THE CONTACT AND COMPRESSION STAGE OF IMPACT CRATERING. H. J. Melosh, Lunar and Planetary, University of Arizona, Tucson, AZ 85721 (jmelosh@lpl.arizona.edu).

Introduction: Impacts at typical planetary encounter velocities, more than a few km/s, are fundamentally different from the low-speed impacts of everyday experience. High-speed impact craters are shallow circular pits whose form is almost independent of the angle of impact, impactor shape or composition. This surprising convergence of form is a consequence of the large amount of energy released in a high-speed impact event, which causes the crater's final size to become much larger than that of the original projectile.

This fact was first appreciated in the early decades of the 20th century by investigators such as E. J. Öpik (1916), H. E. Ives (1919), F. R. Moulton (1922) and A. C. Gifford (1924-1930). Now known as the "impact/explosion analogy", this fundamental insight likens the excavation of an impact crater to an explosion driven by a point source of energy rather than to the familiar indentation of a target by a projectile striking at speeds achievable by human muscular force.

The most distinctive part of this process is the rapid conversion of the kinetic energy of the projectile into heat and motion in the target. This conversion takes place over a period of time roughly equal to the time over which the projectile, moving at velocity v_i with respect to the target, traverses its own diameter L, a period of about L/v_i. During this brief time the projectile slows down, a roughly equal mass of target accelerates, and both are raised to very high pressures and temperatures. The projectile penetrates into the target a distance given approximately by $L\sqrt{\rho_p / \rho_t}$, where the term under the radical is the ratio of projectile density to target density. Having penetrated this far, the high internal energy of the compressed projectile and target asserts itself and the result is a sort of "explosion" driven by the pent-up energy of compression.

Hugoniot Equations: Although the relation between pressure and volume of an ideal gas has been known for several centuries, Boyle's law is a poor approximation to the compression of metal and rocks. P. H. Hugoniot first achieved a correct description of the thermodynamics of shock compression in his 1887 PhD thesis. The three Hugoniot equations relate the thermodynamic properties of material before a sudden, strong compression event to those afterwards using the conservation of mass, energy and momentum. Entropy, however, is not conserved: Sudden (shock) compression events are highly irreversible. Much of the original kinetic energy is converted to heat energy, so that the temperature of shocked material rises sharply and irreversible phase changes may occur.

Equations of State: The Hugoniot relations do not predict a unique relation between pressure and volume valid for all materials. The full relation, in the form of an "equation of state", is a function linking pressure P, density ρ and temperature T (or, equivalently, shock velocity and particle velocity in the compressed material). The Hugoniot equation of state is different for different materials, as well as for different initial states with varying temperature, pressure or porosity. The good news is that the Hugoniot equations of state have been measured for a wide variety of materials in many different initial states and for many different impact velocities. Extensive compilations of available data can be found in the books by Trunin [1] and by Marsh [2]. In addition, there are a number of analytical and semi-analytical equations of state available for theoretical computations of impact processes, some of the best known examples being the Tillotson equation of state [3], the Mie-Gruneisen equation [4] and the computer codes ANEOS [5] and PANDA [6].

The complete thermodynamic path of materials compressed during an impact, followed by adiabatic decompression as the compressed materials rebound, can be computed using modern equations of state. An example for the well-studied material quartz is shown in Figure 1.

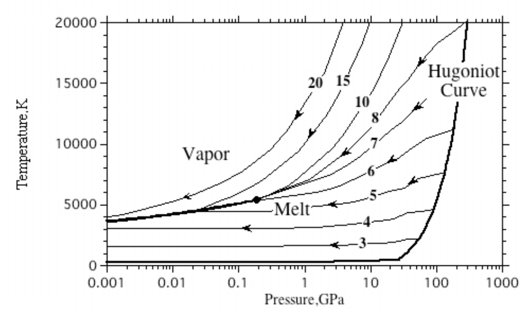

Figure 1: Thermodynamic path of initially dense quartz at room pressure and temperature that is first shock compressed, then released to low pressure during an impact. The numbers on each release curve refer to the maximum particle velocity reached during compression. The particle velocity is approximately half of the impact velocity. Derived from the ANEOS equation of state [7].

Oblique Impacts: The early stages of impact cratering are now relatively well understood for both vertical impacts [8] and oblique impacts [9]. The process of jetting, in which very highly shocked material is ejected from close to the impact site at very high speed, is greatly enhanced in oblique impacts [8]. Once the initial energy is coupled into the target, shock waves radiate outward, irreversibly compressing and accelerating the surrounding material [10]. The subsequent motion, which can be well approximated as an incompressible flow [11], eventually opens the crater. This latter phase, known as the excavation phase, lasts much longer than the initial contact and compression phase. It is characterized by generally subsonic, incompressible, flow [8]. Other speakers will discuss this phase.

Porous Materials: The most recent research into the early phases of shock compression is concerned with modeling the equation of state of complex materials accurately, and consideration of new facets of the material response. One of the most important of these facets is porosity. In general, shock compression of porous material converts much more kinetic energy into heat and thus produces a hotter, more vigorous expansion of the resulting projectile and target material. Figure 2 shows the large differences between the final entropy of Forsterite as a function of initial porosity and shock velocity. Even at low shock velocities, initial porosity in the range of 40% can easily double the final entropy of the shocked material and initiate melting and vaporization at impact velocities that are incapable of causing phase changes in fully dense material.

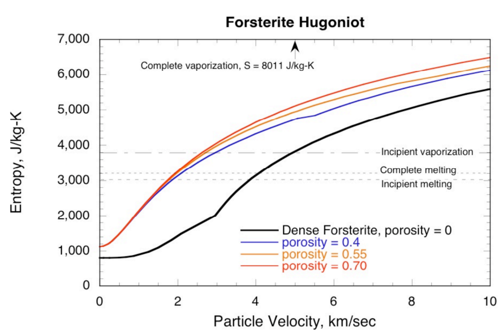

Figure 2. Entropy of magnesian olivine (Forsterite) as a function of initial porosity, derived from the ANEOS equation of state.

Recent advances in numerical methods of modeling porous materials [12] have made it possible to readily simulate impacts into porous targets. Figure 3 shows one such simulation that indicates that, compared to a fully dense target, impacts into porous media not only produce more heat than impacts into dense materials, but the shock wave also attenuates much faster. This type of impact is currently of great interest in the wake of the Deep Impact experiment in which an artificial impact was created on the highly porous comet Tempel 1 [13]. It may also be of importance for impacts onto small, rubble-pile asteroids, of which Itokawa may be our first well-imaged example [14].

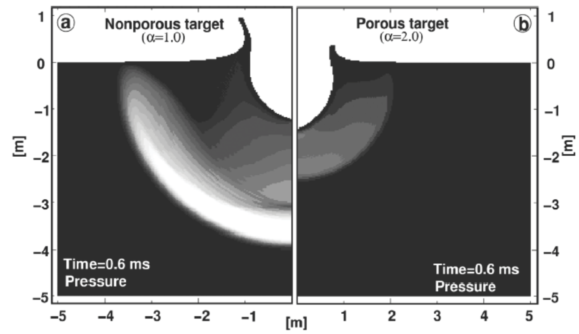

Figure 3: Pressure resulting from a small impact into a dense (left panel) versus a porous (right panel) target [12]. Note the rapid decline of the maximum pressure in the porous target.

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