.38 ± 0.03 | 16.27 ± 0.24      | 17.58 ± 0.17     | 506 ± 2       | 17.89 ± 0.19 |
| Z3422 S6 | TPX             | 17.39 ± 0.03 | 16.36 ± 0.15      | 17.38 ± 0.05     | 308 ± 2       | 17.97 ± 0.24 |

2.2. Post-Shock Thermal Emission

The purpose of this type of experiment is to measure the shock temperature and the temperature of the inertially trapped liquid layer that was described in Section 2.1. The temperature of this layer is the temperature of the liquid vapor phase boundary (point B in Figure 5). This experiment uses VISAR to measure the shock velocity in the sample to determine the shock state. When the shock is released into vacuum, for example, the second from top configuration shown in Figure 2, the thermal emission drops substantially with the onset of decompression. In addition, the thermal emission in the visible region of the electromagnetic spectrum is recorded using an SVS camera. The SVS camera system has previously been demonstrated for use in shock experiments in Root et al. (2018). The SVS diagnostic provides key constraints for temperature as it measures the emission spectrum with resolution in both time and wavelength. The principal method is to use a quartz-referenced calibration that is described in Root et al. (2018), which uses an α-quartz standard window as an in situ calibration source to measure the system response function. The α-quartz temperature and reflectivity response are taken from (Hicks et al., 2006; Millot et al., 2015) with reflectivity corrections from (Celliers et al., 2010).

An example of thermal emission data is shown in Figure 6. The aluminum flyer initially impacts the α-quartz standard, and the shock front in the quartz then propagates into the forsterite sample. As in the reverse experiment, VISAR is utilized to measure $u_s$. The $u_s$ relations for α-quartz and forsterite are well-characterized, such that the shock state is well-determined by a measurement of $u_s$. As in Section 2.1, when the shock front reaches the downrange free surface of the forsterite sample, it decompresses by a rarefaction wave. The result is the same inertially trapped liquid wall as previously described. A small amount of liquid-vapor mixture is decompressed ahead of the liquid layer. If the absorption from the liquid-vapor mixture is small, this liquid layer is the principal source of thermal emission after shock breakout at the free surface.

There are two major concerns in the analysis of the thermal emission from the liquid layer. First, the optical thickness of the inertially trapped liquid wall must be large enough to shield the up range material. Shock fronts for forsterite in the liquid region of the forsterite principal Hugoniot are typically weakly reflecting and opaque (Root et al., 2018). As the sample decompresses from the opaque or reflecting shock state,
the thickness of the inertially trapped liquid layer increases. If the optical depth of the liquid is similar to the thickness of the liquid layer, or transparent, then emission from the hotter and higher density region of the sample will contaminate the measurement. If this were the case, the measured emission spectrum would be a combination of the emission from the liquid layer and emission from higher density, up range material. Second, the decompressing liquid-vapor mixture that leads the liquid layer may absorb a non-negligible amount of photons. Release temperature experiments on silica combined with first principles molecular dynamics simulations noted that vapor thicknesses less than 200 μm have negligible absorption at visible wavelengths (Kraus et al., 2012). For Mg$_2$SiO$_4$, the vapor phase includes Mg and MgO (Townsend et al., 2020) complicating the absorption spectra of the liquid-vapor mixture. Absorption by the liquid-vapor mixture changes with time because of the creation of more vapor as the rarefaction waves propagate up range, thickening the mixed phase layer. Figure 6 shows that during the experiment, the steady shock in the forsterite and subsequent emission upon release are constant in intensity with time and are well fit by ideal greybodies, suggesting that in the visible spectrum, the inertially trapped liquid wall is optically thick and absorption by the vapor is not significant over the length scales of these experiments.

Figure 6. Thermal emission data from SVS4 from shot Z3172 N5 which had a shock pressure of 450.7 ± 4.9 GPa. (a) The SVS streak camera records thermal emission over time, resolved in wavelength. Events of the experiment are easily distinguished; pre-impact before time 0, quartz shock from 0–18 ns, forsterite shock from 20 to 35 ns, and post-shock emission from 40 to 70 ns. (b) Vertical line out over wavelengths 475–485 nm in time from (a). Post shock emission has on order of 100s of counts. (c) Ideal greybody for quartz (red line), horizontal lineout of forsterite data from 24 to 30 ns and (blue), and a fitted greybody (black line). (d) Horizontal lineout of post-shock emission from 50 to 60 ns, and its fitted blackbody (black line). For (c and d) uncertainty for data and fits are given by the associated envelopes. SVS, Streaked Visible Spectrometer.
Table 4
Shock and Release Experiment Thermal Emission Results

| Shot #   | $v_i$ (km/s) | $P$ (GPa) | Sam. $u_s$ (km/s) | S I/K/kg | Win. $u_s$ (km/s) | Sam. $T$ (K) | Sam. $R$ (–) | Rel. $T$ (K) |
|---------|--------------|-----------|-------------------|----------|------------------|--------------|--------------|--------------|
| Z3033 N7 | 18.86 ± 0.06 | 496.8 ± 4.8 | 17.47 ± 0.21      | 5,571 ± 460 | 16.93 ± 0.39     | 16,104 ± 1,654 | 0.081 ± 0.026 | 5,063 ± 522  |
| Z3172 N5 | 17.84 ± 0.05 | 450.7 ± 4.9 | 16.78 ± 0.20      | 5,372 ± 460 | 16.24 ± 0.06     | 13,758 ± 727  | 0.047 ± 0.022 | 5,051 ± 167  |
| Z3172 S5 | 19.25 ± 0.04 | 517.3 ± 5.2 | 17.76 ± 0.23      | 5,650 ± 460 | 17.27 ± 0.04     | 16,770 ± 1,270 | 0.089 ± 0.022 | 5,174 ± 182  |

Notes. The shock states of these experiments were previously reported in Root et al. (2018). Specific Entropy for these shock states are calculated from the forsterite entropy relation in Table 2. Release temperatures are apparent temperatures without correction for leading liquid-vapor mixture.

Apparent shock and release temperatures from our experiments are given in Table 4. Notably these apparent temperatures are from liquid condensates suspended in the vapor cloud. These condensates affect the radiative transfer of emission from the liquid layer, which is discussed in detail in Kraus et al. (2012). This effect is not taken into account in the reported apparent $T$ in Table 4: Instead a simple radiative transfer model is used to aid interpretation of the data in Section 3.2.

3. Results and Discussion

3.1. Liquid Flyer Density

From the reverse impact data, we calculated the density of the liquid forsterite before it impacts the standard window. However, certain material properties must first be known or determined to calculate this liquid density. In this section, we identify the required properties, determine their values, and use them to calculate the density of the liquid layer.

The Rankine-Hugoniot jump conditions relate the thermodynamic states on either side of a shock front, which must satisfy the conservation equations of mass, momentum, and energy. In a steady shock experiment, the shock state of a sample is determined by measuring the shock velocity in the shocked sample and using the impedance matching technique (Figure 7a) yielding $P$ and $\rho_s$. The Hugoniot is the collection of possible end states of a shock starting from a single initial condition, but it is not a thermodynamic path itself. The straight line connecting the two states is the shock thermodynamic path and is called the Rayleigh line and is defined by Equation 2. The Rayleigh line has a slope that is defined by the initial density, $\rho_0$ and the measured $u_s$. In the reference frame of the experiment, the flyer’s Hugoniot is reflected about the flyer velocity, and the intersection of the known flyer velocity and the sample’s Rayleigh line is the shock state of the sample. This method relies on knowledge of the $u_i − u_p$ relationship of the flyer in the experiment,

![Figure 7](image_url)

**Figure 7.** (a) Schematic of a typical steady shock experiment, where the red dashed line is the Rayleigh line, the red curve is the unknown sample Hugoniot, and the black curve is the known flyer Hugoniot. The intersection between the reflected flyer Hugoniot and the sample Rayleigh line is the shock state achieved by the experiment, which lies on the sample Hugoniot by definition. (b) Schematic of the reverse impact experiment, where shock states of the windows are determined by their known Hugoniots. Impedance matching the shock states in the windows with the unknown liquid flyer gives two $P$ and $u_p$ states to use to constrain the initial density of the liquid flyer.
the flyer velocity, and the initial density of the flyer. In a typical shock experiment, these properties are measured before the experiment (initial densities), measured in the experiment (shock velocity and flyer velocity), or known beforehand, as in the case of the \( u_s - u_p \) relationship of the standard flyer.

In a reverse impact, the flyer’s Hugoniot is unknown and we used the standard impedance matching technique to determine the shock state of the liquid during impact with the down range window (Figure 7b). The Rayleigh line for the flyer in the laboratory reference frame is defined by

\[
\rho = \rho_0 (v_f - u_p),
\]

where \( \rho \) is the liquid flyer velocity. For the shock states considered in this work, \( P \) and \( u_p \) are given by the shock state of the window determined by impedance matching, \( P_0 \) is negligible, and \( v_f \) is measured (Table 3). The \( \rho_0 \) and \( u_0 \) of the liquid flyer are both unknown. The shock impedance, \( Z \), is defined here as the product of \( \rho_0 \) and \( u_s \) and is solved from Equation 6, and in the laboratory reference frame is

\[
Z_i = \frac{P}{v_f - u_p},
\]

where the subscript \( i \) denotes the material.

Returning to the Rayleigh lines, high pressure liquid Hugoniots, including liquid silicates have been empirically shown to be well represented by a linear Hugoniot in the mega-bar regime (e.g., Asimow, 2018). Assuming that the liquid flyer follows a linear Hugoniot \( u_s = C_0 + su_p \), Equation 6 becomes

\[
P = \rho_0 (C_0 + s(v_f - u_p)),
\]

where \( C_0 \) is the sound speed in liquid, and \( s \) is the slope of the linear Hugoniot. For a given material, the shock impedance, \( Z_i \) is easily substituted here as

\[
Z_i = \rho_0 u_s = \rho_0 (C_0 + s(v_f - u_p)).
\]

We used two different windows to reach two shock states in the liquid flyer, as shown in Figure 7b, giving two shock impedances for a single \( v_f \) and \( \rho_0 \). Subtracting the shock impedances from one another gives \( \rho_0 \)

\[
\rho_0 = \frac{Z_2 - Z_1}{s(u_{p1} - u_{p2})}.
\]

Thus, if the slope of the linear Hugoniot is known, the initial density can be calculated from shock states reached by a single flyer velocity into two different impedance materials. Substituting Equation 10 into Equation 8 yields,

\[
P = \frac{Z_2 - Z_1}{s(u_{p1} - u_{p2})} (C_0 + s(v_f - u_p))(v_f - u_p).
\]

The only unknowns in this equation are \( s \) and \( C_0 \). We fit Equation 11 to the two window shock states and the initial \( \sim 0 \) pressure state of the flyer using a least squares regression, determining the values of \( s \) and \( C_0 \). We then used these fitted parameters to calculate the initial density using Equation 10.

Experiments on the same Z target panel with the same measured impact velocity, within error, were averaged together, propagating uncertainty as uncorrelated, random error. The fitted Hugoniot for the liquid flyer is well constrained using Equation 11. An example experiment is shown in Figure 8. Small residuals are present in the fitted liquid Hugoniot, as in Figure 8, demonstrating the limits of the assumed linear Hugoniot. The limited number of data points prevents fitting to higher orders without risking an under
Table 5
Averaged Results for Each Z Experiment

| Shot  | Sam. | Liq. | TPX | Shock | Release | T (K) | P (GPa) | s (km/s) | Cₙ (GPa) | u (km/s) | q₁0 | q₂0 | q₁ | q₂ |
|-------|------|------|-----|-------|---------|-------|---------|----------|-----------|----------|-----|-----|----|----|
| Z2792 | 15.4 ± 0.04 | 15.5 ± 0.05 | 15.6 ± 0.07 | 15.7 ± 0.07 | 15.7 ± 0.07 | 15.8 ± 0.07 | 15.9 ± 0.07 | 16.0 ± 0.07 | 16.1 ± 0.07 | 16.2 ± 0.07 | 16.3 ± 0.07 | 16.4 ± 0.07 | 16.5 ± 0.07 | 16.6 ± 0.07 |
| Z2868 | 14.9 ± 0.04 | 15.0 ± 0.05 | 15.1 ± 0.07 | 15.2 ± 0.07 | 15.3 ± 0.07 | 15.4 ± 0.07 | 15.5 ± 0.07 | 15.6 ± 0.07 | 15.7 ± 0.07 | 15.8 ± 0.07 | 15.9 ± 0.07 | 16.0 ± 0.07 | 16.1 ± 0.07 | 16.2 ± 0.07 |
| Z3422 | 14.9 ± 0.04 | 15.0 ± 0.05 | 15.1 ± 0.07 | 15.2 ± 0.07 | 15.3 ± 0.07 | 15.4 ± 0.07 | 15.5 ± 0.07 | 15.6 ± 0.07 | 15.7 ± 0.07 | 15.8 ± 0.07 | 15.9 ± 0.07 | 16.0 ± 0.07 | 16.1 ± 0.07 | 16.2 ± 0.07 |

3.2. Optical Depth and Temperature of the Decompressing Sample

To better understand the physical context of the apparent temperature measurement, it is important to compare the measurement to predictions of the temperature along an isentrope and to examine the optical path in more detail. This section presents a prediction of the liquid-vapor phase boundary temperature using data from Root et al. (2018) and Davies et al. (2020) and then a calculation of how the apparent temperatures of liquid layer are depressed from the true material temperature due to droplets in the optical path, following the methods from Kraus et al. (2012).

Temperature on an isentrope can be calculated using the Grüneisen parameter, γ, as

$$\gamma = -\frac{d \ln T}{d \ln V} \bigg|_S$$  \hspace{1cm} (12)

Under the Mie-Grüneisen approximation, the temperature along an isentrope can be calculated through a finite difference. Approximating infinitesimal steps along the isentrope and substituting specific volume with density, starting from a known temperature and density, temperature on the isentrope is given by

$$T_k = \exp \left( \gamma (\rho_k - \rho_{k-1}) + T_{k-1} \right)$$  \hspace{1cm} (13)

where subscript k are the steps on the isentrope. The ρ(ρ) relationship for forsterite is taken from Davies et al. (2020) and presented in Table 2. Starting from the shock state of experiments in Table 5, temperature is calculated over the decompression path until the liquid density is reached. For densities below 2,597 kg/m³, the 1 bar density of liquid forsterite (Thomas & Asimow, 2013), the γ relation is not valid. Below this density, γ is held constant at the 2,597 kg/m³ value. Holding γ constant effectively makes this prediction an estimate. The predicted liquid temperature for shot Z3422, the highest pressure reverse impact experiment, is hotter than all of the apparent temperatures measured in Section 2.2, despite the measured apparent temperatures being associated to stronger shocks.

To explain the cooler apparent temperatures than predicted, the optical depth of the liquid-vapor mixture in front of the liquid flyer in the optical path must be considered. To calculate the optical depth, the density profile of the decompressing mixture must be calculated.

At a given time, the density profile in Eulerian coordinates can be calculated from the characteristics in Figure 5 by considering conservation of mass:

$$\int_{x_0}^{x(\gamma)} dx = \int_0^{h(\gamma)} \frac{d\rho}{\rho} dh,$$  \hspace{1cm} (14)

where x₀ is a constant of integration that depends on momentum transfer through the release path (Kraus et al., 2012). Density profiles, shown in Figure 5a, were calculated for the example 430 GPa shock experiment at 5, 10, and 15 ns after breakout at the free surface. The profiles were calculated up to the peak shock density, and the x₀ offset is calculated by the sound speed of the highest density characteristic to obtain an estimation of the distance propagated by the rarefaction wave up range into the sample.

With the density gradient in front of the density plateau that defines the liquid layer, the optical depth can be calculated in a similar manner as in Kraus et al. (2012) and Lock et al. (2018). The average absorption, α, for an infinitesimal slice in the liquid-vapor mixture is given as
\[ \alpha(x)dx = \frac{dx}{L_{\text{mfp}}(x)} + \alpha_{\text{vap}}(x)dx, \] (15)

where \( L_{\text{mfp}} \) is the photon mean free path distance in a cloud of spherical liquid condensates, and \( \alpha_{\text{vap}} \) is the absorption coefficient of the vapor phase. This expression assumes that the liquid is perfectly absorbing. Previous work on silica showed that the liquid condensate term is dominant (Kraus et al., 2012), and we assumed that \( \alpha_{\text{vap}} \) for forsterite can be neglected for the length scale of the experiment.

The mean free path of a photon through a cloud of spherical condensates is given as
\[ L_{\text{mfp}} = \frac{4 \rho_{\text{liq}}}{6D \rho_{\text{bulk}}}, \] (16)

where \( D \) is the condensate diameter, \( \rho_{\text{liq}} \) is the liquid density on the phase boundary, and \( \rho_{\text{bulk}} \) is the isentrope bulk density of the liquid-vapor mixture. Each position in Figure 10a is associated to a state on the isentrope, and densities below the density plateau also have an associated liquid density on the liquid-vapor phase boundary. We considered a range of droplet sizes (100–1,000 nm) based on other types of shock-vaporization experiments at the laboratory scale (Sedoi et al., 1998; Tkachenko et al., 2004) because the range of condensate diameters during our experiments is not known.

The average photon from an emitting layer is likely to interact with a silicate droplet where the optical depth is equal to or greater than one,
\[ \int_{x_{fs}}^{x(L=1)} \alpha(x)dx \geq 1, \] (17)

where \( x_{fs} \) is the Eulerian position of the decompressing free surface, \( \sim 150 \mu m \) in the 430 GPa case at 10 ns, and \( x (L = 1) \) is the depth of the emitting layer at an optical depth of one. At Eulerian positions farther from the free surface than \( x (L = 1) \), the emitted photons of the hotter, higher density layers are likely to be absorbed, and the measured emission spectrum reflects a cooler, lower density layer. Thermal emission from cooler, less dense layers are neglected. Figure 10b shows the forsterite model liquid-vapor dome from (Stewart et al., 2020; Root et al., 2018). The ANEOS model for forsterite was recently revised by Stewart et al. (2020) (new ANEOS); the new ANEOS model phase boundaries are shown by black lines and the model Hugoniot in brown lines. The gray line denotes the triple point temperature. The shock states (black points) decompress along an isentrope to intersect the vapor curve (red points).

3.3. Experiment and Measurement Uncertainty

Uncertainties for reverse impact experiments (Table 3) stem from a number of sources. Shock velocity and liquid flyer velocity calculated from time of flight measurements depend on uncertainties in the thickness...
of the samples or gap, as well as uncertainties in the VISAR diagnostic itself. For VISAR measurements of reflecting shock velocities in standard windows, uncertainty is independent of sample thickness.

Experiments with impact velocities within their measured uncertainties, typically on the same shot panel, are averaged together to reduce uncertainty. Uncertainty of each measurement is propagated and combined with the standard deviation for each parameter. Shock states of forsterite, \( \alpha \)-quartz, and TPX (pressure, density, entropy, and temperature) are calculated from the measured shock velocity and the relations in Table 2. Uncertainty for these calculations and the density measurement are propagated through a Monte Carlo uncertainty analysis technique. All variables with measured uncertainty are randomly perturbed according to a normal distribution about their 1\( -\sigma \) uncertainty. The calculations are repeated with such random perturbations until the resulting data cloud converges to a Gaussian, typically after 10,000 steps. The mean of the Gaussian is taken as the fitted value, and the standard deviation to be the 1\( -\sigma \) uncertainty.

The apparent temperature measurement uncertainty is found in a similar way to the density. Parameters are perturbed and the temperature emission is continuously re-fit until the resulting data cloud converges. An additional 2\% uncertainty is added to all temperature measurements to account for the ideal greybody assumption of the quartz standard and possible non-linearity of the SVS response function as described in Root et al. (2018). Shot Z3033 has elevated uncertainty compared to the experiments on shot Z3172 due to light contamination of the of the time window for the experiment. During the final stage of an experiment, expanding material from the experiment impact the probe, creating an intense flash that is recorded in the science frame. Light from this event may bleed or overexpose the science frame. The current experimental setup accounts for this effect by increasing the distance from the free surface of the down range sample to the probe and gating the probe impact in time. Post-shock emission from shot Z3033 is contaminated by probe impact light and a single ideal blackbody does not fit the emission spectrum. However, smaller sections of the emission spectrum are well fit by a blackbody. For shot Z3033, three sub sections of the emission spectrum are fit independent of the others. Wavelengths 440–520 nm are fit by 5,514 ± 351 K, 520–580 nm by 5,142 ± 312 K, and 580–640 nm by 4,534 ± 178 K. These sections are then averaged together, propagating the calculated uncertainties and the standard deviation to receive the result shown in Table 4.

### 3.4. EOS Model Development

Figure 9 shows the measured shock and release data compared to different ANEOS-based models for forsterite. Older material models used in previous works on planetary collisions, ANEOS-C (Canup et al., 2013) and ANEOS-G (Ćuk & Stewart, 2012; Nakajima & Stevenson, 2014), were developed before high-pressure data were available for forsterite. Pressure-density-temperature (Root et al., 2018) and entropy (Davies et al., 2020) data on the forsterite principal Hugoniot showed that these parameter sets over predicted...
temperature and under predicted specific entropy. Furthermore, the liquid-vapor dome states measured here do not agree with the model liquid-vapor dome of either of these older forsterite ANEOS models.

The high pressure measurements on the principal Hugoniot (Davies et al., 2020; Root et al., 2018), preliminary analyses of the experiments presented in this work, and constraints on the critical point, now published in Townsend et al. (2020), were used to constrain a revised forsterite ANEOS-based model (labeled New ANEOS). The ANEOS code package was updated to include a user adjustable heat capacity in the liquid and was focused on fitting high pressure Hugoniot data and the liquid and vapor regions of the phase diagram, see Stewart et al. (2020). This forsterite ANEOS model (version SLVTv1.0G1, Stewart et al., 2019) provides a good fit to the shock Hugoniot, liquid-vapor curve, and isentropes connecting the Hugoniot and vapor curve up to several 100s GPa. This model's critical point also agrees well with ab initio calculations of the forsterite critical point (Townsend et al., 2020) at $\rho_c = 0.52 \pm 0.03$ g/cm$^3$, $T_c = 6,240 \pm 200$ K, and $P_c = 0.13 \pm 0.02$ GPa.

### 3.5. Improved Thermodynamics of Giant Impacts

Past models of the forsterite principal Hugoniot, ANEOS-C and ANEOS-G, underestimate the production of entropy from a shock front (Davies et al., 2020). The forsterite ANEOS (version SLVTv1.0G1) is a better fit to the shock temperatures and entropies generated in the giant impact regime. Furthermore, the liquid-vapor dome has much better agreement with our experimental constraints compared to previous models. Giant impact simulations that rely on this new EOS will have decompression paths that involve more vaporization compared to past models with the same impact parameters. To illustrate the effects of the reformulated EOS, we present the temperature-specific entropy profiles through the Earth after a canonical Moon-forming giant impact (e.g., Canup, 2004), where a Mars-mass body obliquely strikes the proto-Earth near the mutual escape velocity. The giant impact calculations are described in Appendix C of Supporting Information. Two post impact cases of the canonical moon forming giant impact (Canup et al., 2013) are shown. In Figure 11, we compare the thermal states in the mantle with two different EOS models for forsterite (ANEOS-G and New ANEOS). In both examples, the proto-Earth mass was 0.9 $M_{\text{Earth}}$, the impactor was 0.13 $M_{\text{Earth}}$, and the impact velocity was 9.2 km/s. In the ANEOS-G case, the impact parameter was 0.74,

![Figure 11](image-url)
and in the new ANEOS case, the impact parameter was 0.7. The simulations used the GADGET-2 smoothed particle hydrodynamics code with 206,000 particles. Each point represents a mantle particle in the mid-plane at 48 h after the impact.

The enhanced production of entropy on the shock Hugoniot from New ANEOS, a phenomena described in detail in Davies et al. (2020), leads to generally higher entropy in the entire post impact mantle. In the ANEOS-G model, the critical point was at much higher pressures, densities, and temperatures than we expect from current constraints. In simulations using this model, the thermal profile through the Earth after the giant impact fell just above the critical point (as pointed out in [Lock & Stewart, 2017]). Note that the ANEOS-G model did not include a melt curve. Using the New ANEOS forsterite model, the specific entropies are larger compared to the previous model and the critical point is lower. Using criteria for supercritical conditions defined here as $T > T_{\text{critical}}$ and $P > P_{\text{critical}}$, the mass fraction of the mantle that reaches supercritical conditions is 0.123 using ANEOS-G and 0.188 using New ANEOS. As a result, the case that much of the Earth’s mantle reaches the supercritical fluid regime during the Moon-forming giant impact is much more robust with our new experimentally constrained EOS model.

4. Conclusions

This study presents the results from multiple experiments on forsterite that map the thermodynamic path of the shock-and-release process. We presented the results from two types of experiments on the Sandia Z Machine: Shock-and-release experiments to measure the post-shock emission spectrum and reverse impact experiments that constrain the density of the liquid branch of the liquid-vapor phase boundary.

Forsterite is widely used in numerical simulations of planetary collisions as an analog material for the mantles of terrestrial planets. The constraints to the forsterite phase diagram provided here directly augment and improve the effort to understand the formation of terrestrial planets.

Using the data here and in previous studies of forsterite, a new EOS model for forsterite has been formulated to more accurately track the evolution of the thermodynamics of collision events. The thermodynamic structure of a planet after a giant impact is sensitive to the material EOS model. For the extreme shock pressures reached in giant impacts, past models have underestimated the entropy of the forsterite principal Hugoniot. Previously, the liquid-vapor phase boundary was not constrained, and the constraints provided from this work improve the predictions from giant impact simulations. Future studies of impact simulations should implement the experimentally constrained model.

Real mantles of Earth-like planets probably never consist of pure forsterite. However, olivine with about 90% forsterite and 10% fayalite ($Fe_2SiO_4$) makes up about 60% of the Earth’s upper mantle, while the rest is enstatite ($MgSiO_3$), diopside ($CaMgSi_2O_6$), and pyrope ($MgAl_2Si_3O_12$), all with an Fe-content similar to that in olivine. Future experiments should explore the effects that inclusion of these additional components have on the calculated thermodynamic paths in planetary collisions. The experiments and analyses presented here serve as a model for investigating the effects of the additional components that must be present in any Earth-like planetary mantle.

Data Availability Statement

The revised ANEOS parameter set for forsterite, modifications to the ANEOS code, and SESAME and GADGET format EOS tables are available at https://github.com/isale-code/M-ANEOS and Stewart et al. (2019). All scripts used for calculations, supporting spreadsheets, and additional figures in this work are available at Davies et al. (2021).

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