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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

MATERIALS RESEARCH LABORATORY

MELBOURNE, VICTORIA

TECHNICAL NOTE

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AN ASSESSMENT OF THE HULL CODE FOR MODELLING PENETRATIONS INTO CONCRETE

David L. Smith

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ABSTRACT

An assessment is made of the usefulness of the HULL hydrodynamic code for modelling penetrations into concrete. The conditions used for successful modelling and the model's limitations are briefly described.

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CONTENTS

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1. INTRODUCTION

Army Staff Requirement 48.11 defines the Australian Army requirement for a general purpose assault weapon. A study was conducted in DSTO to determine the system limitations and terminal effectiveness of this class of weapon. One of the targets under consideration was concrete. An important factor in the attack of concrete is the penetration of the warhead prior to detonation of the main filling. This prompted interest in whether penetration of such a device into concrete could be modelled effectively using the hydrodynamic computer code HULL [1].

This report describes some preliminary calculations performed with HULL, and compares the results with existing empirical data. Assessments of these calculations are used to predict the utility of HULL modelling for penetration of realistic warhead designs into concrete.

2. REQUIREMENTS

2.1 Requirements for fully realistic calculations

A weapon of the general purpose assault weapon class will consist of a relatively thin metal wall containing the main explosive charge and fuzing system. Impact of such a warhead onto a hard target will result in significant plastic deformation of the case and contents. This implies that a useful model of such an impact would require realistic treatment of the strengths and other constitutive relations for all materials in the warhead. This is in contrast to similar calculations involving heavy walled projectiles such as shell, which can often be represented accurately enough by modelling only the strongest component, ie the metal case, and ignoring the contents other than for their mass contribution. Indeed for some impacts/penetrations, flow in the penetrator can be completely ignored with negligible loss of accuracy. In these cases, the hydrodynamic flow calculations may be simplified by representing the penetrator as a perfectly rigid body, and a simpler engineering stress analysis program may be used later to verify the integrity of the penetrator during the impact [2]. Techniques available in HULL for this type of calculation are described in section 3.3.

Realistic hydrocode modelling would be a valuable design tool for a general purpose assault weapon. The reason for this is that obtaining the required performance data experimentally is both difficult and expensive. Unfortunately this also implies that data for verification of the modelling is scarce. For this reason in the present case an assessment of HULL was made against more readily obtainable existing experimental data.

2.2 Existing data for monolithic penetrators

Empirical formulae abound in the literature for penetration of concrete by essentially monolithic penetrators such as armour piercing shell and bombs. In this study two sources were used. A nomogram for penetration by AP and SAP projectiles [3], is reproduced in Figure 1. An empirical formula for penetration by shell [4] was also used and found to agree well with the nomogram. The formula is as follows:

$$P = \left(\frac{870}{S}\right)^{.5} \times \frac{W}{D^2} \times \left(\frac{D}{C}\right)^{.1} \times \left(\frac{Vs}{1750}\right)^{n} \qquad (1)$$

where P = penetration to nose of projectile in inches

S = compressive strength of concrete in psi

W = mass of projectile in pounds

D = calibre of projectile in inches

C = maximum size of coarse aggregate in the concrete, inches

Vs = striking velocity in feet per second

$n = \dfrac{10.7}{S^{.25}}$

3. MODELLING WITH HULL

3.1 The behaviour of concrete

Concrete is a material that is quite weak in tension, but strong in compression. The compressive strength increases under hydrostatic pressure. At ambient pressures, concrete has a voidage content of 15 to 20%. Under dynamic loading during penetrations, concrete cracks and crushes, and void filling occurs. The kinematics of a penetrator impacting concrete will be largely solved by knowledge of the compressive behaviour of the concrete; however the total effect on the concrete target will be determined largely by the tensile behaviour of the concrete during the passage of rarefactions following the initial compressive loadings. The tensile behaviour of concrete is almost always modified in useful structures by reinforcements to prevent catastrophic failure in tension. One of the difficulties with computer modelling of concrete is the lack of data for the material's dynamic tensile behaviour.

3.2 The concrete equation of state used in HULL

The concrete equation of state model used in HULL is described thoroughly in the HULL Technical Manual [5]. The general ambit of the model is described therein "The plain concrete equation of state model was developed to provide a reasonable response in the 1 to 300 kilobar range. It is based on a very small amount of data, since most available data is at stress levels well below 1 kilobar. However, this routine has been used successfully in scores of penetrations into concrete at velocities from a few hundred to over 1000 feet/second."

The equation of state in HULL uses an empirical fit of Hugoniot pressure against excess compression ($u = p/p0 - 1$). The curve is shown in Figure 2. The equation of state ignores the Gruneisen parameter and Hugoniot pressure is used as total pressure. (The Gruneisen parameter for concrete is claimed as being around 0.1). This means that internal energy has no effect on pressure, and the equation of state can not be used for energy deposition problems.

The yield strength of concrete increases with confining pressure. The yield strength curves are approximated in HULL by three straight line segments:

$$
\begin{aligned}
Y &= 0 && \text{if } P < -0.1f'c \\
Y &= 3\,(P + 0.1f'c/3)/1.1 && \text{if } -0.1f'c/3 < P < f'c/3 \\
Y &= P + 2/3f'c && \text{if } f'c/3 < P < 30f'c \\
Y &= 30.67f'c && \text{if } P > 30f'c \qquad (2)
\end{aligned}
$$

where f'c is the unconfined compressive strength.

Tensile behaviour is approximated by setting a minimum pressure Pmin at $-0.1f'c$, ie 10% of the static compressive strength. Below Pmin the material is assumed to have zero strength.

3.3 Methods available with HULL

3.3.1 Pure Eulerian calculation

The most common calculations with HULL are performed with an Eulerian computational grid, that is the mesh remains fixed in space and materials are transported across cell boundaries. The advantage of an Eulerian grid for penetration calculations is that large material deformations are possible. In the present case the target material (concrete) will deform significantly during the calculation, and would not be treated satisfactorily by a Lagrangian calculation in which the mesh itself deforms.

The disadvantage of an Eulerian calculation is that material interfaces are not properly tracked, and thus the detailed response of the penetrator will not be modelled well.

3.3.2 Linked calculation

A HULL option well suited to calculations where the detailed response of the penetrator is important is the linked calculation. This allows interaction between Lagrangian and Eulerian mesh regions where such interfaces are flagged as interactive. In the present case the penetrator could be defined as a Lagrangian mesh as deformations will be relatively small, and the target as Eulerian. The advantage is that the Lagrangian formulation for the penetrator would give a better behaved model in the elastic/partly plastic regime, and also maintain realistic interface definitions.

The disadvantage of a linked calculation lies in its greatly increased computational cost and complexity. Both meshes must maintain the same time steps, ie the minimum of the two required for stability, and at the end of each time step a large amount of information is exchanged between the two meshes. Increasing the resolution of the interactive interface dramatically increases costs.

3.3.3 Island calculation

A third HULL option available for penetration calculations is the "island" option. In this method, the penetrator is assumed for calculational purposes to be completely rigid, and is represented by a HULL "island", a reflective and incompressible region, within an Eulerian grid. The surrounding medium is given an initial velocity of opposite sense to the penetrator (reverse ballistics), and the forces applied to the island are summed and stored. Knowing the initial penetrator velocity and mass, new velocities and displacements are calculated from the forces and are updated at each time step.

This technique provides computational economy where the detailed response of the penetrator itself is of no interest, or, as mentioned previously, where the only interest in the penetrator can be answered by a simple stress analysis program using the island force history [2].

3.4 Methods used for HULL modelling

HULL modelling was mostly performed in Eulerian mode, both pure Euler and with "island" representation of the penetrator. Some short linked calculations were made to test the method, but the cost of full linked simulations could not be justified for this assessment. Penetrations were into semi-infinite slab, although for interest finite thickness plates were also modelled (see Figure 3 for example). The main precaution needed in this type of calculation is to ensure that the mesh boundaries are well removed from the area of interest. This prevents the numerical signals which are inevitable with transmissive boundaries from affecting the calculation. In the present calculations, for example, small numerically generated negative pressures could set the yield strength to zero in regions of the concrete target.

For most of the calculations performed, a calculational grid of approximately 100 by 250 cells was used. A fine inner grid was used, growing outwards towards the boundaries. In typical calculations, the inner cell resolution was about 10 mm, and the boundary cell resolution about 500 mm. Smaller grids were studied but artificial pressure fluctuations were then found at the boundaries, and different penetrations obtained. With the grids used, the boundaries maintained themselves at ambient pressure throughout the calculations. A full HULL input deck for one of the "island" calculations performed is listed in Appendix A.

3.5 Results

Calculations were performed for 27 kg (60 pound) projectiles travelling at 1000 m/s. Three nose shapes were used to assess the discrimination possible with HULL: blunt (flat ended cylinder), "pointed", and "very pointed". The shapes are shown in Figure 4. The geometries were chosen to give solid steel projectiles a "calibre density" (mass divided by cube of diameter) similar to typical bombs and shell. Note that the HULL calculations assume plain, rather than reinforced concrete, but the effect on average total penetration will be relatively small.

The following table shows the predicted penetrations. Penetrations from the island calculations are calculated internally in HULL and printed in the output; for the pure Euler calculations the penetrations are taken from the position of the tip of the nose of the projectile at the time of zero velocity. The quoted penetrations relate to the projectile behaviour, and not to the crater size after the event.

It is clear from the table that the pure Eulerian calculations predict much lower penetrations than the "island" calculations. This is probably due partly to diffusion, both from the diffusion limiter used in the code, and the lack of material interface resolution. The moving projectiles did not retain their shape well during transport. In the case of the blunt cylindrical projectile, the nose mushroomed excessively during the calculation, as shown in Figure 5. This lowers the pressure on the concrete target, and will decrease the penetration quite dramatically. Another consequence of the diffusion in an Eulerian penetration calculation is shown in Figures 6-8 where the very pointed projectile progressively loses shape and becomes "blunted" during the calculation. Actual deformations in both types of steel projectile would be minor. Using a finer mesh (halving the cell dimensions) did not improve the results.

TABLE 1 Penetrations predicted by HULL

27 kg projectile, velocity 1000 m/s		
Nose shape	Calculation type	Penetration (mm)
blunt	pure euler	380
blunt	island	1110
pointed	pure euler	450
pointed	island	1480
very pointed	pure euler	630
very pointed	island	1670

When the low predicted penetrations for the pure Euler calculations became apparent, the behaviour of the concrete forward of the penetrator was studied. Figure 9 shows a plot of over-density for the blunt penetrator calculation. The contour values have been set very low in order to pick up detail, and in fact much of the plot is simply numerical noise. What is worth noting is that a comparison with Figure 10, the same plot at the same stage of an "island" calculation, shows very similar features. The over-density or compression contours extend a similar shape and distance forward of the penetrator, even though the noise patterns are a little different. This gives confidence that in both calculations the concrete is responding in a similar manner, and the poor results with the Euler calculation are likely to be from the behaviour of the penetrator.

The three nose shapes studied were discriminated by HULL, both in the pure Euler and the island calculations. Penetration increased with increasing pointedness of the projectile nose.

3.6 Comparison with empirical formulae

The formula (equation (1)) derived from Reference [4] and given in section 2.2 was used to predict the penetration of a 27 kg projectile travelling at 1000 m/s. The formula is intended as a general guide for ogival projectiles such as shell and bombs, with nose shapes between 0.8 and 3.5 calibres radius. A penetration of 1870 mm is predicted for 5000 psi reinforced concrete. This compares with a penetration of 1670 mm from Table 1, for the island calculation on the most pointed projectile.

Given the crudity of the assumptions used in the HULL model of the penetrator, ie use of a solid steel penetrator and the lack of detail in the nose shapes, the agreement with the "island" calculations is good. Pure Eulerian calculations gave poor results.

4. CONCLUSIONS

The calculations suggest that HULL could be used to give a reasonable guide to penetrations into concrete. Modelling of realistic warhead designs with HULL should be possible, using the linked mode with a Lagrangian penetrator and Eulerian target. Such calculations would be expensive in terms of computer time. In some cases costs could be cut by modelling the penetration in "island" mode, (a totally rigid penetrator), and later assessing the survivability of the penetrator using an engineering stress analysis program.

5. REFERENCES

1. Matuska, D.A. and Osborne, J.J. HULL Documentation, Volume 2 "HULL Users Manual", Orlando Technology Inc., Florida, 1985.

2. Flores, J. and Gunger, M.E. "Hydrocode Analysis of the Hard Target Weapon Using an Eulerian-Lagrangian Link", AFATL-TR-84-90, April 1985.

3. "Fundamentals of Protective Design (Non-nuclear)", US Army Technical Manual TM 5-855-1, July 1965.

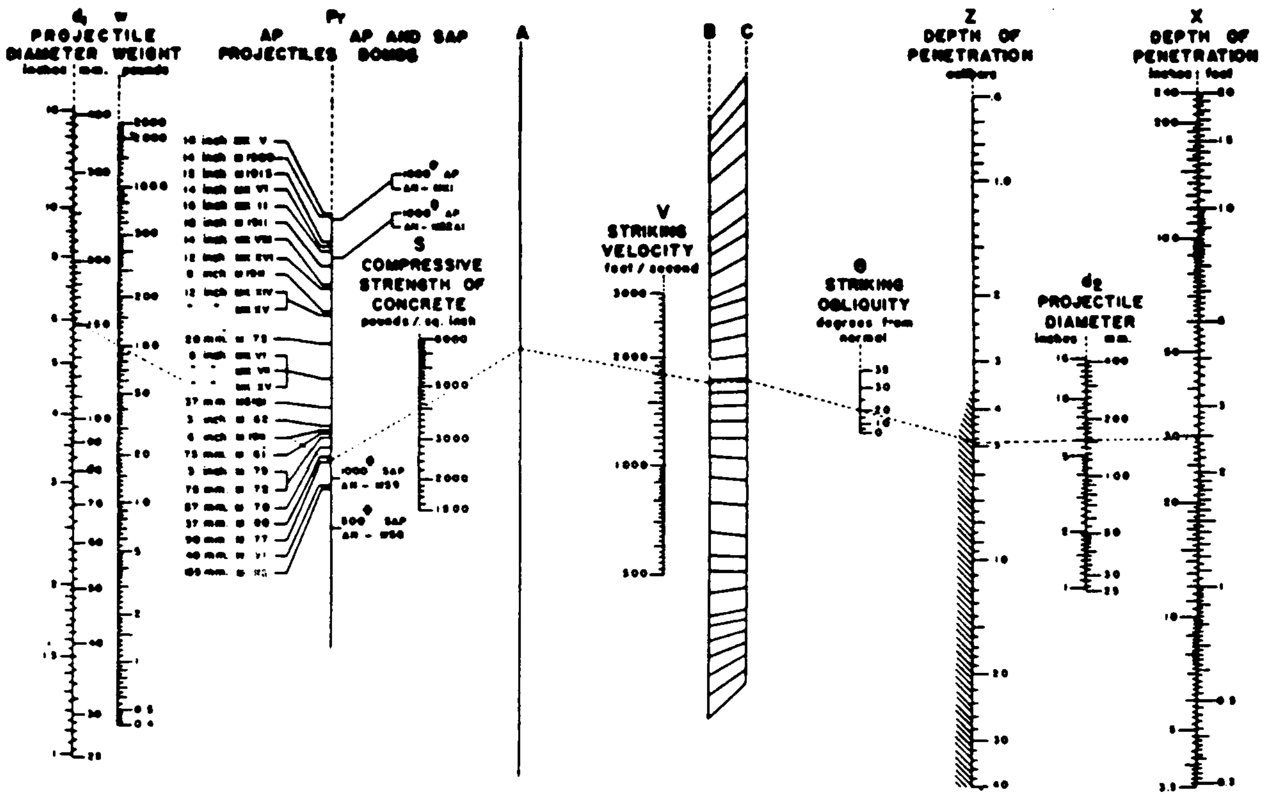
4. Textbook of Air Armament, Part 1, Chapter 3: "Penetration of Projectiles into Concrete, Rock and Soil." UK Ministry of Supply, 1949. (Restricted)

5. Matuska, D.A. and Osborne, J.J. HULL Documentation, Volume 1 "HULL Technical Manual", Orlando Technology Inc., Florida, 1985.

APPENDIX A

Sample HULL Input Deck (island calculation)

```
KEEL PROB=62.07
NM=2 CONCRT=1 AIR-=2
VISC=1 DVISC=0
VELY-10.EO4
ISLAND-2 RIGMAS-27.0E03
IMAX=100 JMAX=240
HEADER
POINTED STEEL CYLINDER INTO CONCRETE 1000 M/S :: ISLAND CALC
MESH
CONSTANT SUBGRID
X0=0 NX=20 XMAX=20
Y0=-5.0 NY=140 YMAX=140
X0LIM=0.0
Y0LIM=-5.0
RXPOS=1.04
RYPOS=1.04
GENERATE
PACKAGE CONCRT V=-10.E04 RECTANGLE YB=30.0
PACKAGE AIR RECTANGLE YT=30
PACKAGE ISLAND RECTANGLE
YT=20.0 YB=0.0 XR=6.39 XL=0.0
PACKAGE ISLAND TRIANGLE
X1=0.0 Y1=20.0 X2=6.39 Y2=20.0 X3=0.0 Y3=30.0
END
HULL PROB=62.07
CYCLE=0
INPUT
MRELER=1.E20
PTSTOP=6000.E-06
TIMES=3 DMPINT=1000.E=06
```



DIRECTIONS - Determine the diameter and weight of that part of the projectile which penetrates the slab (The total weight minus the weight of the windshield will usually be correct.) Draw a line through the proper points on the d_1 scale and w scale at the left of the chart to the Pr scale. (If the projectile is a type listed on this scale, the above may be omitted.) Continue from this point through the S scale to the A scale. From the A scale draw a line through the V scale to the B scale and follow the guide lines to the C scale. From the C scale draw a line through the θ scale to the Z scale. (If the point falls within the shaded area the projectile will probably stick in the target.) From the Z scale draw a line through the d_2 scale and read the depth of penetration from the X scale. For oblique fire this depth is the maximum penetration normal to the target face. If the projectile or bomb causes scabbing (see figure 24) the penetration will be somewhat more than shown here. The penetration for oblique fire at velocities above 2000 ft./sec. may be somewhat more than shown here.

EXAMPLE:
The dotted line shows a 6 inch, 100 pound projectile, striking 4,000 p.s.i concrete with a velocity of 1,800 ft./sec. at an obliquity of 20°. The projectile will penetrate to a depth of 4.9 calibers or 29.4 inches. The projectile will probably stick in the target.

ACCURACY:
This chart gives results accurate within 15%

FIGURE 1 Nomogram for penetration of reinforced concrete by inert armour piercing or semiarmour piercing projectiles or bombs.

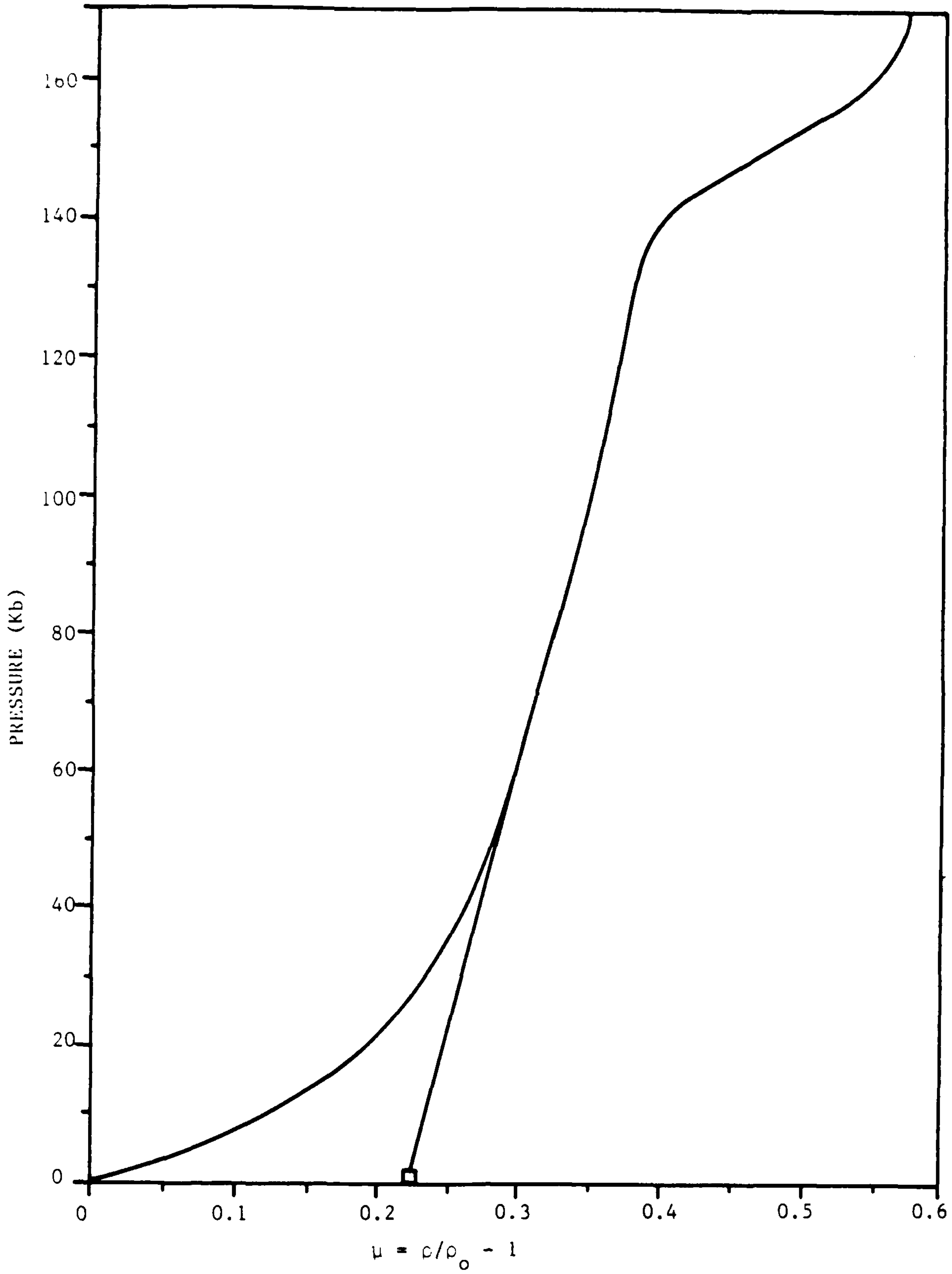


FIGURE 2 HULL fit of Hugoniot pressure vs excess compression for 5000 psi plain concrete.

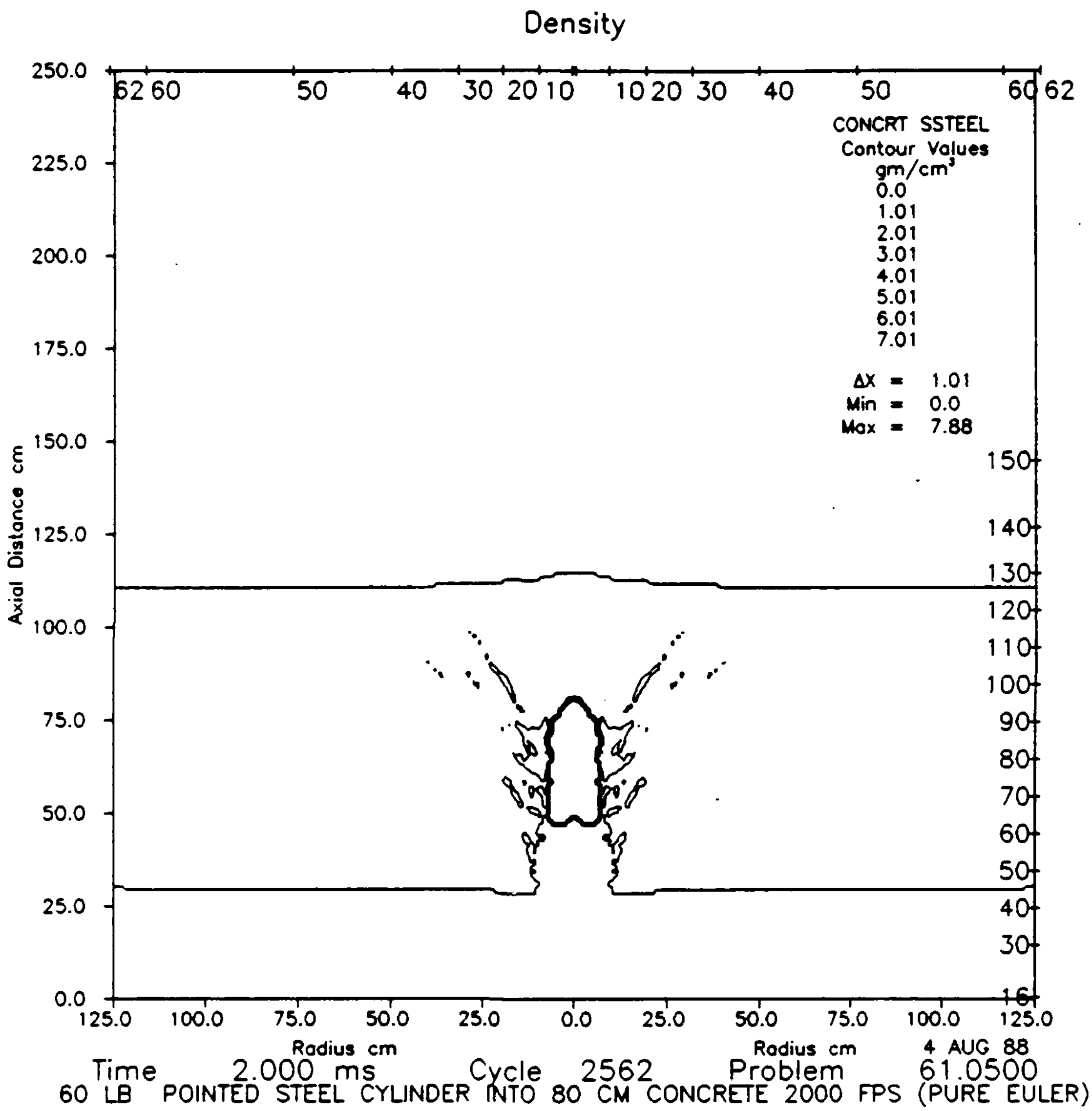


FIGURE 3 An example of a HULL calculation of penetration into an 800 mm slab of concrete.

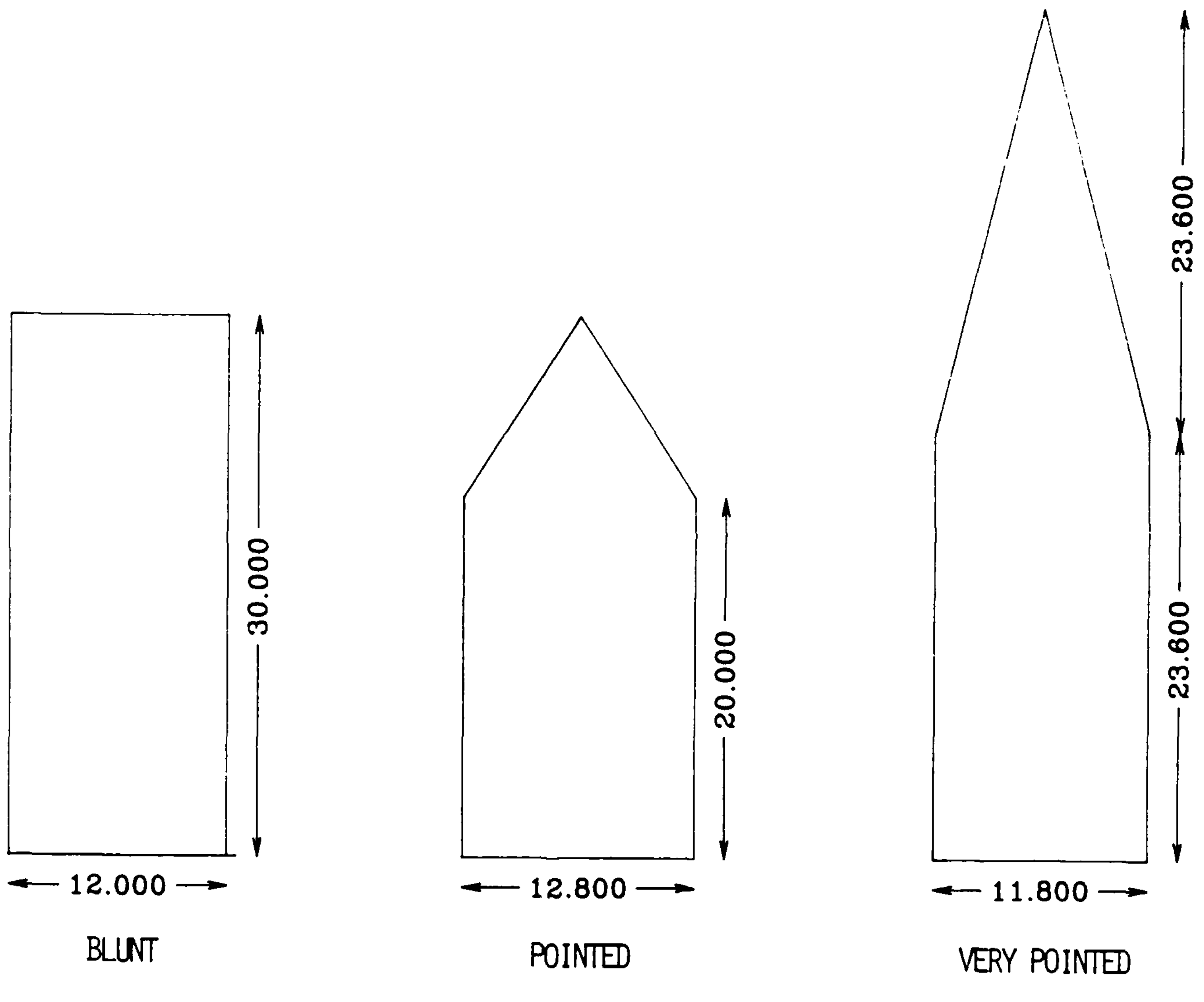


FIGURE 4 Projectile shapes used in HULL penetration calculations. The three projectiles have the same mass.

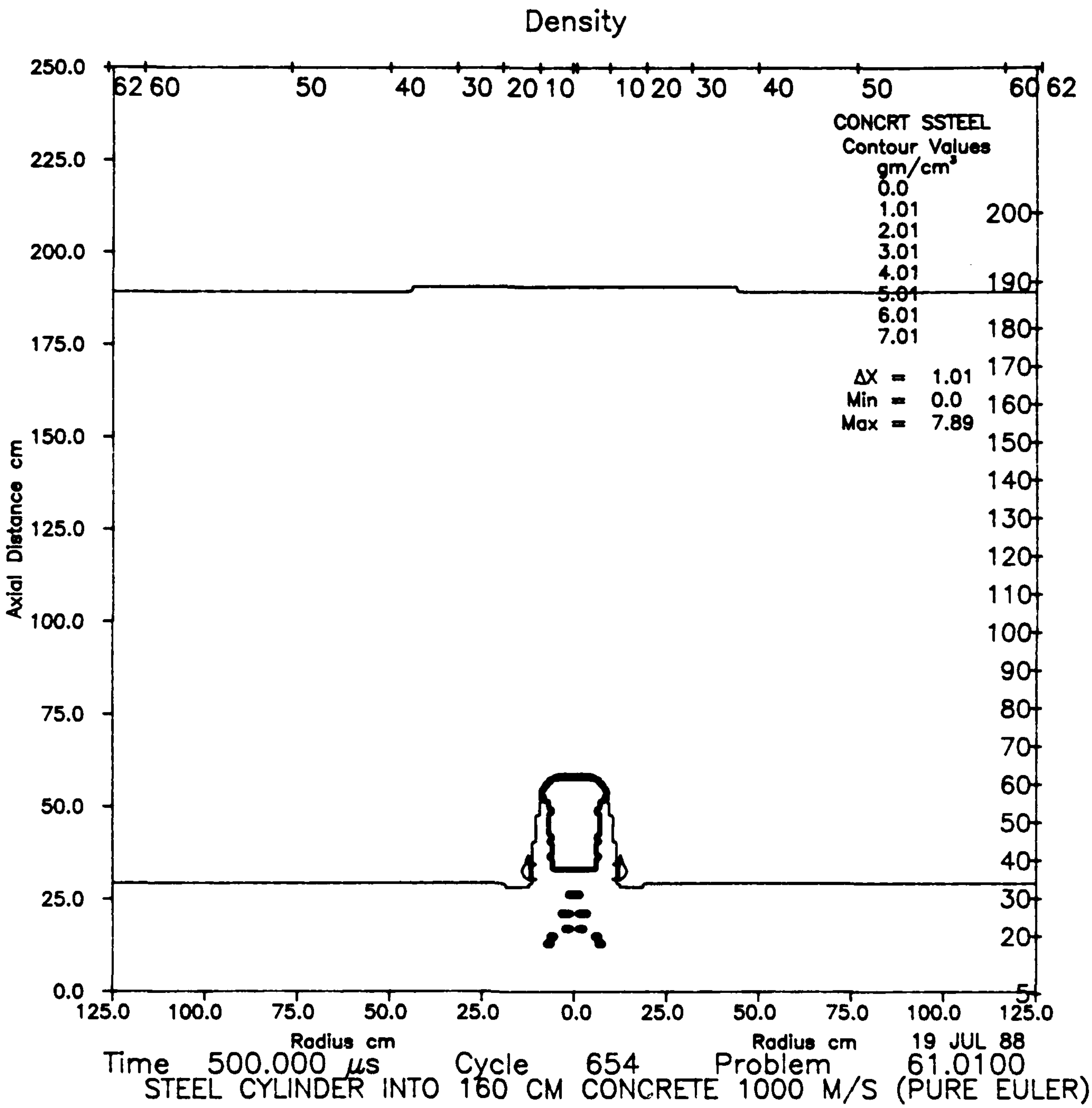


FIGURE 5 Mushrooming of a blunt penetrator early in a pure Euler calculation, resulting in a low predicted penetration.

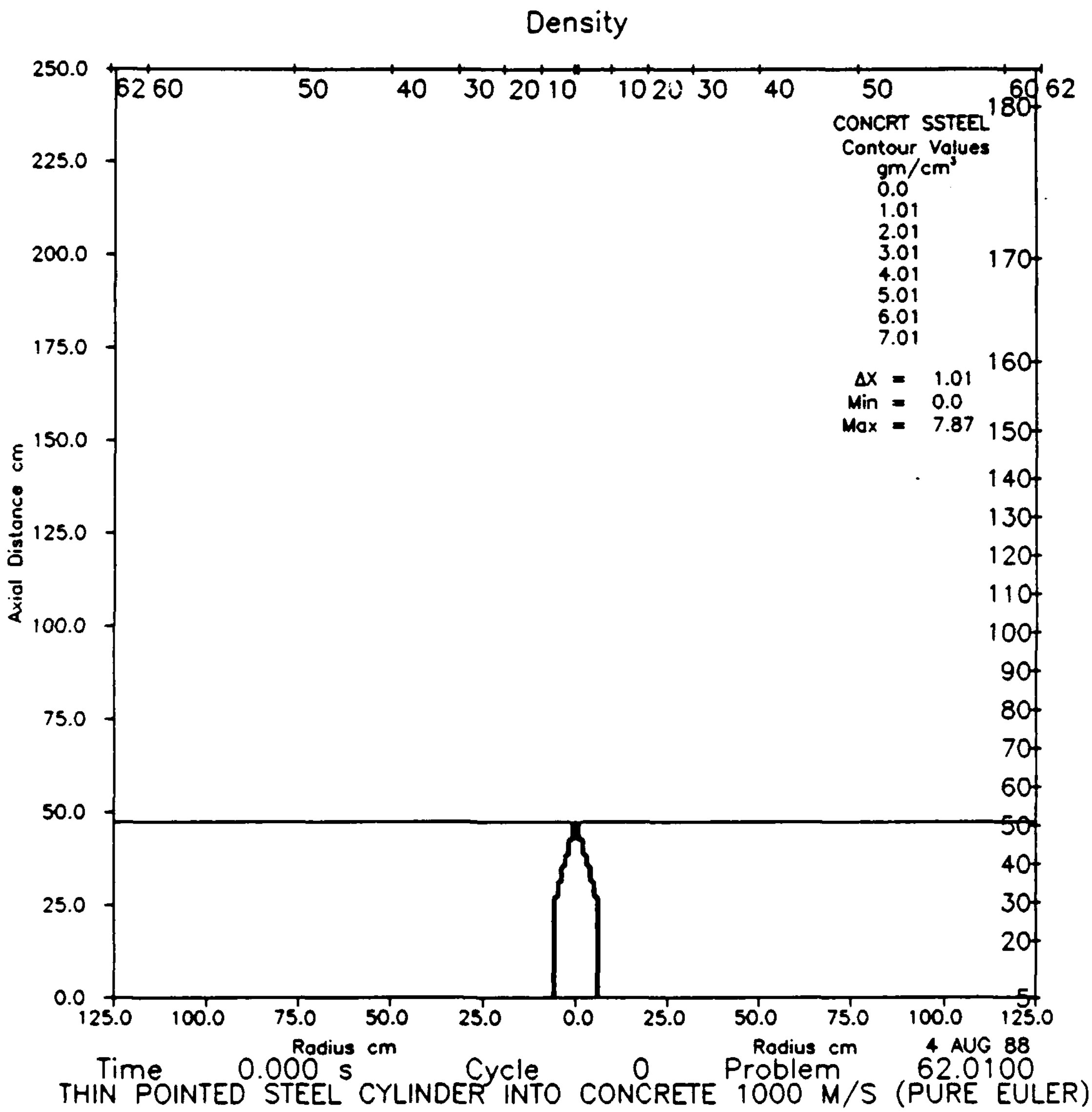


FIGURE 6 Example of the loss of shape of the penetrator due to lack of resolution at material interfaces in a pure Euler calculation. Time = 0.

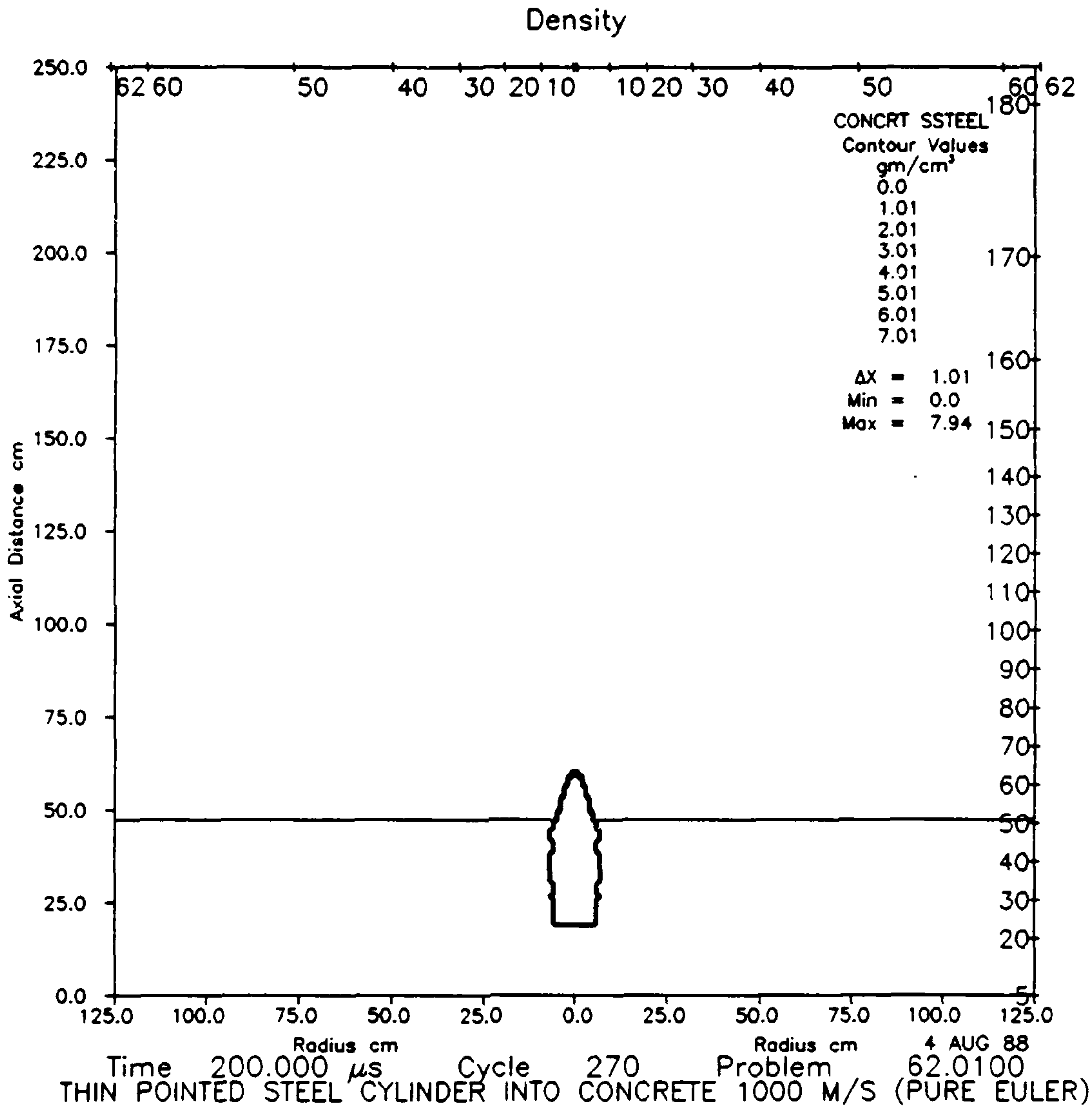


FIGURE 7 Example of the loss of shape of the penetrator due to lack of resolution at material interfaces in a pure Euler calculation. Time = 0.2 milliseconds.

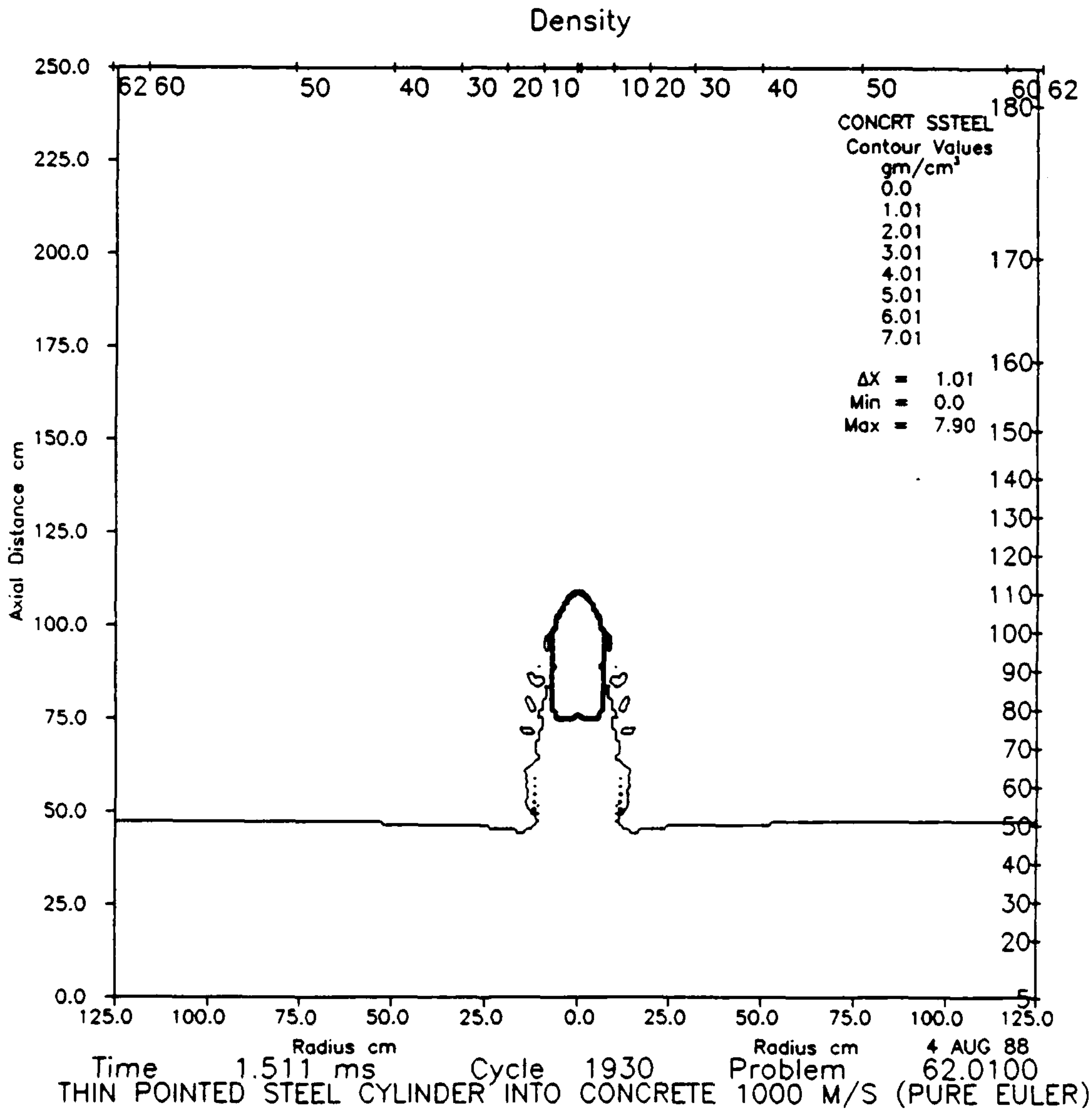


FIGURE 8 Example of the loss of shape of the penetrator due to lack of resolution at material interfaces in a pure Euler calculation. Time = 1.5 milliseconds.

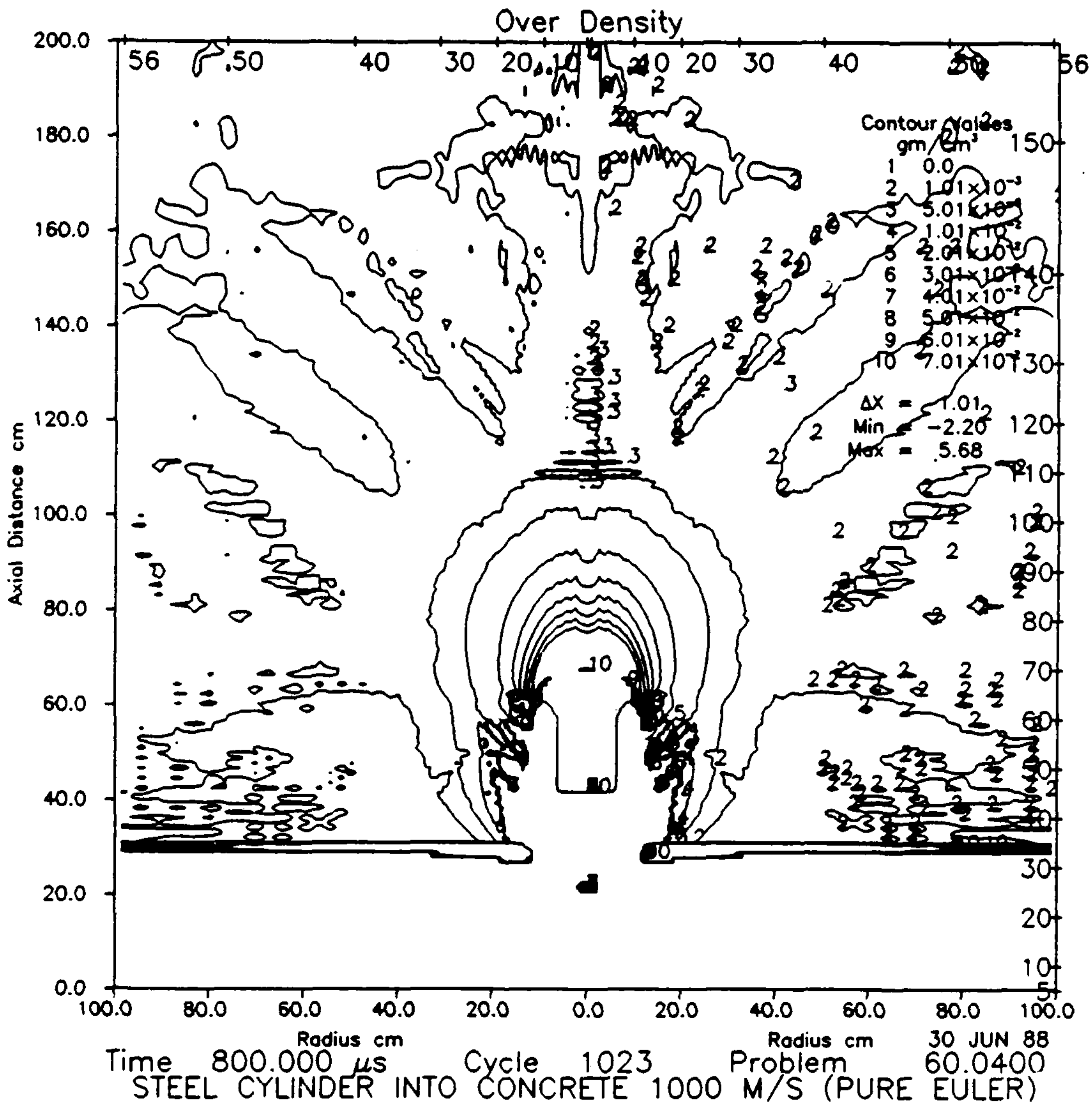


FIGURE 9 Over-density contour plot for pure Euler calculation on blunt penetrator at 800 microseconds.

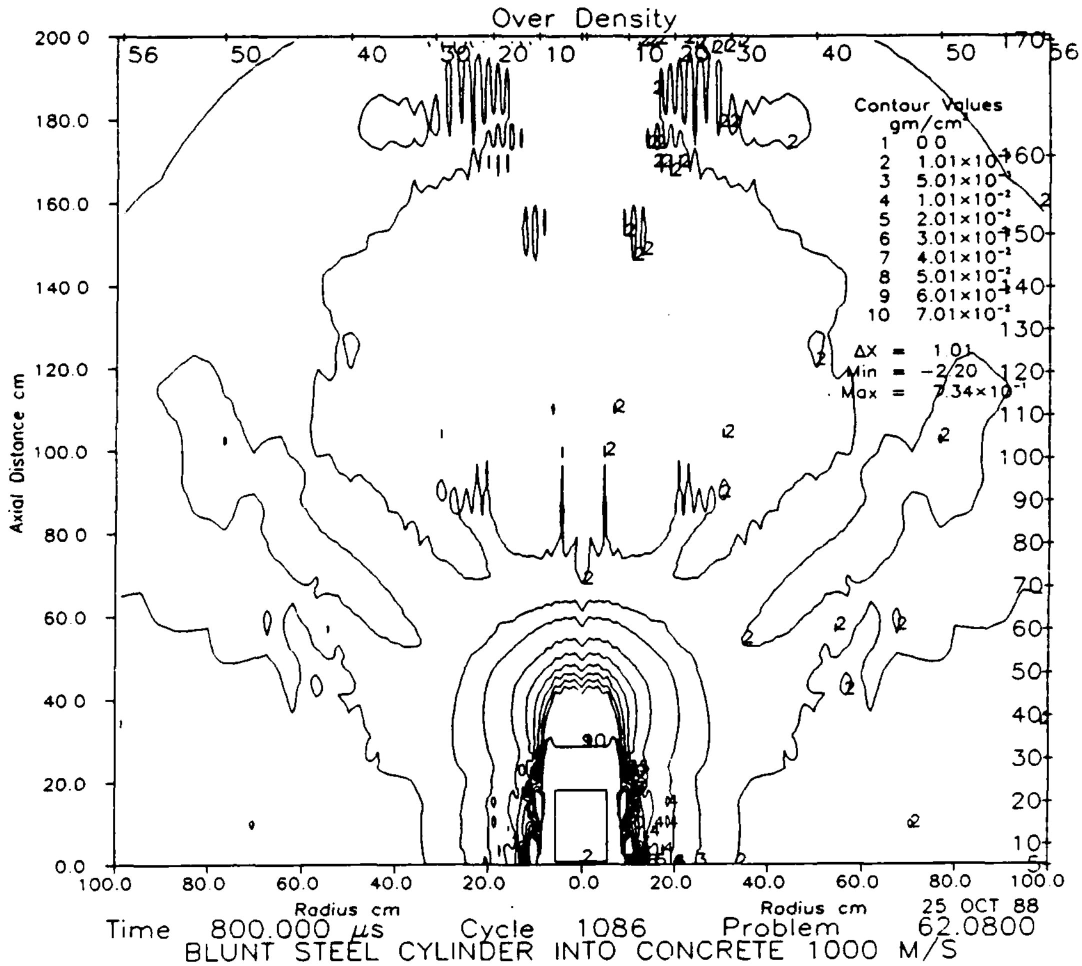


FIGURE 10 **Over-density contour plot for "island" calculation on blunt penetrator at 800 microseconds.**

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