Preprint
UCRL-JC-135647

Dynamic Response of Berea Sandstone Shock-loaded Under Dry, Wet and Water-Pressurized Conditions

M. Hiltl, C.R. Hagelberg, R.P. Swift, T.C. Carney, W.J. Nellis

This paper was prepared for submittal to the
International Conference on High Pressure Science and Technology
Honolulu, HI, July 25-30, 1999

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

September 3, 1999

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

This report has been reproduced
directly from the best available copy.

Available to DOE and DOE contractors from the
Office of Scientific and Technical Information
P.O. Box 62, Oak Ridge, TN 37831
Prices available from (423) 576-8401
http://apollo.osti.gov/bridge/

Available to the public from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Rd.,
Springfield, VA 22161
http://www.ntis.gov/

OR

Lawrence Livermore National Laboratory
Technical Information Department's Digital Library
http://www.llnl.gov/tid/Library.html

Dynamic Response of Berea Sandstone Shock-loaded Under Dry, Wet and Water-Pressurized Conditions

M. Hiltl[1], C. R. Hagelberg[2], R. P. Swift[2], T. C. Carney[2] and W. J. Nellis[1]
[1] *Physics Directorate, Lawrence Livermore National Laboratory, Livermore, CA 94550*
[2] *Geoanalysis Group, Los Alamos National Laboratory, Los Alamos, NM 87545*

A single-stage light-gas gun was used to perform shock-recovery experiments on Berea sandstone under dry, wet and hydrostatically water-pressurized conditions. The samples were impacted by flyer-plates to achieve stress levels in the range 1.3 to 9.8 GPa. The microstructure of the shocked samples was analyzed using scanning electron microscopy (SEM), laser particle analysis and X-ray computed microtomography (XCMT). The dry samples show strongly fragmented and irregularly fractured quartz grains with a considerably reduced porosity, whereas the wet and water-pressurized specimens show less grain damage and less porosity reduction. During shock compression the water in the pores distributes the stresses and therefore the contact force between the grains is reduced. The interaction between the grains during the shock process was modeled by explicitly treating the grain-pore structure using Smooth Particle Hydrodynamics (SPH) and the Disctrete Element Method (DEM). [Berea sandstone, shock-recovery, shock damage, microstructural investigations, computer modeling].

1. Introduction

The dynamic response of geological materials [1, 2] is of great interest in fields such as oil and gas recovery, mining, meteoritic impact, earthquakes and underground explosions. To increase our understanding of the phenomenology of heterogeneous grain to grain interactions under dynamic loading we have carried out a series of shock-recovery experiments to obtain a quantitative assessment of shock-induced grain damage. The experiments provide damage data for correlation and comparison with explicit grain-scale numerical modeling, similar to that described in [3]. Motivation for this study comes in part from the well completion process in oil and gas recovery, where shaped-charge jets are used to perforate the wellbore casing. The perforation provides connectivity to the surrounding reservoir rock but the jet also creates a localized crushed zone [4, 5] surrounding the perforation tunnel. The crushed zone hinders the recovery of hydrocarbons. In the present study we examine grain fragmentation caused by short duration shock-waves similar to perforation loading on Berea sandstone (Table 1). This material is commonly used as a rock standard in petrophysical studies [6].

Table 1: Properties of Berea sandstone.

Porosity:	21.92%
Bulk density:	2.077 g/cm^3
Grain density:	2.631g/cm^3
Average grain size:	0.15 mm
Modal analysis [7]:	75% quartz, 10% clay, 10% feldspar, 5% calcite

2. Experimental setup

A total of 23 shock-recovery experiments under dry, wet and water-pressurized conditions have been performed by using a single-stage light-gas gun with a bore diameter of 35 mm. All sandstone samples, 5 and 15 mm thick with a diameter of 22.4 mm, were confined in an aluminum capsule surrounded by a recovery-fixture of the same material [8]. Stress-levels between 1.3 and 9.8 GPa at the front part of the capsule were achieved by impacting the sample with aluminum, copper and PMMA flyer plates. Finite element computer calculations show that the pressure in the sandstone is between 35 and 40% lower than it is at the front part of the capsule [8, 9]. Flyer thicknesses of 3 mm and 6.25 mm were used to provide shock-pulse durations of approximately 1μs and 2μs, respectively.

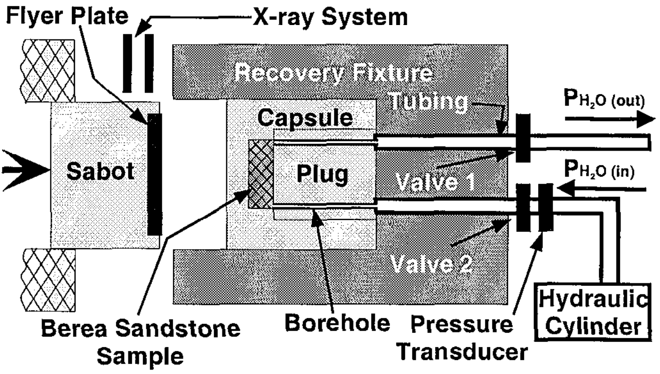

Figure 1: Experimental situation short before the impact.

To simulate the pressure conditions down hole we applied hydrostatic water pressure directly to the samples. This was done by modifying the capsule used originally for the dry samples by fitting two stainless steel tubes, having a diameter of 1.6 mm, from the recovery fixture to the back side of the capsule. A connection was made to two 1-mm boreholes, which end at the surface of the Berea target. The schematic setup for the wet and water-pressurized experiments is shown in Fig. 1. Water-pressurizing the samples was done by pumping approximately 500 ml of water through the tubing and the sandstone to make sure that all air bubbles were out of the system. Then valve 1 (Fig 1) was closed and the sample was pressurized up to 7.9 MPa by using a hydraulic cylinder. The water pressure was measured and controlled by a calibrated pressure transducer. After reaching the correct water pressure, valve 2 was closed to avoid any damage to the pressure transducer during the shock process. The same setup was used for the wet experiments but no water pressure was applied.

3. Experimental results

The shock-recovered samples were cut in two halves (Fig. 2). One half was analyzed using a Noran Instruments Automated Digital Electron Microscope to produce digital SEM images. Laser particle size analysis using a Microtrac-X100 was performed on the other sample half. XCMT images were obtained on the undamaged material and two dry shocked samples at the National Synchrotron Light Source at Brookhaven National Laboratory.

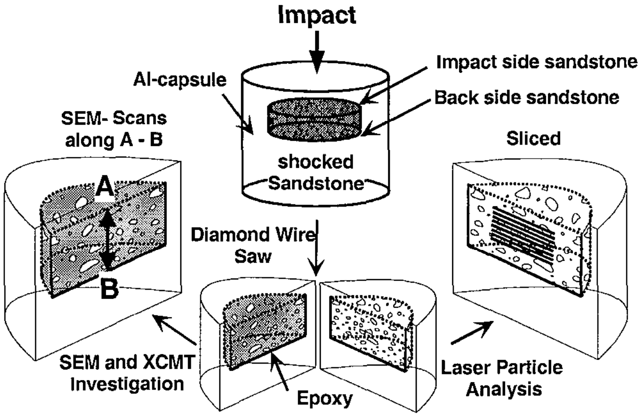

Figure 2: Schematic drawing of the sample preparation

a) Scanning electron microscopy

The center line of the shocked samples were scaned from the impact side to the opposite capsule back side (A-B in Fig. 2) by using backscattered imaging. SEM investigation on the undamaged sandstone (Fig. 3) shows irregulary grain and pore shapes. We observed pre-existing cracks in some quartz grains and the majority of the pores are interconnected.

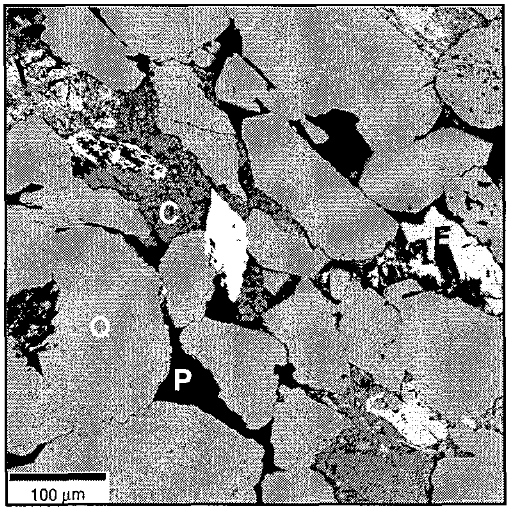

Figure 3: Undamaged Berea sandstone (Q=quartz, F=feldspar, C=clay, P=pore).

In the following we list the pressure which is achieved at the front part of the capsules, not in the sandstone. Near the impact side of the dry samples shocked at 1.4 and 3.1 GPa, all quartz-grains are irregularly fractured and fragmented but still has an observable remnant porosity (Fig. 5). The fragmentation is caused by grains impacting each other as the shock front propagates through the sample. As a result of stress attentuation from the front to the back of the sample, a decrease in damage is observed in the 15 mm thick sample. Much less fragmentation occurred near the back side of the sample. In contrast, the grains in the dry samples shocked at 6.1 GPa (Fig. 5) showed extreme fragmentation and fractures near the impact side. All the pores in this region were closed. The rear of these samples still had observable porosity with less damaged grains. The grains near the impact side in the dry sample loaded to 9.8 GPa (Fig. 5) were completely fragmented with no observable porosity remaining. Near the rear of the sample, pores are still visible and grain damage is significantly less. Compared to the dry samples, the grain damage in the wet specimen is far lower and the reduction of the porosity is significantly less. This is a result of the pore fluid acting to homogenize the material and prevent localization of stress at grain contact points. We observed that the difference in the grain damage between impact side and back side of the wet samples is not as great as observed in the dry material. Specimens shocked with the longer shock pulse showed more grain damage and pore compaction than those shocked with the shorter pulse. We observe no difference in grain damage and porosity between the wet and 7.9 MPa water-pressurized experiments.

b) Laser particle analysis

We probed several depths of each sample and analysed the material with an angular light scattering technique to determine the particle size distributions. Every specific depth for each sample was measured three times and the result was used to calculate an average grain size. The measurements show a clear grain size reduction in all shocked samples when compared to the undamaged material. Figure 4 illustrates the difference in grain size between dry and wet samples impacted at a stress level of about 6.1 GPa, as well as the difference between the regions near the impact side, mid, and the back side of the samples. Nearly all samples, no matter if dry, wet or water-pressurized, have a smaller grain size in the middle region of the sample than in the impact region. We presume that this is caused by rarefaction waves which converge in the mid region from the edges of the capsule containing the sandstone. Computer simulations support this interpretation.

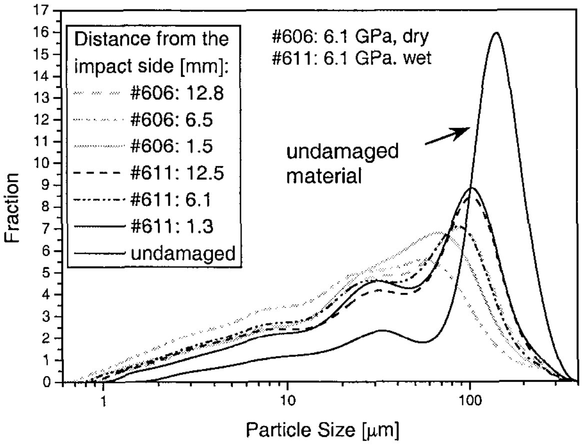

Figure 4: Laser particle analysis for the samples shocked at 6.1 GPa dry and wet.

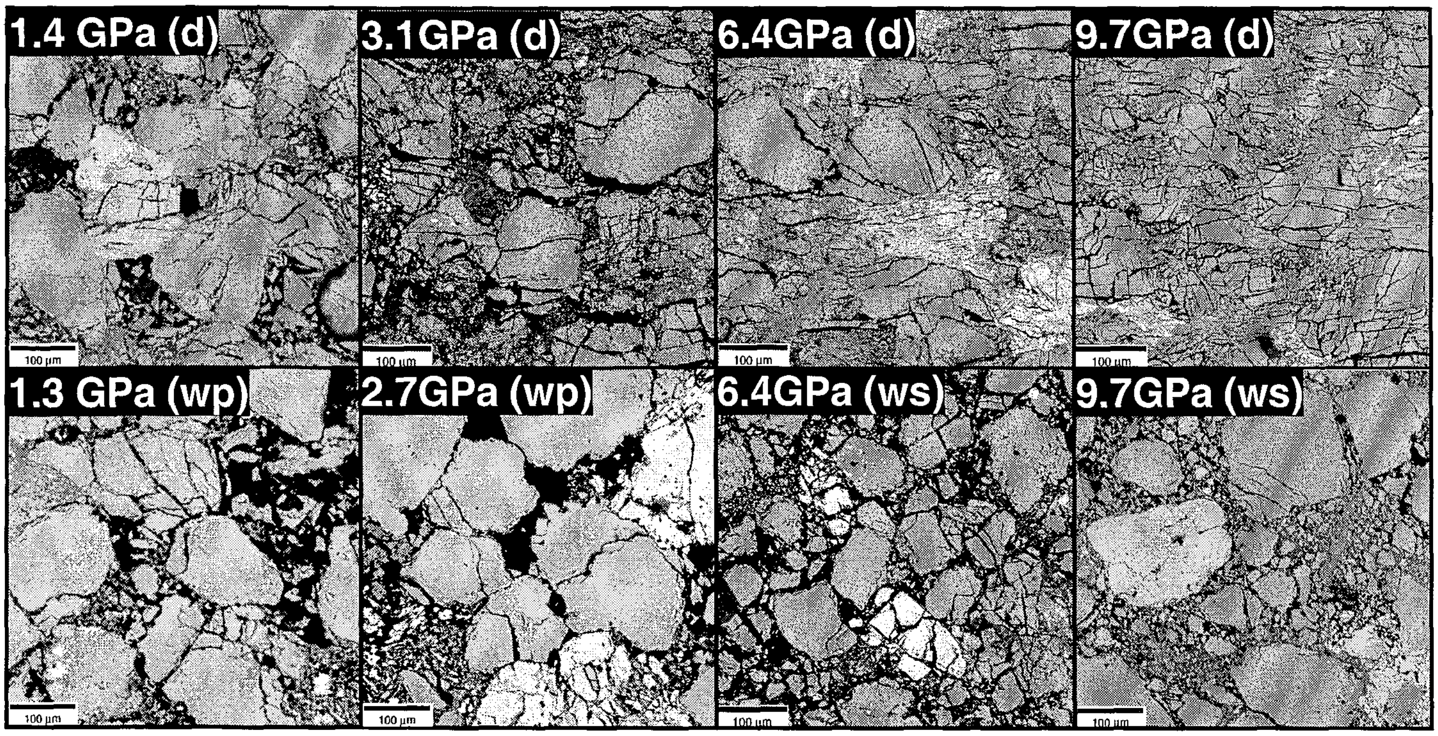

Figure 5: SEM micrographs near the impact side for dry (d), wet (ws) and water-pressurized (wp) samples.

c) X-ray computed micro tomography

Cores with a diameter of 2 mm were taken from the samples parallel to the axis of impact. The XCMT process creates a stack of images each of which lies in plane prependicular to the cylinder axis. Figure 6a shows a undamaged sample and provides an idea of the resolution obtained using XCMT. Figure 6b illustrates a XMCT slice of the 6.1 GPa and dry shocked sample roughly 94 µm from the impact side. Qualitatively, there are a few large grains and many small grains near the impact surface. Further away from the impact surface there are comparatively more large grains left intact.

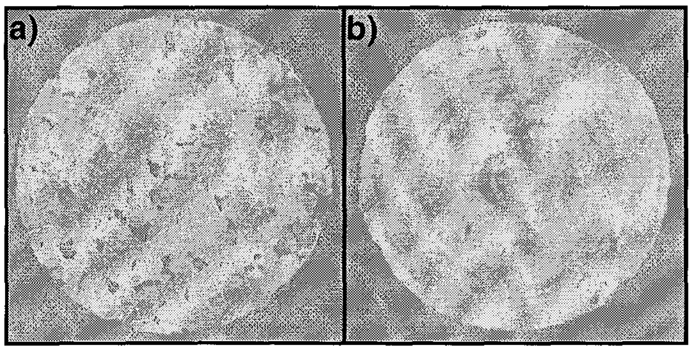

Figure 6: XCMT-micrograph of **a)** undamaged Berea sandstone and **b)** dry sample shocked with 6.1 GPa (3 mm flyer plate)

Overall, the XCMT data has not proven to be quantitatively useful at present due to its relatively coarse resolution (3.6 µm per pixel). At this point the datas are useful for a qualitative comparison and support SEM observations. The XCMT data might prove useful for additional information regarding damage mechanism when further analysis techniques, for example quantitative statistical image analysis in two and three dimensions, are developed,.

4. Modeling

Modeling of several of the experimental conditions was performed and reveals qualitative results of fragmentation similar to that observed in the recovered samples. We used the SPH/DEM SPHINX code [10] to model the heterogeneous behavior of the grain structure. More of the details of the modeling are discussed in [9]. The simulations of the grain structures examine the influence of the pore space being treated as a void or as fluid-filled. Although the simulations are two-dimensional, the results reflect the complex phenomenology associated with the experiments. Simulation of a plate impact loading in a limited domain captures the relationship between stress intensity and the damage observed in the recovery experiments. The initial condition of the grain structure for the simulations is shown in Fig. 7.

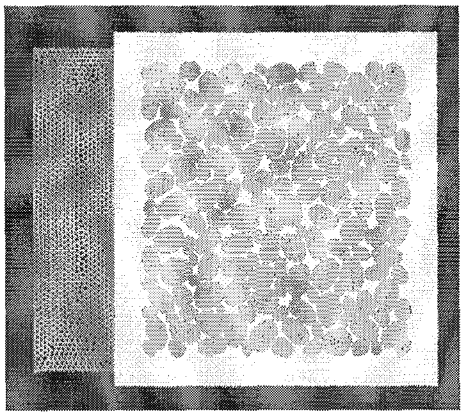

Figure 7: The synthetic grain structure and surrounding aluminum box used for the simulations. This realization contains grains that have generally smoother boundaries than observed grains. The plate impacts the grain-filled box from the left.

Figure 8 shows the crack distribution in the dry (Fig. 8a) and wet (Fig. 8b) sample simulated by the DEM portion of the calculation. The cracks are shown at 1.7 μs after the initial impact (880 m/s). There is much greater compaction and fragmentation evident in the dry sample than in the wet sample.

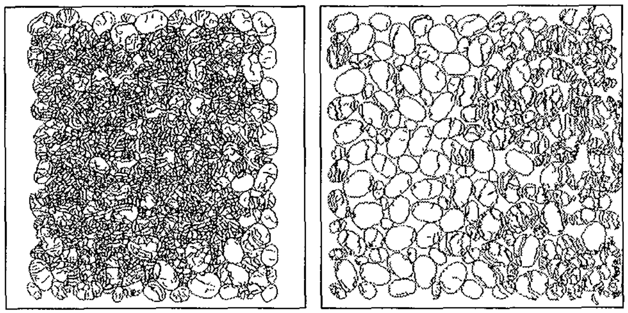

Figure 8: Crack structures (damage) in the **(a)** dry and **(b)** wet sample as simulated by SPH/DEM at 1.7 μs after the initial impact of the flyer plate (not shown) with 880 m/s from the left.

The increased mass and pore pressure of the water provides a cushioning and mitigates the grain to grain interactions that result in the increased damage observed in the dry samples.We can compare the simulations to SEM images of portions of the recovered samples. Figure 9 shows processed images of recovered samples from dry and wet impact experiments. The segmented images represent the character of the crack patterns in the samples. The segmentation consists of outlining the voids in the image, thresholding on the gray-scale, and skeletonizing the result to produce the images of Figure 8. The result is qualitatively comparable to graphical representation of the results of the simulations shown in Figure 8.

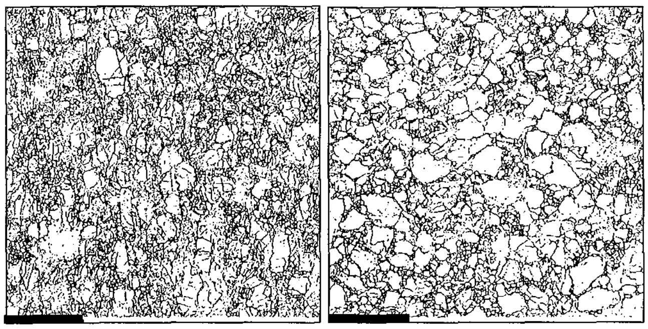

Figure 9: Binary versions of SEM images of the **(a)** dry 6.1 GPa and **(b)** wet 6.1 GPa shocked samples. The original gray-scale image has been processed to enhance the crack and boundary information (Scalebar is 500 μm).

5. Conclusions

EXPERIMENTS: We performed shock-recovery experiments on dry, wet and hydrostatically water-pressurized Berea sandstone in the range between 1.3 and 9.8 GPa using a single-stage light-gas gun. With increasing stress levels we observe considerable grain damage in the dry samples whereas the wet and water-pressurized specimens show much lower damage. The porosity is reduced with increasing shock pressure. There is a significant difference in grain damage and porosity when we compare the dry specimen against the wet and water-pressurized material. We observe decreasing grain damage and increasing porosity with increasing distance from the impact side in the 15 mm thick samples. However, the damage gradients in the wet and water-pressurized samples are not so intense compared to the dry samples. We observe that grain and pore damage increases with shock pulse duration. No difference between wet and water-pressurized samples regarding porosity and grain damage is noticed.

MODELING: We have demonstrated that the combined Smooth Particle Hydrodynamics and Discrete Element Method (SPH/DEM) computational technique is a way to model the dynamics of grain-to-grain interactions on the grain scale. The simulations include the influence of varying the material contents of the pore space. We have used the method to simulate the damage resulting from stress-wave loading on a small domain containing a grain structure and compared the results to the gas-gun impact experiments. Simulations of a plate impact configuration show the influence of explicit heterogeneity of the grain structure and the influence of fluid-filled pores on the propogation of damage thoughout the sample. Qualitative agreement is obtained for simulated damage with the damage observed on the shock-recovered samples of Berea sandstone from the impact experiments. A significant increase in fragmentation and compaction of the dry sample compared to the wet sample is achieved in the simulation. The simulations illustrate the complexity of how heterogeneity affects stress wave behavior which in turns affects damage evolution.

Acknowledgment

This work was performed at Lawrence Livermore National Laboratory under the auspices of the U.S. Department of Energy under contract No. W-7405-Eng-48.

References

[1] Larson, D. B., Anderson, G. D., *J. Geophys. Res.*, **84**, 4592-4600 (1979).

[2] Kieffer, S. W., Phakey, P. P., Christie, J. M., *Contrib. Mineral. Petro.*, **59**, 41-93 (1976).

[3] Swift, R. P., Behrmann, L. A., and Halleck, P. M., *SPE paper 39458,* SPE Proc. of Int. Sym. on Formation Damage Control, 381(1998).

[4] Krueger, R. F., *J. Pet. Tech*,. 131-152 (1986).

[5] Halleck, P. M., *GasTips,* **2**, 39-42 (1996).

[6] Wagner, W. G., Lengyel, B. A., *J. Appl. Phys*,. **34**, 2046-2052 (1963).

[7] Zhang, J., Wong, T.-F., Yanagidani, T., Davis, D. M., *Mechanics of Materials,* **9**, 1-15 (1990).

[8] Hiltl, M., Swift, R. P., Hagelberg, C. R., Carney, T. C. and Nellis, W. J. „Shock-recovery Experiments of Sandstone under Dry and Water-saturated Conditions", in Shock Compression in Condensed Matter-1999, edited by M. D. Furnish, AIP Conference Proceedings, in press.

[9] Hagelberg, C. R., Swift, R. P., Carney, T. C., Greening, D., Hiltl, M., Nellis, W. J. „Modeling Shock Recovery Experiments of Sandstone" in *Shock Compression in Condensed Matter-1999,* edited by M. D. Furnish, AIP Conference Proceedings, in press.

[10] Wingate, C. A. et. al., "SPHINX Manual, Version 11.0", Los Alamos National Laboratory Document, LA-13436-M, (1998).