THE IMPACT HYDROCODE BENCHMARK AND VALIDATION PROJECT: RESULTS OF VALIDATION TESTS. E. Pierazzo[1], N. Artemieva[1,2], E.C. Baldwin[3], J. Cazamias[4], R. Coker[5], G.S. Collins[6], D.A. Crawford[7], T. Davison[6], K.A. Holsapple[8], K.R. Housen[9], D.G. Korycansky[10], K. Wünnemann[11], [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]University College London, Gower St., London WC1E 6BT, UK; [4]Univ. of Alabama at Birmingham, Birmingham, AL 35294, USA; [5]Los Alamos Nat. Labs., Los Alamos, NM 87545, USA; [6]Imperial College London, London SW7 2AZ, UK; [7]Sandia Nat. Labs., P.O. Box 5800, Albuquerque, NM 87185, USA; [8]Univ. of Washington, Seattle, WA 98195, USA; [9]The Boeing Company, Seattle, WA 98124, USA; [10]Univ. of Calif. Santa Cruz, S. Cruz, CA 95064, USA; [11]Natural History Museum, Humboldt-Univ., Berlin 10099, Germany.

Introduction: This work presents initial results of a collective validation and benchmarking effort from the impact cratering and explosion community. When properly benchmarked and validated against observation, computer models offer a powerful tool for understanding the mechanics of impact crater formation. We are following our first benchmarking tests with simple validation tests of a glass sphere impacting water and an aluminum sphere impacting aluminum.

The Validation and Benchmarking Project: The Validation and Benchmarking Project brings together a collective expertise in numerical modeling of impact and explosion events, continuum mechanics and computational physics in an unprecedented effort to enhance, compare, validate and benchmark the computer models ("hydrocodes") used to model solar system impact events. 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 that must be run by the impact codes to compare the different numerical and physical models employed in the codes. Simulations are divided into two classes: 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). Initial results of our first benchmarking tests (Al into Al) were presented at the 38th Lunar and Planetary Conference [1]. The validation component defines a set of well-documented laboratory and field experiments over a wide range of event sizes, geological materials and problem types as type-cases that must be reproduced in detailed and systematic code simulations. Laboratory tests are useful because they are conducted under well-known conditions, although scale may influence the results. Field explosion tests are complementary in that they provide important data over a much larger range of sizes. A set of experimental tests were selected to encompass as many observables as possible and to sample a wide a range of experimental conditions. They include tests in simple materials such as water and metal, and in more complex materials such as soil and rock. All the simulations will test a range of physical mechanisms involved in impact events.

The final objective of this study is to provide the test informations and 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.

Impact Hydrocodes: Some codes were originally developed for specific applications, but they all contain the fundamental physics needed to model high-energy impact/explosion events, and can all be used to model general impact/explosion cratering. The hydrocodes currently used in this validation project include: ALE3D [2], AUTODYN [3], CTH [4], RAGE [5], iSALE/SALEB [6,7], SOVA [8], SPH [9], ZEUSMP2 [10]. Each code has been extensively tested individually, but no collective benchmarking and validation has ever been carried out.

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

Water tests: 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. Our first validation test consists in reproducing 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 quarter-space 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). The container was not affected by the test (no visible signs of deformation). Ambient chamber pressure was around 1-2×10^{-4} dyn/cm^2 (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 is another simple material that has been used in many experiments and has well known properties. Our second validation test consists in reproducing laboratory experiments of an aluminum sphere (Al-2017), 6.35 mm in diameter, impacting at 7 km/s aluminum 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: Simulations are carried out assuming a full impact simulation. Fixed input conditions include the projectile size, impact velocity/angle, shape and material (glass or Al), target material (water or Al), and mesh size. Technical details (including resolution), material models and relative parameters for the materials were chosen by individual modelers. This is an important difference from benchmark testing, which focuses 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.

Water Test: In the early stages of the water impact all the codes appear to follow the experimental data quite closely. The evolution of crater radius and depth with time (e.g., Fig. 1) indicates a variability in results, compared to the experiments of less than 15%. CTH, ALE3D, iSALE, and AUTODYN simulations appear to follow the experimental data quite closely, with a maximum deviation of at most 8%. The RAGE simulation was affected by problems due to the choice of boundary conditions (reflecting boundary causing the shock to be reflected back into the mesh at later times) and low viscosity. At this time, only a preliminary SOVA simulation is available, clearly affected by a limited mesh size (boundary too close to the opening crater). Simulations with ZEUSMP2 (heavily modified to model impact cratering) seem to develop instabilities beyond 2 msec. Possible reasons for the instabilities are problems with boundary conditions, problems at free surfaces and material interfaces.

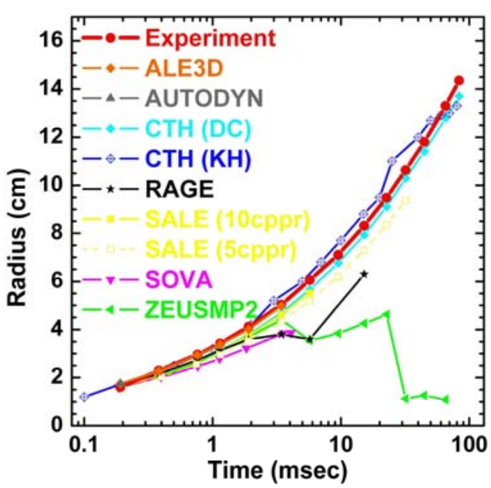

Fig. 1: Crater radius versus time for a 4.64 km/s impact of a glass sphere into water.

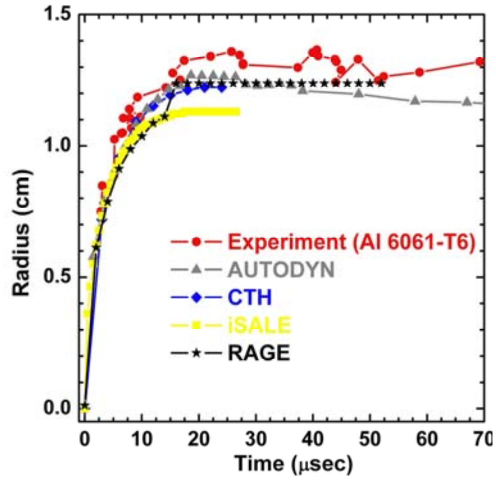

Fig. 2: Crater radius over time for a 7 km/s impact of an Al sphere into Al 6061-T6.

Aluminum Test: Few code results are available at this time for Al 6061-T6 and Al 1100-O targets. Each simulation has been carried out with varying resolution (from AMR in CTH to 10 cppr in RAGE and AUTODYN) 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. 2) and overestimate the crater depth. For impacts into an Al 1100-O target, the AUTODYN, CTH and RAGE simulations are in very good agreement with the experimental data.

Further results of our first validation test will be presented at the meeting.

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References: [1] Pierazzo E. et al. (2007) *LPSC, 38*, Abs. #2015. [2] Sharp R. (2004) *UCRL-MA-152204 Rev.1*. [3] Century Dyn., Inc. (2003) *AUTODYN Theory Manual 4.3*. [4] McGlaun J.M. et al. (1990) *Int. J. Impact Eng., 10*, 351. [5] Gittings M.L. (1992) *Def. Nucl. Agency Num. Meth. Symp., 28-30 April 1992*. [6] Ivanov, B. A. et al. (1997) *Int. J. Imp. Eng., 17*, 375. [7] Wünnemann K. et al. (2006) *Icarus, 180*, 514. [8] Shuvalov V.V. (1999) *Shock Waves, 9*, 381. [9] Benz W., Asphaug E. (1994) *Icarus, 107*, 98. [10] Hayes et al. (2006) Astroph. J. Supp., 165, 188. [11] Schmidt R.M., Housen K.R. (1987) *Int. J. Imp. Eng., 5*, 543. [12] Prater R. (1970) Tech Rep. AD0718461.