Hugoniot experiments are an important means of producing high-pressure states that can be used to benchmark and test modern equation of state (EOS) models. Hugoniot velocity measurements provide stress-density-energy response and constrain the mechanical EOS. With more advanced in situ techniques, temperature measurements [1], ionization states[2] and material structure[3] are all being measured. Advanced perturbation analyses[4] have even enabled direct measurement of material derivatives such as the sound speed and Grüneisen parameter. With all of these techniques combined, the principal Hugoniot state variables and their derivatives can be measured fully constrain the EOS. Recently developed facilities such as the National Ignition Facility (NIF), the Z-Machine, the OMEGA facility and the Laser Mega-Joule (LMJ) facility are capable of producing high-pressure shock states (~0.001 to 10 Gbar) regime where little experimental data exists. Advanced diagnostic (e.g. VISAR[5], SOP[6], and dynamic powder diffraction[3]) and experimental techniques (e.g. Thomson Scattering[1],
the Gbar platform[2] and x-ray spectroscopy[7]) have been fielded to begin probing these regions however, many of these techniques do not produce accurate absolute EOS of measurements, but instead rely upon a standard or underlying theoretical assumptions. For instance, the convergent liner experiments (0.001-0.02 Gbar) on the Z-machine require accurate knowledge of the liner (Al) EOS and conductivity and recent planar EOS measurements on the NIF, which achieved pressure near 0.1 Gbar relied on aluminum standard. To date, the Z-machine has developed standards (aluminum[8] and quartz[9] ) to 0.012 Gbar, while recent work at the NIF using the Gbar platform[2] have produced absolute Hugoniot measurements to 0.8 Gbar. The Gbar platform has only conducted 5 experiments on low-z materials, (CH, CD₂ and diamond) to date. Additional work is needed to reduce the experimental uncertainties, to push to higher pressures and to determine how to measure the EOS of high-z materials. The Gbar platform may be a means of performing impedance matching experiments, but in order to do so, an accurate standard needs to be extended to higher pressures so that we can begin benchmarking the EOS of various materials.

- **Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.**

New experimental techniques will be required to probe the Hugoniot of materials under these extreme conditions. The goal of this white paper is to engage scientists worldwide to begin thinking about the next generation experiments needed to probe materials under experiment conditions. To enable impedance-matching experiments in the 0.012 to 0.1 Gbar regime using planar targets, an impedance matching standard needs to be developed to high accuracy (better than 1%). Recent ‘Gbar’ radiography experiments have probed the principal Hugoniot of low-z materials (CH and diamond) but with uncertainties too large to be used as a standard [2]. New experimental techniques, or old techniques will need to be rebirthed, to develop a platform for absolute Hugoniot experiments at pressures in excess of 0.012 Gbar. Potential platforms for consideration include, ‘GBar’ platform[2], hypervelocity laser drive flyer-plates[10], planar radiography[11] or Doppler shift of resonance peaks[12] to name a few. For next generation facilities, next generation diagnostics and experiments need to be developed. Accurate temperature and ionization state measurements would significantly aid in addressing many of the questions outlined below. Specifically, along the Hugoniot, the compressibility varies significantly as the materials are ionized. Measuring the ionization states, when the shell effects being to affect the Hugoniot will aid in the EOS modeling.

- **Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.**


The study of material response at high-energy-density plasma is crucial to the success of the ICF program. The thermodynamics and hydrodynamics of hot dense plasma cannot be accurately predicted without knowledge of the EOS. Since these new facilities have enabled scientists to begin probing a region of phase space previously unattainable within the laboratory, many fundamental physics questions will be answered within the following decade. What effect does electronic binding in plasmas have on the compressibility of a material under extreme conditions (see Figure 1)? How do we test EOS models in the Gbar regime? Can we fully define the Hugoniot EOS surface? How large are the shell effects on the principal Hugoniot (see Figure 1)? [13] What role do the shell effects play in Hohlraum dynamics, specifically their effect on the electronic specific heat and radiation transport near the Au wall?[14] Does matter at extreme compression (>1 Gbar) approach the 7-fold-compressed state limit for a free-electron gas[13] (see Figure 1)? Do shell ionization and changes in the electronic specific heat destabilize the shock front (Dyakov-Kontorovich criteria for metals) as recently proposed[15]? Developing advanced techniques to begin accurately measuring the EOS of materials at these extreme conditions will address fundamental questions in high-energy-density physics. Further, it is important to note that as we perform measurements in these regimes, the experimental results need to be as independent from theory as possible. Many recent experiments performing measurements in these regimes are of high precision but lack accuracy due to the litany of theoretical assumptions and simulations used in the analysis.[16] As we extend techniques into these regimes, it is important to test theories and to do so the experimental results need to be as independent from theory and simulation as possible.
Figure 1: Figure adopted from the work of Das and Menon [13]. The Hugoniot of aluminum is shown. Near 100 Mbar (.1 GBar) the affect of shell ionization is predicted to reduce the compressibility of aluminum. At higher pressures, it is predicted that the radiation pressure increases the compressibility to the 7-fold limit.
References (maximum 1 page)