THE IMPACT HYDROCODE BENCHMARK AND VALIDATION PROJECT: FIRST BENCHMARK AND VALIDATION TESTS.

E. Pierazzo[1], N. Artemieva[2], E. Asphaug[3], J. Cazamias[4], R. Coker[5], G.S. Collins[6], D.A. Crawford[7], G. Gisler[8], K.A. Holsapple[9], K.R. Housen[10], B. Ivanov[2], D.G. Korycansky[3], H.J. Melosh[11], E.A. Taylor[12], E.P. Turtle[13], K. Wünnemann[14], [1]Planetary Science Inst., 1700 E. Ft. Lowell Rd., Suite 106, Tucson, AZ 85719, USA (betty@psi.edu); [2]Inst. Dyn. Geospheres, Russian Acad. Sci, Moscow, 117979 Russia; [3]Univ. of Calif. Santa Cruz, S. Cruz, CA 95064, USA; [4]Univ. of Alabama at Birmingham, Birmingham, AL 35294; [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 Oslo, 0316 Oslo, Norway; [9]Univ. of Washington, Seattle, WA 98195, USA; [10]The Boeing Company, Seattle, WA 98124, USA; [11]Univ. of Arizona, Tucson, AZ 85721, USA; [12]The Open Univ., Milton Keynes MK7 6AA, UK; [13]APL, Johns Hopkins Univ., Laurel, MD 20723, USA; [14]Natural History Museum, Humboldt-Univ. , Berlin 10099, Germany.

Introduction: Over the last few decades, rapid improvement of computer capabilities has allowed impact cratering to be modeled with increasing complexity and realism, and have paved the way for a new era of hydrocode modeling of the impact process, dominated by full, three-dimensional (3D) simulations. When properly benchmarked and validated against observation, computer models offer a powerful tool for understanding the mechanics of impact crater formation. This work presents initial results of a collective validation and benchmarking effort from the impact cratering and explosion community. We are following our first benchmarking tests with a simple validation test of a Boeing impact experiment consisting of a glass sphere, 2 mm in diameter impacting water vertically.

The Validation and Benchmarking Project: The Validation and Benchmarking Project (VBP) 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. The project involves at least 10 distinct codes and involves over 15 scientists, each with extensive experience in numerical modeling of impact and explosion events, from universities and research institutes worldwide as well as from national laboratories. The VBP identifies 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. 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. All the simulations will test a range of physical mechanisms involved in impact events. This effort has not been undertaken before because it requires the coordination of many modelers that have specific experience with one or two computer codes, augmented by difficulties in accessing the extensive experimental data necessary for the code validation.

Identified standards, code simulations and results will be made widely available to the scientific community through a website dedicated to the project. By providing this information to the broad scientific community it will help prevent the incorrect and misinformed use of the codes and provide a set of rules and test cases to follow in order to properly benchmark and validate hydrocodes to come.

Impact Hydrocodes: hydrocodes currently enlisted for testing in the VBP include: ALE3D [1], AUTODYN [2], CTH [3], GEODYN [4], SAGE/RAGE [5], iSALE/SALEB [6,7], SOVA [8], SPH [9], ZEUSMP2 [10]. Some codes may work better for specific situations, although they all contain the fundamental physics needed to model high-energy impact/explosion events. Each code has been extensively tested individually, but no collective benchmarking and validation has ever been carried out.

Benchmark Testing involves the identification of impact standards, ideal tests to be run by the hydrocodes. It involves detailed comparisons of characteristic quantities that are not routinely measured in experiments. Simulations are divided into two classes:

Early-time simulations focus on the early stages of the dynamic explosion process, the propagation of a shock wave through the target and the projectile. These models focus on maximum shock pressure and its decay, internal energy, temperature, melting/vaporization and tracer particle histories during crater growth.

Late-time simulations focus on the late-time process, which involves the cessation of crater excavation and collapse of the impact crater. Here, a good strength model is important. Late-time model results will focus on the crater final morphology, tracer histories describing crater collapse, and stress/strain fields and their variations during crater collapse.

Initial results of our first benchmarking tests (Al into Al) were presented at the 38th Lunar and Planetary Science Conference last spring [11].

The Validation Testing: Validation testing involves the evaluation of hydrocodes through comparison of simulations with experiments that will provide stringent tests of the physical models used in the codes. The experimental test are drawn from laboratory studies of impact cratering and fragmentation and from large field tests of explosion cratering. 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. It is important to consider as many aspects of the process as possible. A simulation must not only predict the correct final result, but also correctly reproduce the kinematics of the process, including material flow, ejection and stress levels. For this project 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.

Water tests are relatively simple. 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 [12]. 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 few small glass beads floating on the surface.

Preliminary Results: Simulations are carried out assuming a full impact simulation, i.e., the effects of the Al tank were not included. Fixed input conditions included the projectile size, impact velocity/angle, shape and material (glass), target material (water), 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 the previous benchmark testing. Benchmark tests focus on comparing code performances given simple ideal tests. On the other hand, validation testing is also about testing the modelers identification and use of the proper models. One of our goals in this context is to verify how modelers' choices can affect the output results.

At this time there are several active simulations from different modelers. Codes for which we have some output results (currently most of them are still running the validation test) are: CTH, RAGE, iSALE, SOVA, ZEUSMP2.

In the early stages of impact codes appear to follow the experimental data quite closely, as shown in Fig. 1. A brief investigation of the early evolution of crater radius and depth with time shows a variability in results, compared to the experiments of less than 15%. CTH, iSALE and RAGE appear to follow the experimental data quite closely, with a maximum deviation of at most 8%. The SOVA simulation is still in a very early stage (with 2 diagnostic time steps covered so far). Simulations with ZEUSMP2 (heavily modified to model impact cratering) seem to develop instabilities beyond 2 msec. Suggested hypotheses for the problem are not optimal boundary conditions, problems at free surfaces or sharp material interfaces, problems with the Tillotson equation of state used.

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

This work is supported by NASA Grant NNX06AD65G.

References: [1] Sharp R. (2004) *UCRL-MA-152204 Rev.1*. [2] Century Dyn., Inc. (2003) *AUTODYN Theory Manual 4.3*. [3] McGlaun J.M. et al. (1990) *Int. J. Impact Eng., 10*, 351. [4] Lomov I., Rubin M.B. (2003) *J. Phys. IV, 110*, 281. [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] Pierazzo E. et al. (2007) *LPSC, 38*, Abs. #2015. [12] Schmidt R.M., Housen K.R. (1987) *Int. J. Imp. Eng., 5*, 543.

Figure 1: Crater profile for various codes at t=0.191 ms.