THE IMPACT HYDROCODE BENCHMARK AND VALIDATION PROJECT. E. Pierazzo[1], N. Artemieva[1,2], E. Asphaug[3], E.C. Baldwin[4], J. Cazamias[5], R. Coker[6], G.S. Collins[7], D.A. Crawford[8], T. Davison[7], D. Elbeshausen[9], K.A. Holsapple[10], K.R. Housen[11], D.G. Korycansky[3], K. Wünnemann[9]. [1]Planetary Science Inst., 1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ 85719, USA (betty@psi.edu); [2]Inst. Dyn. Geospheres, RAS, Leninsky Pr. 38, 119334 Moscow, Russia; [3]Univ. of Calif. Santa Cruz, S. Cruz, CA 95064, USA; [4]University College London, Gower St., London WC1E 6BT, UK; [5]Univ. of Alabama at Birmingham, Birmingham, AL 35294, USA; [6]Los Alamos Nat. Labs., Los Alamos, NM 87545, USA; [7]Imperial Coll. London, London SW7 2AZ, UK; [8]Sandia Nat. Labs., P.O. Box 5800, Albuquerque, NM 87185, USA; [9]Natural History Museum, Humboldt-Univ., Berlin 10099, Germany; [10]Univ. of Washington, Seattle, WA 98195, USA; [11]The Boeing Company, Seattle, WA 98124, USA.

Introduction: Computer models offer a powerful tool for understanding the mechanics of impact crater formation, but only if properly benchmarked and validated against observations. We present results from the first phase of a project to benchmark and validate shock physics codes used to simulate impact and explosion cratering [1].

The Validation and Benchmarking Project: We have identified a two-part base of standards for comparing and validating hydrocodes. The benchmark component identifies a set of hypothetical explosive and impact events of varying complexity to be run by the impact codes to compare the different numerical and physical models employed in the codes. Simulations are divided into early time, focusing on the early stages of the dynamic explosion process (shock pressure and its decay) and late time, focusing on the crater final morphology (crater collapse and stress/strain fields). The validation component identifies a set of well-documented laboratory and field experiments over a wide range of event sizes, geological materials and problem types to reproduce in code simulations. Laboratory tests are useful because they are conducted under well-known conditions. Field explosion tests provide data over a much larger range of sizes.

The final objective of this study is to provide the test results to the scientific community to help prevent the incorrect and misinformed use of the codes and to provide a set of rules and test cases to follow to properly benchmark and validate hydrocodes to come.

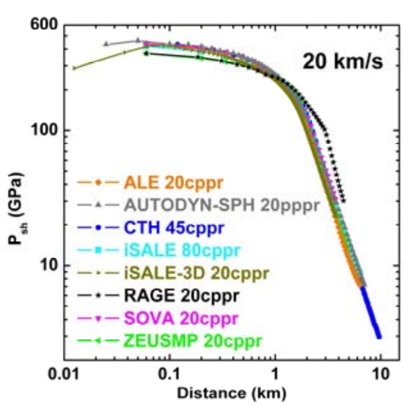

Fig. 1: Shock pressure decay downward from the impact point for a 1-km diameter Al sphere impacting an Al target at 20 km/s.

Impact Hydrocodes: All hydrocodes include the fundamental physics needed to model high-energy impact/explosion events, and can all be used to model general impact/explosion cratering. A variety of 2D and 3D codes were used in this study, from commercial products like AUTODYN [2], to codes developed within the scientific community like SOVA [3], SPH [4], ZEUS-MP [5], iSALE/iSALE3D [6,7], and codes developed at National Laboratories like ALE3D [8], CTH [9], SAGE/RAGE [10]. Each code has been extensively tested individually, but no collective benchmarking/validation has ever been carried out.

Benchmarks: Our first benchmark tests consist of an Al sphere 1km in diameter impacting an Al target at 5 and 20 km/s perpendicularly and at 45° from the surface. Aluminum is a simple material with a well-known and well-modeled equation of state. Different equations of state models are used in the test runs, such as Tillotson, ANEOS tables, SESAME and LEOS tables. To test potential effects of mesh resolution, each code was run at given resolutions, ranging from 5 to 40 cells-per-projectile-radius (cppr) or adaptive mesh refinement (AMR). For the test in question this corresponds to a cell size of 100m down to 12.5m or smaller for AMR.

Figure 1 shows shock pressure decay in the target (early-time stage) for a 20 km/s vertical impact. Overall, shock pressure variability from code to code is within 10 to 15% for the 20 km/s impact simulations. The simulations with lower impact velocities show slightly larger variability. We found that significant variability occurs due to code setup. It is thus important for users to understand the effects of internal code setup such as temporal and spatial stability parameters (Courant number or artificial viscosity).

The Validation Testing: The first validation tests chosen for this project include relatively simple materials like water and aluminum.

Water test: Simulations of impacts and explosions in water do not need a strength model and gravity only needs to be included to model the late stages of crater growth. We modeled the Boeing quarter space laboratory experiment of a glass sphere, 2 mm in diameter, impacting water at 4.64 km/s [11]. This experiment used a rectangular box made from 1.25 cm thick Al, 76cm×38cm×23cm in size (a thick plexiglass window was inserted close to the impact point for viewing purposes). Ambient chamber pressure was around 3400 Pa (above the vapor pressure). Diagnostics measured during the experiment were crater profile at given times (up to 83 msec), and ejection velocities of a few small glass beads floating on the surface.

Aluminum test: We modeled the laboratory experiments of an Al sphere, 6.35 mm in diameter, impacting at 7 km/s Al alloy cylinders (few tens of millimeters in thickness and diameter) of varying strength [12]. For this test we chose two alloys, 1100-O, which has a strain rate dependent strength, and 6061-T6, whose strength is insensitive to strain rate. The diagnostics of the experiment were crater radius and depth over time.

Validation Results: In the simulations projectile size, impact velocity/angle, shape and material (glass or Al), and target material (water or Al) are fixed input conditions. Technical details, material models and relative parameters for the materials were chosen by individual modelers. This is an important difference from benchmark tests that focus on comparing code performances given well-constrained simple tests. One important component of validation testing consists in testing the modelers identification and use of the proper material models. One of our goals in this context is to verify how modelers' choices can affect the output results.

<u>*Water Test*</u>: In the early stages of the water impact all the codes appear to follow the experimental data quite closely (Fig. 2). The early evolution (<3.5 ms) of crater radius and depth with time shows variability in the model results compared to the experiments of less than 15%. The full coverage of the validation test is available for three codes: ALE3D, CTH, and ZEUS-MP2,

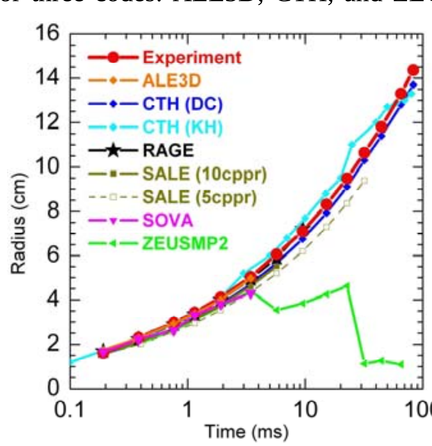

Fig. 2: Crater radius versus time for a 4.64 km/s impact of a glass sphere into water.

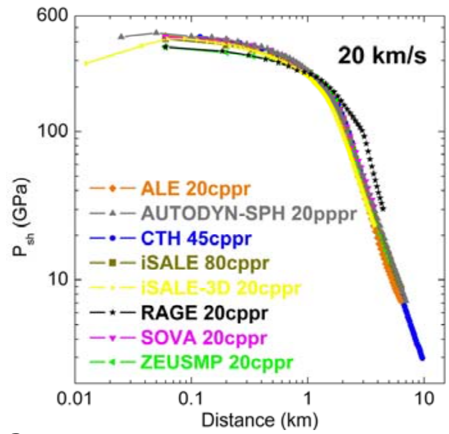

Fig. 3: Crater radius over time for a 7 km/s impact of an Al sphere into Al 6061-T6.

with iSALE covering about half of the experiment duration. Only one time step is available for AUTODYN (not enough for an assessment of its performance). Generally, the codes tend to underestimate the experimental crater diameter and depth. Simulations with ALE-3D, CTH, iSALE, RAGE and SOVA appear to follow the experimental data quite closely. Simulations with ZEUSMP2 (heavily modified to model impact cratering) seem to develop instabilities beyond 2 msec (Fig. 2). Possible reasons for the instabilities are problems with boundary conditions, problems at free surfaces and material interfaces.

<u>*Aluminum Test*</u>: Four code results are available for Al 6061-T6 and Al 1100-O targets. Simulation were carried out with different resolutions (from AMR to 10 cppr) and varying strength model (Johnson-Cook in CTH, Von Mises in iSALE, Steinburg-Guinan in AUTODYN and RAGE). Overall, the code results are in relatively good agreement with the experimental data. For the impacts into Al 6061-T6 targets the numerical codes tend to slightly underestimate the crater radius (Fig. 3) and overestimate the crater depth. For impacts into an Al 1100-O target code results are closer to experimental values.

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