APPENDIX F
PENETRATION OF PROJECTILES INTO EARTH

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An Analysis of UXO Clearance Depths at Ft. Ord

by

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PENETRATION OF PROJECTILES INTO EARTH

1.0 MUNITION IDENTIFICATION

Fort Ord was established in 1917. The facility was used for training and staging infantry troops until 1994. As a result of military training unexploded ordnance (UXO) exists on the surface and in the subsurface of the now closed facility. Fort Ord is being investigated to locate and characterize the presence of UXO. At least fifty-two sites have been identified at Fort Ord where UXO may still remain. During investigation of these sites twenty six projectiles which penetrated the soil have been identified and evaluated.

2.0 SOIL IDENTIFICATION

Seven series of soils have been identified at Ft. Ord including: Antioch Series, Arnold Series, Santa Inez Series, Oceano Series, Baywood Series, Dune Land Series, and Xerorthents Series. These soil series include sands, silts and clays, but sand is the predominant soil type at the former Ft. Ord.

3.0 PENETRATION ANALYSIS

3.1 WATERWAYS EXPERIMENT STATION (WES) EQUATION

An equation developed by the Waterways Experiment Station (WES) provides fragment[Note1] penetration prediction for soils ranging from clay to dry sand [1]. This equation is given as:

$$t_p = 1.975\, W_f^{(1/3)} k_p \log(1 + 4.65(\frac{V_s}{10^3})^2)$$

where

t_p = penetration depth (in)

W_f = fragment weight (oz)[Note1]

k_p = constant depending on soil type (see Table 1)

Note 1: The "fragment" was assumed to be an entire munition for this analysis.
The munition information needed to use this equation includes the weight of the projectile and the velocity of the projectile. As a conservative value, the muzzle velocity has been used. Table 2 lists the projectile weight and velocity.

A summary of the results is presented in Appendix A. The penetration of each of the munitions has been determined using the WES equation. The maximum penetration depths for each munition in clay, loam, and sand as well as the maximum detection depth (see Section 4.0) are shown in Appendix B.

TABLE 1 SOIL PENETRATION CONSTANTS [1]

Soil Type	k_p (in/oz$^{1/3}$)
Limestone	0.775
Sandy Soil	5.29
Soil Containing Vegetation	6.95
Clay Soil	10.6

TABLE 2 PROJECTILE WEIGHT AND VELOCITY

Projectile	Projectile Weight (lb)	Muzzle Velocity (fps)
35 mm Subcal M73	0.32	497
37 mm, HE, M63	1.61	2650
Rifle Grenade, M9	1.5	155
40 mm, HE, M822 (AA)	2.0	1100
60 mm HE, M49A2	3.07	520
2.36" Rocket	3.4	265
75 mm	14.5	1250
81 mm HE, M43A1	7.5	834
25 lb Fragmentation Bomb	24.9	500 (assumed)
8" HE M106	206	2330

3.2 HYDROCODE ANALYSIS

As a check of the WES equation, the penetrations of several munitions have been determine using a hydrocode analysis. The results using the HULL hydrocode have been compared to the results using the WES equation

The HULL hydrocode was originally designed and coded by R.E. Durrett and D.A. Matuska in 1972 at the Air Force Weapons Laboratory (AFWL) for simulation of nuclear weapons effects. HULL is a system of programs that solve two and three dimensional, multi-material, multi-phase dynamic continuum mechanics problems in Eulerian and /or Lagrangian frameworks. In the HULL hydrocode, continuum mechanics equations describe the behavior of continuous media by applying the principles of conservation of mass, momentum, and energy from a macroscopic point of view. An equation of state is employed to relate pressure, density, and internal energy. In addition, a constitutive equation describes the relationship between stress and strain, work hardening, and thermal softening. The conservation equations, being non-linear, coupled, partial differential equations with no closed form solution, must be solved numerically.

The first stage in the numerical solution is to discretize the region of solution. This is done by creating a mesh of points in the solution region and expressing the spatial and temporal derivatives in the governing equations as finite difference algorithms. By doing this, the set of governing partial differential equations becomes a set of algebraic equations that are solved for each value of time throughout the computational mesh. Results from this analysis can be plotted as material "moves" through the mesh as a function of time.

Hydrocode calculations can provide a good deal of insight and detailed information about the physical processes which are occurring during high-speed impacts. The ability to trace the time history of various points of interest and to plot snapshots of the impact at various time intervals allows one to perform the most highly "instrumented" test possible at a fraction of the cost of conventional testing.

The OTI*HULL code is currently being maintained by Dan Matuska, John Osborne, and Ned Piburn of Orlando Technology, INC of Shalimar, FL.

Results of the hydrocode analyses of the penetration of various munitions into sand are presented in Appendix C.

3.3 COMPARISON OF RESULTS

The penetrations of several projectiles have been determined using both the WES Equation and the HULL hydrocode. These projectiles include the 2.36" Rocket, the 155 mm M107, the 75 mm M48, the 105 mm M1, the 37 mm M63, and the 40 mm M822. Both sets of results are listed in Table 3.

TABLE 3 PENETRATION OF PROJECTILES INTO SAND

Projectile	Penetration using WES Equation (ft)	Penetration using HULL (ft)
2.36" Rocket	0.40	0.46
155 mm M107	14.0	16.8
75 mm M48	4.9	5.7
105 mm M1	7.7	9.4

4.0 PREDICTING BURIED UXO DETECTION DEPTHS

Buried UXO is usually detected by one of three types of geophysical instruments; magnetometers, time-domain conductivity meters, and mine/coin detectors. The Army Environmental Center (AEC) has sponsored a series of tests at Jefferson Proving Ground (Reference 2) that measures the effective UXO detection depth of different geophysical detection systems. Huntsville Center Corps of Engineers has also performed similar tests at a number of sites contaminated with UXO.

Huntsville Center has evaluated the AEC and project data and determined that maximum UXO detection depths can be estimated based upon type of instrument used and the diameter of the munition. The equation for estimating detection depths (in meters) of particular diameter (in millimeters) munitions for each type of geophysical instrument is as follows:

Magnetometers:

$$\log(\text{depth})=1.354\ (\log(\text{dia})) - 2.655)$$

Time Domain Conductivity Meters:

$$\log(\text{depth}) = (1.002\ (\log(\text{dia})) - 1.961)$$

Mine/Coin Detectors:

$$\log(\text{depth}) = (0.1179\ (\log(\text{dia})) - 0.6265)$$

Each of the different instruments has inherent capabilities & limitations to detect different kinds of buried UXO and to operate in particular geologic conditions. It is necessary for a person with an understanding site conditions including composition of UXO at the site, site geology and project goals to match a geophysical instrument with a project.

5.0 REFERENCES

1. DOE/TIC-11268, "A Manual for the Prediction of Blast and Fragment Loadings on Structures", US Department of Energy, February 1992.

2. SFIM-AEC-ET-CR-96170, *"Unexploded Ordnance Advanced Technology Demonstation Program at Jefferson Proving Ground (Phase II)",* US Army Environmental Center, June 1996.

APPENDIX A

SUMMARY OF RESULTS

FT ORD MUNITION PENETRATION ANALYSIS

	Range Number	Range Name	Design UXO[1]	Information Source	Maximum Munition Penetration Depth	Maximum Munition Detection Depth
1.	1	Flame Thrower Range	Landmine	HFA	n/a	-
2.	2	Pete's Pond	2.36" Rocket	ASR	0.4 ft	1.9 ft
3.	3	Old Demo Tng Area Range 49	81mm Mortar	HFA	2.7 ft	2.8 ft
4.	4A	CBR Area	35mm Subcal M73	HFA	0.5 ft	0.9 ft
5.	4B	CBR Area	40mm grenade	HFA	0.2 ft	1.1 ft
6.	4C	CBR Area	Rifle Grenade	HFA	0.1 ft	1.7 ft
7.	5	South of East Garrison	3.5" Rocket	ASR	0.8 ft	3.2 ft
8.	6	Booby Traps & Landmines	Landmine	HFA	n/a	-
9.	7	Booby Traps & Landmines	Rifle Grenade	HFA	0.1 ft	1.7 ft
10.	8	Booby Traps & Landmines	Rifle Grenade	HFA	0.1 ft	1.7 ft
11.	9	Booby Traps & Landmines	57mm RR Ctg Case	HFA	surface	-
12.	10	Leary Hill & Elliot Hill Region	81mm Mortar	UXB/CMS	3.5 ft	2.8 ft
13.	11	Demolition Training Area	Hand Grenade	HFA	surface	-
14.	12	Picnic Canyon	40mm AA Projectile	ASR	2.3 ft	1.1 ft
15.	13A	Practice Mortar Range	81mm Mortar, Practice	ASR	2.7 ft	2.8 ft
16.	13B	Practice Mortar Range See note 2	Landmine	HFA	n/a	-
17.	14	Pilarcitos Canyon & Lookout Ridge	8" Naval Projectile	ASR	18.4 ft	9.7 ft
18.	14 SE	14 SE	Rifle Grenade	UXB	0.2 ft	1.7 ft
19.	16	2.36" Rocket Moving Target Range	2.36" Rocket	ASR	0.4 ft	1.9 ft
20.	17	Anti-Tank Practice Mine Area	Landmine	ASR	n/a	-
21.	18	100lb Bomb See Note3	concrete fill/unfuzed	HFA	surface	-
22.	19	Rifle Grenade Range	Rifle Grenade	HFA	0.1 ft	1.7 ft
23.	20	Recoiless Rifle Training Range	None	ASR, HFA	n/a	-
24.	21	Mudhen Lake	Rifle Grenade	UXB	0.2 ft	1.7 ft
25.	22	Beach Ranges Trainfire Ranges See Note 4	60mm Mortar	HFA	1.1 ft	1.9 ft
26.	23	Demolition Area	M49 Tripflare	SASR	surface	-
27.	24A	Practice Rifle Grenade Range	Rifle Grenade	SASR	0.1 ft	1.7 ft
28.	24B	Practice Rifle Grenade Range	None	SASR	n/a	-
29.	24C	Live Grenade Range	None	SASR	n/a	-
30.	24D	Booby Traps	None	SASR	n/a	-
31.	24E	Practice Rifle Grenade Range	None	SASR	n/a	-
32.	25	Firing Point	None	ASR, SASR	n/a	-
33.	26	Hilltop within P-5	Booby Trap Simulator	SASR	surface	-
34.	28	MOUT Site	Simulators	Bayuga	surface	-
35.	LS BT	Laguna Seca Bus Turn Around	Rifle Grenade	UXB	0.2 ft	1.7 ft

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	Range Number	Range Name	Design UXO [1]	Information Source	Maximum Munition Penetration Depth	Maximum Munition Detection Depth
36.	LS OS	Laguna Seca Open Spaces	None		n/a	-
37.	LS T11	Laguna Seca Turn 11	75mm Projectile	UXB	5.1 ft	2.5 ft
38.	CSU Footprint	CSU Footprint	Rifle Grenade	HFA	0.1 ft	1.7 ft
39.	OWR 1	Oil Well Road 1	Signal, Illumination	UXB	surface	-
40.	OWR 2	Oil Well Road 2	Smoke Grenade	UXB	surface	-
41.	OWR 3	Oil Well Road 3	81mm Mortar	UXB	3.5 ft	2.8 ft
42.	TS24	Training Site 24	Rifle Grenade	UXB	0.1 ft	1.7 ft
43.	TS25	Training Site 25	Signal, Illumination	UXB	surface	-
44.	FRC	Range Control	Signal, Illumination	UXB	surface	-
45.	LOR 2	Lookout Ridge II	22mm subcal	HFA,UXB	1.9 ft	0.5 ft
46.		Wolf Hill	75mm Projectile	UXB	5.1 ft	2.5 ft
47.		Fritzsche AAF	2.36" Rocket	UXB	0.4 ft	1.9 ft

NOTES:

1. "Design UXO" is the deepest penetrating UXO found by on-site investigators or previous studies. However, the Design UXO used for this analysis may not be used as the Design UXO in the EE/CA if it is determined that the item was placed on the site, rather than fired, and represents a unique event.
2. This site contained a 220 lb Fragmentation Bomb which was inert and was most likely a training aid; therefore, the landmine was used for the deepest UXO.
3. This bomb contained no hazards and was most likely a training aid; therefore, the landmine is used for the deepest UXO.
4. Only one set of fins from the 60mm mortar were found. If this area were actually a mortar range more residue should have been found.

APPENDIX B

UXO CLEARANCE DEPTH EVALUATION

Ft. Ord Ordnance Penetration Table

Ordnance Item	Depth of Penetration (ft) in Sand	in Loam	in Clay	Max. Detection Depth[1] (ft)
14.5 mm Trainer/Spotter, M181-3A1	-0.2	-0.3	-0.4*	-0.3
22 mm Subcal for 81 mm mortar	-1.4*	-1.9*	-2.8*	-0.5
35 mm Subcal M73	-0.5	-0.7	-1.0*	-0.9
37 mm, M63	-3.9*	-5.2*	-7.9*	-0.9
40 mm, M822 (AA)	-2.3*	-3.0*	-4.5*	-1.1
40 mm, M677 (Mk 19)	-0.2	-0.3	-0.4	-1.1
40 mm, M381 (M203/M79)	-0.2	-0.3	-0.4	-1.1
57 mm, M306A1	-2.7*	-3.6*	-5.5*	-1.7
M9 Rifle Grenade	-0.1	-0.2	-0.2	-1.7
60 mm, M49A1 (charge 4)	-1.1	-1.5	-2.3*	-1.9
2.36” Rocket, M6A1	-0.4	-0.5	-0.8	-1.9
66 mm, M72 LAW	-0.9	-1.2	-1.8	-2.1
66 mm TPA, M74	-0.7	-0.9	-1.4	-2.1
75 mm, M48	-4.9*	-6.4*	-9.8*	-2.5
75 mm, M310	-3.9*	-5.1*	-7.8*	-2.5
81 mm, M43A1 (charge 8)	-2.7	-3.5*	-5.4*	-2.8
83 mm SMAW Mk 3	-2.8	-3.6*	-5.6*	-2.9
84 mm, M136 (AT-4)	-2.5	-3.7*	-5.0*	-2.9
3.5” Rocket, M28	-0.8	-1.1	-1.7	-3.2
90 mm, M371A1	-2.0	-2.7	-4.1*	-3.2
25 lb Frag Bomb[2]	-2.1	-2.8	-4.3*	-3.2
105 mm, M1 (charge 7)	-7.7*	-10.1*	-15.4*	-4.0
106 mm, M344A1	-6.5*	-8.5*	-13.0*	-4.0
Dragon Rocket	-0.9	-1.1	-1.7	-4.3
106 mm, M344A1	-6.5*	-8.5*	-13*	-4.0
4.2”, M3 (max charge)	-4.1	-5.4*	-8.3*	-4.1
155 mm, M107	-14.0*	-18.4*	-28.0*	-6.7
8”, M106 (charge 8)	-18.4*	-24.2*	-36.9*	-9.7

[1]Maximum detection depth using a magnetometer.
[2]Maximum depth of penetration assuming a velocity of 500 fps.
*Indicates that maximum penetration depth exceeds maximum detection depth. In such cases it may be necessary to implement institutional controls at a site since a complete ordnance removal cannot be assured.

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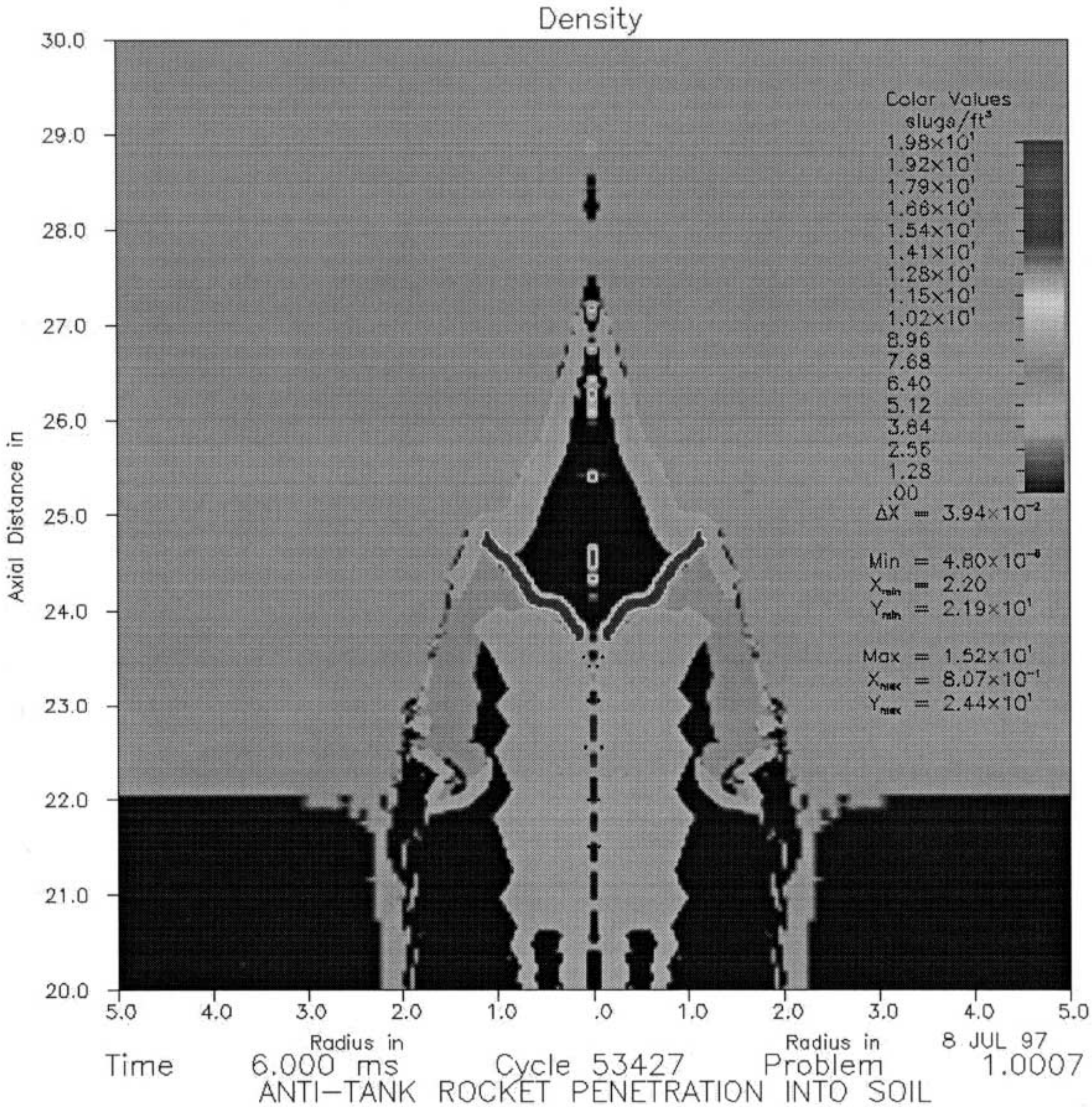
APPENDIX C

HULL RESULTS


Density
Color Values
slugs/ft³
1.98×10¹
1.92×10¹
1.79×10¹
1.66×10¹
1.54×10¹
1.41×10¹
1.28×10¹
1.15×10¹
1.02×10¹
8.96
7.68
6.40
5.12
3.84
2.56
1.28
.00
ΔX = 3.94×10⁻²
Min = 4.80×10⁻⁶
Xmin = 2.20
Ymin = 2.19×10¹
Max = 1.52×10¹
Xmax = 8.07×10⁻¹
Ymax = 2.44×10¹
Axial Distance in
30.0
29.0
28.0
27.0
26.0
25.0
24.0
23.0
22.0
21.0
20.0
5.0 4.0 3.0 2.0 1.0 .0 1.0 2.0 3.0 4.0 5.0
Radius in
Radius in
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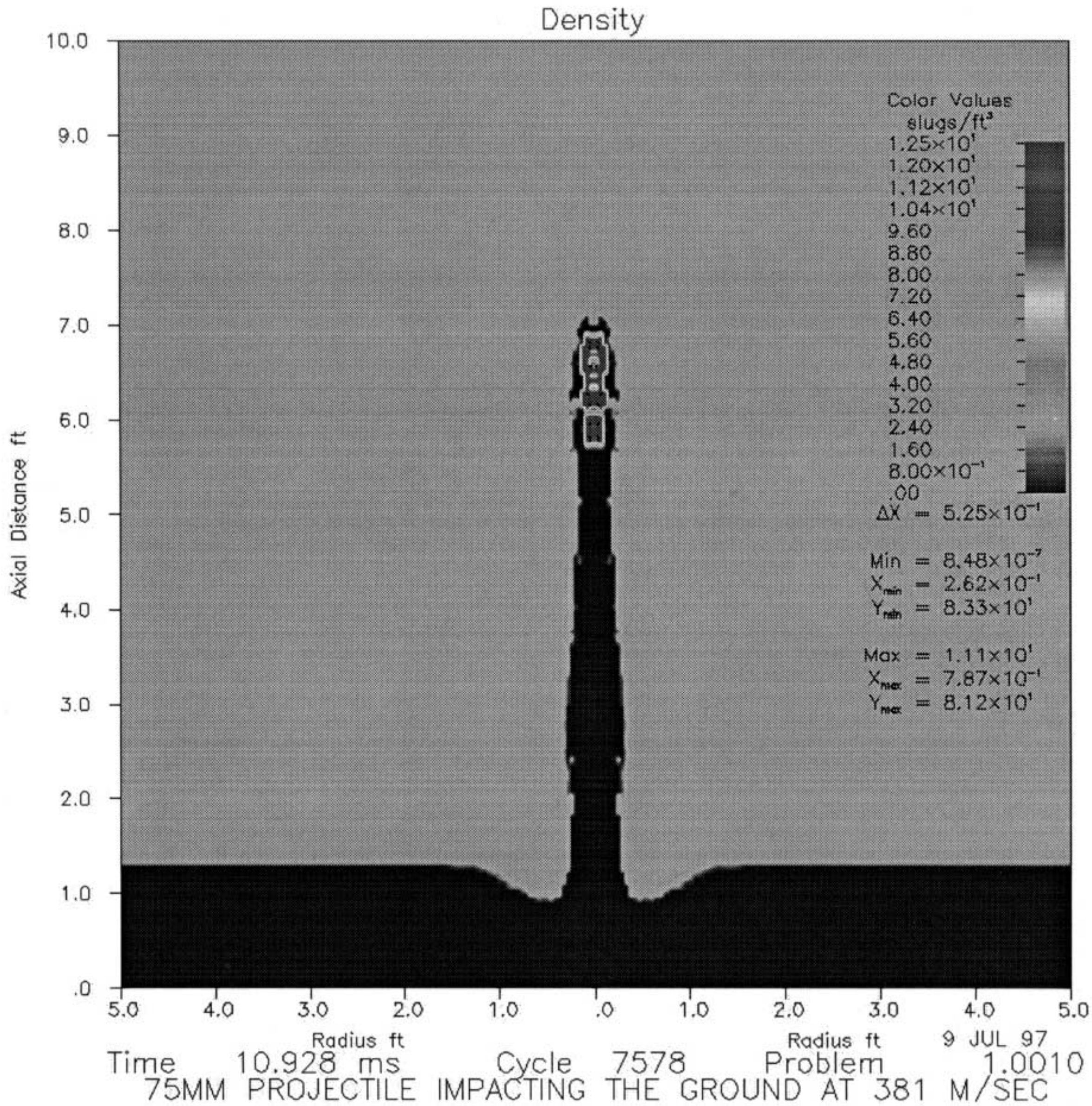
Time 6.000 ms Cycle 53427 Problem 1.0007
ANTI-TANK ROCKET PENETRATION INTO SOIL



Density
Color Values
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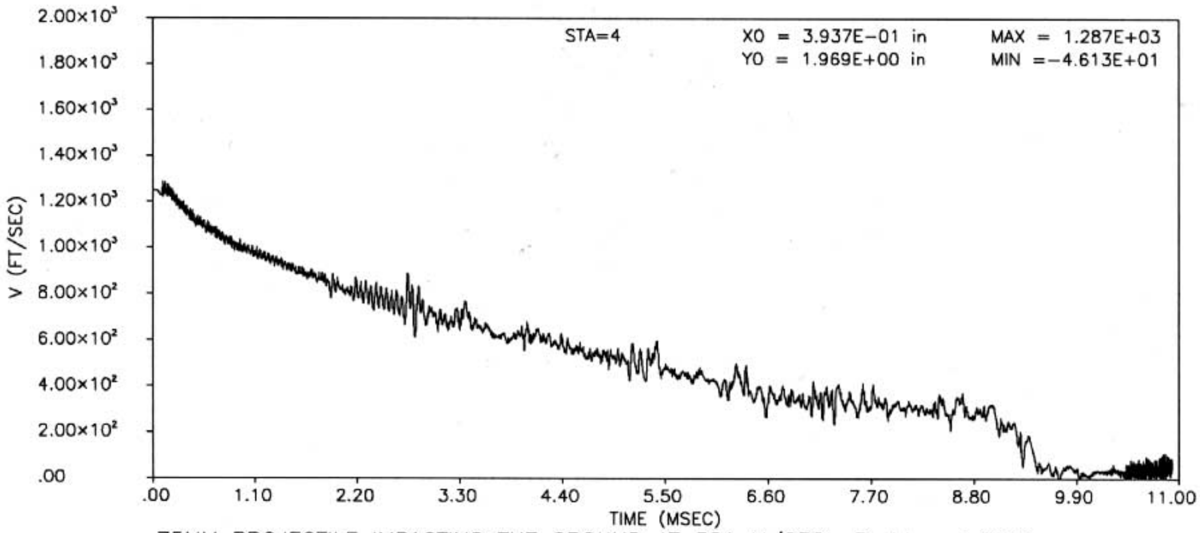
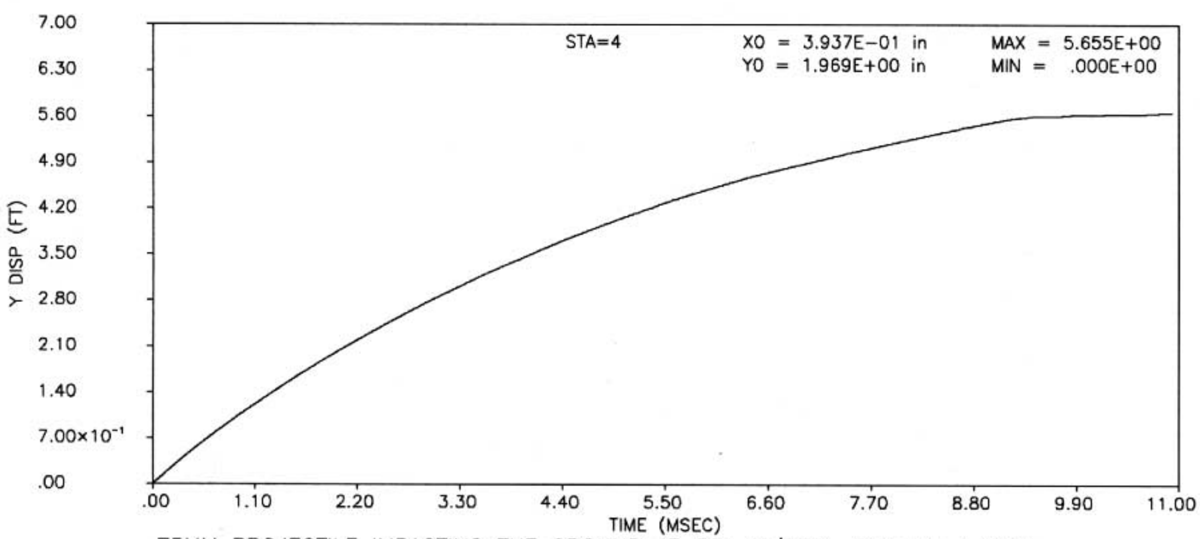
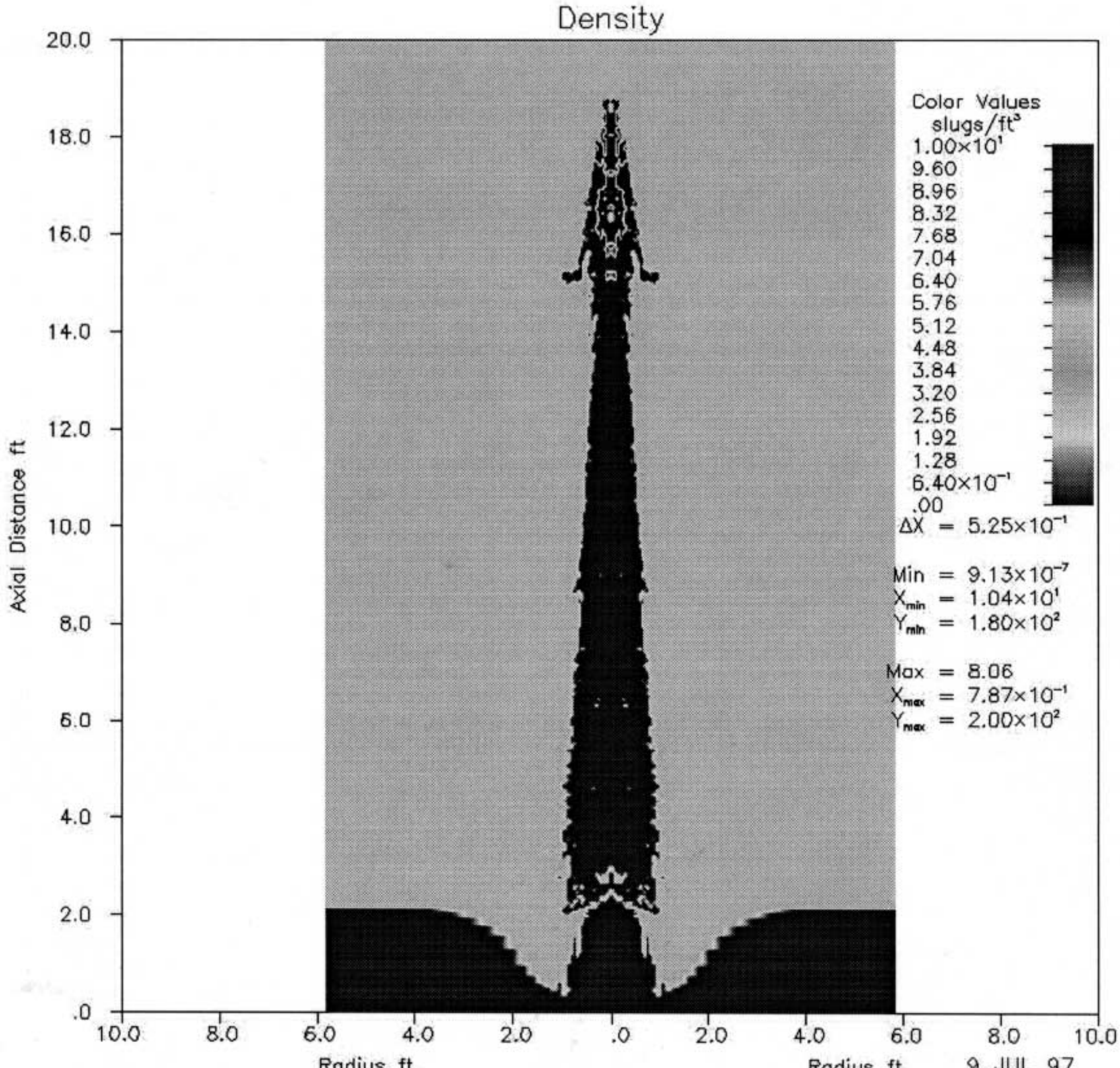
1.20×10¹
1.12×10¹
1.04×10¹
9.60
8.80
8.00
7.20
6.40
5.60
4.80
4.00
3.20
2.40
1.60
8.00×10⁻¹
.00
ΔX = 5.25×10⁻¹
Min = 8.48×10⁻⁷
X_min = 2.62×10⁻¹
Y_min = 8.33×10¹
Max = 1.11×10¹
X_max = 7.87×10⁻¹
Y_max = 8.12×10¹
Axial Distance ft
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
.0
5.0
4.0
3.0
2.0
1.0
.0
1.0
2.0
3.0
4.0
5.0
Radius ft
Radius ft
9 JUL 97
Time 10.928 ms Cycle 7578 Problem 1.0010
75MM PROJECTILE IMPACTING THE GROUND AT 381 M/SEC



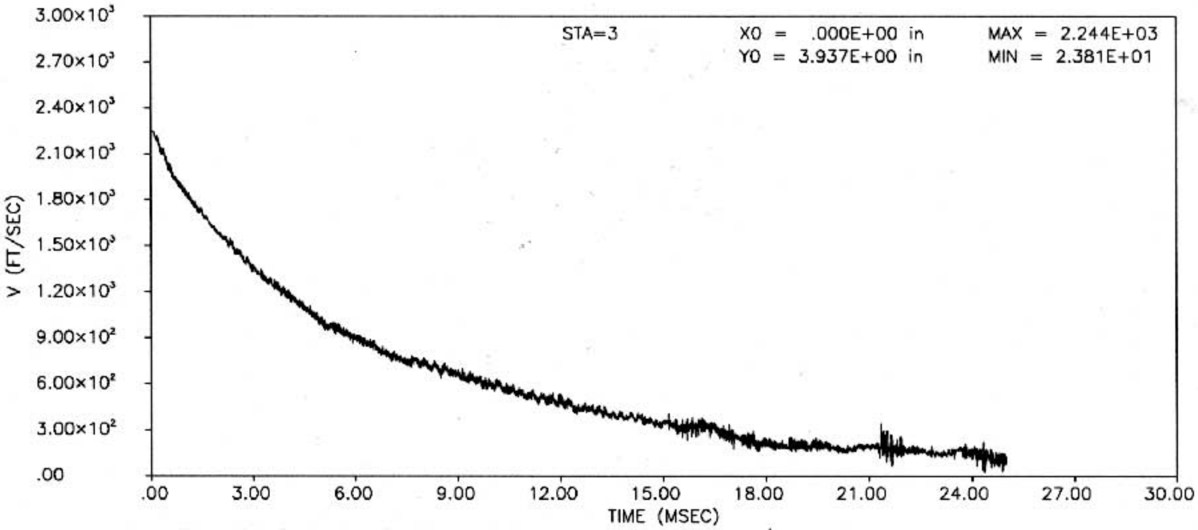
75MM PROJECTILE IMPACTING THE GROUND AT 381 M/SEC Problem 1.0010



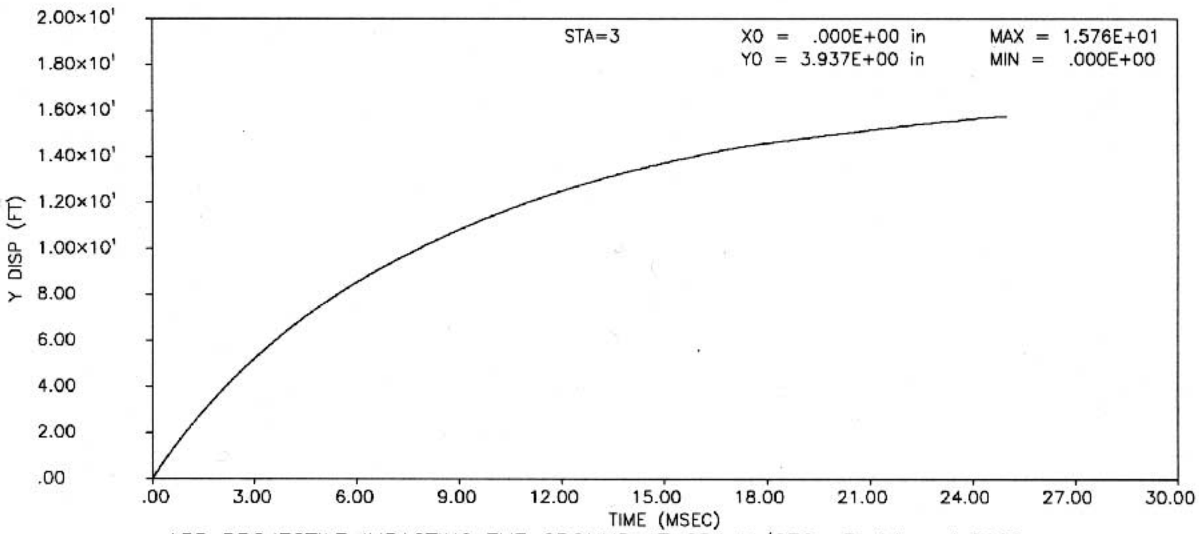
75MM PROJECTILE IMPACTING THE GROUND AT 381 M/SEC Problem 1.0010



Time 25.000 ms Cycle 17472 Problem 1.0009
155 PROJECTILE IMPACTING THE GROUND AT 684 M/SEC



155 PROJECTILE IMPACTING THE GROUND AT 684 M/SEC Problem 1.0009



155 PROJECTILE IMPACTING THE GROUND AT 684 M/SEC Problem 1.0009