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Characterization of Jets From Exploding Bridge Wire Detonators

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A combined experimental and numerical study was conducted to characterize the jets from small exploding bridge wire detonators, which are small shaped charges. Two- and three-dimensional numerical results are compared to the experimental data.
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Acknowledgments

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Executive Summary

A combined experimental and numerical program was conducted at the U.S. Army Research Laboratory to characterize jets formed by three different Reynolds Industries Systems, Inc., exploding bridge wire (EBW) detonators. The detonators were designated as RP-1 SC EBW, a small (10.41-mm diameter) shaped charge (SC) with a conical liner; RP-4 SFF EBW, a 25.65-mm overall diameter detonator with a self-forging fragment (SFF) or explosively formed penetrator (EFP) liner; and RP-4 SC EBW, a 25.65-mm overall diameter detonator with a conical liner. The experimental study was conducted to determine the jet tip speeds and jet shapes. CTH\textsuperscript{1} hydrocode simulations were also conducted to model the jet formation for each EBW detonator by means of an axis-symmetric (two-dimensional) mesh. A comparison between CTH two- and three-dimensional simulations for the RP-4 SC EBW was performed. Numerical and experimental results were compared.

\textsuperscript{1}CTH is not an acronym.
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1. Background

A combined numerical and experimental program was conducted at the U.S. Army Research Laboratory (ARL) to characterize small jets from conical liners and a small explosively formed penetrator (EFP) by three different off-the-shelf detonators from Reynolds Industries Systems, Inc. (RISI). The simulations were completed before the experiments. This report describes the modeling techniques used for both the conical shaped charge (SC) and EFP formation simulation. Three types of exploding bridge wire (EBW) detonators, provided by RISI, were investigated in this study. The RISI catalogue designations were RP-1 SC EBW shaped charge part number (PN) 167-8673, the RP-4 SC EBW shaped charge PN 188-7377, and the RP-4 SFF EBW self-forging fragment (SFF) PN 188-7378. The jet properties from these charges have never been characterized. Therefore, the focus of this study sought to characterize the jets (i.e., jet shape, velocity, etc.). Figure 1 depicts the RP-1 SC EBW detonator geometry. The liner was made from copper, the sleeve from brass, and the explosive fill was pressed pentaerythrite tetranitrate (PETN). Figure 2 depicts the RP-4 SC EBW detonator geometry. The liner was a 60-degree copper cone and the explosive fill was plasticized hexogen (RDX). Figure 3 shows the geometry of the RP-4 SFF EBW detonator. The liner was made from copper and the explosive fill was plasticized RDX. Details of the liners and detonator assemblies were provided by RISI and are discussed later. The detonators were to be used in another application, which necessitated the conical SC and EFP characteristics. The other application involves using the formation simulation results to obtain the performance characteristics of the jets from the conical and EFP liners against various target scenarios.

Figure 1. RP-1 SC EBW shaped charge PN 188-7355. (Parts description: 1. RP-1 standard detonator head; 2. bridgewire: gold, 0.0015 inch diameter, 0.040 inch long; 3. PETN pressed: 530 mg; 4. cone: copper; 5. sleeve: brass, 0.050 inch thick.)
2. Experiments

The testing was performed at ARL’s experimental facility 108 at Aberdeen Proving Ground, Maryland, since this was the only facility available for this program. Three 150-kilo-electron volt (keV) x-ray tubes were placed 4 inches (102 mm) apart along a horizontal axis. The charge was positioned so that it pointed perpendicular to the x-ray axis at the location of the middle x-ray head. Because of limitations of the experimental facility, only 10 inches (254 mm) of vertical film coverage was possible. For the RP1 SC EBW detonator, in particular, the radiographic measurements were extremely difficult to resolve because of the extremely small particle size produced by the charge.
The jet and EFP free flight flash radiographs are shown in figures 4 through 9. Figures 4 through 6 show the flash radiographs for the RP-1 SC EBW for shot numbers 814, 815, and 817, respectively. The radiographs show that the RP-1 SC EBW is not a well-formed shaped charge jet (SCJ) in that the jet particles were not collinear. In addition, the experimentally determined jet tip velocities vary significantly, as listed in table 1. The jet tip velocity was determined to range from 2,653 to 4,867 m/s plus or minus the error measurement. This is because of limitations of the experimental facility, the fact that the shaped charges were not precision manufactured, and difficulty in the determination of the exact location of the leading particle in the radiographs.

Figure 4. RP-1 SC EBW shot No. 814. (X-ray flash times are 13.7, 23.6, and 33.6 µs.)
Figure 5. RP-1 SC EBW shot No. 815. (X-ray flash times are 13.6, 23.5, and 33.5 µs.)
Figure 6. RP-1 SC EBW shot No. 817. (X-ray flash times are 13.4, 23.4, and 33.5 µs.)
Figure 7 shows the free flight jet for the RP-4 SC EBW at three radiograph flash times. The figure shows that the RP-4 SC EBW produces a well-formed jet. The jet remains relatively collinear and cohesive. At 23.6 µs, some necking near the rear of the jet is evident. The jet tip velocity was determined to be around 5,313 m/s (see table 1). The jet diameter for this charge was requested by RISI, and the measured jet diameter was 3.1 mm at the tip, 1.05 mm in the middle of the jet, and 3.0 mm at the tail. These values were measured at the latest flash time (23.6 µs), but the jet was still stretching.

Figure 7. RP-4 SC EBW shot No. 816. (X-ray flash times are 10.7, 18.7, and 23.6 µs.)
Figures 8 and 9 show the free flight EFP for the RP-4 SFF EBW charge with the radiograph flash times given in the figure captions, for shot numbers 779 and 778, respectively. Figure 8 shows the EFP in the early stages of formation and figure 9 shows the EFP at the later stages of formation. The velocity of the leading edge of both is between 2,900 and 3,000 m/s (see table 1). Figures 8 and 9 show that although the leading edge velocity of the EFP is fairly consistent, the EFP’s final shape can vary considerably.

Figure 8. RP-4 SFF EBW shot No. 779. (X-ray flash times are 15.1 and 30.7 µs.)
Figure 9. RP-4 SFF EBW shot No. 778. (X-ray flash times are 50.6 and 75.5 µs.)
### Table 1. Experimental results.

<table>
<thead>
<tr>
<th>Shot No.</th>
<th>Jet Tip Velocity (m/s)</th>
<th>Error (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>814</td>
<td>4867 ±147</td>
<td></td>
</tr>
<tr>
<td>815</td>
<td>2653 ±53</td>
<td></td>
</tr>
<tr>
<td>817</td>
<td>4243 ±133</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shot No.</th>
<th>Jet Tip Velocity (m/s)</th>
<th>Error (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>816</td>
<td>5313 ±125</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shot No.</th>
<th>Tip Velocity (m/s)</th>
<th>Error (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>778</td>
<td>2984</td>
<td>±36</td>
</tr>
<tr>
<td>779</td>
<td>2953</td>
<td>±51</td>
</tr>
</tbody>
</table>

Any significant errors in the charge velocities can be attributed to three main sources of error: 1) placement of the charge with reference to the x-ray tubes, 2) measurements from the radiographs, and 3) the measurement of time between the x-ray flashes. The placement errors included translational errors in the X and Y planes, as well as rotational errors attributable to angular departure from perfectly plumb. These placement errors totaled approximately $\frac{1}{8}$ inch (3.2 mm) and contributed to changes in the correction factor used to remove the magnification of the radiographic images. The error for the film measurements was ±0.010 inch (0.25 mm) per measurement. The timing error was $1 \times 10^{-7}$ seconds for each measurement. In general, we obtained the velocities by dividing a small distance by a short time, thereby magnifying the effect of the accumulated errors. Based on the errors just discussed, the jet tip or EFP velocities and associated errors are given in table 1.

### 3. Simulation Setup

Three two-dimensional (2-D) axis-symmetric simulations were conducted with a fine resolution mesh, one for each detonator type. An additional three-dimensional (3-D) simulation of the jet formation was performed for the RP-4 SC EBW SC with the same cell size of the coarse resolution mesh needed for 3-D simulations involving a target. Thus, the 3-D simulation would be used to determine whether the coarse mesh would still adequately model small jets.

The simulations were performed with the March 1999 version of the CTH hydrocode (2), which is a state-of-the-art, second order accurate, Eulerian hydrocode undergoing continuous development at the Sandia National Laboratories, Albuquerque, New Mexico. CTH is capable of solving complex problems in shock physics in one, two, or three dimensions. The code provides several constitutive models, including an elastic-perfectly plastic model with provisions for work hardening and thermal softening, the Johnson-Cook model (3), the Zerrilli-Armstrong model (4), the Steinberg-Guinan-Lund model (5, 6), an undocumented power-law model, and
others. High explosive detonation can be modeled via the programmed burn model, the Chapman-Jouguet volume burn models, or the history variable reactive burn model (7). Several equation-of-state (EOS) options are available, including tabular (i.e., SESAME\(^2\)), analytical equation of state (ANEOS), Mie-Grüneisen, and Jones-Wilkins-Lee (JWL) (8). Material failure occurs when a threshold value of tensile stress or hydrostatic pressure is exceeded. In addition, the Johnson-Cook fracture model (9) is available. When failure occurs in a cell, void is introduced until the stress state of the cell is reduced to zero. Recompression is permitted. To reduce the diffusion typically encountered in Eulerian simulations, several advanced material interface tracking algorithms are provided, including the high-resolution interface tracking algorithm (available for 2-D simulations only), the simple line interface calculation algorithm (10), and the Sandia-modified Young’s reconstruction algorithm (11).

Initial simulations of the SCJs and EFP were performed in 2-D axis-symmetric configuration. The RP-4 SC EBW was repeated with quarter symmetry in a 3-D model with a mesh resolution similar to that needed to model jet-target impacts. The detonator geometries used in the CTH simulations for the RP1 SC EBW, RP4 SC EBW, and RP4 SFF EBW were simplified from the drawings shown in figures 10 through 12. The origin of the coordinate system used in all simulations was placed at the base of the liner. For the axis-symmetric simulations, the mesh consisted of \(650 \times 6600\) cells for the RP1 SC EBW simulation and \(1500 \times 7500\) cells for both the RP4 SC EBW and RP4 SFF EBW simulations. The cell size for all axis-symmetric simulations was \(0.001 \times 0.001\) cm and was uniform throughout the meshes. The 3-D RP4 SC EBW mesh consisted of \(150 \times 750 \times 150\) cells having a uniform size of \(0.01 \times 0.01 \times 0.01\) cm with planes of symmetry at \(x = 0\) and \(z = 0\). A Lagrangian tracer particle was placed at the origin of the coordinate system of each simulation to capture the jet tip or EFP leading edge velocity.

![Figure 10. RP-1 SC EBW geometry used for simulation. (Dimensions are in centimeters.)](image)

\(^{2}\)Not an acronym
Figure 11. RP-4 SC EBW geometry used for simulation. (Dimensions are in centimeters.)

Figure 12. RP-4 SFF EBW EFP geometry used for simulation. (Dimensions are in centimeters.)
The copper liners were modeled with standard copper properties for the Johnson-Cook constitutive model and CTH library values for the Mie-Grüneisen EOS. The same holds true for the brass case for the RP1 SC EBW simulation. The aluminum case for the RP4 SC EBW and RP4 SFF EBW simulations was modeled with the Johnson-Cook constitutive model and the SESAME tabular EOS available in the CTH material library. Failure in the metals was modeled with a simple tensile pressure criterion so that failure for copper, brass, and aluminum would occur when the tensile pressure would exceed 0.345, 1.300, and 0.400 GPa, respectively. The explosives, PETN and plastic-bonded explosive (PBX) 9407, were treated as fluids (i.e., they do not support strength). The JWL EOS was used to model the pressure-volume-energy behavior of the detonation products with parameters reported by Dobratz (12). A simple programmed burn model was used to model explosive initiation. In the axis-symmetric simulations, the explosive was initiated along a line at the bottom of the explosive and in the 3-D simulation, the explosive was initiated at a disk at the bottom of the explosive. A complete listing of the CTH input for the axis-symmetric simulations for the RP1 SC EBW, RP4 SC EBW, and RP4 SFF EBW is given in appendices A through C, respectively. The CTH input for the 3-D simulation of the RP4 SC EBW is shown in appendix D.

4. Results and Discussion

4.1 RP-1 SC EBW Simulation

Figure 13 shows the jet formation of the RP-1 SC EBW charge at times that roughly correspond to the times shown in the flash radiographs in figures 4 through 6. Like the jet in the experiments, the jet particulates early. Figure 14 shows the axial velocity profile of the jet at 13 $\mu$s. The jet tip velocity is 3.3 km/s, which is within the range of tip velocities listed in table 1. The RP-1 SC EBW charge produced a poorly formed jet.

4.2 RP-4 SC EBW Simulations

Figure 15 shows the RP-4 SC EBW 2-D axis-symmetric simulation results at 0, 11, and 19 $\mu$s. These free flight times were chosen to roughly match the flash radiographs in figure 7. The general shape of the jet in both the experiment and the simulation agrees. However, there seems to be a time mismatching between the experiment and simulation. Time zero for the simulation corresponds to when the explosive was line initiated at the base of the explosive charge, as shown in figure 11. Time zero in the experiments corresponds to when an electrical current was applied to the standard detonator head (item 1 in figure 2). Thus, the time-zero offset suggests that the simulation times correspond to later experimental times. It is estimated that the difference between the experiments and simulation is about 5 $\mu$s.
Figure 13. RP-1 SC EBW jet formation at (a) 0 µs, (b) 13 µs, (c) 23 µs, and (d) 33 µs.

Figure 16 shows the RP-4 SC EBW 3-D simulation results at 0 and 11 µs. The purpose of this simulation was to determine whether a coarser 3-D mesh could accurately capture the jet formation and jet tip velocity, since a coarse mesh would be needed to model jet-target interactions. A comparison of figures 15(b) and 16(b) indicates little difference between the jet formation of the 2-D and 3-D simulations. Thus, the mesh for the 3-D simulation is adequate. Figure 17 shows the axial jet velocity profile of the RP-4 SC EBW charge at 12 µs for the 2-D and the 3-D simulations. Note that there are only minor differences in the velocity profile, most notably at the leading edge of the jet. The jet tip velocity was determined to be 5.7 km/s for the
2-D simulation, while it was 5.6 km/s for the 3-D simulation. Thus, the simulations over-predict the experimentally determined tip velocity, 5.313 ± 0.125 km/s, by approximately 7%. However, with only one experiment, the data scatter is unknown.

Figure 14. RP-1 SC EBW axial jet velocity profile at 13 µs.
Figure 15. RP-4 SC EBW jet formation at (a) 0 µs, (b) 11 µs, and (c) 19 µs.
4.3 RP-4 SFF EBW Simulation

Formation of the EFP is shown in figure 18 at times that roughly correspond to the experimental radiograph flash times in figures 8 and 9. Again, there is some difference in time because of the difference in time zero between the experiments and the simulation, with the simulation time being later than the experiments. The estimated time difference is about 5 µs. At 20 µs, a global velocity transformation was performed to subtract 2.9 km/s in the axial direction from the mesh to freeze the EFP’s forward motion while allowing it to continue to deform, thereby minimizing the size of the mesh needed to complete the simulation to 50 µs. The leading edge velocity
determined from the simulation was 2.8 km/s and agrees very well with the velocities determined from two experiments (see table 1). The EFP shape shown in figures 8 and 9 varies a great deal. These experiments show that the RP-4 SFF EBW detonator forms penetrators that fail to create a consistent shape. Thus, it is difficult to say how well the EFP shape determined from simulation agrees with the experiments.

Figure 18. RP-4 SFF EBW EFP formation at (a) 0 µs, (b) 15 µs, (c) 31 µs, and (d) 50 µs.
5. Conclusions

The results of numerical simulations of the free flight characteristics of two conical SC and one EFP were presented. The charges were on the order of 1 inch in diameter. The simulations were compared to experimental data and were performed in advance of the experiments. The 2-D jet formations were simulated with a very fine Eulerian computational mesh. A 3-D simulation involving a target impact scenario would require a much coarser computational mesh. The results for both the 2-D and 3-D simulations of the RP-4 SC EBW are in good agreement.

The off-the-shelf detonators were not precision manufactured devices, and thus, there was a lot of scatter in the experimental data. The RP-1 SC EBW jet particles do not remain collinear nor do they have a consistent jet tip velocity. The jet tip velocity obtained numerically fell within the scatter of the experimental data. The RP-4 SC EBW detonator produced a well-formed jet, as observed in the experiment and simulations. Based on one experiment for the RP-4 SC EBW detonator, free flight jet characteristics such as overall shape and tip velocity show good agreement between the experiment and simulations. The tip velocity of the EFP (RP-4 SFF EBW detonator) predicted by the simulation is also in good agreement with the limited experimental results.

Generally, the CTH simulations predicted jet characteristics that are in good agreement with the limited experimental data for off-the-shelf EBW detonators.

![Figure 19. RP-4 SFF EBW axial EFP velocity profile at 15 µs.](image)
6. References


12. Dobratz, B. M. *LLNL Explosives Handbook*; UCRL-5299; Lawrence Livermore Laboratory, University of California: Livermore, CA 1981.
Appendix A. Input Deck for RP-1 SC EBW Simulation

* 
* id=1 - Starting baseline configuration 
* 
*eor*cgenin
* 
ID=1: EBW Shaped Charge RP-1 SC 
* 
control 
  ep 
  mmp 
endcontrol 
* 
mesh 
  block  geometry 2dc  type e 
    x0=0.0 
    x1  n=650  dx=0.001 rat=1. 
  endx 
  y0=-2.5 
  y1  n=6600 dyf=0.001 rat=1. 
  endy 
*  xact=0.0,1.0 
*  yact=0.0,5.0 
endblock 
endmesh 
* 
insertion of material 
  block 1 
* 
    package 'Cu Liner' 
      material 1 
      numsub 50 
      insert circle 
        center  0.0000  -0.4103 
        radius  0.1524 
      endinsert 
      delete circle 
        center  0.0000  -0.4103 
        radius  0.1270 
      enddelete 
    delete uds 
      p1      0.0000   0.0000 
      p2      0.3835   0.0000 
      p3      0.1320  -0.4865 
      p4      0.1100  -0.4738 
      p5      0.0000  -0.4738 
    enddelete 
endpackage 
* 
    package 'Cu Liner' 
      material 1 
      numsub 50 

insert uds
  p1  0.3835  0.0000
  p2  0.3835 -0.0508
  p3  0.1320 -0.4865
  p4  0.1100 -0.4738
endinsert
endpackage
*
package 'PETN Explosive'
material 2
numsub 50
insert uds
  p1  0.3835 -0.0504
  p2  0.3835 -1.4111
  p3  0.0000 -1.4111
  p4  0.0000 -0.5627
  p5  0.1320 -0.4865
endi
delete circle
center  0.0000  -0.4103
radius  0.1524
enddelete
endpackage
*
package 'Brass Case'
material 3
numsub 50
insert box
  p1  0.3835  0.0000
  p2  0.5205 -1.4111
endi
endpackage
*
endblock
endinsertion
*
epdata
*
matep 1  johnson-cook copper     poisson 0.340
matep 3  johnson-cook brass      poisson 0.340
vpsave
mix 3
endep
*
eos
mat1 mgrun  copper
mat2 jwl    petn1
mat3 mgrun  brass
endeos
*
heburn
material 2  d 5.17e5  pre 1.0e12
dline 0.0000  -1.4111 to 0.3835  -1.4111  ti 0.0  radius 0.05
endheburn
*
tracer
  add  0.0  0.0
endtracer
*
*eor*cthin
*
ID=1: EBW Shaped Charge RP-1 SC
*
control
tstop=50.e-6
cpshift=900.
rdumpf=3600
ntbad 100000000
endcontrol
*
restart
time=1.e-6
endr
*
cellthermo
  mmp2
endcell
*
convct
  convect=1
  interface=high
endc
*
discard
*
  material 1 density -.001 pressure 1.0e12  ton 1.1e-6
  material 2 density -0.01 pressure 5.0e6 ton 1.1e-6
  material 2 density 10.00 pressure 1.0e12 ton 2.8e-6 toff 2.9e-6
endd
*
edit
  shortt
time=0. dtf=10000.
ends
longt
time=0. dtf=10000.
endl
plott
time=0. dtf=0.05e-6
endp
plotdata
  volume
  mass
  temperature
  pressure
  velocity
endplotdata
restt
time=0  dtf=1.e-6
endr
histc
cycle=0 dcfreq=1
  htracer1
endh
endedit
*   
  mindt  
      time=0.  dtmin=1.0e-13  
  endm  
  *
  fracts
      pressure
      pf1rac1=-3.45e9
      pf1rac2=-1e9
      pf1rac3=-13.00e9
      pfmix=-5.0E20
      pfvoid=-5.0E20
  endf
  *
  boundary
      bbydro
          block=1
          bxbot 0
          bxtop 2
          bybot 2
          bytop 2
      endb
  endh
  endb
  *
  *eor*pltin
  *

Appendix B. Input Deck for RP-4 SC EBW Simulation

*  
* id=1 - Starting baseline configuration  
*  
eor*cgemin  
*  
ID=1: EBW Shaped Charge RP-4 SC  
*  
control  
  ep  
  mmp  
endcontrol  
*  
mesh  
  block  geometry 2dc type e  
    x0=0.0  
    xl  n=1500  dxf=0.001 rat=1.  
endx  
    y0=-2.5  
    yl  n=7500 dyf=0.001 rat=1.  
endy  
  *  
  xact=0.0,1.0  
  yact=0.0,5.0  
endblock  
endmesh  
*  
insertion of material  
  block 1  
*  
    package 'Cu Liner'  
      material 1  
      numsub 50  
    insert circle  
      center 0.0000 -1.3958  
      radius 0.1270  
    endinsert  
    delete circle  
      center 0.0000 -1.3958  
      radius 0.0762  
    enddelete  
    delete uds  
      p1 0.0000 0.0000  
      p2 0.9525 0.0000  
      p3 0.8425 -1.4593  
      p4 0.8279 -1.4339  
      p5 0.0000 -1.4339  
    enddelete  
endpackage  
*  
    package 'Cu Liner'  
      material 1  
      numsub 50  
  

insert uds
  p1  0.8938  0.0000
  p2  0.9525  0.0000
  p3  0.1100 -1.4593
  p4  0.0660 -1.4339
endinsert
endpackage

*package 'PBX 9407 Explosive'
material 2
numsub 50
insert uds
  p1  0.9525  0.0000
  p2  0.9525 -0.6653
  p3  0.4435 -1.9698
  p4  0.0000 -1.9698
  p5  0.0000 -1.5228
  p6  0.1100 -1.4593
endi
delete circle
center  0.0000 -1.3958
radius  0.1270
enddelete
endpackage

*package 'Aluminum Case'
material 3
numsub 50
insert uds
  p1  0.9525  0.0000
  p2  1.2825  0.0000
  p3  1.2825 -0.8131
  p4  0.9033 -1.7850
  p5  0.9033 -1.9698
  p6  0.4435 -1.9698
  p7  0.9225 -0.6653
endi
endpackage

*endblock
endinsertion

*epdata
*
mat1 johnson-cook copper     poisson 0.340
mat2 johnson-cook aluminum   poisson 0.330
vpsave
mix 3
endeep

*eos
mat1 mgrun copper
mat2 jwl pbx-9407
mat3 sesame aluminum feos='/ha/cta/unsupported/CTH/CTH_9903/data/sesame'
endeos

*heburn
material 2  d 7.91e5  pre 1.0e12
dline 0.0000 -1.9698 to 0.4435 -1.9698  ti 0.0  radius 0.05
endheburn
*
tracer
   add 0.0 0.0
endtracer
*
*eor*cthin
*
ID=1: EBW Shaped Charge RP-4 SC
*
control
tstop=50.e-6
cpshift=900.
rdumpf=3600
ntbad 100000000
endcontrol
*
*restart
*  time=2.e-6
*endr
*
cellthermo
   mmp2
endcell
*
convct
   convect=1
   interface=high
endc
*
discard
*  material 1  density -.001 pressure 1.0e12  ton 1.1e-6
   material 2  density -0.01  pressure 5.0e6  ton 2.1e-6
   material 2  density 10.00  pressure 1.0e12  ton 4.0e-6 toff 4.1e-6
   material 3  density 10.00  pressure 1.0e12  ton 4.0e-6 toff 4.1e-6
enda
*
edit
   shortt
      time=0. dtf=10000.
end
   longt
      time=0. dtf=10000.
endl
   plott
      time=0. dtf=0.05e-6
endp
plotdata
   volume
   mass
   temperature
   pressure
   velocity
endplotdata
restr
time=0  dtf=1.e-6
endr
histc
cycle=0  dcfreq=1
htracer1
endh
endedit
*
mindt
time=0.  dtmin=1.0e-13
endm
*
fracts
pressure
pfrac1=-3.45e9
pfrac2= -1e9
pfrac3=-4.00e9
pfmix =-5.0E20
pfvoid=-5.0E20
endf
*
boundary
bhydro
block=1
bxbot 0
bxtop 2
bybot 2
bytop 2
endb
endh
endb
*
*eor*pltin
*
Appendix C. Input Deck for RP-4 SFF EBW Simulation

*  
* id=1 - Starting baseline configuration  
*  
eor*cgenin  
*  
ID=1: EBW Shaped Forging Fragment RP-4 SFF  
*  
control  
  ep  
  mmp  
endcontrol  
*  
mesh  
  block  geometry 2dc  type e  
    x0=0.0  
      x1  n=1500  dxf=0.001  rat=1.  
    endx  
    y0=-2.5  
      y1  n=7500  dyf=0.001  rat=1.  
    endy  
*  
  xact=0.0,1.0  
*  
  yact=0.0,5.0  
endblock  
endmesh  
*  
insertion of material  
  block 1  
*  
  package 'Cu Liner'  
    material 1  
      numsub 50  
      insert circle  
        center 0.0000 2.6941  
        radius 2.9108  
      endinsert  
    delete circle  
      center 0.0000 2.6941  
      radius 2.8575  
    enddelete  
    delete box  
      p1 0.0000 0.0000  
      p2 10.0000 10.0000  
    enddelete  
    delete box  
      p1 0.9525 -10.0000  
      p2 10.0000 10.0000  
    enddelete  
  endpackage  
*  
  package 'PBX 9407 Explosive'  
    material 2  

31
numsub 50
insert uds
  p1  0.0000  0.0000
  p2  0.9525  0.0000
  p3  0.9525 -0.6653
  p4  0.4435 -1.9698
  p5  0.0000 -1.9698
endi
delete circle
  center 0.0000 2.6941
  radius 2.9108
enddelete
endpackage
*
package 'Aluminum Case'
material 3
numsub 50
insert uds
  p1  0.9525  0.0000
  p2  1.2825  0.0000
  p3  1.2825 -0.8131
  p4  0.9033 -1.7850
  p5  0.9033 -1.9698
  p6  0.4435 -1.9698
  p7  0.9225 -0.6653
endi
endpackage
*
endblock
endinsertion
*
epdata
*
matep 1 johnson-cook copper poisson 0.340
matep 3 johnson-cook aluminum poisson 0.330
vpsave
mix 3
endeo
*
eos
  mat1 mgrun copper
  mat2 jwl pbx-9407
  mat3 sesame aluminum feos='/ha/cta/unsupported/CTH/CTH_9903/data/sesame'
endeos
*
heburn
  material 2  d 7.91e5 pre 1.0e12
dline 0.0000 -1.9698 to 0.4435 -1.9698 ti 0.0 radius 0.05
endheburn
*
tracer
  add  0.0   0.0
endtracer
*
eor*cthin
*
ID=1: EBW Shaped Forging Fragment RP-4 SFF
* 
control 
tstop=50.e-6
cpshift=900.
nsccycle=110000
rdumpf=3600
ntbad 1000000000
endcontrol 
* 
*restart 
time=19.e-6
*endr 
* 
cellthermo
mmp2
endcell
* 
convct
conve=1
interface=high
endc
* 
discard 
* material 1 density -.001 pressure 1.0e12 ton 1.1e-6 
material 2 density 0.01 pressure 5.0e6 ton 2.1e-6 
material 2 density 10.00 pressure 1.0e12 ton 4.0e-6 toff 4.1e-6 
material 3 density 10.00 pressure 1.0e12 ton 4.0e-6 toff 4.1e-6
endd
* 
vadd
block=1
tadd 20e-6 
yvel -2.9e5
endvadd
* 
edt 
shortt
time=0. dtf=10000.
ends
longt
time=0. dtf=10000.
endl
plott
time=0. dtf=0.05e-6
endp
plotdata
volume
mass
temperature
pressure
velocity
endplotdata
restt
time=0 dtf=1.e-6
endr
histc
cycle=0 dcfreq=1
htracer1
endh
dedite
*

time=0.  dtmin=1.0e-13
dedm
*
fracts
pressure
pfrac1=-3.45e9
pfrac2= -1e9
pfrac3=-4.00e9
pfrac4 =-5.0E20
pfracv=-5.0E20
endf
*
boundary
bhydro
  block=1
  bxbot 0
  bxtop 2
  bybot 2
  bytop 2
endb
dedh
dedm
*
*eor*pltin
Appendix D. Input Deck for RP-4 SC EBW 3-D Simulation

* id=1 - Starting baseline configuration
* eor*cgenin
* ID=1: 3D EBW Shaped Charge RP-4 SC
* control
ep
mmp
endcontrol
* mesh
  block  geometry 3dr  type e
    x0=0.0
    x1  n=150  dx=0.01  rat=1.
  endx
    y0=-2.5
    y1  n=750  dy=0.01  rat=1.
  endy
    z0=0.0
    z1  n=150  dz=0.01  rat=1.
  endz
  *  xact=0.0,1.0
  *  yact=0.0,5.0
  endblock
endmesh
* insertion of material
  block 1
  *
    package 'Cu Liner'
    material 1
    numsub 10
    insert sphere
      center  0.0000  -1.3958   0.0000
      radius  0.1270
    endinsert
    delete sphere
      center  0.0000  -1.3958   0.0000
      radius  0.0762
    enddelete
delete r2dp
cel  0.0000  0.0000  0.0000
cel  0.0000  1.0000  0.0000
p1   0.0000   0.0000
p2   0.9525  0.0000
p3   0.8425  -1.4593
p4   0.8279  -1.4339
p5   0.0000  -1.4339
enddelete
endpackage
*
package 'Cu Liner'
material 1
numsub 10
insert r2dp
  ce1 0.0000 0.0000 0.0000
  ce2 0.0000 1.0000 0.0000
  p1 0.8938 0.0000
  p2 0.9525 0.0000
  p3 0.1100 -1.4593
  p4 0.0660 -1.4339
endinsert
endpackage
*
package 'PBX 9407 Explosive'
material 2
numsub 10
insert r2dp
  ce1 0.0000 0.0000 0.0000
  ce2 0.0000 1.0000 0.0000
  p1 0.9525 0.0000
  p2 0.9525 -0.6653
  p3 0.4435 -1.9698
  p4 0.0000 -1.9698
  p5 0.0000 -1.5228
  p6 0.1100 -1.4593
endi
delete sphere
  center 0.0000 -1.3958 0.0000
  radius 0.1270
enddelete
endpackage
*
package 'Aluminum Case'
material 3
numsub 10
insert r2dp
  ce1 0.0000 0.0000 0.0000
  ce2 0.0000 1.0000 0.0000
  p1 0.9525 0.0000
  p2 1.2825 0.0000
  p3 1.2825 -0.8131
  p4 0.9033 -1.7850
  p5 0.9033 -1.9698
  p6 0.4435 -1.9698
  p7 0.9225 -0.6653
endi
endpackage
*
endblock
endinsertion
*
epdata
*
  matep 1  johnson-cook copper     poisson 0.340
  matep 3  johnson-cook aluminum   poisson 0.330
vpsave
mix 3
endep
*

eos
mat1 mgrun copper
mat2 jwl pbx-9407
mat3 sesame aluminum feos=':/ha/cta/unsupported/CTH/CTH_9903/data/sesame'
endeos
*
heburn
  material 2 d 7.91e5 pre 1.0e12
ddisk 0.0000 -1.9697 0.0000
to 0.4435 -1.9697 0.0000
and 0.0000 -1.9697 0.4435
ti 0.0 radius 0.05
endheburn
*
tracer
  add 0.0 0.0 0.0
endtracer
*
*eor*cthin
*
ID=1: EBW Shaped Charge RP-4 SC
*
control
tstop=25.e-6
cpshift=900.
rdumpf=3600
ntbad 10000000000
endcontrol
*
restart
time=4.0e-6
* cycle=1911
endr
*
cellthermo
mmp2
endcell
*
convct
convect=1
interface=smyra
endc
*
discard
material 1 density -.001 pressure 1.0e12 ton 4.3e-6
material 2 density -0.01 pressure 5.0e6 ton 2.1e-6
material 2 density 10.00 pressure 1.0e12 ton 4.3e-6 toff 4.4e-6
material 3 density 10.00 pressure 1.0e12 ton 4.3e-6 toff 4.4e-6
endd
*
edi
t shortt
time=0. dtf=10000.
### Acronyms

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<td>3-D</td>
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<td>ANEOS</td>
<td>analytic equation of state package</td>
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<td>ARL</td>
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<td>EBW</td>
<td>exploding bridge wire</td>
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<td>explosively formed penetrator</td>
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<td>equation of state</td>
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<td>JWL</td>
<td>Jones-Wilkins-Lee</td>
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<td>RISI</td>
<td>Reynolds Industries Systems, Incorporated</td>
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<td>SC</td>
<td>shaped charge</td>
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<td>SCJ</td>
<td>shaped charge jet</td>
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<td>SFF</td>
<td>self-forging fragment (old terminology for an EFP)</td>
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ATTN AMSRD ARL WM MB W DEROSSET  
R DOWDING  
BLDG 4600 |
| 1            | US ARMY RESEARCH LABORATORY  
ATTN AMSRD ARL WM T B BURNS  
BLDG 309 |
| 1            | US ARMY RESEARCH LABORATORY  
ATTN AMSRD ARL WM TA W GILICH  
BLDG 309 |
| 11           | US ARMY RESEARCH LABORATORY  
ATTN AMSRD ARL WM TA W GOOCH  
M BURKINS (5 CYS) T HAVEL  
M KEELE D KLEPONIS  
J RUNYEON S SCHOENFELD  
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R BANTON R LOTTERO  
J STARKENBERG  
BLDG 309 |
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R COATES T FARRAND  
E KENNEDY K KIMSEY  
L MAGNESS S SCHRAML  
D SCHEFFLER (6 CYS)  
B SORESEN R SUMMERS  
C WILLIAMS W WALTERS (6 CYS)  
R ANDERSON M FERMEN-COKER  
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