Numerical Modeling of Crater Formation by Meteorite Impact and Nuclear Explosion

Charles L. Mader

Abstract The NOBEL code for modeling compressible fluid dynamics is used to model the formation of the Arizona meteor crater by a 50 meter diameter iron asteroid impacting basalt at 12 kilometers/second. The code is also used to model the crater generated by the SEDAN 104 kiloton nuclear explosion. To reproduce the observed crater sizes it is necessary to include the properties of pulverized rock created by the shocking and rarefaction of the rock.

1 The NOBEL Code

The U.S. Department of Energy's Accelerated Strategic Computing Initiative (ASCI) during 2000 to 2005 resulted in major advances in computer technology and in methods for improving the numerical resolution of compressible reactive hydrodynamic calculations.

In NOBEL, the three-dimensional partial differential equations for compressible flow are solved by a high resolution differencing scheme using an adaptive grid technique described in reference 1. The solution technique uses Continuous Adaptive Mesh Refinement (CAMR). The decision to refine the grid is made cell-by-cell continuous throughout the calculation. The computing is concentrated on the region of the problem which require high resolution.

Refinement occurs when gradients in physical properties (density, pressure, temperature, material constitution) exceed defined limits, down to a specified minimum cell size for each material. With the computational power concentrated on the regions of the problem which require higher resolution, very large computational volumes and substantial differences in scale can be simulated.

Dr. Charles L. Mader
Mader Consulting Co., Honolulu, HI 96825-2860, e-mail: mccohi@aol.com

The code can describe one-dimensional slab or spherical geometry, two-dimensional slab or cylindrical geometry, and three-dimensional Cartesian geometry.

The code incorporates multiple material equations of state (analytical or SESAME tabular). Every cell can in principle contain a mixture of all the materials in a problem assuming that they are in pressure and temperature equilibrium. The assumption of temperature equilibrium is inappropriate for mixed cells with interfaces between different materials. The errors increase with increasing density differences. The problem is minimized by using fine numerical resolution at interfaces. The amount of mass in mixed cells is kept small resulting in small errors being introduced by the temperature equilibrium assumption. The strength is treated using the Hooks Law, Von Mises yield model described in reference 1.

A variety of boundary conditions is available, the most important being reflective boundary walls, reflective internal boundaries, and “freeze regions” which allow specific inflows and unrestricted outflows of material.

Very important for cavity generation and collapse is the capability to initialize and describe gravity correctly, which is included in the code. The initial density and initial pressure changing with depth or altitude is correctly included.

The code was developed for general applications to run on a wide variety of computers from desktop PC’s (Windows, Linux and Apple Macintosh) to the latest MMP or SMP supercomputers. The code has operated on different super computers, the oldest being the ASCI Red teraflop system installed at Sandia National Laboratory in 1996 to the Roadrunner pentaflop computer installed at Los Alamos National Laboratory in 2008.

The code has all the techniques for modeling reactive flow and detonation chemistry and physics described in reference 1. It has been used to model Richtmyer-Meshkov and shock induced instabilities. Also modeled using Nobel is the 1958 Lituya Bay impact landslide generated 485 meter high tsunami, the water cavities generated by projectiles and explosions and resulting water waves, the 1883 Krakatoa hydrodynamic volcanic explosion and resulting tsunami, shaped charge jet formation and penetration, detonation wave propagation and failure, corner turning, desensitization by preshocking, explosive performance and applications such as cylinder tests, underwater explosions, denting of metal plates, Mach and regular shock and detonation wave interactions and the problems associated with explosive hazards from accidental inititiation. The K-T impact 65 million years ago at Chicxulub by a 10 kilometer diameter granite asteroid moving 15 kilometers/second has been modeled using RAGE which is a version of NOBEL with radiation. These applications of the NOBEL code are described in references 1 and 2.

2 Modeling the Arizona Meteor Crater

The Arizona Barringer meteor crater was generated about 50,000 years ago by an iron asteroid about 50 meters in diameter and impacted the earth at about 12 kilometers/second. A picture of the crater is shown in Figure 1. A sketch of the crater is shown in Figure 2. The crater is 1.2 kilometers in diameter, currently 175 feet deep with a 50 meter high rim. In addition there is about 250 meters of rubble below the current bottom of the crater making the initial asteroid generated crater about 500 meters deep from the top of the rim The impacted rock was basalt.

The rim of the crater was generated by the rock ejecta folding over the crater rim as shown in Figure 3. The 640 kilogram iron-nickel fragment found near the crater is shown in Figure 4.

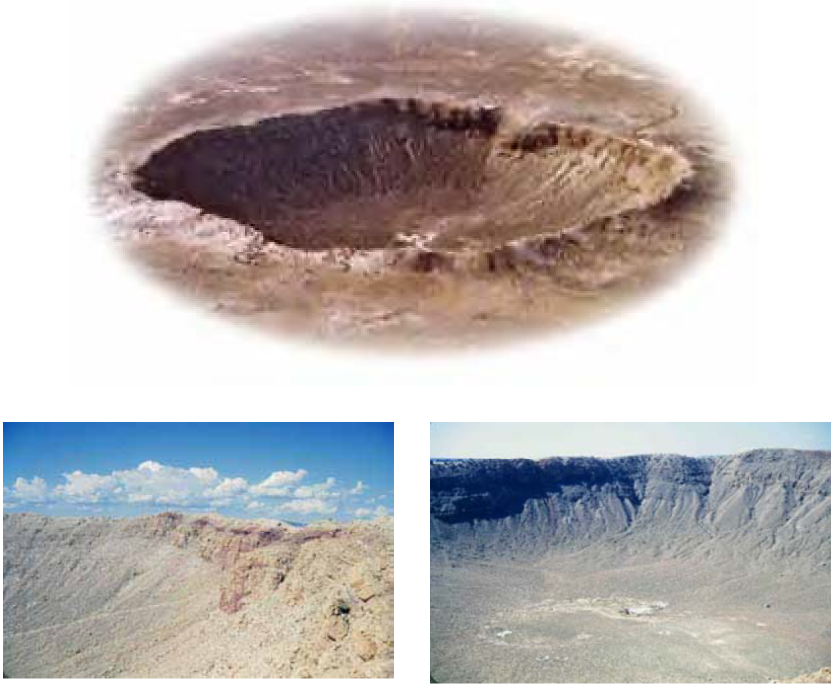

Fig. 1 The Arizona Barringer meteor crater.

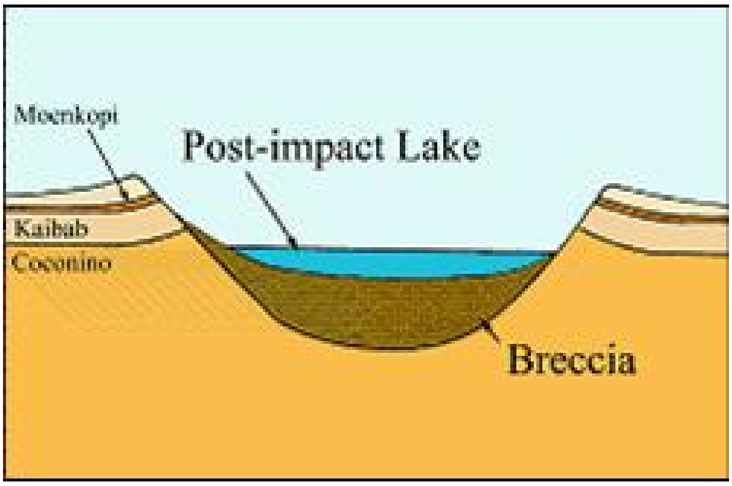

Fig. 2 Sketch of the geometry of the Arizona meteor crater.

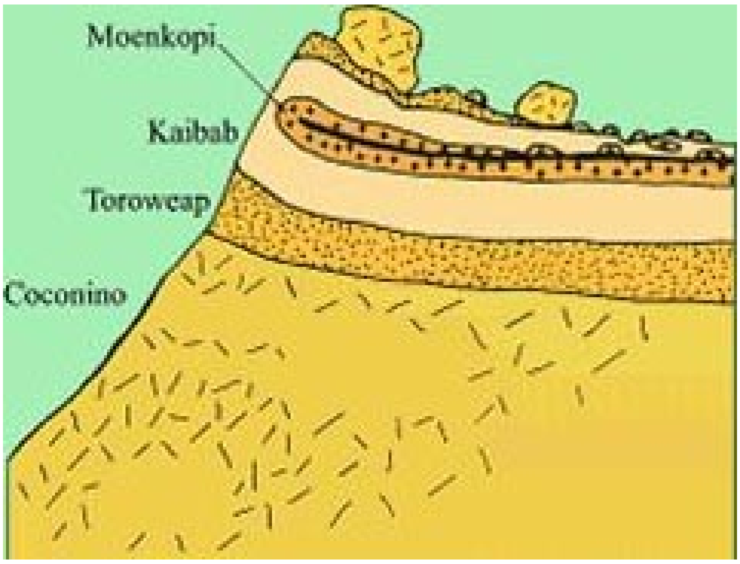

Fig. 3 Sketch of the geometry of the folded rim of Arizona meteor crater.

Fig. 4 A 640 kilogram iron-nickel meteorite fragment found near the Arizona Barringer crater.

The impact of a 50 meter diameter iron asteroid moving at 12 kilometer/second with Basalt was modeled using NOBEL. The equation of state used for iron was the Sesame table number 4270. The iron shock Hugoniot was described by the shock velocity (Us) and particle velocity (Up) fit Us = 0.458 + 1.49 Up where the velocity units are centimeters/microsecond. The initial iron density is 7.896 grams/cc. The equation of state used for Basalt was the Sesame table number 7530. The shear modulus used was 0.25 and the yield was 0.02 kilobar. Gravity was included in the calculation.

The geometry of the calculation was cylindrical with 0.5 kilometer of air above 2.0 kilometers of Basalt. Calculations were performed for a 50 meter and a 25 meter mesh. The calculations were performed using personal computers.

If the Basalt is modeled as a fluid with a yield of 0.0 kilobar, the density profiles at various times are shown in Figure 5. After the cavity has been created, it collapses and forms a jet that then falls back and forms waves just as does a rock projected into water.

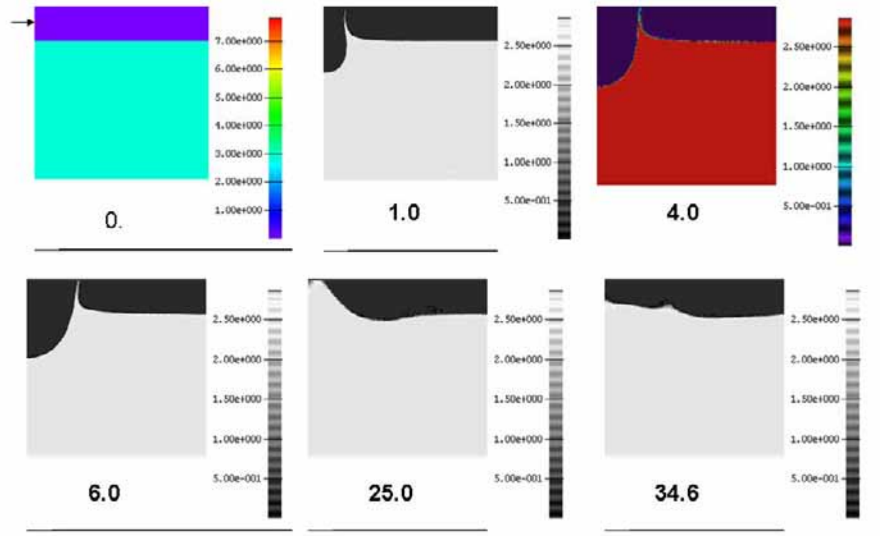

Fig. 5 The density plots for a 50 meter diameter iron asteroid impacting Basalt modeled as a fluid with a yield of zero. The basalt is 2 kilometers high and 2.5 kilometers wide in cylindrical geometry with the axis on the left side of the figures. The time is shown in seconds. The initial position of the asteroid is shown by the arrow next to the red sphere in the first frame.

If the basalt has a yield of 0.05 kilobar the final crater diameter is too small and if the yield is 0.01 kilobar the crater is too large. A yield of 0.02 kilobar results in a crater about the diameter of the crater and permits a rebound from the maximum depth to about the final depth of the Arizona meteor crater. The density plots at various times are shown in Figure 6.

The small yield for the basalt is a result of the basalt being initially shocked and melted and then rarefied to form a pulverized material with not much strength. The term for the process is the basalt has been “fluidized” . The yield required to describe the basalt behavior represents the fluidized rock. In the SEDAN crater modeling that process is represented by an initially large yield and after the cavity is generated and fluidization has occurred the crater rebound is described by a smaller yield for the fluidized rock.

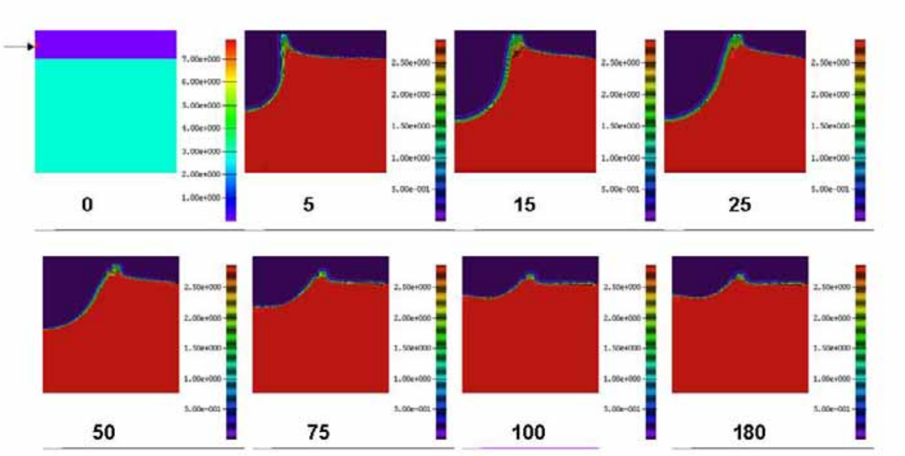

Fig. 6 The density plots for a 50 meter diameter iron asteroid impacting Basalt modeled with a yield of 0.02 kilobar. The basalt is 2 kilometers high and 2.5 kilometers wide in cylindrical geometry with the axis on the left side of the figures. The time is shown in seconds. The initial position of the asteroid is shown by the arrow next to the red sphere in the first frame.

The final crater geometry for Basalt with a yield of 0.02 kilobar for calculations with an initial mesh of 50 x 50 cells and initial cell sizes of 50 and 25 meters are shown in Figure 7.

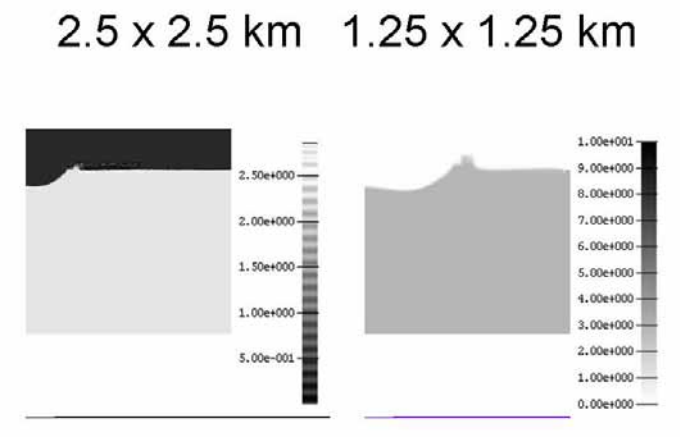

Fig. 7 The final crater geometry for Basalt with a yield of 0.02 kilobar for calculations with an initial mesh of 50 x 50 cells and initial cell sizes of 50 and 25 meters.

3 Modeling the SEDAN Crater Created by a Nuclear Explosion

The SEDAN nuclear test was performed July 6, 1962 as part of the Plowshare series of tests designed to develop earth evacuating techniques using the energy from nuclear explosions that resulted in low levels of residual radioactivity. The major application was believed to be for the creation of a sea level channel to replace the Panama canal.

The nuclear explosive device was buried 194 meters deep in the Nevada Tuff rock. The energy of the explosion was equivalent to 104 kilotons of TNT. The height of the dome before breach was 90 meters which occurred 3 seconds after the explosion. The final crater diameter was 360 meters, the final crater depth was 97 meters. After the explosion, drilling determined that the maximum depth of melt was 246 meters. The final crater dimensions are shown in Figure 8 and the crater is shown in Figure 9. The explosion moved 12 million tons of earth. The Richter magnitude of the event was 4.75.

The explosion is shown in Figure 10 about 10 seconds after the dome breach. The picture is taken from a film of the explosion that is available at www.mccohi/crater/sedanshot.mpeg .

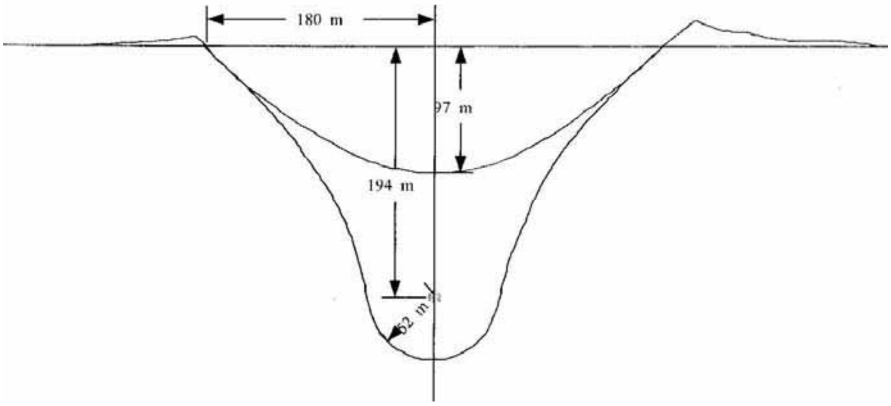

Fig. 8 The crater geometry. The nuclear explosive was located 194 meters below the surface. The final crater was 180 meters in radius and 97 meters deep with a melt zone shown by the outer line with a maximum depth of 246 meters.

Fig. 9 The SEDAN crater in 1963 and 2003 with Los Alamos National Laboratory Scientists on viewing platform. Author is second from right.

Fig. 10 A frame from a film taken of the nuclear explosion after the dome breach. The film is available at www.mccohi.com/crater/sedanshot.mpeg .

The NOBEL model for the SEDAN nuclear explosion was modeled by a 30 meter diameter water sphere at 194 meter depth in Tuff with an initial energy of 104 kilotons or 4.353 x 10^{23} ergs. The Nevada test site Tuff has been extensively characterized and the Sesame table number 7111 was used for modeling its equation of state. The Tuff shock Hugoniot was described by the shock velocity (Us) and particle velocity (Up) fit Us = 0.199 + 1.22 Up where the velocity units are in centimeters/microsecond. The initial Tuff density was 1.39 grams/cc. The shear modulus was 0.25 megabar. The Tuff yield was 0.1 kilobar for the first 2.5 seconds which is approximately the time of maximum cavity size. The yield was then lowered to 0.004 kilobar to account for the lower strength of pulverized Tuff that has been shocked and rarefied or “fluidized”. Bingham first introduced the concept in his book “Fluidity and Plasticity” (reference 3). The concept and book was suggested by Dr. Bill Van Dorn during our current efforts to model craters on the moon and their rings and mascons.

Calculations for Tuff without strength (a yield of 0.0) results in a cavity diameter that is more than twice too large. If the Tuff initially has a yield of 0.1 kilobar and then lowered to 0.003 kilobar the cavity diameter is about as observed but there is too much cavity collapse – the final cavity depth is smaller than observed.

As shown in Figure 9 the SEDAN crater is not exactly spherical and as shown in Figure 10 the ejecta pattern was very irregular. The NOBEL numerical model assumes that the SEDAN event can be modeled with cylindrical symmetry which is only a first approximation of the actual complicated nature of the Tuff which has significant density and composition inhomogenities.

The cylindrical geometry of the calculation was modeled by an initial mesh of 32 meters square and 32 x 64 cells or 1 kilometer radius and 2 kilometers high with 1 kilometer of air and 1 kilometer of Tuff. The calculations included gravity and were performed using personal computers.

If the Tuff is modeled with a yield of 0.1 kilobar for the first 2.5 seconds and then the yield is lowered to 0.004 kilobar, the resulting density profiles are shown in Figure 11. The SEDAN crater dimensions are reproduced by the calculation.

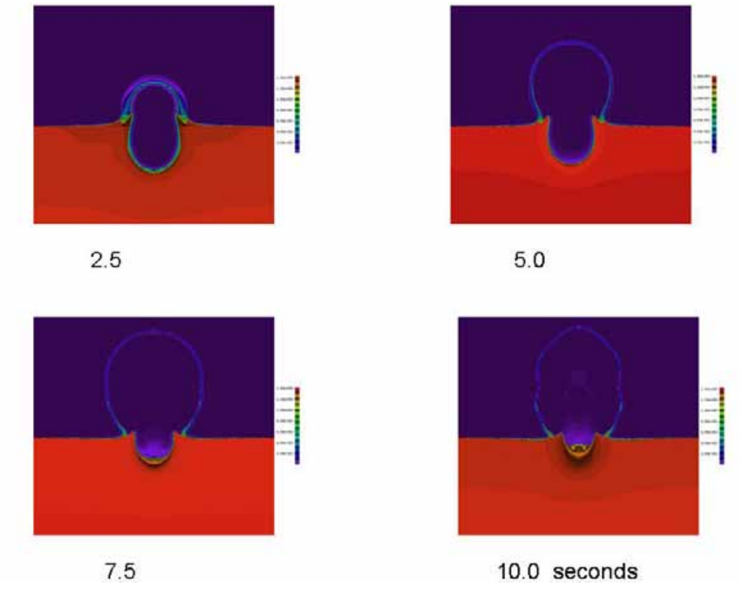

Fig. 11 The SEDAN crater formation by a 104 kiloton nuclear explosive with a Tuff yield of 0.1 kilobars for the first 2.5 seconds, which is at about at the time of maximum cavity generation and then lowered to 0.004 kilobars to account for the lower strength of the pulverized Tuff that has been “fluidized”.

The final cavity density profiles for a pulverized Tuff yield of 0.004 kilobar are shown in Figures 12. The 0.004 yield results in a cavity similar to that of the SEDAN nuclear explosion.

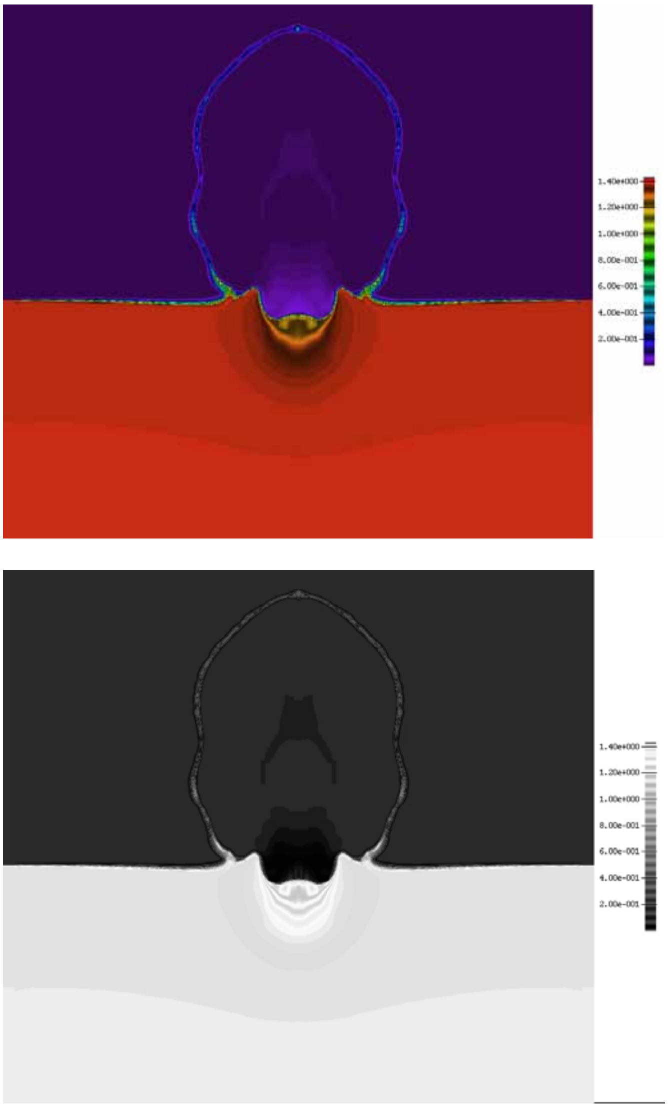

Fig. 12 The density profile of the SEDAN crater modeled including "fluidization".

Conclusions

The NOBEL code for modeling compressible fluid dynamics was used to model the formation of the Arizona Barringer crater by a 50 meter diameter iron asteroid impacting at 12 kilometers/second. The strength of the basalt required to reproduce the final crater dimensions had to be small (0.02 kilobar yield) because the basalt was shocked and pulverized. Most of the ejecta was propelled outside the crater as was a significant amount of the iron asteroid with only a small amount falling back into the final crater.

The SEDAN crater created in Nevada Tuff by a 105 kiloton nuclear explosion buried 194 meters deep was modeled. To reproduce the crater dimensions the initial yield of the Tuff was 0.1 kilobar for 2.5 seconds when the crater was at maximum size and then the yield was reduced to 0.004 kilobar to model the pulverized or “fluidized” Tuff.

PowerPoint presentations and the AVI and MPEG movies of the NOBEL modeling of the Arizona Meteorite crater and SEDAN nuclear explosion generated crater are available at www.mccohi.com/crater/crater.htm. .

This modeling of craters is part of a program to calibrate crater modeling for our study (with Dr. Van Dorn) of the multi-ringed lunar maria and underlying mascons - the so called “Lunar Tsunamis” because they are similar to frozen tsunami waves.

References

1. Mader, Charles L. : Numerical Modeling of Explosives and Propellants, and CD-ROM. CRC Press (2008).
2. Mader, Charles L. : Numerical Modeling of Water Waves, and 2008 DVD, CRC Press (2004).
3. Bingham, Eugene C. : Fluidity and Plasticity , McGraw Hill (1922).