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Abstract

Two-dimensional axisymmetric hydrodynamic models were developed using GEODYN to simulate the propagation of air blasts resulting from a series of high explosive detonations conducted at Kirtland Air Force Base in August and September of 2007. Dubbed Humble Redwood I (HR-1), these near-surface chemical high explosive detonations consisted of seven shots of varying height or depth of burst. Each shot was simulated numerically using GEODYN. An adaptive mesh refinement scheme based on air pressure gradients was employed such that the mesh refinement tracked the advancing shock front where sharp discontinuities existed in the state variables, but allowed the mesh to sufficiently relax behind the shock front for runtime efficiency. Comparisons of overpressure, sound speed, and positive phase impulse from the GEODYN simulations were made to the recorded data taken from each HR-1 shot. Where the detonations occurred above ground or were shallowly buried (no deeper than 1 m), the GEODYN model was able to simulate the sound speeds, peak overpressures, and positive phase impulses to within approximately 1%, 23%, and 6%, respectively, of the actual recorded data, supporting the use of numerical simulation of the air blast as a forensic tool in determining the yield of an otherwise unknown explosion.

Introduction

Determining the yield and height or depth of burst of an explosive detonation posteriori, whether it be nuclear, chemical, or mechanical are essential to forensic analysis of explosions. It's postulated that both the magnitude and positive phase impulse of the air blast (i.e. the integration of the overpressure time-history curve over the first positive pulse), coupled with the recorded seismic ground motions from the detonation could be used to determine the yield, and height or depth of burst of an explosion. LLNL is developing a tool to do just that. As part of that ongoing effort, the feasibility of using air blast data was partially investigated here by determining the adequacy to which a hydrodynamic modeling code, such as GEODYN, could simulate an actual explosive air blast. Other factors such as buildings, terrain, wind, and air temperature affect the air blast data recorded at some remote sensor. These factors were not investigated here, but some insights as to their effects are given in Marrs et al. (2009).

Humble Redwood I Configurations

In August and September of 2007, a series of high explosive detonations was conducted at Kirtland Air Force Base. Dubbed Humble Redwood I (HR-1) and documented in Foxall et al.

(2011), these high explosive detonations consisted of seven shots of varying height or depth of burst. Each shot contained 1450 lbs of ammonium nitrate and fuel oil (ANFO) that produced an explosive yield of approximately 0.54 tons of TNT. The ANFO and pentolite or C-4 boosters were encased in cylindrical Sonotubes that had radii and heights of 0.91 and 1.22 meters, respectively. There were four above ground and three buried shots ranging from +/- 5 meters from ground surface. Each shot was instrumented with multiple seismic and air pressure sensors, including Validyne pressure transducers installed by the Defense Threat Reduction Agency (DTRA) with an intended range of approximately 250 meters from ground zero. The Validyne sensors measured differential pressure across a diaphragm and had a low enough frequency response to capture the positive phase impulse of the air blast. Table 1 summarizes the HR-1 series of shots as well as the actual range between the Validyne pressure transducer and ground zero for each shot.

Table 1: HR-1 Shot Series

Shot	Height or Depth Of Burst	Range to ~250 m Pressure Sensor	DTRA Validyne Pressure Data?
A	HOB=5 m	266 m	No
B	HOB=3 m	278 m	Yes
C	HOB=1.5 m	275 m	Yes
D	DOB=1.5 m	277 m	Yes
E	HOB=0.5 m	287 m	Yes
F	DOB=0.5 m	263 m	Yes
G	DOB=5 m	290 m	Yes

Environmental and Geologic Conditions

The site of the HR-1 detonations was relatively flat, as seen in Figure 1. Figure 2 is a depiction of the geology of the site. Due to the complexity in meshing introduced by the right leaning fault that outcrops at the far east end of the site, only the geology to the west of the ground-zero was modeled in this effort. This allowed the domain to be depicted using a two-dimensional cylindrical (r-z) mesh as described in a subsequent section. The environmental conditions at the time of each shot are given in Table 2. Of particular importance to this study is the air pressure and temperature as it directly affects the speed of sound and hence the propagation speed of the blast wave.

Figure 1: Photograph of Shot E at approximately 40 µs after detonation. Taken from Marrs et al. (2009).
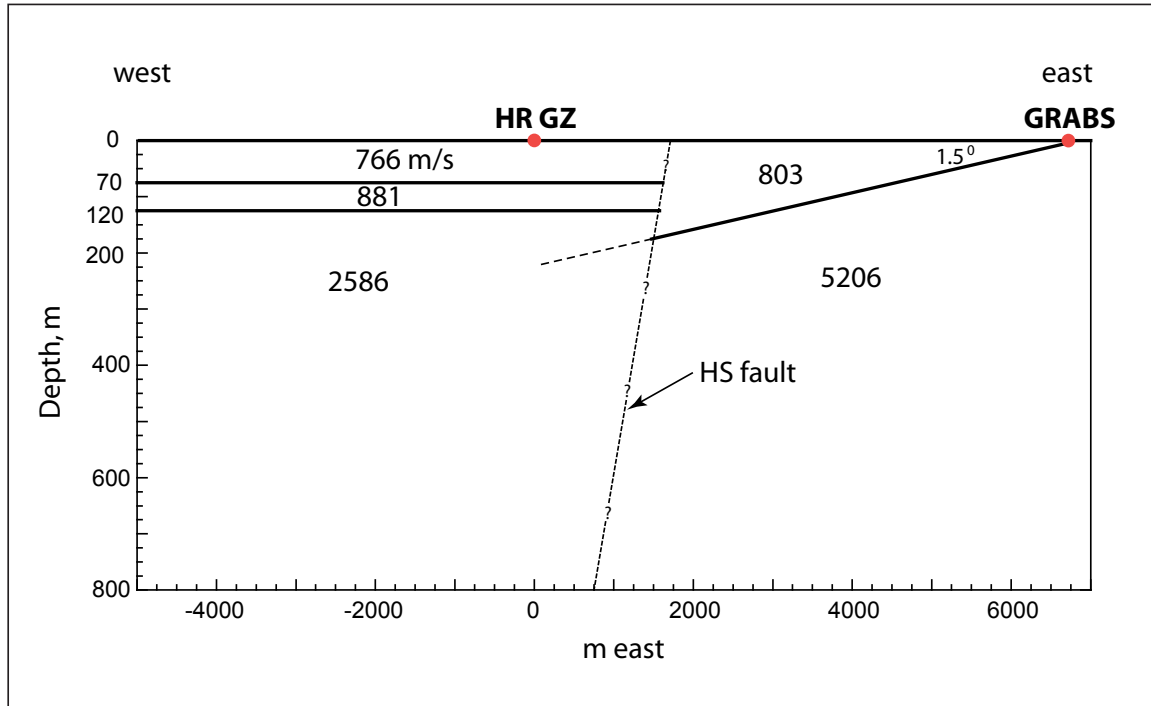
Figure 2: West-east seismic geology and velocity profile through the HR I ground-zero location. Vertical exaggeration is 7:1. Taken from Foxall et al. (2011).

Table 2: HR-1 Environmental Conditions

Shot	Temperature (°F)	Wind (mph @ degrees)	Relative Humidity (%)	Barometric Pressure (inHg)	Dew Point (°F)
A	88.5	7.6 @ 238.2	23.7	24.6	46.8
B	79.8	4.9 @ 320.9	34.6	24.8	49.4
C	89.1	9.8 @ 309.6	22.4	24.7	45.8
D	74	4.9 @ 176.4	51.7	25.0	55.1
E	81.2	1.5 @ 198.1	37.4	24.9	52.8
F	78	4.4 @ 229	46	24.8	55.1
G	85	11 @ 200	33	24.8	52.8

GEODYN Model Description

GEODYN is a multidimensional, multiphysics, parallel, Eulerian adaptive mesh refinement (AMR) code. It includes multi-fluid hydrodynamics with real equation-of-state (EOS) behavior and solid material mechanics such elastic-plastic strains and deformations in geologic media. GEODYN was chosen for its capability to accurately model the physics of a propagating blast/shock wave in the atmosphere coupled with the seismic/mechanical response of the underlying geologic materials to an explosive detonation.

Input and Explosive Source Parameters

The atmosphere is modeled using constant parameters and the standard equation-of-state. Since the subsurface response is not the focus of this report, the reader is directed to Foxall et al. (2011) and Vorobiev (2008) for the model parameters and functions used for the layered alluviums.

The yield was calculated as follows:

$$yield = \rho \cdot vol \cdot e_0$$

where

> $yield$ = explosive energy in kJ or tons of TNT where 1 ton of TNT = 4.184×10^9 J
> ρ = density of the explosive source in kg/m^3
> vol = volume of the explosive source in m^3 (cylindrical in this case)
> e_0 = specific energy of the explosive source in kJ/kg

The source parameters for the HR-1 series of detonations were calculated using the numerical code CHEETAH and calibrated to test data. Table 3 summarizes the explosive source parameters, and also includes the yield parameters for the SHAMRC modeling conducted by Marrs et al. (2009). There was about a 7.4% difference in the yield calculated from the CHEETAH calibrations to the yield used in the SHAMRC modeling Mars et al. (2009). This is due to the inherent uncertainty in exactly quantifying the material properties of the chemical explosive.

Table 3: Explosive Source Parameters for GEODYN and SHAMRC Models

Explosive Source Parameters	GEODYN	SHAMRC
Density	820 kg/m^3	829 kg/m^3
Radius	0.4572 m	0.455 m
Height	1.2192 m	1.22 m
Mass	656.5 kg (1447 lbm)	657.7 lb (1450 lbm)
Specific Energy	3723.45 kJ/kg	3434.20 kJ/kg
Yield	2.445×10^6 kJ (0.58 tons of TNT)	2.2594×10^6 kJ (0.54 tons of TNT)

Mesh Refinement Scheme

For this modeling effort, a 2-d layered cylindrical mesh was used with an adaptive mesh refinement scheme. As shown previously in Figure 2, a constant atmospheric layer was used above layered alluviums. The atmospheric layer was 250 meters in height, while the layered alluviums went to a depth of 750 meters below the ground surface. The domain in its entirety was 1000 meters in radius by 1000 meters in height or the z-direction. At a radius of 0 meters, a symmetry boundary condition was employed. At the other edges of the domain, open flow boundaries were used.

Developing an appropriate mesh refinement scheme first involved determining a cell size that leveraged the scale of the physics involved with computational efficiency. A cell size of 1 meter in radius by 1 meter in height (z-direction) was deemed sufficient. The next step in developing the mesh refinement scheme was to determine the level of mesh refinement needed. Four different levels were explored:

1. No mesh refinement.
2. A 1×4 scheme where a 1 meter × 1 meter cell was divided one time by 4 to give sub-cells that were 0.25 meters × 0.25 meters.

3. A 2×4 scheme where the 1 meter × 1 meter cell was divided two times by 4 to give sub-cells that were 0.25 meters × 0.25 meters and sub-sub-cells that were 0.0625 meters × 0.0625 meters.

4. A 3×4 scheme where the 1 meter × 1 meter cell was divided three times by 4 to give sub-cells that were 0.25 meters × 0.25 meters, sub-sub-cells that were 0.0625 meters × 0.0625 meters, and sub-sub-sub-cells that were 0.015625 meters × 0.015625 meters.

The sensitivity of the subsurface seismic response to changes in mesh refinement was found to be more pronounced than that of the atmospheric pressure response. Therefore, the vertical velocities in the subsurface for the deepest buried shot (Shot G) were used to determine an appropriate level of mesh refinement. As shown in Figure 3, significant gains in accuracy were observed by going from no mesh refinement to the 1×4 level, and from the 1×4 level to the 2×4 level. Less gain was observed going from the 2×4 level to the 3×4 level. Thus, the 2×4 was deemed sufficient.
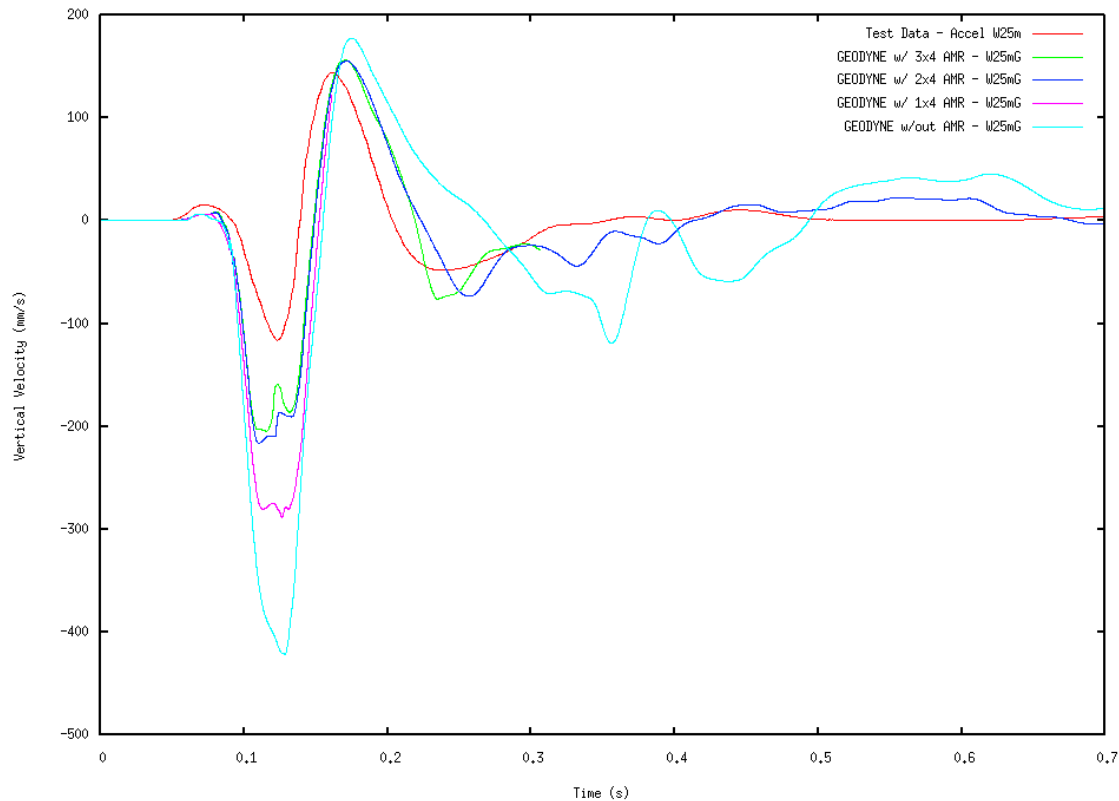

Figure 3: Plot of vertical velocity (mm/s) versus time (s) out to 0.7 s for Shot G comparing the near-field vertical velocity data taken from station W25m to GEODYN results for four models with varying levels of mesh refinement that range from no refinement to 3 levels of refinement.

The final step in the determining an appropriate mesh refinement scheme was to determine the physical parameters that would trigger the refinement and the level of relaxation. In the alluvium layers of the subsurface, mesh refinement was triggered using velocity magnitudes. In the atmosphere, the mesh was refined based on pressure gradients such that the mesh refinement tracked the advancing shock front where sharp discontinuities existed in the state variables, but allowed the mesh to relax behind the shock front for runtime efficiency. The following figures show the mesh refinement in the atmospheric layer at four progressive time steps during a model

run. These figures illustrate how the mesh is refined around the propagating shock front where the pressures are most discontinuous, indicated by the "blackened" regions, as well as how the mesh relaxes to the base mesh size behind the advancing shock front.
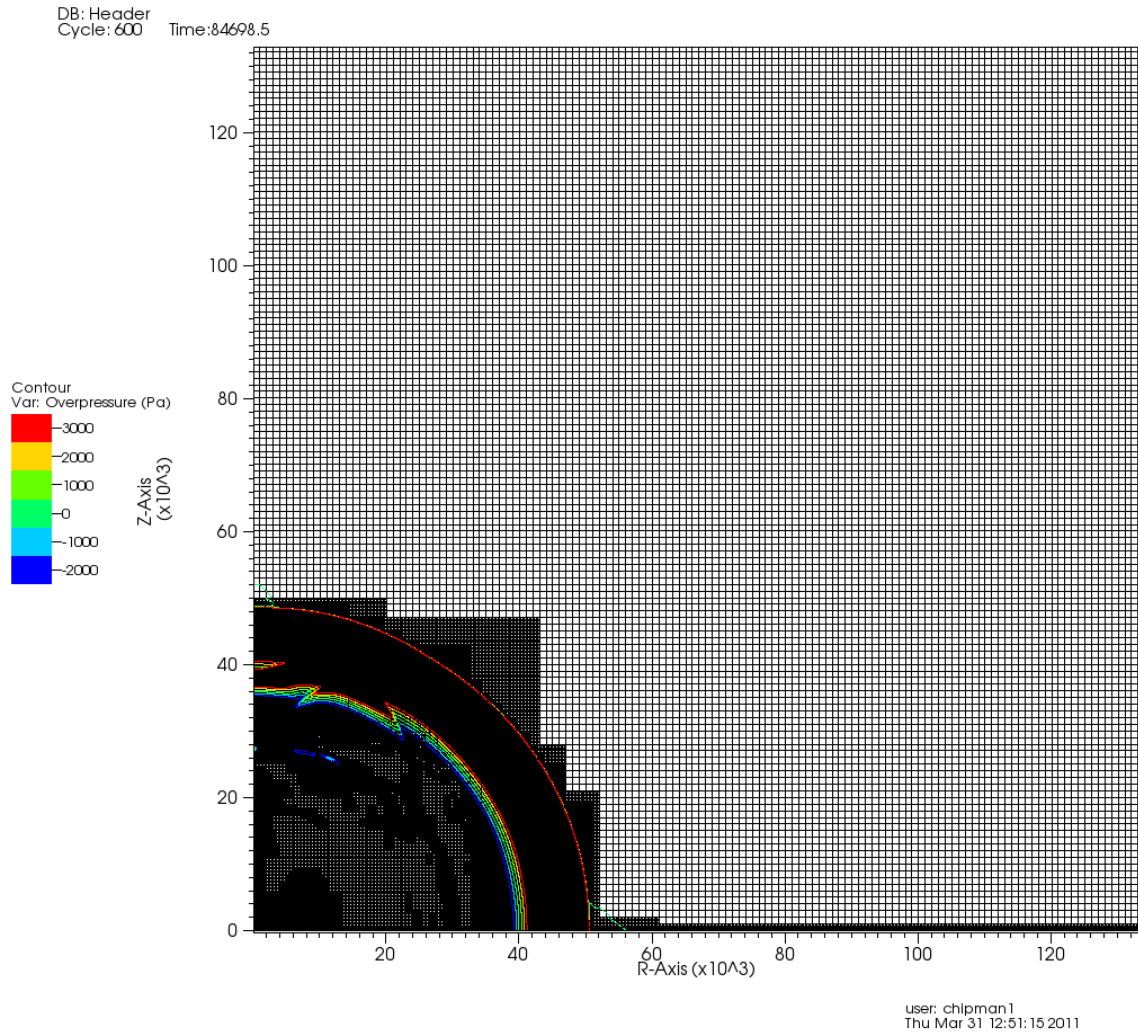

Figure 4: Mesh refinement for the HR-1 GEODYN model at Time=0.0846985 s. The "blackened" area represents the highest level of mesh refinement.
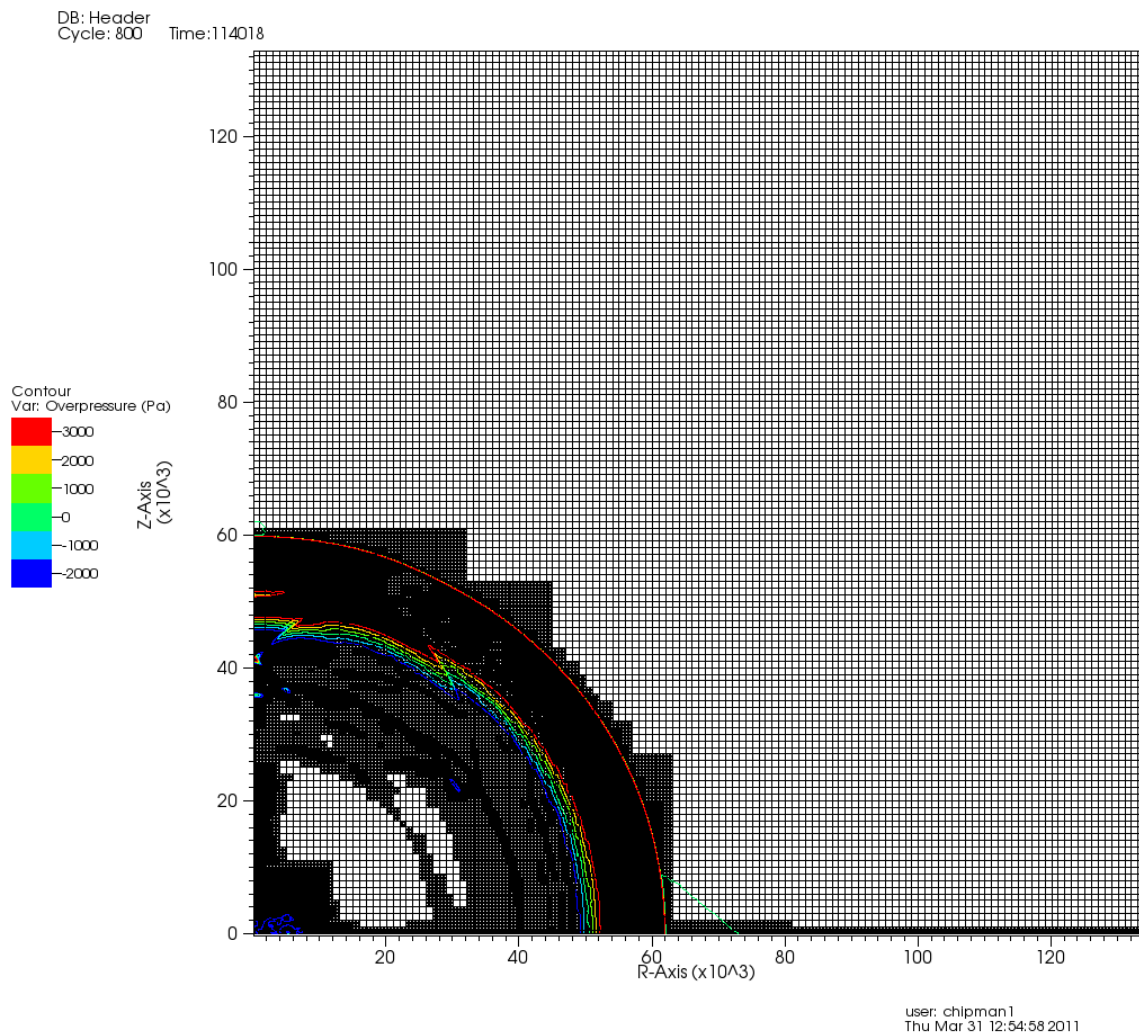
Figure 5: Mesh refinement for the HR-1 GEODYN model at Time=0.114018 s. The "blackened" area represents the highest level of mesh refinement.
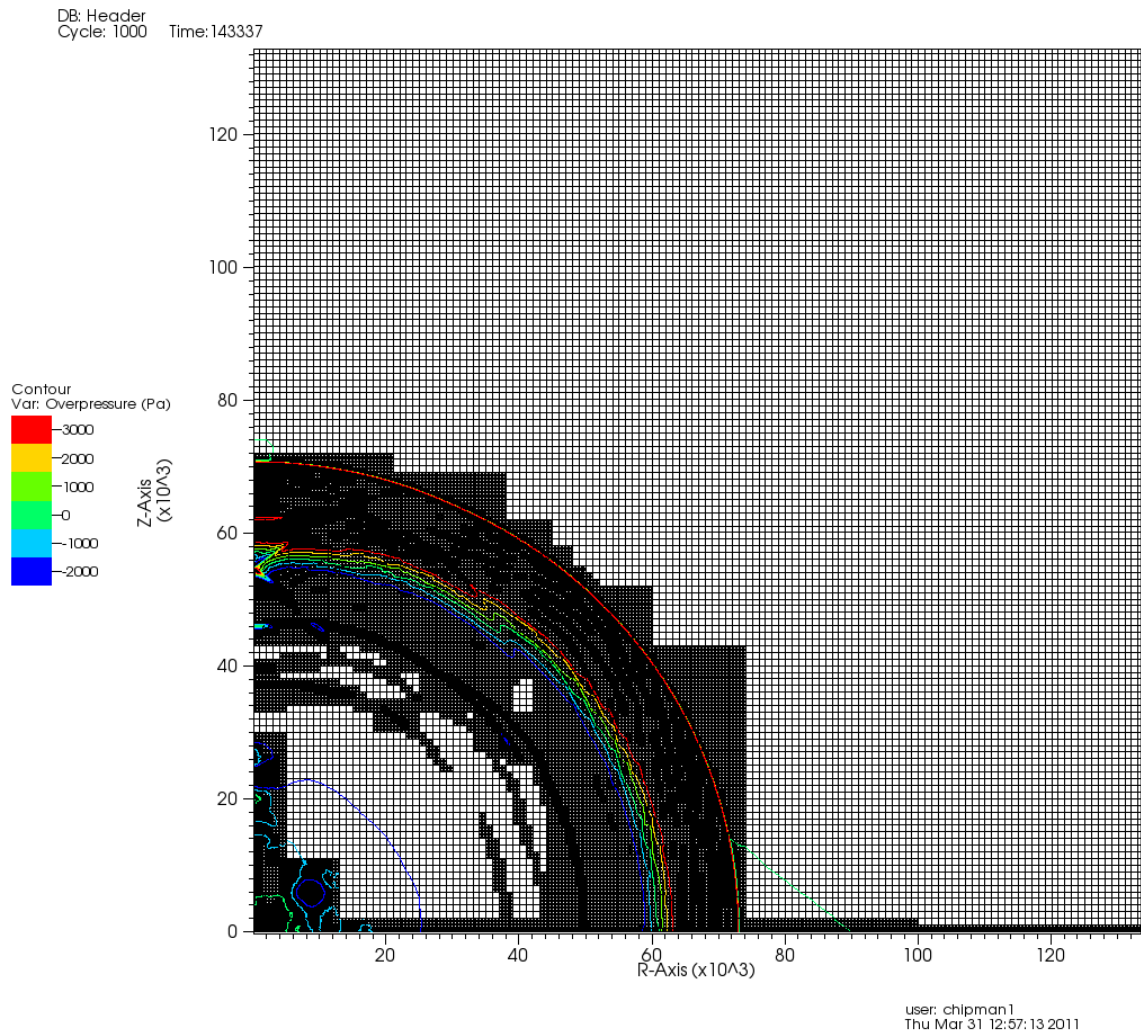
Figure 6: Mesh refinement for the HR-1 GEODYN model at Time=0.143337 s. The "blackened" area represents the highest level of mesh refinement.
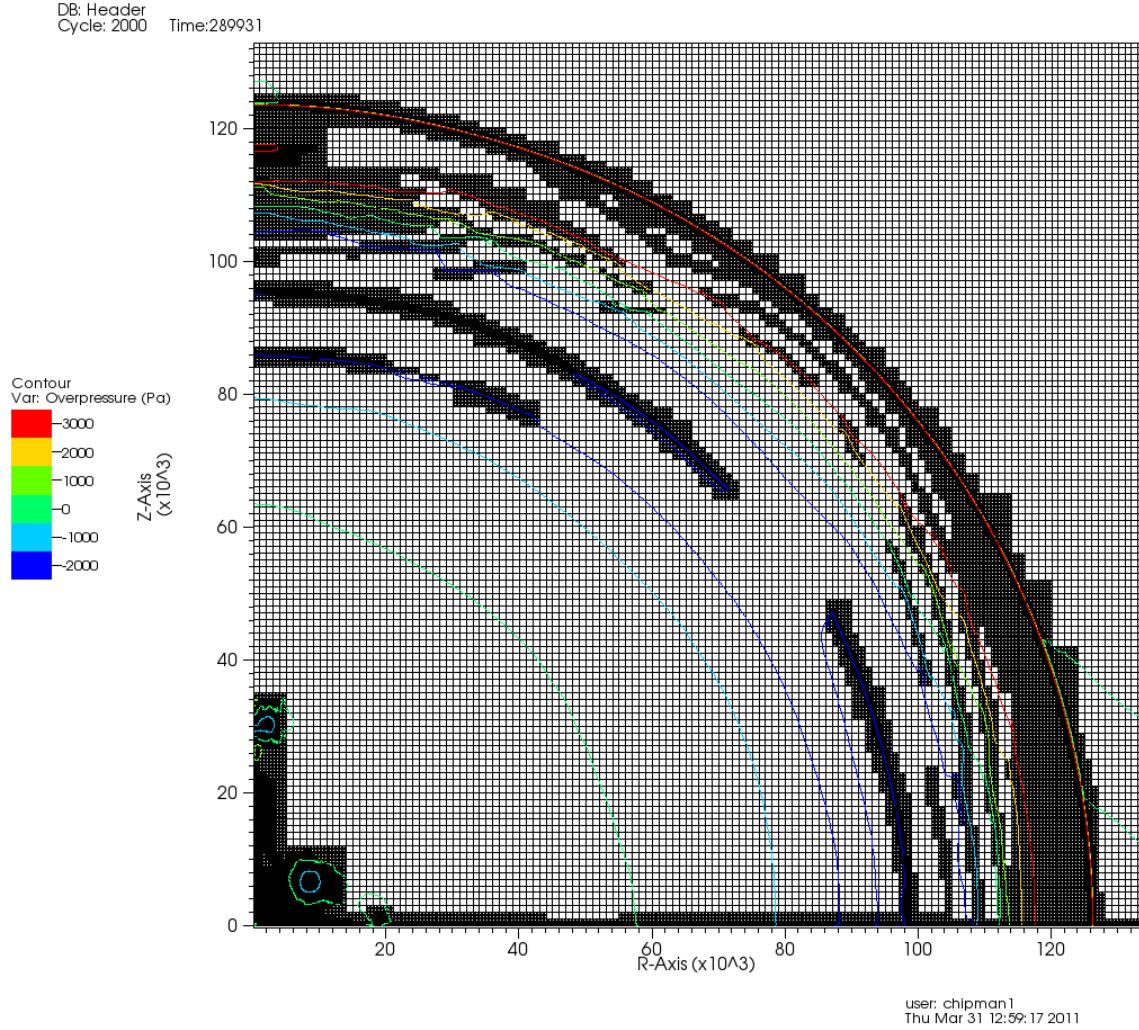
Figure 7: Mesh refinement for the HR-1 GEODYN model at Time=0.289931 s. The "blackened" area represents the highest level of mesh refinement.

Modeling Results

Each shot was modeled using the yield parameters outlined in Table 3. The arrival of the first impulse was adjusted to coincide with that of the data recorded by the respective pressure sensor at the ranges shown in Table 1 by effectively adjusting the bulk speed of sound in the atmosphere. The atmospheric sound speed was calculated from the environmental data using the standard equation:

$$a = \sqrt{\gamma \cdot R \cdot T}$$

where

a = speed of sound (m/s)
γ = ratio of specific heats for the medium = 1.4 for standard air

R = gas constant = 287 J/kg·K
T = temperature in degrees Kelvin

As shown in Table 4, the calibrated sound speeds matched those calculated from the environmental conditions summarized in Table 2 within approximately 1%. Figures 8 through 14 show plots of overpressure versus time for Shots A through G. Note that for Shot A reliable pressure data was not recorded, so the arrival of the first impulse was based solely on the sound speed calculated from the atmospheric data reported in Table 2. Also note that because of the depth of burial for Shot G, a SHAMRC model was not calculated for that particular shot (Marrs et al. 2009). Additionally, the peak overpressure and positive phase impulse was calculated for each shot by importing the test data and the GEODYN overpressure results into MathCad. Those values are summarized in Tables 5 and 6, and the impulses plotted in Figure 15.

With the exception of Shots A (for lacked reliable pressure data) and G (deeply enough buried to not a produce a significant impulse), the GEODYN model was able to accurately simulate the overpressure response due to an explosion at varying heights or depths of burst. The magnitude of the first positive overpressure peak for each of the GEODYN models had a slightly higher magnitude than that of the respective recorded data. As well, the positive phase impulses (i.e. the integration of the first positive peak from its breakthrough time to the time it changes sign) were slightly higher, but in all matched the recorded test data well. In addition, it would appear that from the comparisons of Shots D and G (1.5 and 5 meters DOB, respectively), the deeper the depth of burial the more pronounced the differences between the model and the recorded data. It should be noted that the difference in positive phase impulse between the model and the recorded data falls within the uncertainty reported earlier in the yield of the chemical explosive. The accuracy of the model in predicting the characteristics of the air blast are therefore directly coupled to the uncertainty of the yield as determined by the material properties of the explosive source, and thus represents a limit to the accuracy of the model.
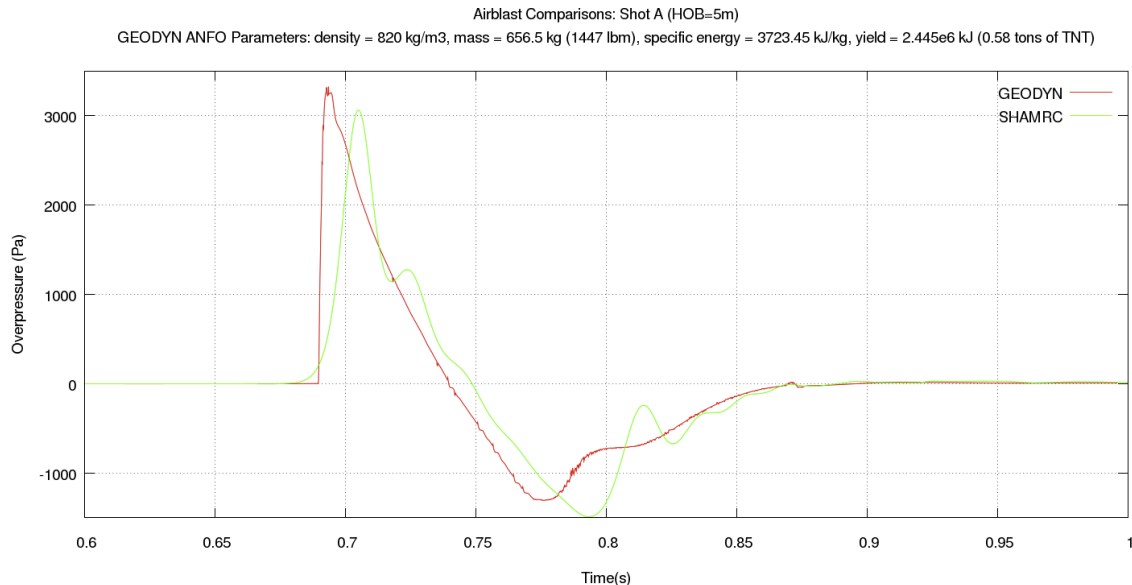

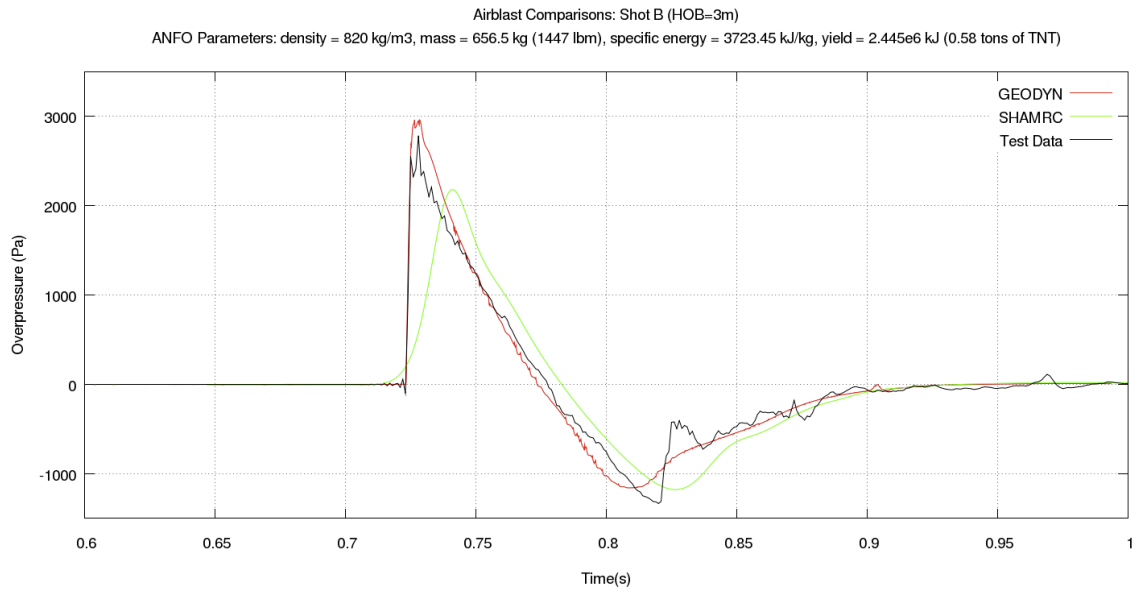**Figure 8:** Overpressure versus time for Shot A.

Airblast Comparisons: Shot B (HOB=3m)
ANFO Parameters: density = 820 kg/m3, mass = 656.5 kg (1447 lbm), specific energy = 3723.45 kJ/kg, yield = 2.445e6 kJ (0.58 tons of TNT)

Figure 9: Overpressure versus time for Shot B.

Airblast Comparisons: Shot C (HOB=1.5m)
GEODYN ANFO Parameters: density = 820 kg/m3, mass = 656.5 kg (1447 lbm), specific energy = 3723.45 kJ/kg, yield = 2.445e6 kJ (0.58 tons of TNT)
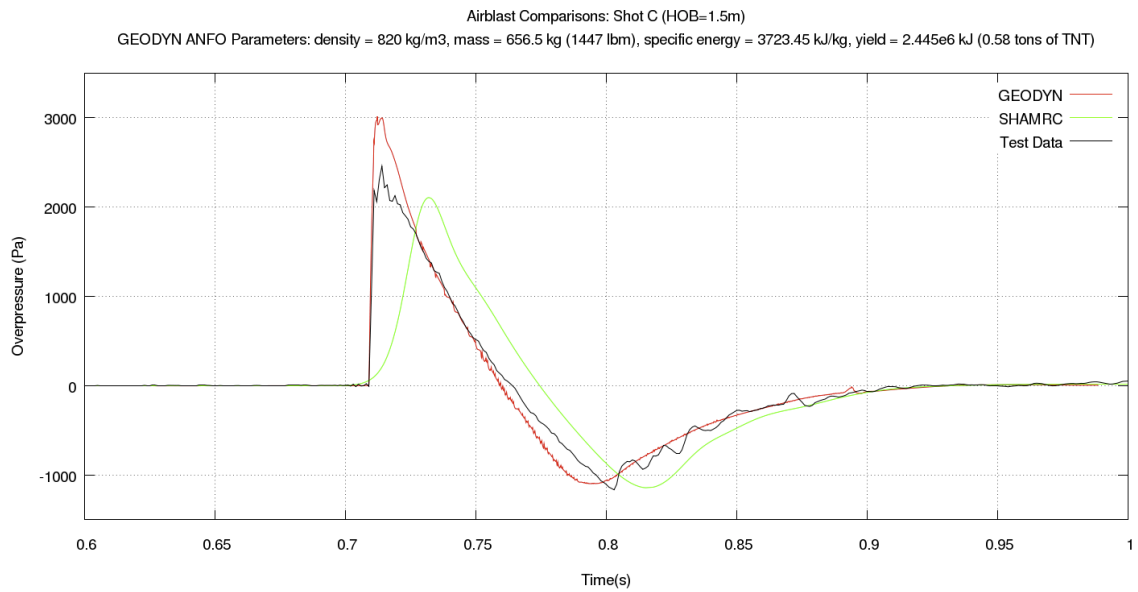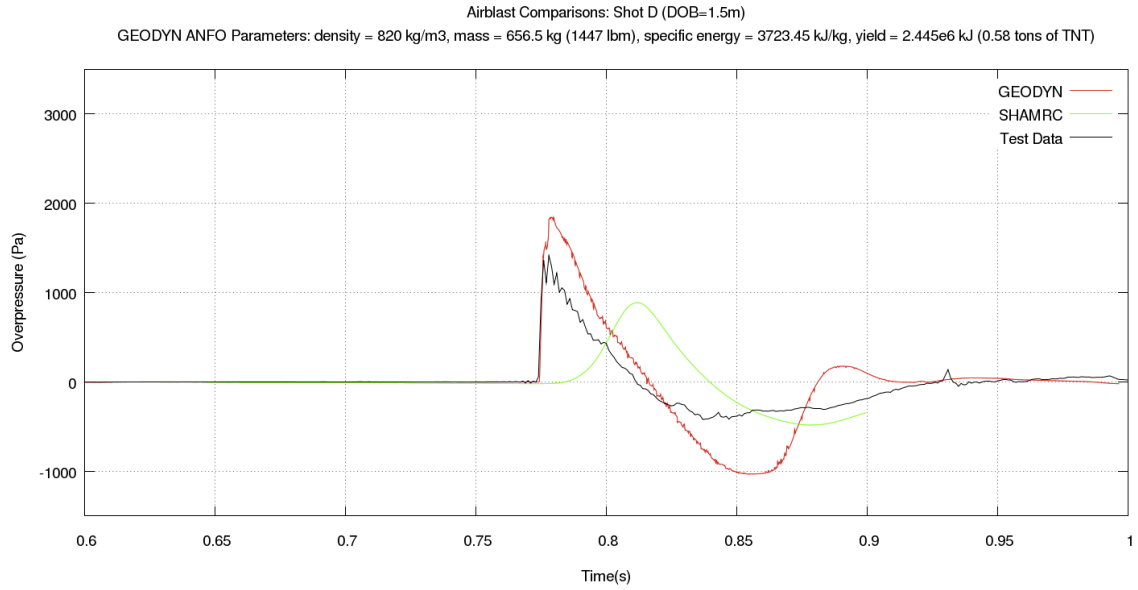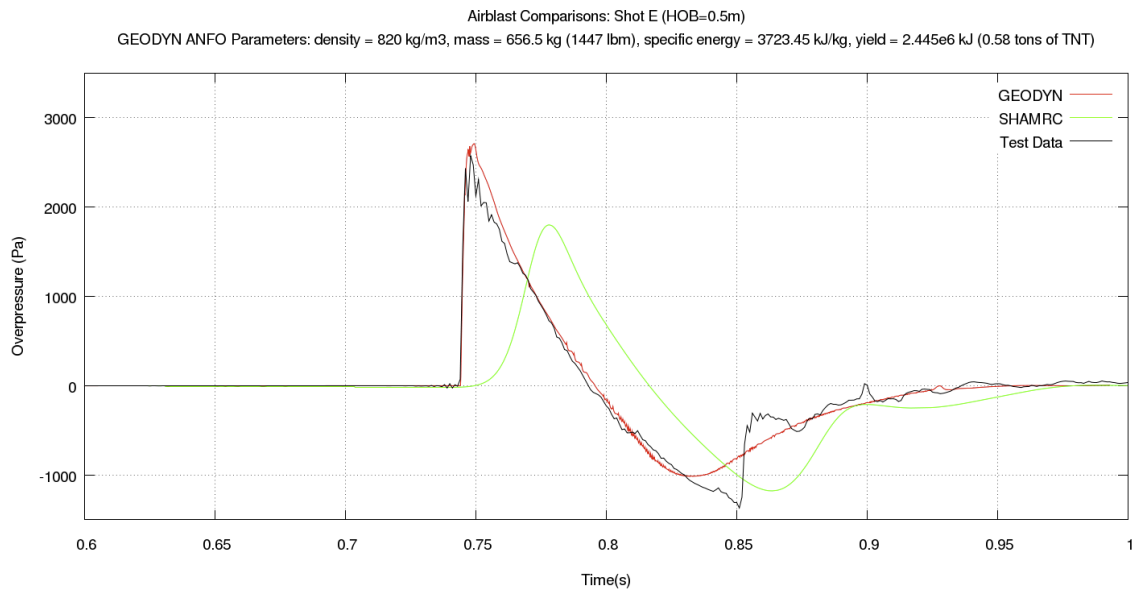

Figure 10: Overpressure versus time for Shot C.

Figure 11: Overpressure versus time for Shot D.

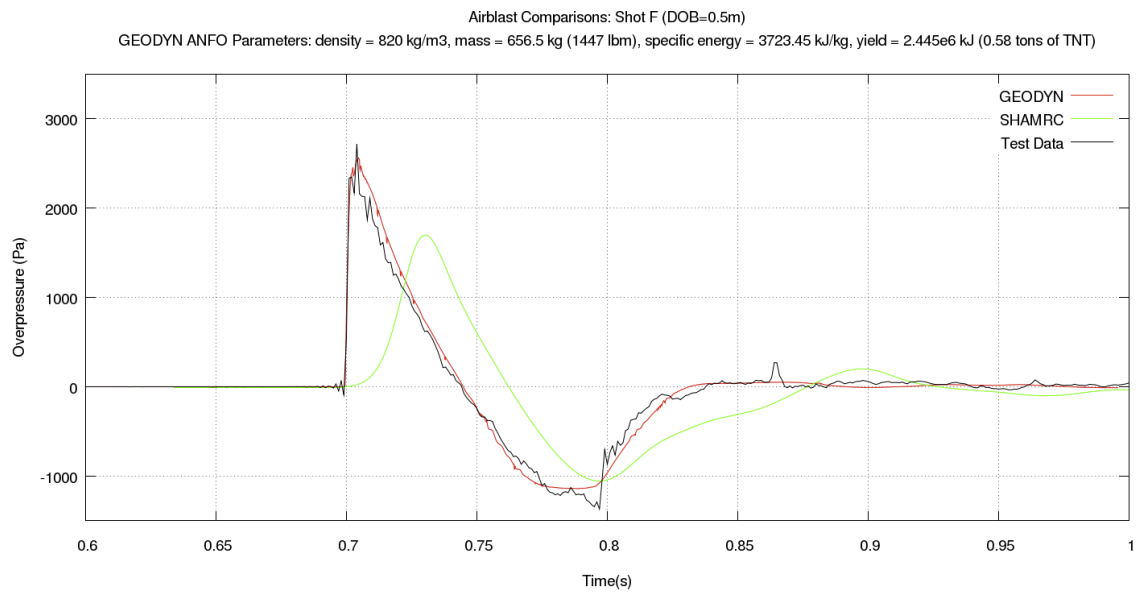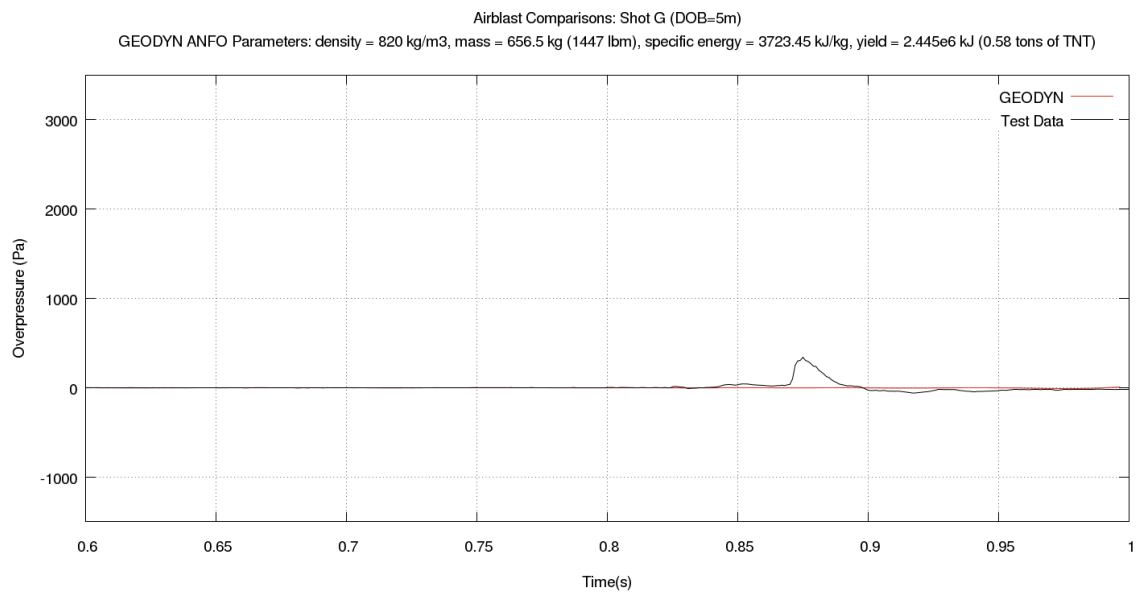**Figure 12:** Overpressure versus time for Shot E.

Airblast Comparisons: Shot F (DOB=0.5m)
GEODYN ANFO Parameters: density = 820 kg/m3, mass = 656.5 kg (1447 lbm), specific energy = 3723.45 kJ/kg, yield = 2.445e6 kJ (0.58 tons of TNT)

Figure 13: Overpressure versus time for Shot F.

Airblast Comparisons: Shot G (DOB=5m)
GEODYN ANFO Parameters: density = 820 kg/m3, mass = 656.5 kg (1447 lbm), specific energy = 3723.45 kJ/kg, yield = 2.445e6 kJ (0.58 tons of TNT)

Figure 14: Overpressure versus time for Shot G.

Table 4: Sound Speeds

Shot	Sound Speed (m/s)		
	Based on Recorded Environmental Conditions ($\gamma=1.4$)	GEODYN	% Error
A	349.81	349.81	N/A
B	347.02	343.94	0.89%
C	350.00	346.30	1.06%
D	345.15	342.81	0.68%
E	347.47	346.75	0.21%
F	346.44	345.07	0.40%
G	348.69	N/A	N/A

Table 5: Peak Overpressures

Shot	Peak Overpressures (Pa)		
	Test Data	GEODYN	% Error
B	2783.6	2961.1	-6.4%
C	2458.2	3015.1	-22.7%
D	1414.0	1844.0	-30.4%
E	2574.4	2710.5	-5.3%
F	2717.4	2559.6	5.8%

Table 6: Positive Phase Impulses

Shot	Positive Phase Impulse (Pa·s)		
	Test Data	GEODYN	% Error
B	65.6	69.5	-5.9%
C	63.1	64.7	-2.5%
D	23.5	35.6	-51.5
E	58.6	62.2	-6.1%
F	50.0	50.8	-1.6%
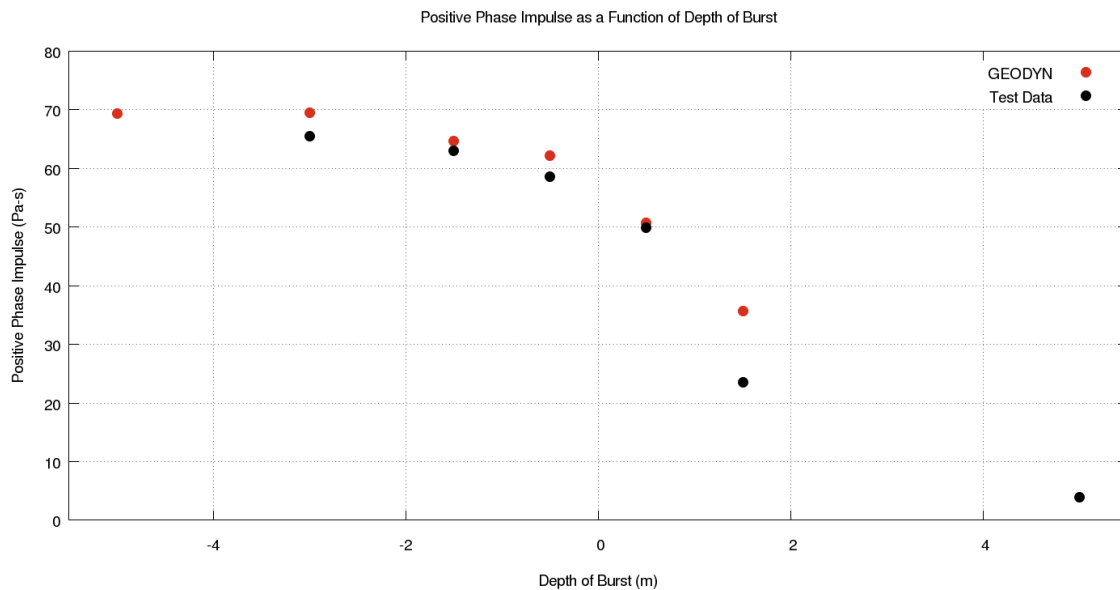
Figure 15: Positive phase impulse as a function of depth of burst for Shots B through F (a negative depth of burst indicates = a height of burst).

Conclusions

GEODYN was able to accurately simulate both the overpressure responses and the positive phase impulses for the series of Humble Redwood I chemical high explosive detonations. The limit to the accuracy of the model is directly coupled to the uncertainty in quantifying the material properties of the chemical explosive that make up the yield. The results of the modeling showed that with an appropriate mesh refinement scheme, GEODYN was able to predict the breakthrough as well as the shape of the actual overpressure response for an above ground detonation and shallowly buried shots. GEODYN appears to be a more than adequate tool to model an air blast, and it appears feasible to use air blast data posteriori in a GEODYN model in conjunction with other pieces of forensic information to ascertain the yield and height or depth of burst of an explosive detonation.

References

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