THE IMPACT HYDROCODE BENCHMARK AND VALIDATION PROJECT: INITIAL RESULTS. E. Pierazzo[1], N. Artemieva[2], E. Asphaug[3], J. Cazamias[4], R. Coker[5], G.S. Collins[6], G. Gisler[7], K.A. Holsapple[8], K.R. Housen[9], B. Ivanov[2], C. Johnson[1], D.G. Korycansky[3], H.J. Melosh[10], E.A. Taylor[11], E.P. Turtle[12], K. Wünnemann[13], [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]Univ. of Oslo, 0316 Oslo, Norway; [8]Univ. of Washington, Seattle, WA 98195, USA; [9]The Boeing Company, Seattle, WA 98124, USA; [10]Univ. of Arizona, Tucson, AZ 85721, USA; [11]The Open Univ., Milton Keynes MK7 6AA, UK; [12]APL, Johns Hopkins Univ., Laurel, MD 20723, USA; [13]Natural History Museum, Humboldt-Univ. , Berlin 10099, Germany.

Introduction: The use of computer codes to model and predict impact events has become widespread. There are many codes and models used by different researchers, often with conflicting results and claims. This work presents initial results of a collective validation and benchmarking effort from the impact cratering and explosion community. Several impact codes routinely used to model impact and explosion events are being compared using a simple benchmark case of an aluminum projectile on an aluminum target impact.

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 deals with 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 are:

ALE3D [1] is a 3D, arbitrary-Lagrange-Eulerian, finite element code that treats fluid and elastic-plastic response of materials on an unstructured grid. Major components of the code are explicit and implicit continuum-mechanics, thermal diffusion, and chemistry. An incompressible flow model also exists.

AUTODYN [2] uses finite difference, finite volume and finite element techniques to solve a wide variety of non-linear problems in solid, fluid and gas dynamics. It allows the use of multiple solution techniques, including Lagrange, Euler, ALE, and SPH (mesh-free).

CTH [3] is a two-step, second-order accurate Eulerian code. It includes adaptive mesh refinement (AMR) and can be run in several modes of geometry (rectangular, spherical, cylindrical) and dimensionality (1D, 2D, 3D). Up to 10 materials and void can occupy a computational cell at once.

GEODYN [4] is a parallel 3D Eulerian Gudonov code with AMR capabilities and a high order interface reconstruction algorithm, used to simulate a wide range of problems involving the interaction of shock waves with geologic media.

SAGE/RAGE [5] is an adaptive grid Eulerian code with a high-resolution Godunov scheme. It employs continuous AMR, and can be run in several modes of geometry (rectangular, spherical, cylindrical) and dimensionality (1D, 2D, 3D). RAGE also includes a separate module for implicit, gray, non-equilibrium radiation flux-limited diffusion.

iSALE/SALEB are multi-material multi-rheology extensions to the SALE code [6], an explicit arbitrary Lagrangian Eulerian finite difference code for calculating 2D (planar or cylindrical geometry) fluid flow. iSALE/SALEB can model up to 3 materials and vacuum in any computation cell and include strength models with different failure mechanisms for solid materials. A 3D version is in development.

SOVA [7] is a two-step Eulerian 3D code. It allows up to three different materials in any single cell. It also includes a procedure to describe particles motion in an evolving ejecta-gas plume and their momentum-energy exchange (2-phase hydrodynamics) coupled to a size frequency distribution routine to model fragment sizes.

SPH [8] uses a Lagrangian gridless technique well suited to intensely deforming systems evolving within mostly empty space. Material evolution is recorded by estimating its state and dynamical variables at discrete nodes (of given mass) smoothed over spherical overlapping weighting functions. It is used in 2D and 3D.

TEKTON [9] is a finite element code developed for tectonic problems, and it is especially appropriate for modeling crater collapse. It can be used with different geometries (2D and 3D) and rheologies (Newtonian, power-law, exponential, plastic). The 2D version of Tekton is routinely used to model crater collapse.

ZEUSMP [10-11] originally built to model the behavior of gases in astrophysical situations, has been modified for use in 2D and 3D impact calculations. It includes the "p-alpha" model to treat material porosity and Lagrangian tracers to provide density/temperature histories for individual mass elements. At present, a material strength model is not included in ZEUSMP.

The Benchmark Testing: Benchmark testing involves the identification of impact standards, events that are not necessarily reproduced in the laboratory or in the field, 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 (when applicable). Therefore, these models focus on maximum shock pressure, shock pressure decay, internal energy, temperature, melting/vaporization, and tracer particle histories during crater growth. Impact angle strongly affects the early stages of the impact, thus benchmark tests will involve vertical as well as 45º impact simulations to be carried out in 3D.

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.

Preliminary Results: We have started our first benchmark test, consisting of the impact of an Al sphere 1km in diameter impacting perpendicularly an Al target at 5 km/s. 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 cells-per-projectile-radius (cppr) to 40 cppr or 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 initial results of shock pressure decay in the target (early-time stage) corresponding to the best resolution case run (so far) for each code. All codes produce very similar results in the pressure-decay region, beyond about 0.5 km from the impact point, where pressure and particle velocity decay rapidly with a power law of distance. Close to the impact point is the isobaric core, where pressure decay with distance is small. This is the region with the biggest discrepancies among the various codes. More tests with a better distribution of tracer particles are needed to address such discrepancies.

Further results of early-time benchmark tests of Al-Al impacts, including simulations at 20 km/s and 45° from the surface will be presented at the meeting.

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Figure 1: Shock pressure decay from the impact point, along the vertical, in the target. Parentheses show the mesh resolution used in the runs..