Energy Transfer of a Shaped Charge

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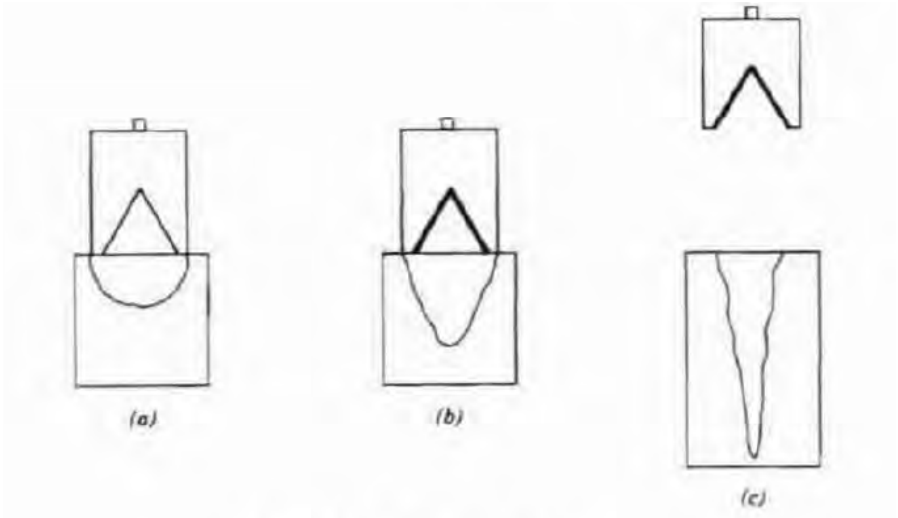
Background information

Cylindrical Shaped Charge Concept

A cylinder of explosive with a hollow cavity on one and a detonator at the other is considered a hollow charge. When the explosive is detonated the detonation products form a localized intense force. If the hollow charge is placed near or in contact with a steel plate then the damage to the plate is greater than a solid cylinder of explosive even though there is a greater amount of explosive in the latter charge. The hollow cavity can take almost any geometrical shape with differing amounts of damage associated with each shape. This phenomenon is known in the United States as the Munroe effect.

If the hollow cavity is lined with a thin material, usually a ductile metal or ceramic, or any solid material, the liner may form a jet. In most cases the hollow cavity is formed into a conical shape or hemispherical. As the explosive is detonated a spherical shock wave propagates outward, sweeping along the liner driving the metal inward and collapsing on a centerline forces the liner to flow into the form of a jet in which velocities can exceed 10km/s. Due to collapse of the liner there exists a velocity gradient between the tip of the jet and the rear of the jet called the slug. The slug velocities are on the order of 1-3km/s. The jet will continue to stretch until it breaks into jagged fragments or particles. This process generates high temperature and pressures. Pressure much higher than the ultimate stress of the material allows the modeling of the jet as an inviscid fluid. The average temperature is 20-50% of melt temperature. The jet does not melt through the target, which is a common misconception from the acronym H.E.A.T. which stands for High Explosive Anti-Tank. The cavity formed from the jet impact is not due to thermal effects but rather the lateral displacement of the target material. The cavity depth formed in the target material can be increased with the same charge by increasing the distance from the charge to target, standoff, to an optimum. This charge is called a lined hollow charge or shaped charge.



Although a conical shaped charge is of the most common, a lined shaped charge can take almost any shape as mentioned before. A shaped charge can be tailored to a specific application, for example a conical shaped charge with cone angle of 60° will have a very narrow jet with high tip speeds and low slug speeds, and is therefore a stretching jet. As the cone angle decreases the gradient between the tip and slug degrease and the jet diameter increases. Another common liner shape is a hemispherical liner. A hemispherical liner behaves much more like a shallow angle conical liner but is less affected by liner imperfections due to tolerance.

Gurney velocity approximations

In early shaped charge development there was a desire to predict the performance of a shaped charge without the use of advanced computer codes and flash radiography. One of the early methods of determining how explosives drive metals is the Gurney method. R.W. Gurney was a researcher at the US Army Ballistic Research Laboratory in the 1940's and studied explosively driven metal plates. The Gurney method assumes that all chemical energy of the explosive is converted into kinetic energy of the fragment and expansion of explosive products. The Gurney method also assumes that the gaseous detonation products expand uniformly with a constant density. The Gurney method is an engineering approximation that is surprisingly accurate, usually within 10% of experimental results. The accuracy of this method lends itself to offsetting errors. The Gurney method does not account for rarefaction waves in the explosive which would cause the calculated velocity to be higher than experimental results, The assumption of constant density of the explosive products throughout rather than higher density near the surface of the causes the calculations to under predict the velocity.

An open faced sandwich configuration consists of an explosive on one side and a metal plate of the other and is detonated on the side of the explosive.

Figure XX. Open faced sandwich configuration.

When the explosive is detonated, a velocity gradient is assumed and with the assumption of constant density throughout the explosive products we can show that

$$\rho_{gas} y_0 = c$$

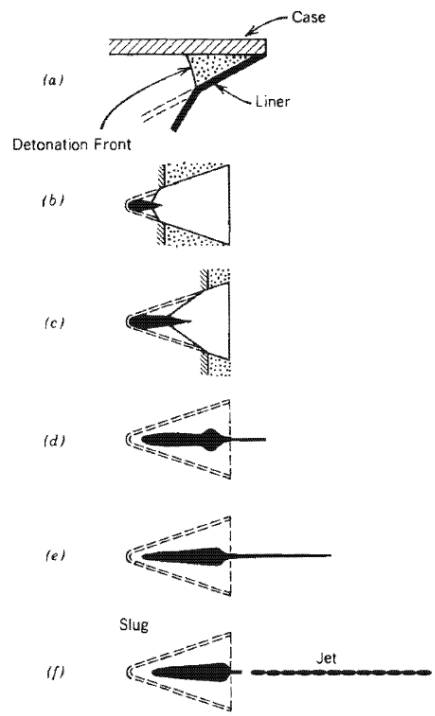
Where y_0 is the initial thickness of explosive and the assumption of constant gas density holds true for all time. The velocity distribution for this configuration is given as

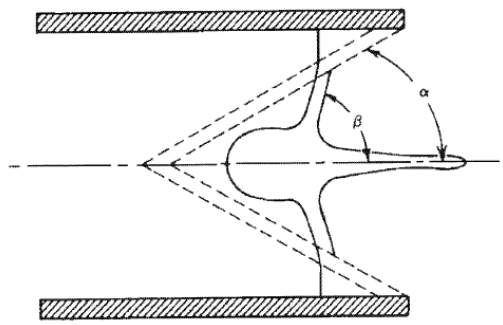
$$V_{gas} = (V_0 + V)\frac{y}{y_o} - V$$

$$V = \sqrt{2E}\left(\frac{1}{3}\left(\left(\frac{2m}{c}\right)^2 + \frac{5m}{c} + 1\right)\right)^{-\frac{1}{2}}$$

Shaped charge jet formation

This section shows an examination of predicting the performance of a shaped charge jet. Birkhoff (1948) and others developed a theory of predicting shaped charge performance with the assumptions that the pressures generated by the explosive are so much higher than the yield strength of the metal that the strength of the metal can be ignored. This allows the modeling of jets to be inviscid, incompressible fluids





Shaped charge penetration

Conclusion and Transition to Kinetic Energy

With a nearly infinite number of configurations of shaped charges, the question may be asked, what shaped charge is better? The obvious and simplest answer is it depends. Each configuration of shaped charge may have a different application depending on its jet characteristics. For example, a conical shaped charge has a small jet diameter, a high jet tip speed, large and slow slug, and is very sensitive to manufacturing tolerances in the liner. A hemispherical liner on the other hand has a relatively large jet diameter, lower jet tip speed, and a negligible slug. In many applications the choice between liner types is not always obvious so it would make sense to use a method that captures the amount of energy transferred to compare different shaped charges. This paper will discuss the method of energy transfer of a shaped charge through and barrier into a momentum trap mass and analyze the amount of energy used for kinetic energy transfer, deformation and the amount of energy lost to temperature increase.

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Total Energy

To analyze the amount of energy of a shaped charge jet we can first look at the total energy stored in the explosive itself. Using Composition C4, the amount of energy per gram is 6.3 kJ/g. For a 75 gram charge the total available energy is 472.5 kJ.

To estimate the total available kinetic energy of a shaped charge jet we can use two methods. The first method uses a global sum of material kinetic energy over the simulation. The second method integrates the kinetic energy that passes through a small window within the simulation.

Our numerical simulation tool allows us to measure the KE of each material in time. A limitation of this method is the lack of knowledge about material that has flown out of the simulation region. This causes an artificial decrease in total KE over time. Below is a graph showing the KE over time within a copper liner of a shaped charge.

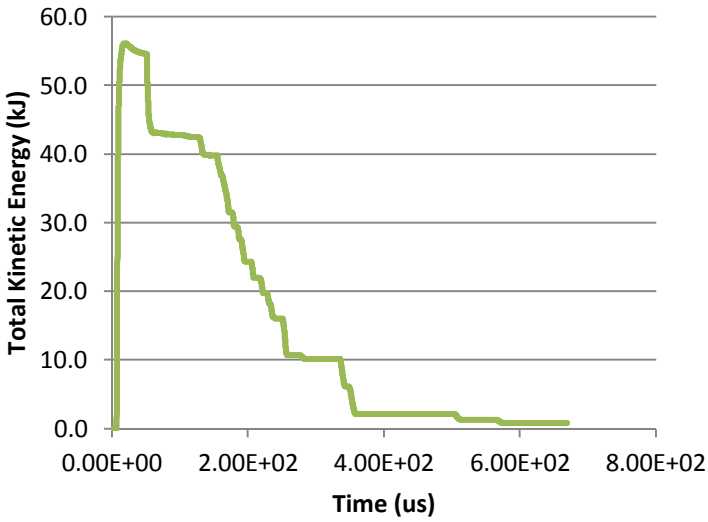


Figure XX. Method 1

The shaped charge jet impacts two plates (at 51.5 us and 130.2 us respectively) before beginning to flow out of the simulation region (at 150 us).

It is difficult to calculate the total KE that reaches a target using the method described above. We can learn more about the charge by measuring the KE that reaches a given region within the simulation (additionally, we can measure multiple regions to learn the impact of intermediary barriers). To do this, we can construct a small window within which we will measure jet properties such as mass and average velocity and integrate the values over the length of the jet. Figure XX below shows the two methods

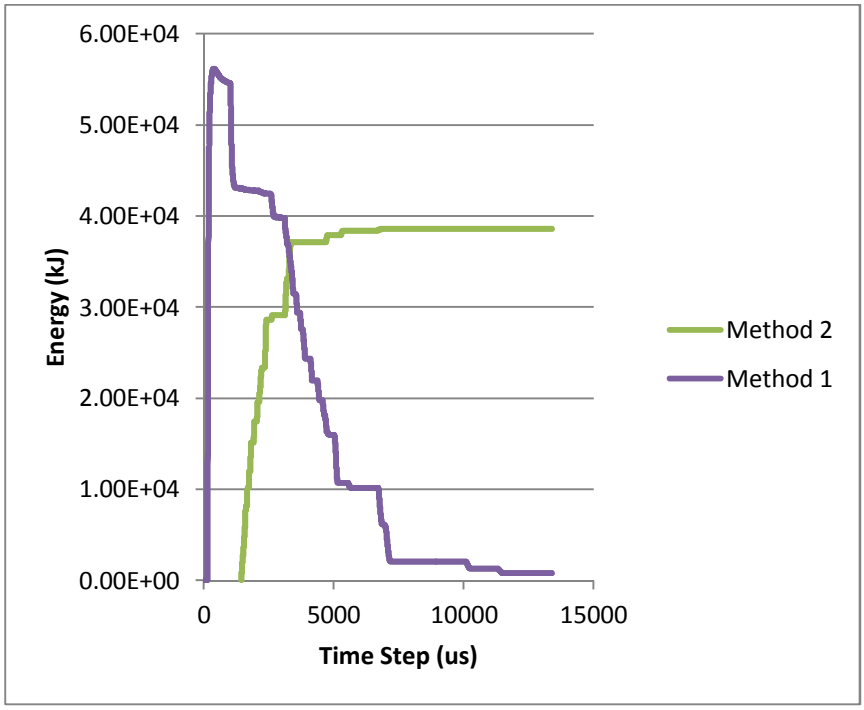


Figure XX.

Method 2 shows the gradual increase as the numerical simulation sums up all particles of the jet to a maximum of 39 kJ of kinetic energy.

Kinetic Energy

. To capture the kinetic energy in the following experiments the charge will be have a standoff from a Barrier Plate, the jet will pass through a $\frac{1}{2}$ inch barrier, travel between barriers to the next $\frac{1}{4}$ inch Witness Plate and then 4 inches to the Momentum Trap Mass.

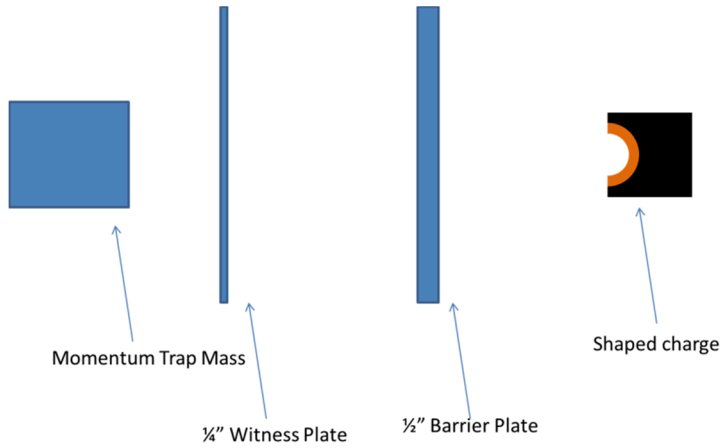


Figure. Momentum trap setup.

In the course of this paper, two variants of the same charge will be evaluated. Using Composition C-4 as the explosive for both charges the first charge is built in which the explosive is molded into the charge by hand. The second charge is a precision manufactured charge where the same explosive is molded and then pressed to 20 tons for 99% theoretical maximum density (TMD).

To estimate the velocity of the jet after it has penetrated the $\frac{1}{2}$ inch barrier; flash radiography is used with a fiducial pre-exposed onto the film. The first image shows 2 moments in time of the jet after formation and 2 images after penetrating the first barrier.

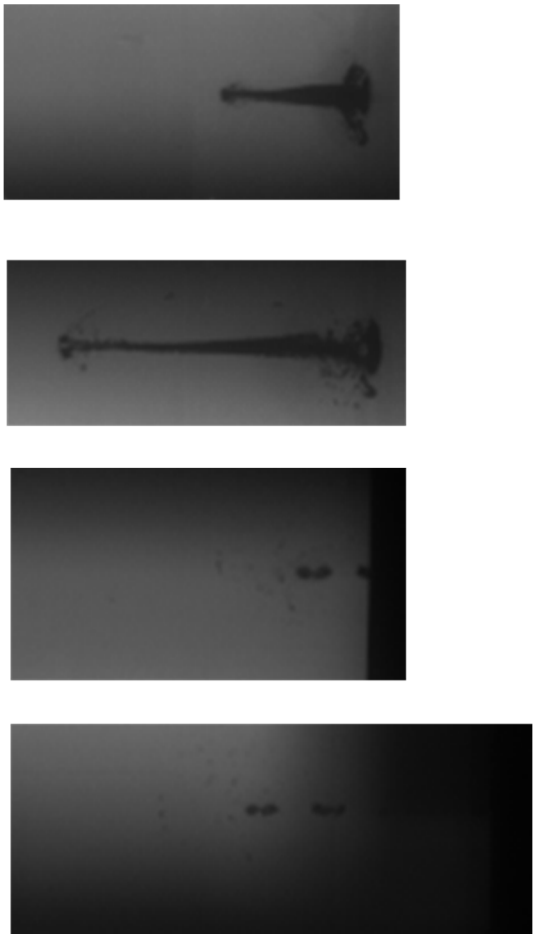


Figure. X-ray image of the same jet at 4 moments in time. 2 images before barrier penetration and 2 images post penetration.

Using the known distances of the notches in the fiducial and the flash times from the flash radiography system we can calculate the average post-penetration velocities of the jet from the hand-packed charge.

Standoff (in)	Pre_Penetration velocity (km/s)		Post Penetration Velocity (km/s)
7.5	5.711864407		4.918518519
7.5	5.194915254		4.177777778
7.5	5.347457627		4.555555556

Table. Average velocity of hand packed charges.

7.5	5.108695652		no data
7.5	5.05033557		4.469756481

Table. Velocities of precision manufactured charges.

Table XX above shows the velocities of the precision manufactured charge.

To capture the velocity of the Momentum Trap Mass a Phantom 2511 High Speed camera was place perpendicular to the axis of the charge and mass. After the jet penetration of the mass, the camera software can be used to measure the distance moved from the initial position, using the diameter of the mass as a scale factor. With a known inter-frame time of the camera the velocity profile of the mass can be captured.

Standoff (in)	KE (J)
7.5	No Data
7.5	15.81
7.5	9.837

Table. Kinetic Energy of hand packed charge.

Aerojet 7.5_2	37.23

Table XX. Energy of precision charge.

The large spread in kinetic energy of the hand packed charge is due to the particulation of the front of the jet. These small fragments of the jet are stripped off by the first barrier and do not penetrate, reducing the amount of the jet that penetrates into the mass. The manufactured charge shows 2-3 times more kinetic energy than the hand packed even though the velocities of the manufactured charge are on the order of .5 km/s slower than the hand packed charge. We can see the how much more coherent the jet is of the manufactured charge which allows more of the jet to penetrate to the momentum trap mass and increasing the kinetic energy measured.

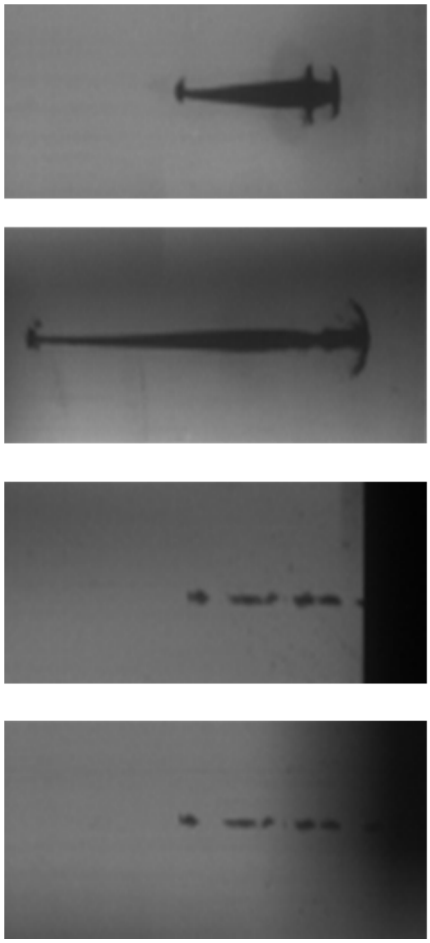


Figure. Flash radiography image of manufactured charge.

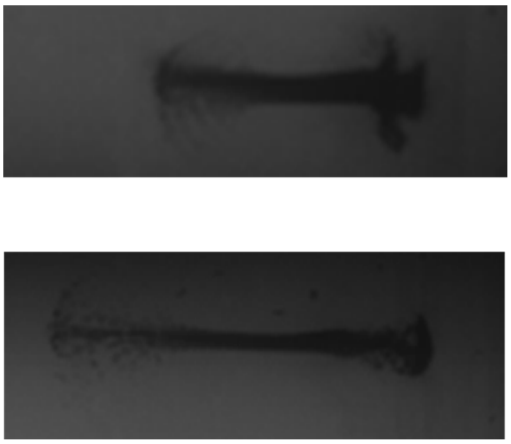
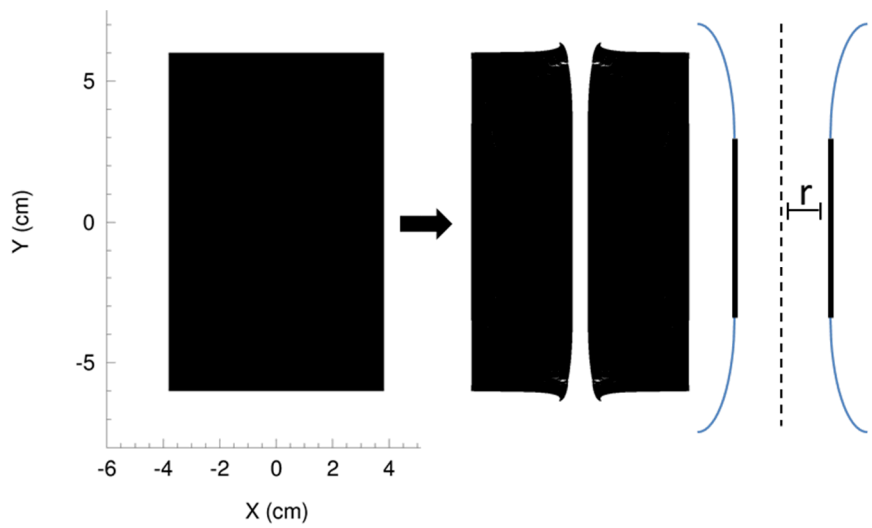


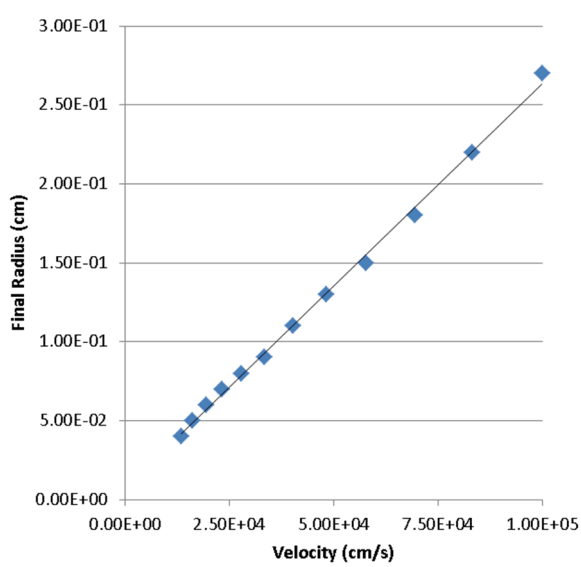
Figure XX Shows breakup and particulation of the front of the jet lowering the measured kinetic energy to due to less mass of the jet reaching the momentum trap.

Strain Energy

To calculate the energy of deformation, we will make the assumption that strain energy is equivalent to the kinetic energy required to make the hole. That is, the same energy will be required during a test as is required to initialize a region within a cylinder of metal with a velocity (an initial KE) and generate the same hole profile.

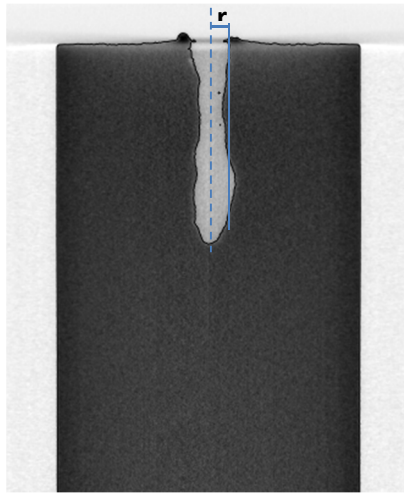


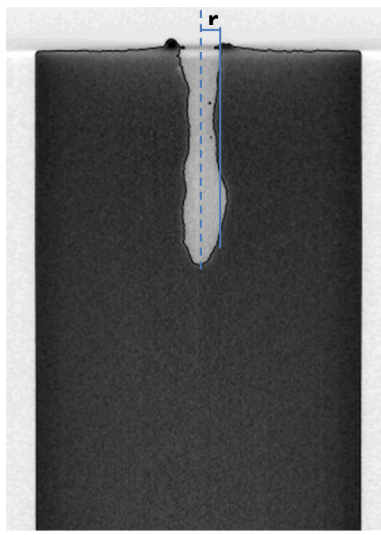
Using a numerical code, we can find an approximate equation for the velocity required to produce a hole through a cylinder of steel,



$$Velocity = \frac{Hole\ Radius - 0.007}{3x10^{-6}}$$

For a specific test, the hole radius was 0.225 cm, thus





$$Velocity = \frac{0.225 - 0.007}{3x10^{-6}} = 726.6\frac{m}{s}$$

From this equation, we can calculate the initial kinetic energy required to produce the deformation seen in the tests,

$$Input\ KE = \frac{1}{2}mv^2$$

$$= \frac{1}{2}(\rho\pi r^2 h)(v)^2$$

We selected $r = 0.3\ cm$ and $\rho = 7.85 \frac{g}{cm^3}$ in our model and have $h = hole\ depth = 7.17\ cm$ from test results.

Thus,

$$Input\ KE = \frac{1}{2}(7.85 * \pi 0.3^2 * 7.17)(726.6)^2$$

$$= 4.2\ kJ$$