VERIFICATION OF IMPACT MELT AND VAPOR DETERMINATION METHODS IN CTH.  S. N. Quintana, D. A. Crawford, and P. H. Schultz, Brown University, Department of Geological Sciences, 324 Brook Street, Providence, RI, Sandia National Laboratories, Albuquerque, NM.

Introduction: Impact cratering is a ubiquitous process; however, it is not expressed on all planetary bodies in the same way. While remote and direct observation of craters establishes the aftermath of cratering, laboratory experiments and numerical modeling are essential to understand the cratering process and its effects on both a regional and global scale. Laboratory experiments are helpful for witnessing the entire cratering process from start to finish and are essential for benchmarking analytical models. However, the scale and velocity attainable in the laboratory is too small to fully explain some impact processes (especially melting and vaporization) in many non-porous materials of interest. Thus, computational modeling provides a key to understanding planetary scale processes.

Background: The Eulerian shock physics analysis package, CTH, was developed at Sandia National Laboratories (SNL) [1]. CTH is extremely useful for studying early-stage planetary impact processes (e.g. [2, 3]) that require accurate melt and vapor representation. However, CTH is limited because it cannot directly determine phase information for all equations of state (EoS). To overcome the difficulty of directly determining phase information two common strategies for determining melting and vaporization in CTH and other hydrocodes were developed: Peak pressure (Pmax), as a surrogate for entropy (S), as often used in the planetary community (e.g. [4]); and final release-state temperature (Tf), which is sometimes used outside the planetary community.

In the peak pressure method, the melting entropy or pressure is determined using NIST-JANAF Thermochemical Tables [5]. These values can then be used in a filter within CTH that records the mass of any material with a value (either pressure or entropy) greater than the filter value. When the pressure method is used, the maximum pressure of the material is recorded in CTH by the extremum variable. The same process can be performed for vaporization entropy or pressure. The NIST-JANAF Thermochemical Tables can be used to determine melting or vaporization temperature, which can be applied in a similar filter for the temperature method.

Typically, only one of these two methods, either pressure or temperature, is employed to study the impact process. We hope to show that it is useful and necessary to consider more than one method to determine melting and vaporization. For example, final temperature must be used along with peak pressure to more completely understand the role that porosity or material strength plays in melting and vaporization. Final temperature must also be used to understand multiple shock effects. Some late-time processes depend on correct early-time phase changes; so, it is imperative to actually melt and vaporize the material in the model.

This study addresses the use of these two methods of melt and vapor determination in 1D and 2D models. We performed the following sequence of calculations: (1) a purely hydrodynamic study without including gravity; (2) a hydrodynamic study including gravity; and (3) a series of strength studies including gravity. Our goal is to show that we can use more tools with CTH to help us understand the impact cratering process. In particular, we wish to demonstrate that temperature can be used to complement pressure calculations, which are commonly used in the planetary community.

1D: A series of 1D and 2D impact calculations using CTH with the analytical EoS, ANEOS [6], provided a comparison of melt and vapor determination methods. The 1D case provides a simple benchmark test to ensure CTH and the EoS are performing as expected. The impact in 1D is simply a flyer plate impacting an infinite target of the same material. Pressure, temperature, and entropy of melting for several materials and impact velocities were examined. Comparison between the P-S Hugoniot from ANEOS and the melt/vapor entropy used in Pierazzo et al.’s work verified that ANEOS and CTH can match the NIST-JANAF Thermochemical Tables and prior studies by Pierazzo et al. [4]. We also verified the isentropic pressure release and final material temperature increase, as expected following a shock, as in Fig. 1 [7].

![Figure 1](image1.png)

*Figure 1* - 1D calculation of an aluminum-aluminum impact at 6 km/s demonstrating a) the expected isentropic pressure release and b) the increased temperature (final release state temperature) after the shock wave passes.

2D: While the 1D calculations verified CTH and ANEOS gave us expected results, 2D calculations allow us to directly compare methods of melt and vapor determination. We first ran a purely hydrodynamic study with various materials and impact velocities in...
order to verify this study with results from Pierazzo et al. [4]. We then extended previous work to study the effects gravity and material properties.

**Hydrodynamic, no gravity.** Our first study was purely hydrodynamic (no gravity, strength, or porosity in the model). We followed the pressure method, to compare with Pierazzo et al. [4] but also used the temperature method. The results are shown in Figure 2. Here, we compare Pierazzo et al.’s work using the pressure method with our work using the temperature method. Figure 2 demonstrates good agreement with Pierazzo et al. [4], thereby showing that, for certain applications and with a good EoS, both \( P_{\text{max}} \) and \( T_f \) can be used to determine melting and vaporization.

**Hydrodynamic, with gravity.** Martian gravity (3.72 m/s\(^2\)) was included in the next series of calculations. We again recorded mass from \( P_{\text{max}} \) and \( T_f \) filters for a variety of materials and impact velocities. Because gravity primarily affects melting and vaporization in the early time by increasing the initial hydrostatic pressure of the target materials, it did not have a significant effect for the size of crater studied.

**Strength and gravity.** The next step in our study includes both Martian gravity and a strength model. As a proof of concept, we initially used a Von Mises strength model for all materials. Future work will include more realistic strength models; however for this initial study, we focused on how target strength affected the amount of material melted and vaporized in the impact. We expect, with further study, that target strength may change the results of the pressure and temperature methods from what we determined in the hydrodynamic case. We plan to develop guidelines for when each method is appropriate to use.

**Conclusion and Future Work:** In both the pure hydrodynamic and the hydrodynamic with gravity cases, most of the materials tested showed that both \( P_{\text{max}} \) and \( T_f \) can be used to determine melting and vaporization. Using a well-developed EoS, such as ANEOS, is important in such calculations. The temperature method can be used to complement the pressure method, and this strategy then allows the study of material properties and impact processes in greater detail than the pressure method alone. Future efforts include the effect that material properties (e.g., strength and porosity) have on melting and vaporization. We will then extend this work to three dimensions and validation with appropriate materials in laboratory experiments, including using proxies to generate melting and vaporization.

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