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# Modeling Threshold Velocity of Hemispherical and Ogival-Nose Tungsten-Alloy Penetrators Perforating Finite Aluminum Targets

by Daniel R. Scheffler

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## **Modeling Threshold Velocity of Hemispherical and Ogival-Nose Tungsten-Alloy Penetrators Perforating Finite Aluminum Targets**

**Daniel R. Scheffler**

Weapons and Materials Research Directorate, ARL

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## **Abstract**

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This study examines the ability of the CTH hydrocode to predict the effect of rod nose-shape on the transition from rigid body to eroding rod penetration for tungsten alloy long-rod penetrators perforating finite aluminum targets. Two rod nose-shapes and two target alloys were considered. The rod nose-shapes were hemispherical and ogival, and the target alloys were 7.62-cm-thick 5083 and 7039 aluminum. Results are compared to an experimental study that delineated the effect of nose-shape on the threshold velocity at which tungsten alloy penetrators transition from rigid body to eroding rod when perforating finite aluminum targets.

## Acknowledgments

The author would like to thank Dr. Steven B. Segletes and Mr. Kent D. Kimsey for their helpful comments and suggestions regarding this paper. The author would especially like to thank Dr. Lee S. Magness, Jr. for discussions regarding his experiments and assuring the accuracy of the discussions of them. Additional thanks go to Dr. Stewart A. Silling of Sandia National Laboratories for discussions regarding his boundary layer interface algorithm and for providing an advanced copy of parts of his user manual.

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# 1. Introduction

In examining the convergence characteristics of the Eulerian CTH hydrocode [1] as a function of spatial resolution, Zukas [2] found that the code could not accurately predict perforation of armor plate by a hard projectile at low velocities (less than 1.5 km/s). A penetrator, which, in experiments, perforated a finite steel target with significant residual length and velocity, was predicted to be unable to perforate the target. Previously, this problem had been modeled successfully using an in-house version of the EPIC Lagrangian hydrocode. Zukas observed that, regardless of the mixed cell strength formulation used (several are available in the CTH hydrocode), high-strength penetrator material included in a mixed cell was modeled as being significantly softer—an unrealistic treatment that caused excessive deformation in the penetrator. The net effect was that the CTH hydrocode could not accurately model the rigid-body penetration of a soft target, an eroding projectile penetrating harder targets at low velocities or the sliding between two material interfaces.

A new boundary layer algorithm for sliding interfaces (BLINT) was recently incorporated into the CTH hydrocode for two-dimensional problems only [3]. The algorithm relocates the slip layer outside of mixed cells into the softer material, thus allowing hard materials to penetrate as rigid bodies. Good correlation with experiments has been obtained using the BLINT algorithm by Silling [4] and Kmetyk and Yarrington [5]. Both modeled hard penetrators impacting soft targets knowing, a priori, that the penetrators would remain rigid.

This study examined the ability of the CTH hydrocode (August 1993 release) to predict the impact velocity at which a penetrator would transition from rigid-body to eroding-rod, the effect of the rod's nose shape on this transition velocity and its residual velocity and shape while perforating finite aluminum targets. The perforation of soft aluminum targets by tungsten alloy (95W-2.5Ni-1.0Fe-1.5Co, cold worked by swaging to a 21% reduction in area) long rods was modeled. To gauge the accuracy of the CTH hydrocode with the BLINT algorithm, the simulation results were compared to the experimentally determined residual penetrator velocity and shape [6].

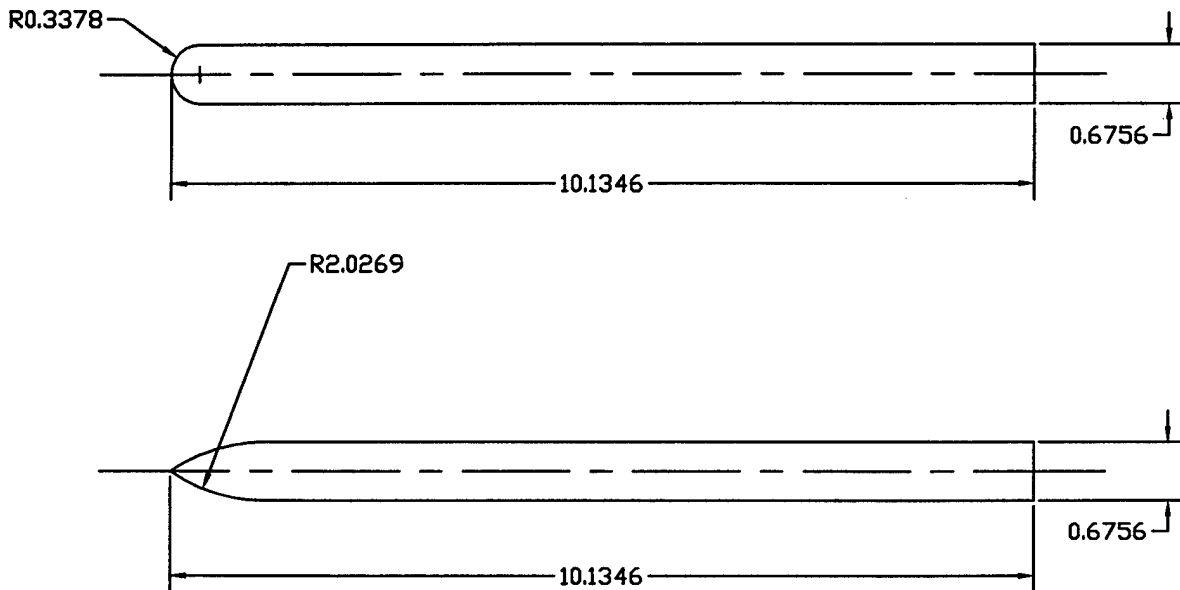
Two rod nose-shapes and two target alloys were considered. The rod nose-shapes were hemispherical and ogival, and the target alloys were 7.62-cm (3 in)- thick 5083 and 7039 aluminum.

A subset of the results of this study first appeared at the Symposium on Structures Under Extreme Loading Conditions as part of the 1996 ASME Pressure Vessel and Piping Conference that took place in Montreal, Canada from 21–26 July 1996 [7]. A companion paper [8] and report [9] also exist, which provide the simulation results for impacts with 53.34-cm-thick aluminum targets where results are compared with experimental depth-of-penetration (DOP) tests. The companion report provides more detail than the companion paper. This report differs from the original paper by including additional simulations and experiments, a more detailed discussion of the BLINT model, the examination of effective plastic strains, as well as the input decks used for the simulations.

The CTH hydrocode is a state-of-the-art, second-order accurate, Eulerian hydrocode developed by Sandia National Laboratories which 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 [10], the Zerrilli-Armstrong model [11], the Steinberg-Guinan-Lund model [12, 13], and an undocumented power-law model. High-explosive detonation can be modeled using the programmed burn model, the Chapman-Jouguet volume burn models, or the history variable reactive burn model [14]. Several equation-of-state (EOS) options are available, including tabular (i.e., SESAME), analytical (ANEOS), Mie-Grüneisen, and Jones-Wilkins-Lee (JWL) [15]. Material failure occurs when a threshold value of tensile stress or hydrostatic pressure is exceeded. In addition, the Johnson-Cook failure model [16] is also 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 (HRIT) algorithm (available for two-dimensional simulations only), the simple line interface calculation (SLIC) algorithm [17], and the Sandia-modified Young's reconstruction algorithm (SMYRA) [18].

## 2. Problem Setup

The two geometries for the tungsten alloy penetrators are shown in Figure 1. Both of the penetrators have a length of 10.1346 cm (3.99 in) and a diameter of 0.6756 cm (0.266 in). Due to their different nose shapes, the masses of the penetrators differ slightly. The mass of the hemi-nose penetrator is approximately 65 g, and that of the ogival-nose penetrator is approximately 63 g.



All Dimensions Are In Centimeters

**Figure 1. Penetrator Geometries.**

Three different constitutive models were used in the simulations to model the deviatoric response of the materials. The choice of the constitutive model used for a material was governed by the availability of material data. Material data were not available for the 95W-2.5Ni-1.0Fe-1.5Co, 21% swaged tungsten alloy penetrators used in the experiments. Therefore, the alloy was approximated using 95W-3.5Ni-1.5Fe tungsten alloy data for the Steinberg-Guinan-Lund strain-rate-independent model reported in Steinberg [19]. This tungsten alloy has the same percentage of tungsten and same approximate density as the 95W-2.5Ni-1.0Fe-1.5Co, 21% swaged alloy. For the 7039 aluminum

target, the Johnson-Cook constitutive model was used with the parameters reported in Johnson and Cook [10]. For the 5083 aluminum target, a power-law constitutive model was used with the parameters reported in Silling [3] and originally reported in Forrestal et al. [20].

The Mie-Grüneisen EOS was used for all materials. EOS data were obtained from a data file provided with the CTH hydrocode. The EOS parameters for 5083 aluminum, 7039 aluminum, and 95% tungsten content tungsten alloy were not available. Therefore, they were approximated using parameters for 6061 aluminum, 7075 aluminum, and 90W-7Ni-3Fe tungsten alloy, respectively. The initial densities of the 6061 and the 7075 aluminum alloys were changed to reflect those for 5083 and 7039 aluminum, as reported in the Metals Handbook Desk Edition [21]. The initial density of the 90W-7Ni-3Fe alloy was changed to reflect the initial density of the 95W-3.5Ni-1.5Fe alloy reported in Steinberg [19]. The EOS parameters used for the materials are listed in Table 1.

**Table 1. Equation-of-State Parameters**

Material	Density $\rho_0$ (g/cm <sup>3</sup> )	Sound Speed $c_0$ (km/s)	Slope Us-Up (s)	Grüneisen Parameter ( $\Gamma_0$ )	Specific Heat $c_v$ (erg/g/eV)
W Alloy	18.16	4.03	1.237	1.67	1.66e10
5083 Al	2.66	5.34	1.40	1.97	1.07e11
7039 Al	2.77	5.20	1.36	2.20	1.07e11

Failure in most of the simulations was modeled using a threshold-pressure criterion. The tensile pressure at which the tungsten alloy, the 5083 aluminum, and the 7039 aluminum were assumed to fail was 3.5, 0.45, and 0.50 GPa, respectively. Additional simulations used a strain-based failure criterion that is described later in this report.

All simulations used a two-dimensional cylindrical coordinate mesh consisting of 85 × 832 cells. The mesh in the radial direction starts at the axis of symmetry with a constant cell size of 0.0422275 cm out to a radius of 1.6891 cm. Thereafter, cell dimensions expand by 5% increments

out to the outer radius of the target. This mesh provides eight cells across the radius of the penetrator. The mesh in the axial direction mesh has a constant cell size of 0.0422275 cm. Thus, cells in the penetrator-target interaction region have a one-to-one aspect ratio.

Parameters for the BLINT model were chosen to be similar to those reported in Kmetyk and Yarrington [5]. Thus, the boundary-layer distance ( $w_{bl}$ ) and the slip-layer distance ( $w_{sl}$ ) were chosen to be twice the zone size of cells in the penetrator-target interaction region. The boundary-layer distance defines which cells will be included in the boundary layer. If the cell center of a cell is located  $w_{bl}$  away from a cell whose center is included in the interface layer, it is considered to be part of the boundary layer. Materials defined as "hard" make up the hard boundary layer and materials defined as "soft" make up the soft boundary layer. The interface layer, which is about two cell widths thick, contains all cells whose hard and soft material volume vector gradient magnitudes are both greater than or equal to 0.1. The slip-layer distance defines which cells will be included in the slip layer. If the cell center of a cell located in the soft boundary layer is  $w_{sl}$  from a cell whose center is included in the interface layer, it is considered part of the slip layer. Cells located in the slip layer have their flow stresses set to zero, allowing sliding to occur in these cells. An option to automatically increase the yield strength of the penetrator material by a factor equal to

$$\left( \frac{r_o + w_{bl}}{r_o} \right)^2$$

(where  $r_o$  is the outer radius of the penetrator) was used. This ratio represents the cross-sectional area of the penetrator plus the boundary-layer distance over the original penetrator cross-sectional area. The option was used because numerical noise can cause shear stresses close to the yield stress to exceed the yield stress, causing premature irreversible deformation of the penetrator. An additional option allows for the inclusion of friction; however, friction between the target and penetrator was not accounted for in this study. Kmetyk and Yarrington [5] showed that the BLINT model tended to overpredict penetration in deep penetration problems unless friction was included.

The CTH hydrocode (August 1993 version) cannot convect velocity in a manner such that both momentum (MV) and kinetic energy (KE) are both conserved exactly. The default option allows

conservation of KE such that total energy is conserved during the convection phase of a computational cycle; however, MV is not conserved. A second option convects velocity such that MV is conserved during the convection phase of a computational cycle and any KE discrepancies are discarded. Simulations were run for both of these convection options. A final option conserves both MV and total energy during the convection phase of a computational cycle by depositing the KE discrepancy into internal energy. This can have the effect of artificially heating a material [22], and therefore, this option was not used. (Note: With the March 1995 release of the code, a half index shifted momentum scheme was introduced as the only convection option, thus the choice of convection options discussed previously are no longer available in code versions later than August 1993.)

Complete listings of the CTH input decks used for the simulations are given in Appendices A–F. If the only difference in the input decks was the penetrator striking velocity, conservation method, or whether or not the BLINT model with or without the strength correction factor was used, then those decks are not listed. Notes in the input decks describe the required changes needed for the input decks not listed.

### 3. Results and Discussion

Initial impact conditions and ballistic test results [6] from the experiments are provided in Table 2 and simulation results are provided in Appendix G. The total penetrator yaw in the experiments was small (in most cases less than 1°). However, these values still exceed the critical yaw as defined in Bjerke et al. [23, 24] since the penetration channel diameter is about the same as the penetrator shank diameter for rigid body penetration of soft targets (e.g., see Forrestal et al. [25]). Any effects of yaw were not treated in the simulations.

In the following discussion, simulations will be designated by the options used. The designation will be of the form XX-XX-XX-X, where the first set of X's represents whether or not KE or MV was conserved during the convection phase of a computational cycle, the second set of X's represents whether the BLINT model was used (BL) or not used (NB), the third set of X's represents whether the yield strength correction factor was used with the BLINT model (CO) or not used (NC),

**Table 2. Initial Impact Conditions and Ballistic Test Results**

Shot No.	Total Yaw (o)	Striking Velocity (m/s)	Original Mass (g)	Residual Velocity (m/s)	Comments
Hemi-Nose Penetrators vs. 7.62-cm-Thick 7039 Aluminum					
4326	0.56	1,198	65.2	1,020	Eroded
4327	0.71	1,038	65.2	964	Rigid?
4328	0.71	1,093	65.5	961	Bulge, Fractured
Hemi-Nose Penetrators vs. 7.62-cm-Thick 5083 Aluminum					
4329	0.25	1,283	65.7	1,168	Eroded
4330	0.35	1,201	65.7	1,109	Slight Bulge
4331	0.25	1,147	65.8	1,069	Rigid, Fractured
Ogival-Nose Penetrators vs. 7.62-cm-Thick 5083 Aluminum					
4332	0.25	1,286	63.2	1,245	Rigid
4333	0.56	1,399	63.5	1,352	Rigid
4334	0.35	1,534	63.5	1,493	Rigid
4335	0.00	1,600	63.6	1,562	Rigid
Ogival-Nose Penetrators vs. 7.62-cm-Thick 7039 Aluminum					
4336	1.03	1,474	63.3	1,414	Rigid, Fractured
4337	0.56	1,595	63.5	1,528	Rigid, Fractured
4451	0.00	1,755	~63.5	1,677	Slight Bulge
4452	0.79	1,768	~63.5	1,652	Eroded, Bent

and the final X represents whether the threshold pressure failure model was used (P) or the strain-based failure model was used (S). For example, the designation KE-BL-CO-P Sim would mean that this simulation conserved KE during the convection phase of a computational cycle, that the BLINT model was used with the strength correction factor, and that the threshold pressure was used to model failure. The designations KE-BL-CO-P and MV-BL-CO-P represent the baseline simulations and will for simplicity also be called KE Sim(s) or MV Sim(s), respectively.

**3.1 Residual Shapes for Baseline Simulations.** Figure 2 compares the hemi-nose penetrator shapes predicted by the KE and MV Sims with tracings of residual penetrator shapes obtained from radiographs of the experiments against the 5083 aluminum targets. While the simulation results are all to the same scale and can be directly compared to their initial geometry (Figure 2a), the experimental penetrator shapes may not be at the same scale. The effective plastic strains in the penetrator for the simulations are also shown with strains less than 5% not being plotted. Visible deformation of the penetrator occurs when plastic strains between 45 and 55% (represented by green) appear on axis of the penetrator. The tracings show that the experimental hemi-nose penetrator remained rigid (although its tail fractured) at a striking velocity of 1,147 m/s (Figure 2b). At a striking velocity of 1,201 m/s, the onset of plastic deformation of the nose was observed (Figure 2c), and at a striking velocity of 1,283 m/s, the penetrator was significantly eroded (Figure 2d). The condition of the hemi-nose penetrator predicted by the KE Sim of the 1,147-m/s test was also rigid, although the fracture of the tail observed experimentally did not occur (Figure 2b). Erosion of the penetrator is evident in the KE Sim for the striking velocity of 1,201 m/s (Figure 2c). At a striking velocity of 1,283 m/s, the residual penetrator predicted by the KE Sim shows about the same amount of nose deformation and rod length as in the experiment (Figure 2d). For the MV Sims, the hemi-nose penetrator also remains rigid at a striking velocity of 1,147 m/s (Figure 2b). At striking velocities of 1,201 m/s and 1,283 m/s (Figures 2c and 2d), the MV Sims displayed much less plastic deformation and erosion of the rod nose than the experiments or the KE Sims.

The final hemi-nose penetrator shapes from both the experiments and the baseline simulations for the 7039 aluminum targets are shown in Figure 3. The apparent yaw seen in the figure for the experiments is not representative of any yaw the penetrator may have experienced in the experiments. Experimentally, the hemi-nose penetrators fractured at the two lower velocities tested (Figures 3b and 3c). At a striking velocity of 1,038 m/s it is unclear whether the penetrator in the experiment remained rigid (Figure 3b). Erosion, plastic deformation, and bending of the penetrator are evident at a striking velocity of 1,093 m/s (Figure 3c). At a striking velocity of 1,198 m/s, the eroded penetrator shows a sizable bulge at the nose as well as yaw into or out of the page (Figure 3d). The penetrator in the KE Sims remained essentially rigid at a striking velocity of 1,038 m/s (Figure 3b). Plastic deformation occurred at a striking velocity of 1,093 m/s (as seen by

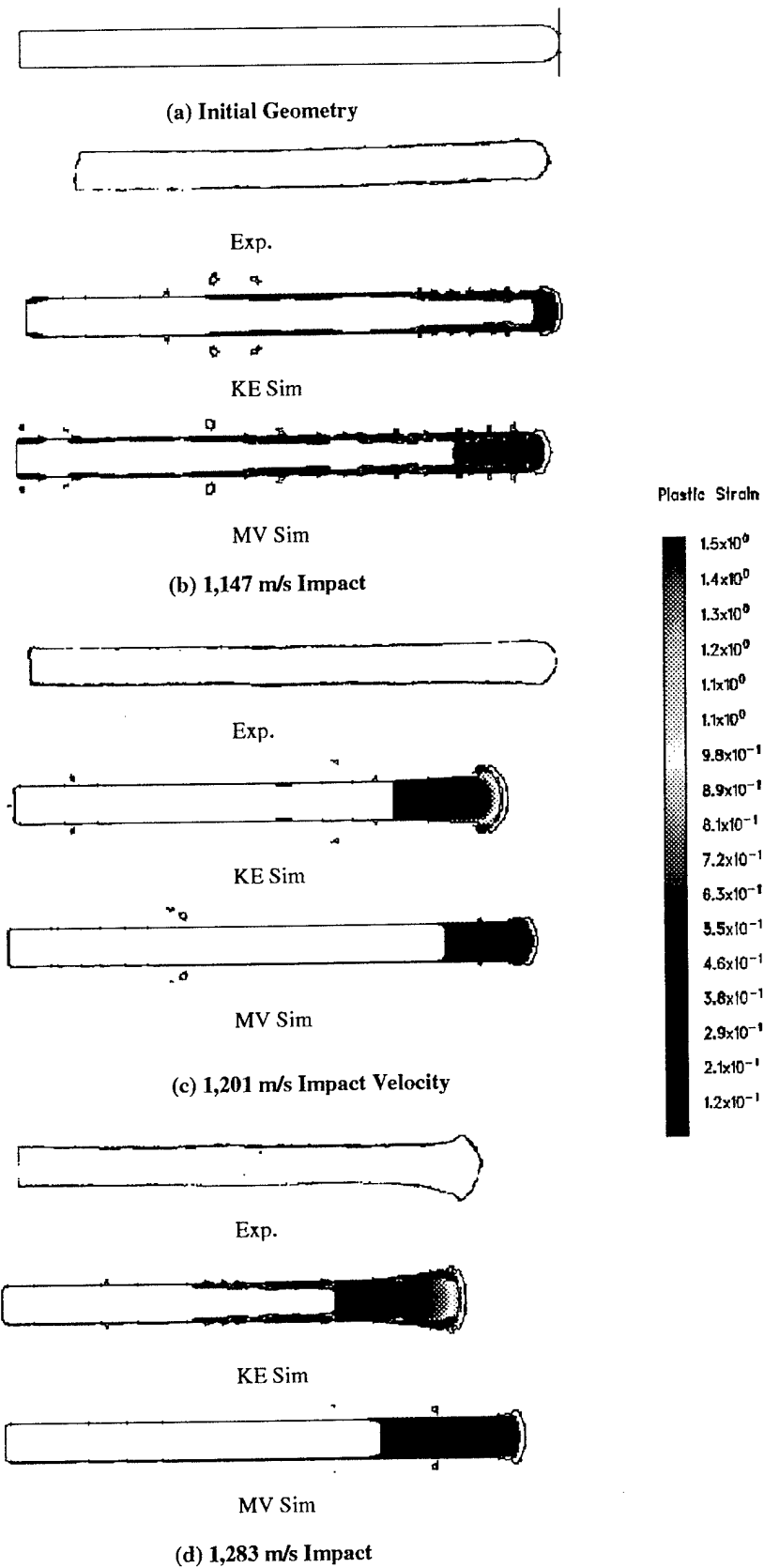


Figure 2. Comparison of Hemi-Nose Penetrator KE and MV Sims Residual Shapes With Experiment After Perforating 5083 Aluminum Targets.

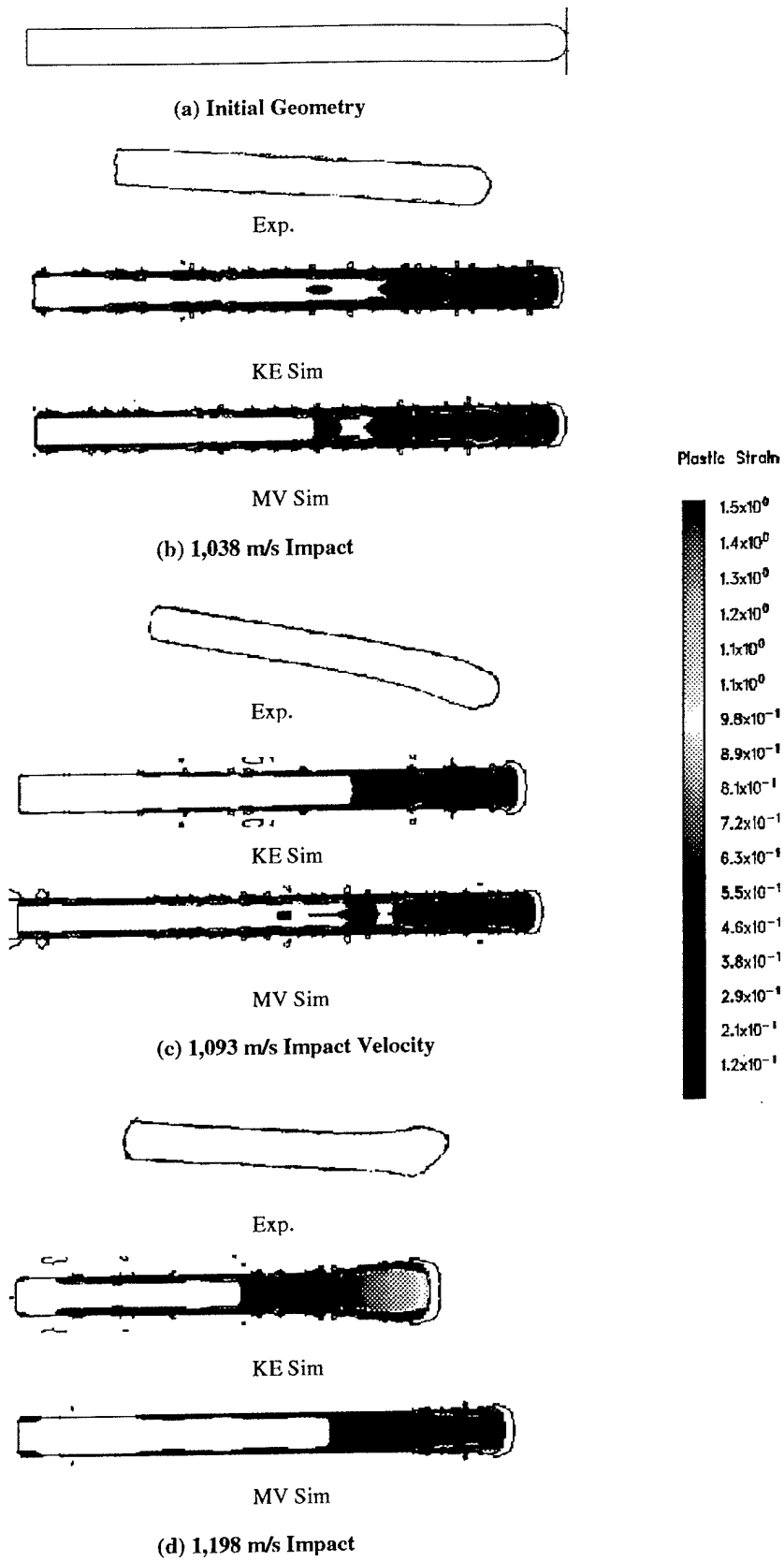


Figure 3. Comparison of Hemi-Nose Penetrator KE and MV Sims Residual Shapes With Experiment After Perforating 7039 Aluminum Targets.

the green color in the nose in Figure 3c). A large bulge and erosion in the penetrator are evident at a striking velocity of 1,198 m/s (Figure 3d). For the MV Sims, the penetrator also remains rigid at a striking velocity of 1,038 m/s (Figure 3b). The predicted length and shape of the penetrator at a striking velocity of 1,093 m/s were about the same as they had been at a striking velocity of 1,038 m/s (Figure 3c). The penetrator is clearly deformed at a striking velocity of 1,198 m/s as seen from plastic strains in the green range at the axis in the nose of the penetrator (Figure 3d).

Because the KE Sims and hemi-nose options seem to predict the onset of visible deformation and predict rod shape better than the MV Sims, most additional simulations were all modeled with the KE convection conservation option. Results for the ogival-nose penetrator MV Sims will be presented only at striking velocities for which experimental data were available at the time of the original paper [8]; therefore, no additional MV Sims will be presented. Predictions of the ogival-nose penetrator's threshold velocity were completed in advance of the experiments. Because it was felt that the threshold velocity of the ogival-nose penetrator may exceed the experimental gun system's maximum launch velocity and because of funding constraints, experiments were not completed for the 5083 aluminum target.

Figures 4 and 5 show the residual shapes and plastic strains for the ogival-nose penetrator after perforating 5083 aluminum targets for the KE and MV Sims, respectively. The experimental penetrator shapes are not shown because they remain rigid at all striking velocities tested (see Table 2). It can be seen from Figure 4 that the amount of plastic stain experienced by the penetrators increased with striking velocity. Not until the penetrator experienced plastic strain between 46 and 55% (beginning of the green range) on the penetrator axis can one see significant difference in the residual shape of the penetrator (Figure 4h). From Figure 4, it is clearly evident that visible plastic deformation occurs at striking velocities between 1,900 and 2,000 m/s for the KE Sims. At a striking velocity of 2,100 m/s, the KE Sim ogival-nose penetrator is clearly eroded (Figure 4i). The MV Sim ogival-nose penetrators of Figure 5 seem to experience larger plastic strain at the same corresponding striking velocity than do their KE Sim counterparts (Figure 4).

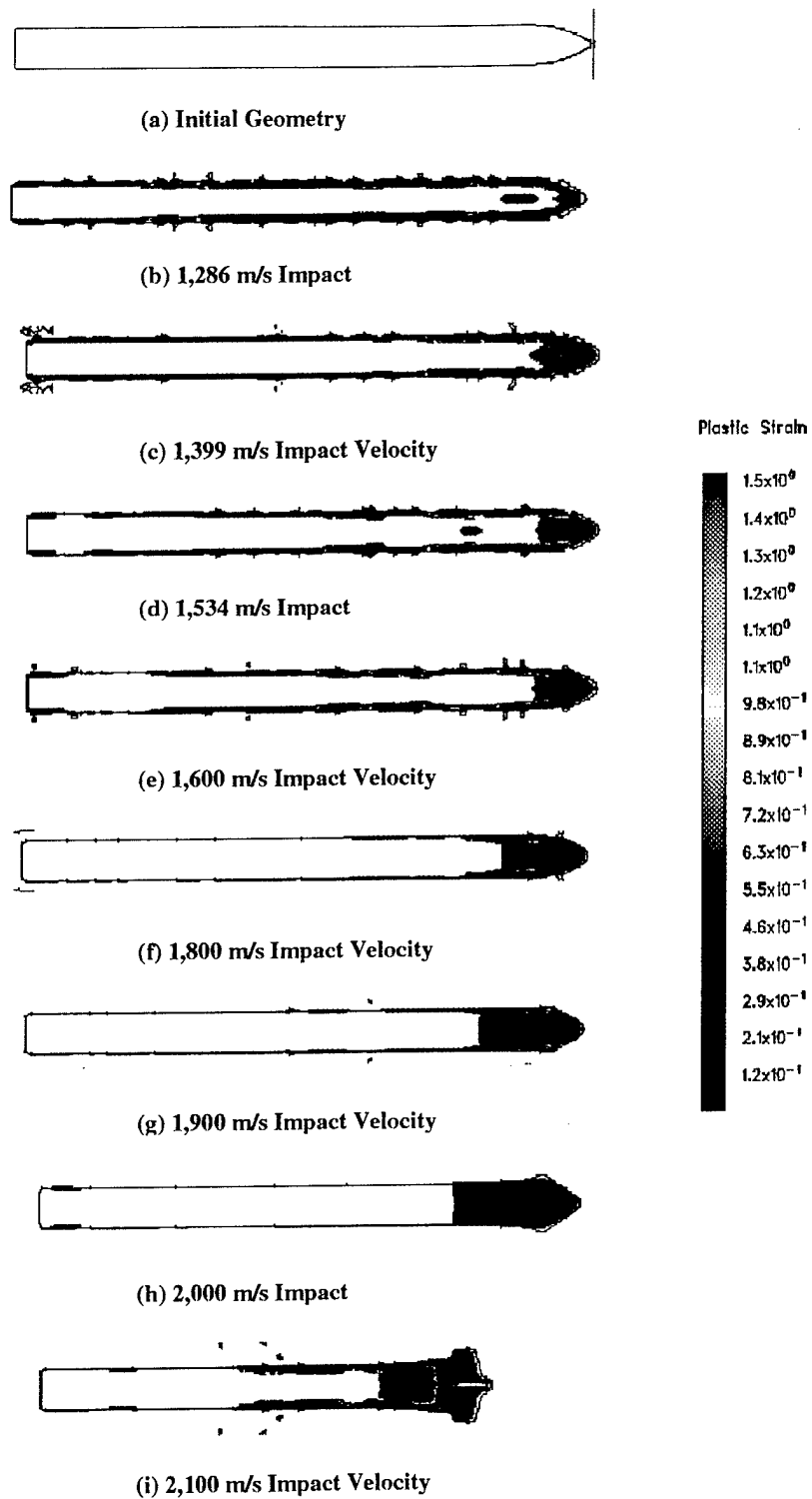
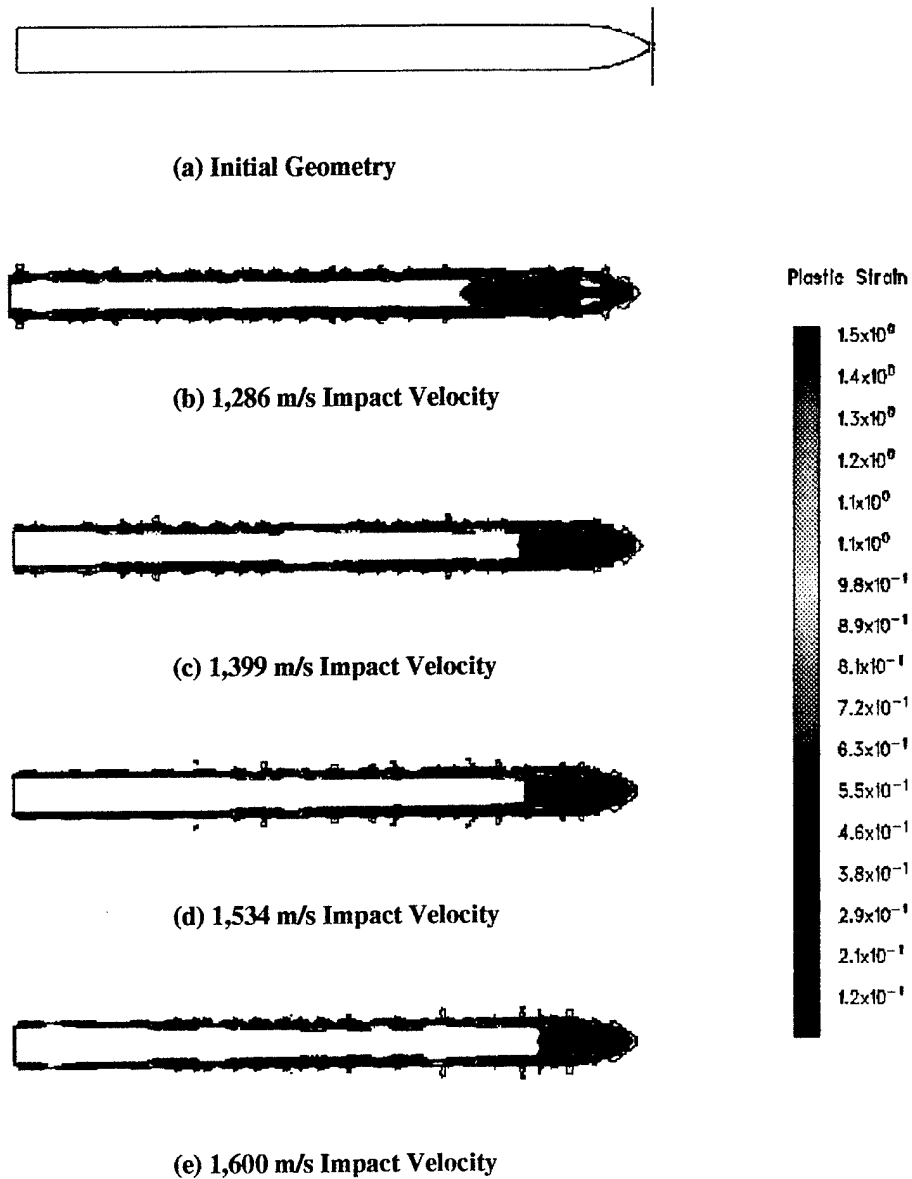
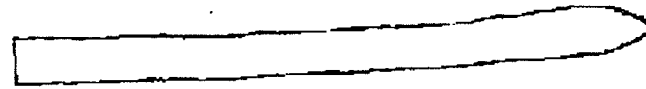


Figure 4. Residual Shapes of the Ogival-Nose Penetrator KE Sims After Perforating 5083 Aluminum Targets.

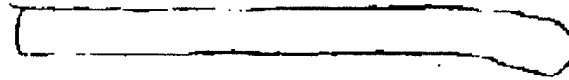


**Figure 5. Residual Shapes of the Ogival-Nose Penetrator MV Sims After Perforating 5083 Aluminum Targets.**

Figures 6, 7, and 8 show the residual shapes for the ogival-nose penetrator impacting 7039 aluminum targets from the experiments, KE Sims and MV Sims, respectively. For the experiments, only two shapes are shown at the striking velocities between which the transition from rigid-body penetration to eroding rod occurred. These two experiments were conducted after the simulations were completed. Residual shapes of lower velocity ogival-nose penetrator experiments are not shown as they all remain rigid. In the experiments, plastic deformation and bending of the penetrator



(a) 1,755 m/s Impact Velocity

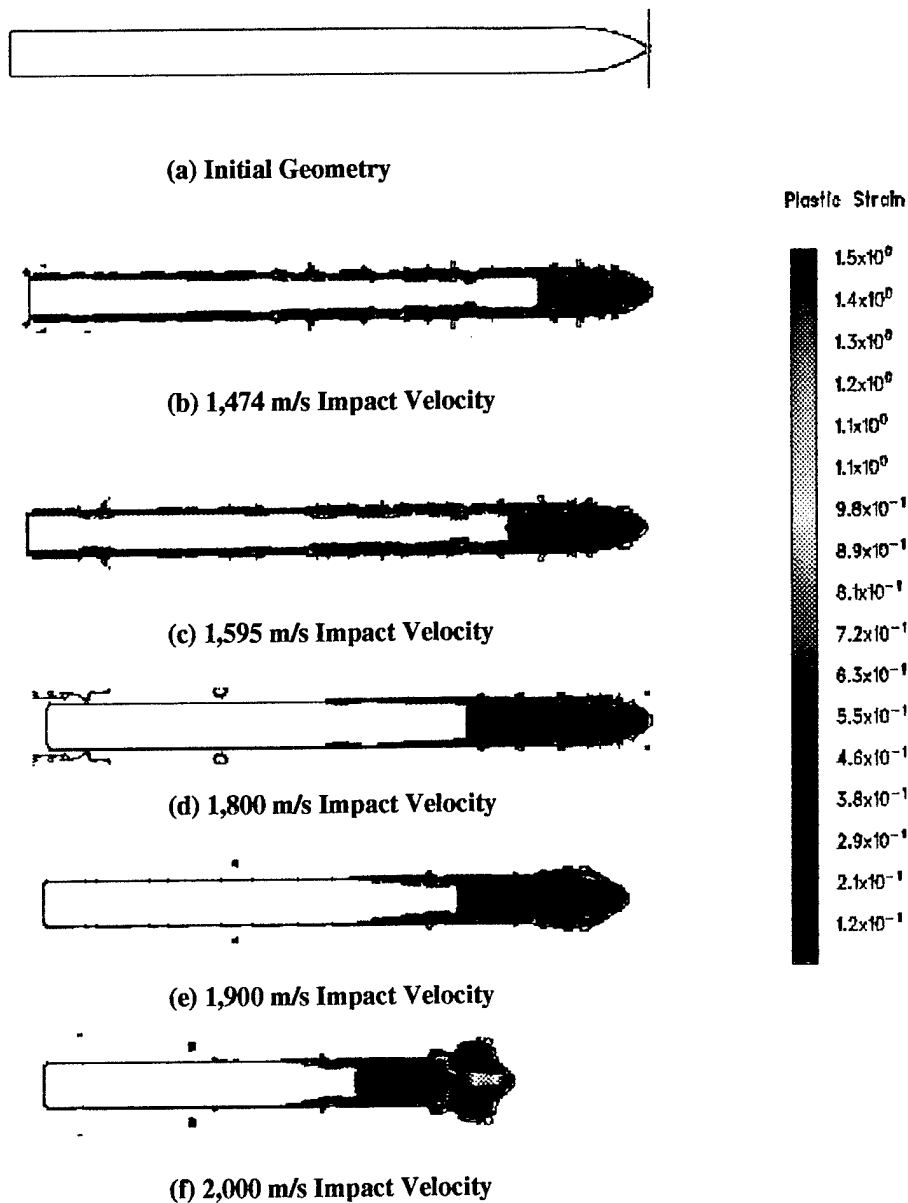


(b) 1,768 m/s Impact Velocity

**Figure 6. Experimentally Determined Residual Shapes of the Ogival-Nose Penetrator After Perforating 7039 Aluminum Targets.**

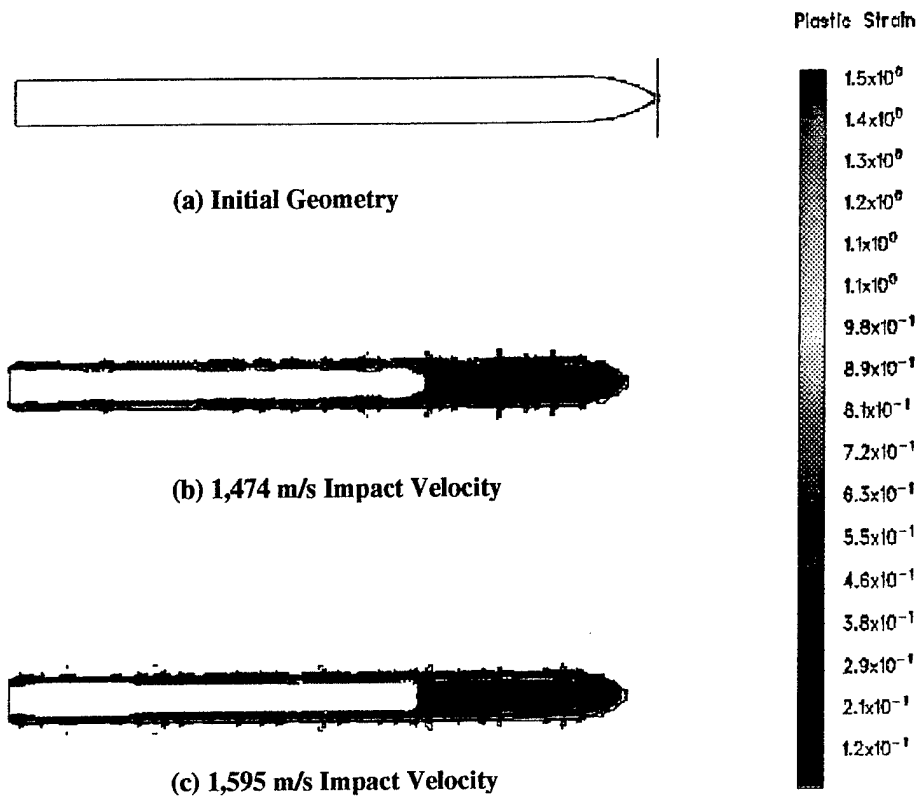
are evident for a striking velocity of 1,755 (Figure 6a). With an increase in striking velocity of 13 m/s, the penetrator is clearly eroded (Figure 6b), suggesting that the transition velocity lies between a striking velocity of 1,755 and 1,768 m/s. The KE Sims predicted that the onset of plastic deformation occurred between a striking velocity of 1,800 and 1,900 m/s (Figures 7d and 7e) and that erosion occurred between a striking velocity of 1,900 and 2000 m/s. Again the MV Sims seem to show much larger plastic strains at the corresponding striking velocity than do the KE Sims (Figures 7 and 8).

**3.2 Residual Velocity for Baseline Simulations.** Figure 9 compares the predicted residual velocity of the penetrators to the experimentally determined residual velocity for the 5083 aluminum targets. The experimental results are represented with solid symbols, the KE Sims are represented with hollow symbols, and the MV Sims are represented with half-filled symbols. In addition, the hemi-nose penetrators are represented by circles and the ogival-nose penetrators are represented by squares. In all cases, the predicted residual velocities are less than the experimentally determined ones. Not much difference is seen in the predicted residual velocities of the ogival-nose penetrator, though the KE Sims show a slight improvement over the MV Sims. Most ogival-nose predictions were within 8.1% of the experimentally determined residual velocities with the exception being the MV Sim at a striking velocity of 1,286 m/s, which differed by 13.1%. For the hemi-nose penetrators,



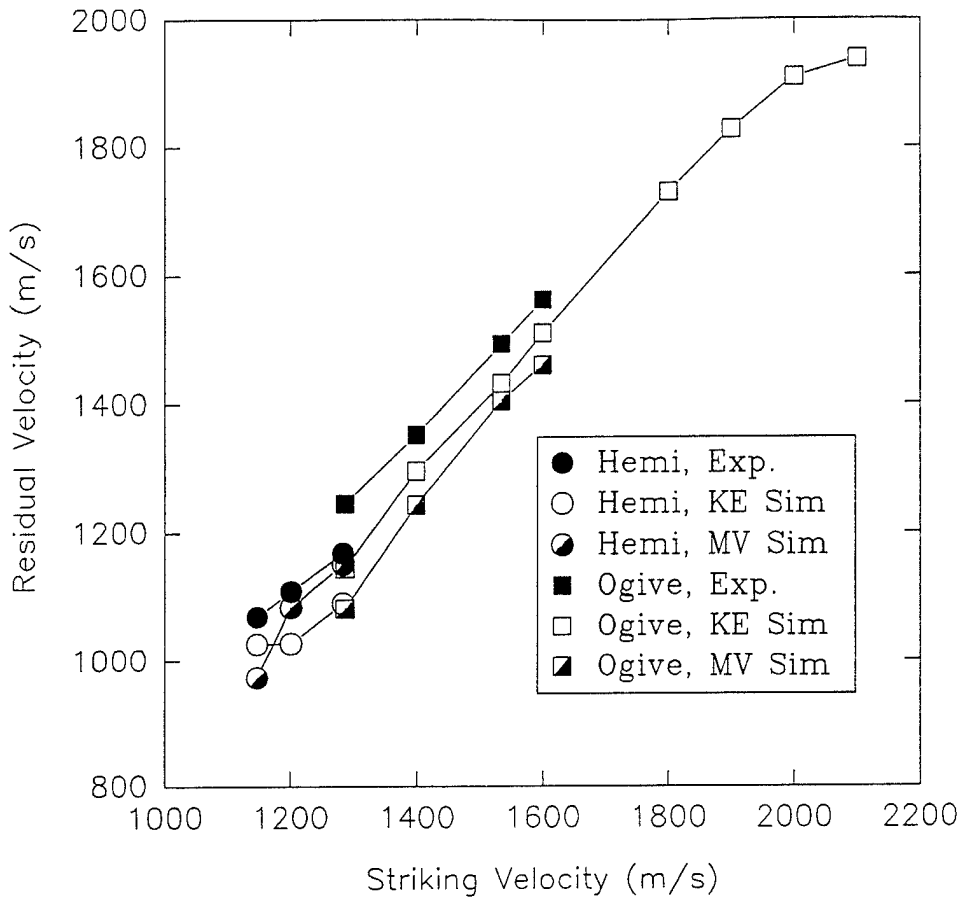
**Figure 7. Residual Shapes of the Ogival-Nose Penetrator KE Sims After Perforating 7039 Aluminum Targets.**

the predicted residual velocities for the simulations were much better for the MV Sims than for the KE Sims, except for the datum at the lowest striking velocity. In general, the difference between the predicted and the experimentally determined residual velocities for the hemi-nose penetrators was less than 7.4% for KE Sims and less than 2.3% for MV Sims, except for the datum at the lowest striking velocity, which differed by 9.0%.



**Figure 8. Residual Shapes of the Ogival-Nose Penetrator MV Sims After Perforating 7039 Aluminum Targets.**

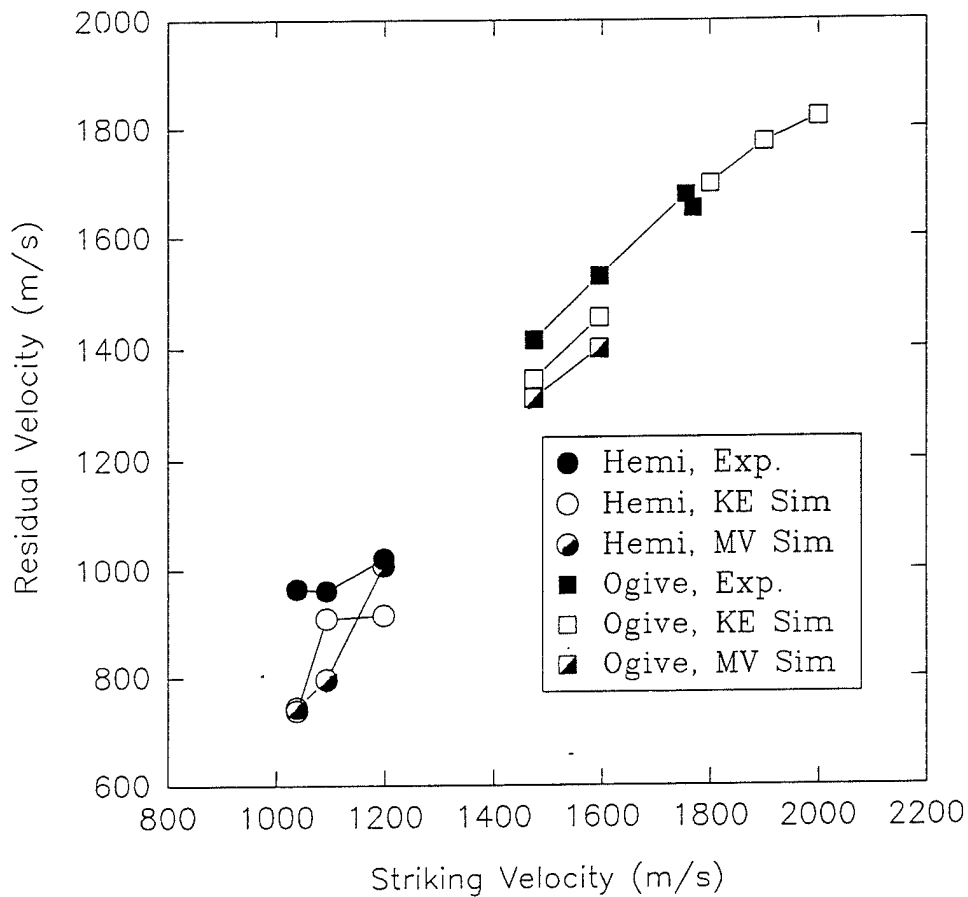
Figure 10 compares the experimental residual velocity data with the baseline simulations' predicted residual velocity for the 7039 aluminum targets. The symbols are the same as were used in Figure 10 for the 5083 aluminum target. Again, the CTH hydrocode's predicted residual velocities are less than those obtained experimentally for all cases considered. The predicted residual velocities for the ogival-nose penetrator were within 8.4% of those obtained experimentally, with only a slight difference in the predictions between the KE and MV Sims. The fact that the hemi-nose penetrator experiments show almost identical residual velocities for the striking velocities of 1,038 m/s and 1,093 m/s suggests a transition from rigid body penetrator to eroding/deforming penetration between these two velocities. The hemi-nose KE Sims show near identical residual velocities for striking velocities of 1,093 m/s and 1,198 m/s suggesting that the transition velocity lies between these two velocities. For the MV Sims, it is not clear from looking at the residual velocities whether a transition from rigid body to eroding rod penetration took place. The predicted



**Figure 9. Residual Velocity Comparison Between Experiment, KE, and MV Sims After Perforating 5083 Aluminum Targets.**

residual velocities for the KE Sims are closer to the experimentally determined residual velocities than are the MV Sims, for all but one datum.

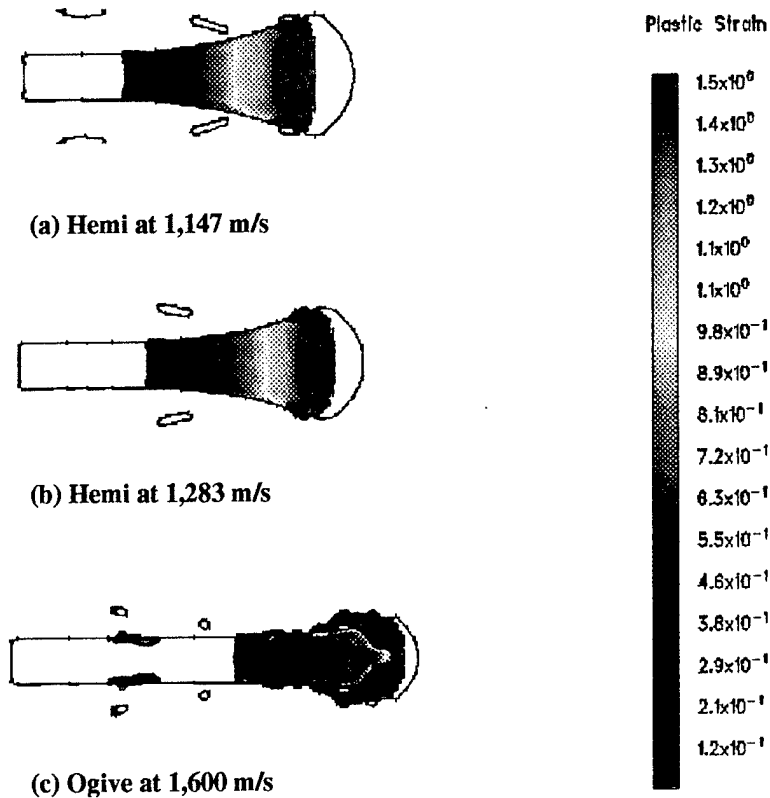
**3.3 BLINT Model Parameters.** To show the differences that using the BLINT model can make in predictions, three of the KE Sims for the 5083 aluminum targets were repeated without the BLINT model active (KE-NB-NC-P Sims). The repeated simulations include the hemi-nose penetrator shown in Figure 2b (which remained rigid), the hemi-nose penetrator shown in Figure 2d (which was visibly deformed/eroded), and the ogival-nose penetrator at the highest velocity tested (Figure 5e, which remained rigid). Figure 11 shows the predicted shapes of the three KE Sims that were repeated without the BLINT model active. The hemi-nose penetrator that was previously predicted to remain rigid (Figure 2b) is now excessively deformed (Figure 11a). The hemi-nose penetrator that



**Figure 10. Residual Velocity Comparison Between Experiment, KE, and MV Sims After Perforating 7039 Aluminum Targets.**

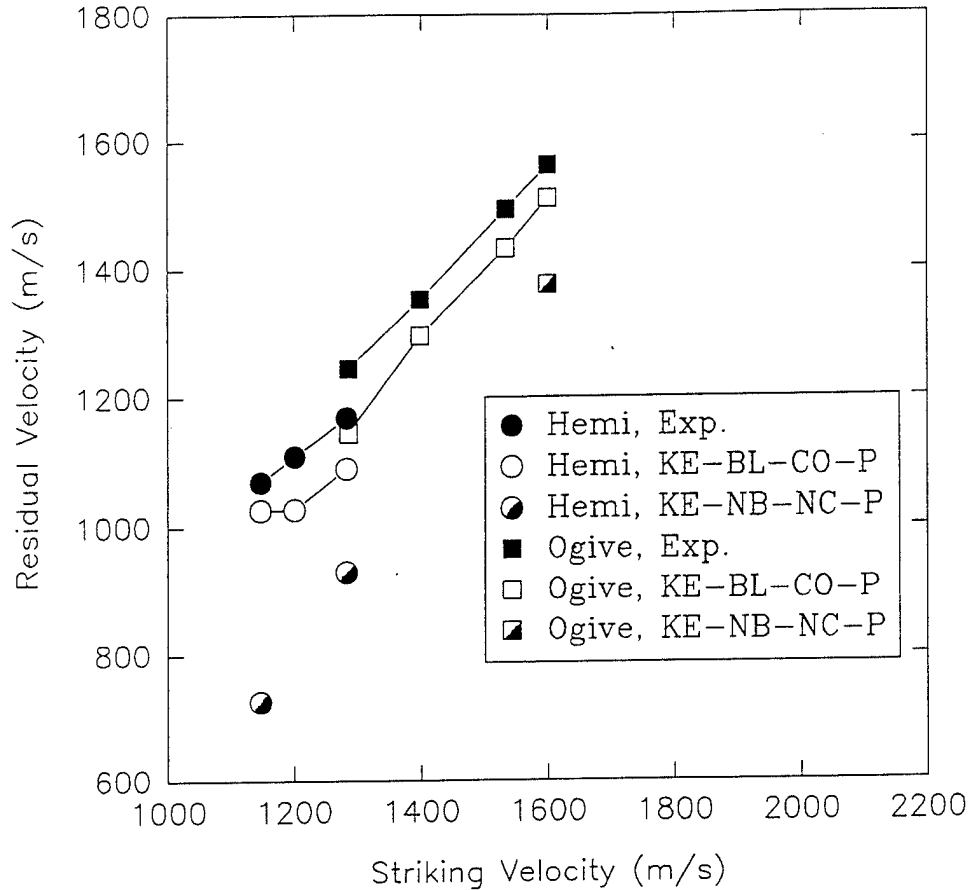
was previously predicted to erode (Figure 2b) is now predicted to deform and erode excessively (Figure 11b). Finally, with the BLINT model active, all the ogival-nose penetrators were predicted to remain rigid at all striking velocities simulated; however, without the BLINT model, erosion is predicted (Figure 11c). Figure 12 compares the residual velocities of the KE Sims with and without the BLINT model to the experimentally determined values. In all cases, the predicted residual velocities for the KE-NB-NC-P Sims underpredicted those with the BLINT model active. The degree to which the KE-NB-NC-P Sims underpredicted experiment seems to increase at the lower initial striking velocities.

To examine the effect the yield strength correction factor has on simulation results, the hemi- and ogival-nose KE Sims against the 5083 aluminum target were repeated without the strength correction



**Figure 11. Residual Shapes of KE-NB-NC-P Sims After Perforating 5083 Aluminum Targets.**

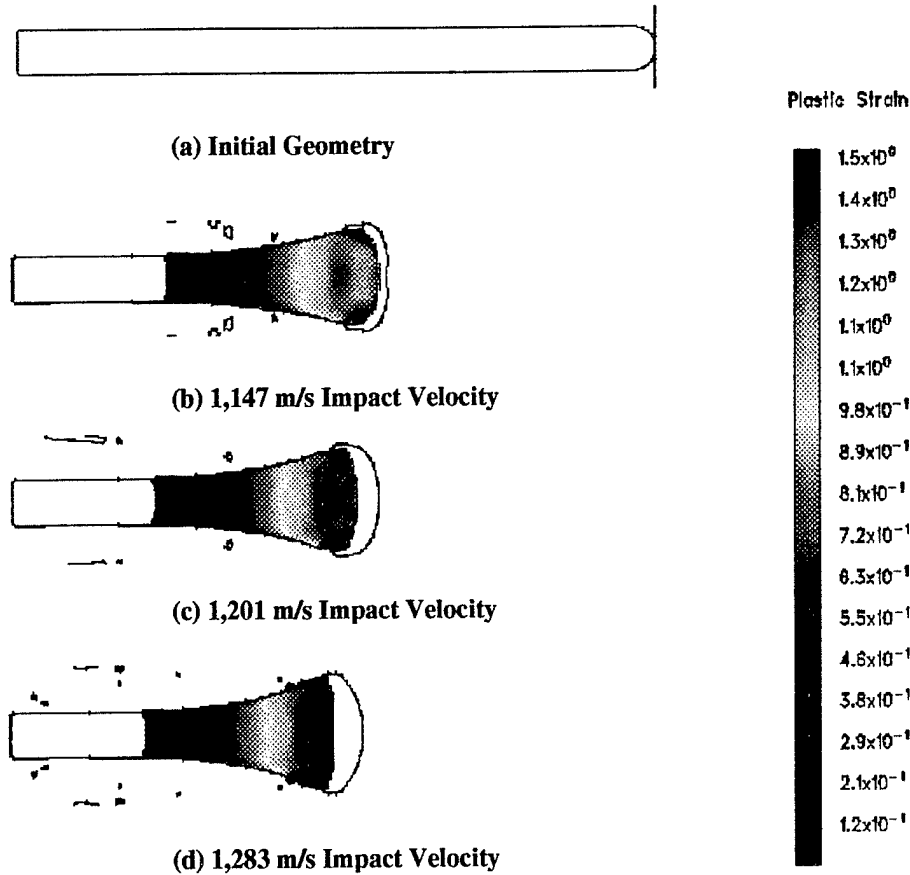
factor (KE-BL-NC-P Sims). Residual shapes and plastic strains of the hemi- and ogival-nose penetrators are shown in Figures 13 and 14, respectively. The hemi-nose KE-BL-NC-P Sims (Figure 13) appear to deform in a manner similar to the hemi-nose KE-NB-NC-P Sims (Figures 11a and 11b). The baseline KE Sims for the ogival-nose penetrators shown in Figures 4b–4e remained rigid. Without the strength correction factor, the ogival-nose penetrator shows visible deformation at the very tip of the nose at a striking velocity of 1,286 m/s (Figure 14b) that progressively increases with striking velocity (Figures 14c–14e). The residual velocity for the KE-BL-NC-P Sims is compared to the experimental results and the KE-BL-CO-P baseline simulations in Figure 15. The KE-BL-NC-P Sims underpredict the experimental determined residual velocity to a greater extent than the baseline KE Sims. At striking velocities of 1,286 m/s and 1,399 m/s, the predicted residual



**Figure 12. Comparison of Residual Velocity for KE-NB-NC-P Sims With Experiment and Baseline KE Sims After Perforating 5083 Aluminum Targets.**

velocities for the ogival-nose penetrator are close to the baseline predictions, because the penetrator was only slightly deformed (Figures 14b and 14c).

**3.4 Failure Model Effects.** In examining the effects of nose shape on the threshold velocity at which tungsten alloy penetrators transition from rigid body to eroding rods when penetrating deep aluminum targets, it has been shown that the failure model used can influence the predicted penetration depth [8, 9]. Magness has suggested a more appropriate failure model would be one based on strain [26], the reasons for which are given in Magness [27]. Therefore, all KE Sims for the 5083 aluminum targets using the BLINT model were redone using the Johnson-Cook failure with all but the first parameter set to zero, such that all materials would fail when they exceeded a threshold value of 150% strain or when they exceeded the threshold value of tensile pressure



**Figure 13. Residual Shapes for Hemi-Nose Penetrator KE-BL-NC-P Sims After Perforating 5083 Aluminum Targets.**

reported earlier. The predicted shapes for the KE-BL-CO-S hemi-nose penetrators (Figure 16) do not differ significantly from the baseline KE Sims (Figures 2b–2d), and the predicted threshold velocity remains the same (between 1,147 and 1,201 m/s). Even the levels of effective plastic strain observed are similar. The KE-BL-CO-S ogival-nose penetrators (Figure 17) remained rigid for all striking velocities considered as did the baseline KE Sim counterparts (Figures 4b–4e); however the KE-BL-CO-S experienced larger plastic strains for the same striking velocity. Using a strain-based failure criteria reduced the predicted residual velocity for all simulations when compared to the baseline KE Sims and experimental results other than for the hemi-nose penetrator with a striking velocity of 1,201 m/s (Figure 18).

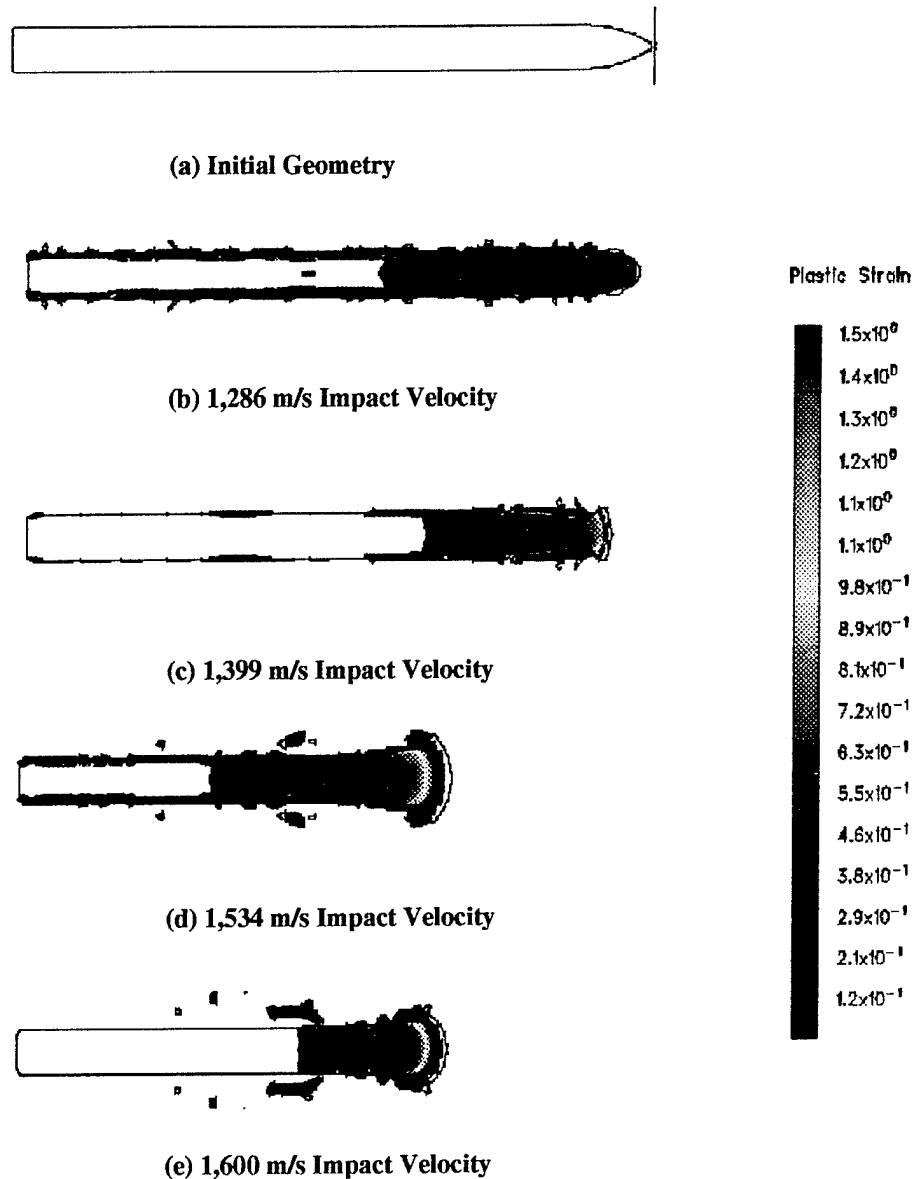
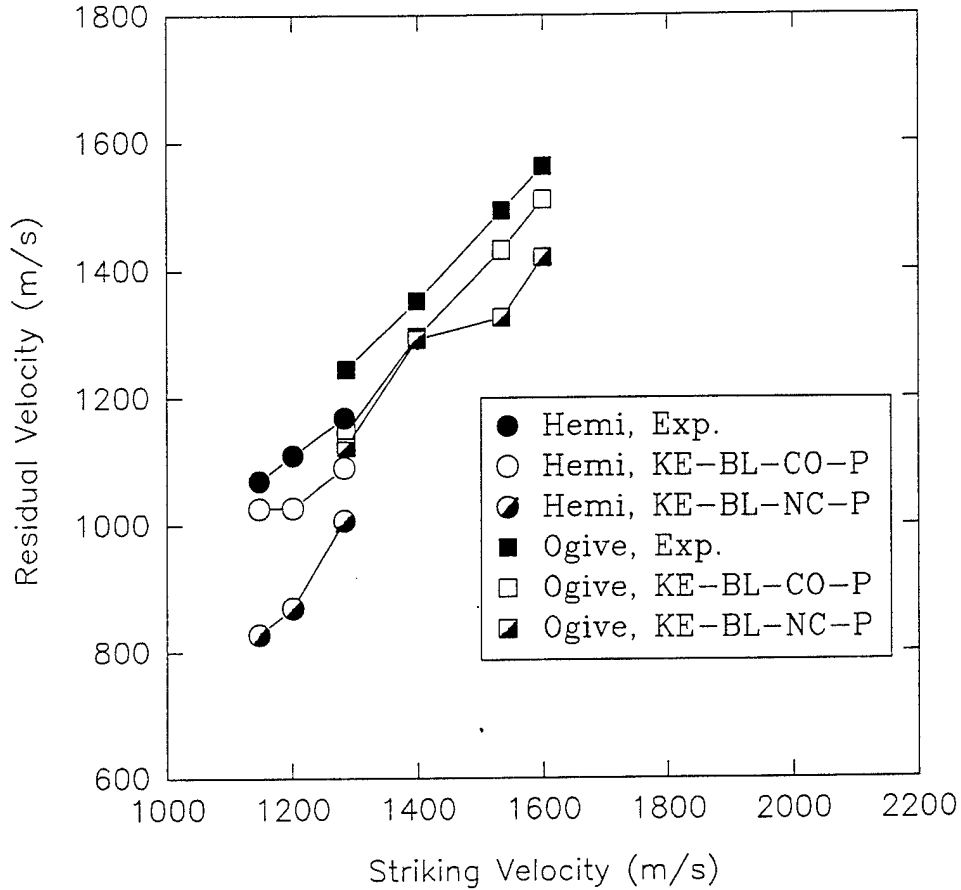


Figure 14. Residual Shapes for Ogival-Nose Penetrator KE-BL-NC-P Sims After Perforating 5083 Aluminum Targets.

## 4. Conclusions

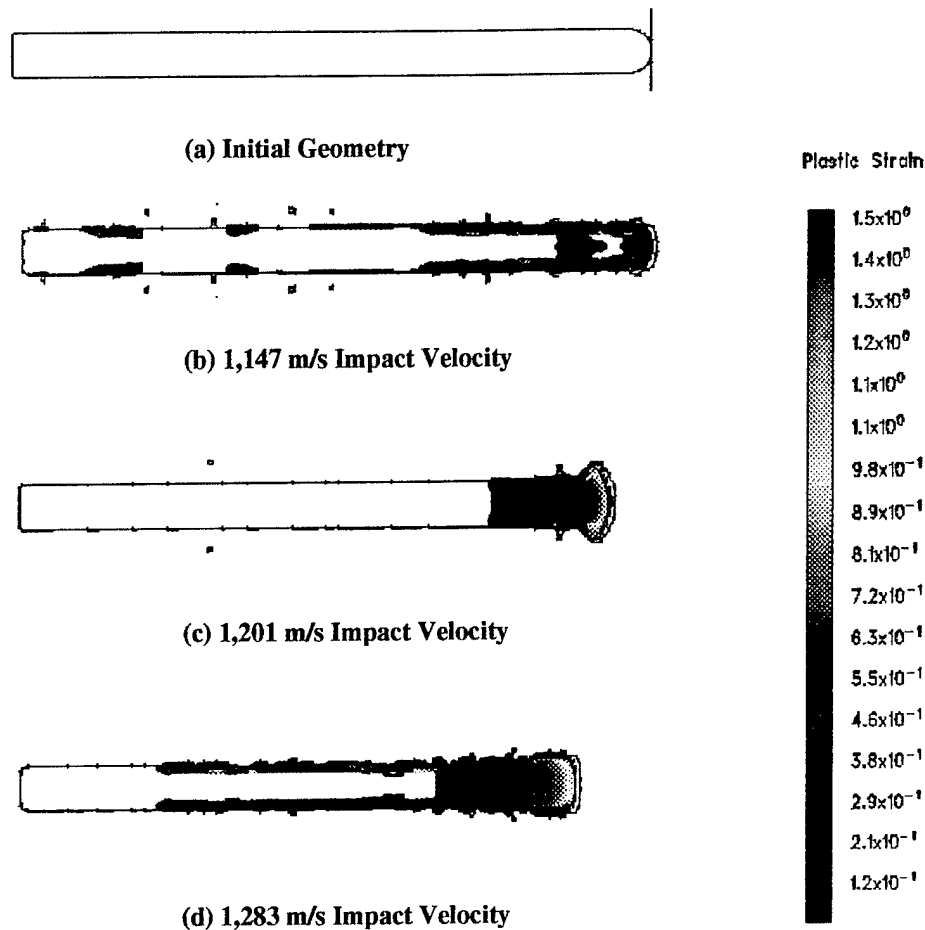
It is known that the constitutive response of tungsten alloy is dependent on strain, strain rate, temperature, percentage tungsten content, tungsten grain size, and amount of swaging [28]. In addition, for solid-solid impacts at velocities of 500–2,000 m/s, impact pressures rapidly decay to values comparable to the strength of the material; therefore, the constitutive model is of primary



**Figure 15. Comparison of Residual Velocity for KE-BL-NC-P Sims With Experiment and Baseline KE Sims After Perforating 5083 Aluminum Targets.**

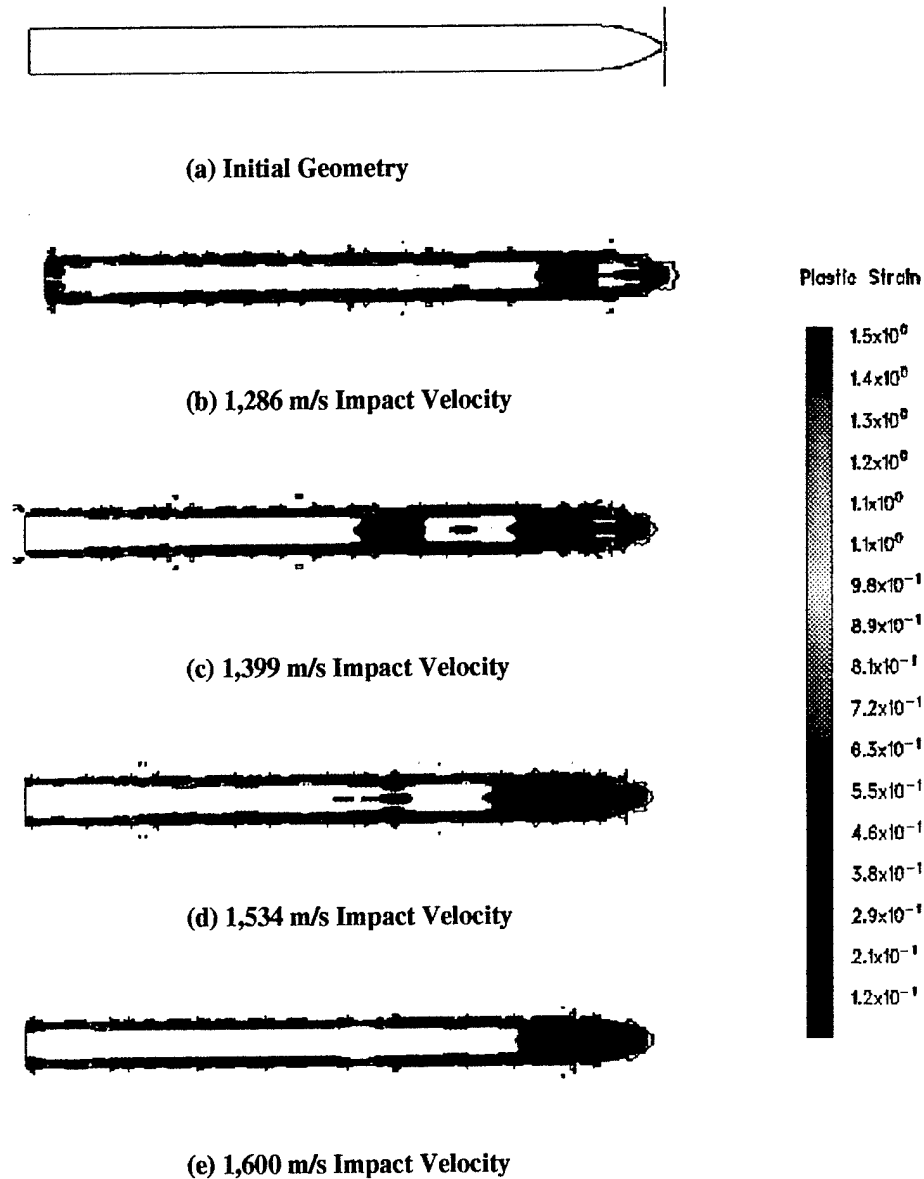
importance and the EOS is of secondary importance [29]. Therefore, it is unrealistic to expect the results of the simulations, with the constitutive model approximations used for the 95W-2.5Ni-1.0Fe-1.5Co, 21% swaged alloy, to provide an exact match with the experimental data. Nevertheless, the following conclusions are offered.

The BLINT model represents a drastic improvement in the predictive capabilities in the CTH hydrocode for certain types of penetration scenarios, such as rigid body penetrations. The hydrocode was able to predict the effect of rod nose-shape on the threshold velocity at which transition from rigid body to eroding rod penetration occurs. The code successfully estimated the velocity at which the hemi-nose penetrators begin to deform in penetrating either 5083 or 7039 aluminum. The transition occurs at a much higher striking velocity for an ogival-nose penetrator than for a hemi-



**Figure 16. Residual Shapes for Hemi-Nose Penetrator KE-BL-CO-S Sims After Perforating 5083 Aluminum Targets.**

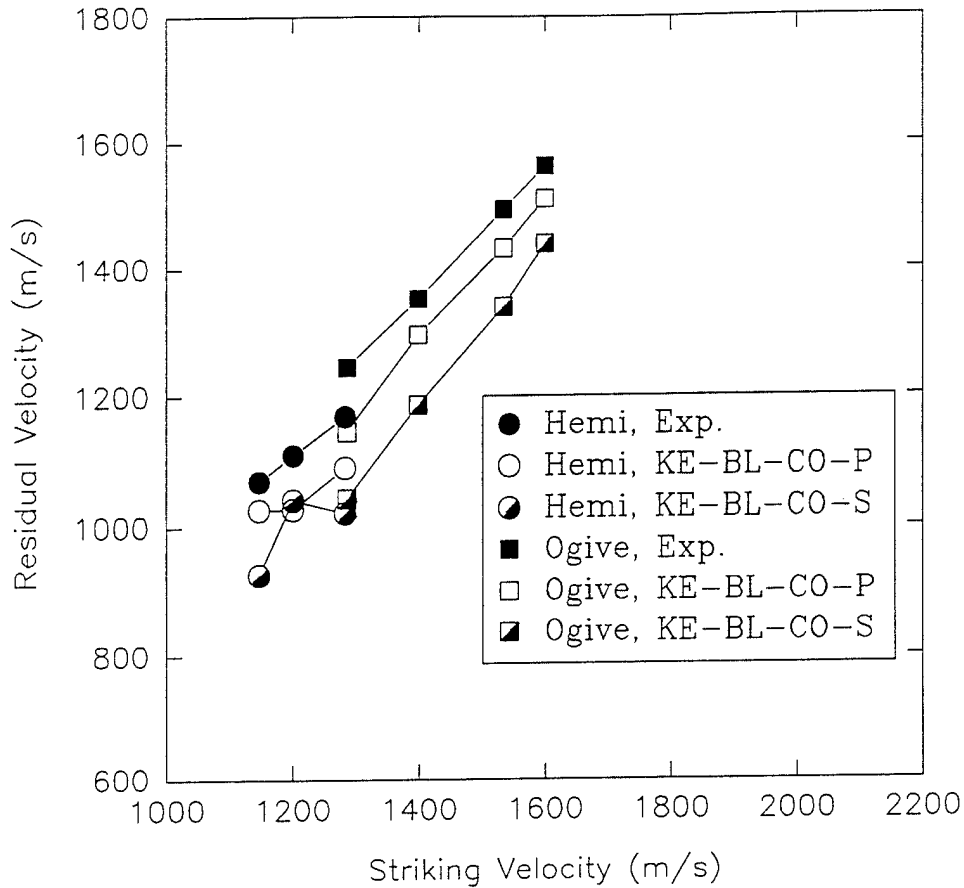
nose penetrator. Experimentally, the transition occurred with the onset of plastic deformation of the hemi-nose penetrator at a striking velocity of 1,201 m/s to full erosion at a striking velocity of 1,283 m/s when impacting a 5083 aluminum target. The KE Sims predicted the transition velocity for the hemi-nose penetrator would occur between a striking velocity of 1,147 and 1,201 m/s for the 5083 aluminum target. The MV Sims hemi-nose penetrator only predicted minimal plastic deformation in the range of striking velocities between 1,147 and 1,283 m/s for the 5083 aluminum target. Experimentally, the transition velocity for the ogival-nose penetrator impacting the 5083 aluminum target was never determined. The KE Sims predicted the visible plastic deformation would occur at a striking velocity between 1,900 and 2,000 m/s and erosion of the penetrator would



**Figure 17. Residual Shapes for Ogival-Nose Penetrator KE-BL-CO-S Sims After Perforating 5083 Aluminum Targets.**

occur at a striking velocity between 2,000 and 2,100 m/s for the ogival-nose penetrator impacting a 5083 aluminum target. The transition velocity was not determined for the ogival-nose MV Sims.

Experimentally, for the hemi-nose penetrator impacting a 7039 aluminum target, plastic deformation occurred between a striking velocity of 1,038 and 1,093 m/s and erosion occurred between a striking velocity of 1,093 and 1,198 m/s. The same result was predicted by the hemi-nose



**Figure 18. Comparison of Residual Velocity for KE-BL-CO-S Sims With Experiment and Baseline KE Sims After Perforating 5083 Aluminum Targets.**

KE Sims for the 7039 aluminum target. The MV Sims predicted visible plastic deformation would occur between a striking velocity of 1,093 and 1,198 m/s for a 7039 aluminum target. Experimentally, the transition velocity occurred between a striking velocity of 1,755 and 1,768 m/s for the ogival-nose penetrator impacting a 7039 aluminum target. The ogival-nose KE Sims predicted visible plastic deformation would occur at a striking velocity between 1,800 and 1,900 m/s and erosion at a striking velocity between 1,900 and 2,000 m/s when impacting a 7039 aluminum target.

While the simulations were not in complete agreement with experiment, they did a reasonable job at predicting the transition velocities and did an excellent job predicting all the experimental trends. The simulations predicted the large difference in the transition velocity for a hemi-nose and

ogival-nose penetrator, and they correctly predicted the effect of target materials. In general, the baseline KE Sims did much better at predicting final rod shape than did the MV Sims.

The baseline KE Sims did better in predicting residual velocity than did the MV Sims for both target materials. Both the ogival-nose KE and MV Sims were within 8.1% of the experimentally determined residual velocity, except for one datum. The hemi-nose MV Sims were closer to predicting the experimentally determined residual velocity for the 5083 aluminum target, and the KE Sims were closer to predicting the experimentally determined residual velocity for the 7039 aluminum target. For the 5083 aluminum target, the hemi-nose KE and MV Sims predicted the residual velocity within 9%. For the 7039 aluminum target, the hemi-nose KE and MV Sims under predicted residual velocity by as much as 24%.

It has been shown that without the BLINT model CTH cannot accurately model transition velocity or the perforation of finite target plates. Hemi- and ogival-nose penetrators that were previously predicted to remain rigid, eroded and deformed excessively without the BLINT model active. A hemi-nose penetrator previously predicted to erode, eroded and deformed excessively. Due to excessive deformation predicted with the BLINT model inactive, the predicted residual velocities were significantly underpredicted. It was also shown that the yield strength correction factor greatly influenced simulation results. Without the yield strength correction factor, hemi-nose penetrator simulation results were similar to those without the BLINT model active. Without the yield strength correction factor, the ogival-nose penetrators deformed and eroded prematurely. As a result, most simulations run without the yield strength correction factor under predicted residual velocity by a significant amount.

Finally, it was shown that the choice of material failure models could influence simulation results. The residual shapes and residual velocities predicted using a strain-based failure model did not differ significantly for the hemi-nose simulations. The predicted residual velocity was greatly influenced by the choice of failure models. No attempt was made to predict the transition velocity for ogival-nose simulations using a strain-based failure model. However, the effective plastic strains in the ogival-nose penetrators were greater than the baseline simulations, suggesting that the

transition velocity might be lower. The residual velocities predicted by the ogival-nose penetrator using a strain-based failure model were somewhat reduced.

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**Appendix A:**

**Input for Hemi-Nose KE-BL-CO-P Sims vs. 5083 Aluminum  
Targets - Changes for MV, NB, and NC Sims Given in Notes**

**INTENTIONALLY LEFT BLANK.**

```

* Run History
*
*eor* cgenin
*
nose shape tests: hemi v=1147 target=5083 al finite
*
control
ep
mmp
viscosity bl=.1 bq=2 bs=0.1
endcontrol
*
mesh
block 1 geom=2dc type=e
x0 0.00
x1 n 40 w 1.6891 rat 1.0
x2 n 45 dxf 0.0422275 rat 1.05
endx
y0 -10.219055
y1 n 832 dyf 0.0422275 rat 1.0
endy
xactive 0.0 0.4
yactive -10.219055 0.0
endblock
endmesh
*
insertion
block 1
package '5083 Al target'
material 1
numsub 50
insert box
p1=0.0 0.0
p2=7.6 7.62
endinsert
endpackage
package 'w alloy rod nose'
material 2
numsub 100
*
* NOTE: striking velocity (yvel) is changed below
*
yvel 1.147e5
insert circle
ce=0.0 -0.33782

```

```

    r= 0.33782
    endinsert
    endpackage
    package 'w alloy rod body'
    material 2
    numsub 50
*
* NOTE: striking velocity (yvel) is changed below
*
    yvel 1.147e5
    insert box
    p1=0.0 -0.33782
    p2=0.33782 -10.1346
    endinsert
    endpackage
    endblock
endinsertion
*
epdata
vpsave
*
* NOTE: poisson ratio from for Tungsten from Metals Handbook, that for 5083
*       Aluminum from Forrestal, M.J., V. K. Luk, and N. S. Brar, "Perforation of
*       aluminum with conical-nose projectiles", Mechanic and Materials 10 (1990)
*       pp. 97-105.
*
* NOTE: properties for 5083 aluminum from Silling, S. A., "CTH Reference Manual:
*       Boundary Layer Algorithm for Sliding Interfaces in Two Dimensions", Sandia
*       National Laboratories Report SAND93-2487, January 1994.
*
* NOTE: 5083 aluminum using undocumented power law
*
    matep 1
    johnson-cook='USER'
        ajo=-2.76e9 bjo=254.7 cjo=0.0
        mjo=1.0 njo=0.084 tjo=6.68e-2
        poisson 0.333
*
* NOTE: actual tungsten alloy was 95W-2.5Ni-1.0Fe-1.5Co (21% swaged) with r0=18.1.
*       95W-3.5Ni-1.5Fe is being used to approximate the w alloy.
*
    matep 2
    steinberg='TUNGSTEN_NI_FE'
        r0st=18.16 tm0st=0.195002 atmst=1.3
        gm0st=1.67 ast=1.03e-12 bst=1.76396

```

```
nst=0.13  c1st=0.0  c2st=0.0
g0st=1.45e12  btst=7.7  eist=0.0
ypst=0.0  ukst=0.0  ysmst=0.0
yast=0.0  y0st=18.7e9  ymst=40.e9
poisson=0.280
```

\*

\* NOTE: parameters for boundary layer algorithm taken similar to:  
\* Kmetyk, L. N. and P. Yarrington, "CTH Analysis of Steel Rod Penetration  
\* Into Aluminum and Concrete Targets with Comparisons to Experimental Data",  
\* Sandia National Laboratories Report SAND94-1498, October 1994.

\*

\* NOTE: if no BLINT model, next line is commented out. If no yield strength correction  
\* factor 'corr' is omitted

\*

```
blint 1 soft 1 hard 2 wsl 0.084455 wbl 0.084455 fric=0.0 corr
mix 3
```

```
endep
```

\*

```
tracer
```

```
block 1
```

```
add 0. 0. to 0. -10.134 n 10
```

```
endtracer
```

\*

```
edit
```

```
block 1
```

```
noexpanded
```

```
endblock
```

```
endedit
```

\*

```
eos
```

\*

\* NOTE: EOS properties from cth mgrun library

\*

\* NOTE: 5083-H131 Aluminum eos approximated with 6061-t6 Aluminum

\* density reduced to reflect that for 5083 Aluminum from

\* Metal's Handbook.

\*

```
mat1 mgrun eos=6061-t6_al r0=2.66  cs=0.534e6  s=1.4
```

```
g0=1.97  cv=1.07e11
```

```
mat2 mgrun eos=tungsten_ni r0=18.16  cs=0.403e6  s=1.237
```

```
g0=1.67  cv=1.66e10
```

```
endeos
```

\*

```
*cor* cthin
```

\*

```

nose shape tests: hemi v=1147 target=5083 al finite
*
control
  tstop 300.e-6
  rdumpf 3600
  cpshift 999.
endcontrol
*
restart
* file='rsct1'
  time=0.e-6
endr
*
cellthermo
  mmp
  ntbad=99999
endc
*
convct
*
* NOTE: if KE Sim convection=0, if MV Sim convection=1
*
  convection=0
  interface=high_resolution
endconvct
*
edit
  shortt
    time 0. dtfrequency 150.e-6
  ends
  longt
    time 0. dtfrequency 600.e-6
  endl
  plott
    time 0. dtfrequency 50.e-6
  endp
  histt
    time 0. dtfrequency 0.3e-6
  htracer1
  htracer2
  htracer3
  htracer4
  htracer5
  htracer6
  htracer7

```

```
htracer8
htracer9
htracer10
endh
ende
*
boundary
bhydro
  block 1
    bxbot 0
    bxtop 2
    bybot 2
    bytop 2
  endb
endh
endb
*
fracts
  pressure
  pfrac1 -4.5e9
  pfrac2 -35.0e9
  pfmix -1.0e20
  pfvoid -1.0e20
endf
*
*eor* pltinp
*
```

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## **Appendix B:**

**Input for Ogival-Nose KE-BL-CO-P Sims vs. 5083 Aluminum  
Targets - Changes for MV, NB, and NC Sims Given in Notes**

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\*\* Run History

\*

\*eor\* cgenin

\*

nose shape tests: ogive v=1286 target=5083 al finite

\*

control

ep

mmp

viscosity bl=.1 bq=2 bs=0.1

endcontrol

\*

mesh

block 1 geom=2dc type=e

x0 0.00

x1 n 40 w 1.6891 rat 1.0

x2 n 45 dxf 0.0422275 rat 1.05

endx

y0 -10.219055

y1 n 832 dyf 0.0422275 rat 1.0

endy

xactive 0.0 0.4

yactive -10.219055 0.0

endblock

endmesh

\*

insertion

block 1

package '5083 Al target'

material 1

numsub 50

insert box

p1=0.0 0.0

p2=7.6 7.62

endinsert

endpackage

package 'w alloy ogive nose rod'

material 2

numsub 100

\*

\* NOTE: striking velocity (yvel) is changed below

\*

yvel 1.286e5

insert uds

point 0.0 0.0

point 0.050437038 -0.08003015622  
point 0.095867718 -0.1600603124  
point 0.136665799 -0.2400904687  
point 0.173135779 -0.3201206249  
point 0.205527612 -0.4001507811  
point 0.234047376 -0.4801809373  
point 0.258865148 -0.5602110935  
point 0.280120900 -0.6402412498  
point 0.297928948 -0.7202714060  
point 0.312381319 -0.8003015622  
point 0.323550306 -0.8803317184  
point 0.331490355 -0.9603618746  
point 0.336239443 -1.040392031  
point 0.337820 -1.120422187  
point 0.337820 -10.1346  
point 0.0 -10.1346  
point 0.0 0.0

endinsert

endpackage

endblock

endinsertion

\*

epdata

vpsave

\*

\* NOTE: poisson ratio from for Tungsten from Metals Handbook, that for 5083  
\* Aluminum from Forrestal, M.J., V. K. Luk, and N. S. Brar, "Perforation of  
\* aluminum with conical-nose projectiles", Mechanic and Materials 10 (1990)  
\* pp. 97-105.

\* NOTE: properties for 5083 aluminum from Silling, S. A., "CTH Reference Manual:  
\* Boundary Layer Algorithm for Sliding Interfaces in Two Dimensions", Sandia  
\* National Laboratories Report SAND93-2487, January 1994.

\* NOTE: 5083 aluminum using undocumented power law

\*

matep 1

johnson-cook='USER'

ajo=-2.76e9 bjo=254.7 cjo=0.0  
mjo=1.0 njo=0.084 tjo=6.68e-2  
poisson 0.333

\*

\* NOTE: actual tungsten alloy was 95W-2.5Ni-1.0Fe-1.5Co (21% swaged) with r0=18.1.  
\* 95W-3.5Ni-1.5Fe is being used to approximate the w alloy.

\*

matep 2

steinberg='TUNGSTEN\_NI\_FE'

r0st=18.16 tm0st=0.195002 atmst=1.3  
gm0st=1.67 ast=1.03e-12 bst=1.76396  
nst=0.13 c1st=0.0 c2st=0.0  
g0st=1.45e12 btst=7.7 eist=0.0  
ypst=0.0 ukst=0.0 ysmst=0.0  
yast=0.0 y0st=18.7e9 ymst=40.e9  
poisson=0.280

\*

\* NOTE: parameters for boundary layer algorithm taken similar to:  
\* Kmetyk, L. N. and P. Yarrington, "CTH Analysis of Steel Rod Penetration  
\* Into Aluminum and Concrete Targets with Comparisons to Experimental Data",  
\* Sandia National Laboratories Report SAND94-1498, October 1994.

\*

\* NOTE: if no BLINT model, next line is commented out. If no yield strength correction  
\* factor 'corr' is omitted

\*

blint 1 soft 1 hard 2 wsl 0.084455 wbl 0.084455 fric=0.0 corr  
mix 3

endep

\*

tracer

block 1  
add 0. 0. to 0. -10.1345 n 10

endtracer

\*

edit

block 1  
noexpanded  
endblock

endedit

\*

eos

\*

\* NOTE: EOS properties from cth mgrun library

\*

\* NOTE: 5083-H131 Aluminum eos approximated with 6061-t6 Aluminum  
\* density reduced to reflect that for 5083 Aluminum from  
\* Metal's Handbook.

\*

mat1 mgrun eos=6061-t6\_al r0=2.66 cs=0.534e6 s=1.4  
g0=1.97 cv=1.07e11  
mat2 mgrun eos=tungsten\_ni r0=18.16 cs=0.403e6 s=1.237  
g0=1.67 cv=1.66e10

```
endeos
*
*eor* cthin
*
nose shape tests: ogive v=1286 target=5083 al finite
*
control
  tstop 300.e-6
  rdumpf 3600
  cpshift 999.
endcontrol
*
restart
* file='rsct1'
  time=0.e-6
endr
*
cellthermo
  mmp
  ntbad=99999
endc
*
convct
*
* NOTE: if KE Sim convection=0, if MV Sim convection=1
*
  convection=0
  interface=high_resolution
endconvct
*
edit
  shortt
    time 0. dtfrequency 150.e-6
  ends
  longt
    time 0. dtfrequency 600.e-6
  endl
  plott
    time 0. dtfrequency 50.e-6
  endp
  histt
    time 0. dtfrequency 0.3e-6
  htracer1
  htracer2
  htracer3
```

```
htracer4
htracer5
htracer6
htracer7
htracer8
htracer9
htracer10
endh
ende
*
boundary
bhydro
block 1
  bxbot 0
  bxtop 2
  bybot 2
  bytop 2
endb
endh
endb
*
fracts
pressure
pfrac1 -4.5e9
pfrac2 -35.0e9
pfmix -1.0e20
pvoid -1.0e20
endf
*
*eor* pltinp
*
```

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## **Appendix C:**

**Input for Hemi-Nose KE-BL-CO-P Sims vs. 7039 Aluminum  
Targets - Changes for MV, NB, and NC Sims Given in Notes**

INTENTIONALLY LEFT BLANK.

```

* Run History
*
*eor* cgenin
*
nose shape tests: hemi v=1038 target=7039 al finite
*
control
ep
mmp
viscosity bl=.1 bq=2 bs=0.1
endcontrol
*
mesh
block 1 geom=2dc type=e
  x0 0.00
  x1 n 40 w 1.6891 rat 1.0
  x2 n 45 dxf 0.0422275 rat 1.05
  endx
  y0 -10.219055
  y1 n 832 dyf 0.0422275 rat 1.0
  endy
  xactive 0.0 0.4
  yactive -10.219055 0.0
endblock
endmesh
*
insertion
block 1
  package '7039 Al target'
  material 1
  numsub 50
  insert box
  p1=0.0 0.0
  p2=7.6 7.62
  endinsert
endpackage
package 'w alloy rod nose'
  material 2
  numsub 100
*
* NOTE: striking velocity (yvel) is changed below
*
  yvel 1.038e5
  insert circle
  ce=0.0 -0.33782

```

```

    r= 0.33782
endinsert
endpackage
package 'w alloy rod body'
    material 2
    numsub 50
*
* NOTE: striking velocity (yvel) is changed below
*
    yvel 1.038e5
    insert box
        p1=0.0 -0.33782
        p2=0.33782 -10.1346
    endinsert
endpackage
endblock
endinsertion
*
epdata
    vpsave
*
* NOTE: poisson's ratio from Metals Handbook
*
    matep 1
        johnson-cook='7039_ALUMINUM'
            ajo=3.3672e9 bjo=3.4293e9 cjo=0.01
            mjo=1.0 njo=.41 tjo=7.76342e-2
            poisson 0.345
*
* NOTE: actual tungsten alloy was 95W-2.5Ni-1.0Fe-1.5Co (21% swaged) with r0=18.1.
*       95W-3.5Ni-1.5Fe is being used to approximate the w alloy.
*
    matep 2
        steinberg='TUNGSTEN_NI_FE'
            r0st=18.16 tm0st=0.195002 atmst=1.3
            gm0st=1.67 ast=1.03e-12 bst=1.76396
            nst=0.13 c1st=0.0 c2st=0.0
            g0st=1.45e12 btst=7.7 eist=0.0
            ypst=0.0 ukst=0.0 ysmst=0.0
            yast=0.0 y0st=18.7e9 ymst=40.e9
            poisson=0.280
*
* NOTE: parameters for boundary layer algorithm taken similar to:
*       Kmetyk, L. N. and P. Yarrington, "CTH Analysis of Steel Rod Penetration
*       Into Aluminum and Concrete Targets with Comparisons to Experimental Data",

```

```

*      Sandia National Laboratories Report SAND94-1498, October 1994.
*
* NOTE: if no BLINT model, next line is commented out. If no yield strength correction
*       factor 'corr' is omitted
*
  blint 1 soft 1 hard 2 wsl 0.084455 wbl 0.084455 fric=0.0 corr
  mix 3
endep
*
tracer
  block 1
  add 0. 0. to 0. -10.134 n 10
endtracer
*
edit
  block 1
  noexpanded
endblock
endedit
*
eos
*
* NOTE: EOS properties from cth mgrun library
*
* NOTE: 7039 Aluminum eos approximated with 7075-t6 Aluminum
*       density reduced to reflect that for 7039 Aluminum from
*       Johnson and Cook (1983).
*
  mat1 mgrun eos=7075-t6_al r0=2.77  cs=0.520e6  s=1.36
           g0=2.20  cv=1.07e11
  mat2 mgrun eos=tungsten_ni r0=18.16 cs=0.403e6 s=1.237
           g0=1.67  cv=1.66e10
endeos
*
*eor* cthin
*
nose shape tests: hemi v=1038 target=7039 al finite
*
control
  tstop 300.e-6
  rdumpf 3600
  cpshift 999.
endcontrol
*
restart

```

```

* file='rsct1'
  time=0.e-6
endr
*
cellthermo
  mmp
  ntbad=99999
endc
*
convct
*
* NOTE: if KE Sim convection=0, if MV Sim convection=1
*
  convection=0
  interface=high_resolution
endconvct
*
edit
  shortt
    time 0. dtfrequency 150.e-6
  ends
  longt
    time 0. dtfrequency 600.e-6
  endl
  plott
    time 0. dtfrequency 50.e-6
  endp
  histt
    time 0. dtfrequency 0.3e-6
    htracer1
    htracer2
    htracer3
    htracer4
    htracer5
    htracer6
    htracer7
    htracer8
    htracer9
    htracer10
  endh
ende
*
boundary
  bhydro
  block 1

```

```
bxbot 0
bxtop 2
bybot 2
bytop 2
endb
endh
endb
*
fracts
pressure
pfrac1 -5.0e9
pfrac2 -35.0e9
pfmix -1.0e20
pfvoid -1.0e20
endf
*
*eor* pltinp
*
```

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## **Appendix D:**

**Input for Ogival-Nose KE-BL-CO-P Sims vs. 7039 Aluminum  
Targets - Changes for MV, NB, and NC Sims Given in Notes**

**INTENTIONALLY LEFT BLANK.**

```

* Run History
*
*eor* cgenin
*
nose shape tests: ogive v=1474 target=7039 al finite
*
control
ep
mmp
viscosity bl=.1 bq=2 bs=0.1
endcontrol
*
mesh
block 1 geom=2dc type=e
x0 0.00
x1 n 40 w 1.6891 rat 1.0
x2 n 45 dxf 0.0422275 rat 1.05
endx
y0 -10.219055
y1 n 832 dyf 0.0422275 rat 1.0
endy
xactive 0.0 0.4
yactive -10.219055 0.0
endblock
endmesh
*
insertion
block 1
package '7039 Al target'
material 1
numsub 50
insert box
p1=0.0 0.0
p2=7.6 7.62
endinsert
endpackage
package 'ogive nose rod'
material 2
numsub 100
*
* NOTE: striking velocity (yvel) is changed below
*
yvel 1.474e5
insert uds
point 0.0 0.0

```

```

point 0.050437038 -0.08003015622
point 0.095867718 -0.1600603124
point 0.136665799 -0.2400904687
point 0.173135779 -0.3201206249
point 0.205527612 -0.4001507811
point 0.234047376 -0.4801809373
point 0.258865148 -0.5602110935
point 0.280120900 -0.6402412498
point 0.297928948 -0.7202714060
point 0.312381319 -0.8003015622
point 0.323550306 -0.8803317184
point 0.331490355 -0.9603618746
point 0.336239443 -1.040392031
point 0.337820 -1.120422187
point 0.337820 -10.1346
point 0.0 -10.1346
point 0.0 0.0
endinsert
endpackage
endblock
endinsertion
*
epdata
vpsave
*
* NOTE: poisson's ratio from Metals Handbook
*
matep 1
johnson-cook='7039_ALUMINUM'
ajo=3.3672e9 bjo=3.4293e9 cjo=0.01
mjo=1.0 njo=.41 tjo=7.76342e-2
poisson 0.345
*
* NOTE: actual tungsten alloy was 95W-2.5Ni-1.0Fe-1.5Co (21% swaged) with r0=18.1.
* 95W-3.5Ni-1.5Fe is being used to approximate the w alloy.
*
matep 2
steinberg='TUNGSTEN_NI_FE'
r0st=18.16 tm0st=0.195002 atmst=1.3
gm0st=1.67 ast=1.03e-12 bst=1.76396
nst=0.13 c1st=0.0 c2st=0.0
g0st=1.45e12 btst=7.7 eist=0.0
ypst=0.0 ukst=0.0 ysmst=0.0
yast=0.0 y0st=18.7e9 ymst=40.e9
poisson=0.280

```

\*  
\* NOTE: parameters for boundary layer algorithm taken similar to:  
\* Kmetyk, L. N. and P. Yarrington, "CTH Analysis of Steel Rod Penetration  
\* Into Aluminum and Concrete Targets with Comparisons to Experimental Data",  
\* Sandia National Laboratories Report SAND94-1498, October 1994.  
\*

\* NOTE: if no BLINT model, next line is commented out. If no yield strength correction  
\* factor 'corr' is omitted  
\*

blint 1 soft 1 hard 2 wsl 0.084455 wbl 0.084455 fric=0.0 corr  
mix 3

endep

\*

tracer

block 1

add 0. 0. to 0. -10.1345 n 10

endtracer

\*

edit

block 1

noexpanded

endblock

endedit

\*

eos

\*

\* NOTE: EOS properties from cth mgrun library

\*

\* NOTE: 7039 Aluminum eos approximated with 7075-t6 Aluminum

\* density reduced to reflect that for 7039 Aluminum from

\* Johnson and Cook (1983).  
\*

mat1 mgrun eos=7075-t6\_al r0=2.77 cs=0.520e6 s=1.36

g0=2.20 cv=1.07e11

mat2 mgrun eos=tungsten\_ni r0=18.16 cs=0.403e6 s=1.237

g0=1.67 cv=1.66e10

endeos

\*

\*eor\* cthin

\*

nose shape tests: ogive v=1474 target=7039 al finite

\*

control

tstop 300.e-6

rdumpf 3600

```
cpshift 999.
endcontrol
*
restart
* file='rsct1'
time=0.e-6
endr
*
cellthermo
mmp
ntbad=99999
endc
*
convct
*
* NOTE: if KE Sim convection=0, if MV Sim convection=1
*
convection=0
interface=high_resolution
endconvct
*
edit
shortt
time 0. dtfrequency 150.e-6
ends
longt
time 0. dtfrequency 600.e-6
endl
plott
time 0. dtfrequency 50.e-6
endp
hitt
time 0. dtfrequency 0.3e-6
htracer1
htracer2
htracer3
htracer4
htracer5
htracer6
htracer7
htracer8
htracer9
htracer10
endh
ende
```

```
*
boundary
  bhydro
    block 1
      bxbot 0
      bxtop 2
      bybot 2
      bytop 2
    endb
  endh
endb
*
fracts
  pressure
  pfrac1 -5.0e9
  pfrac2 -35.0e9
  pfmix -1.0e20
  pfvoid -1.0e20
endf
*
*eor* pltinp
*
```

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**Appendix E:**

**Input for Hemi-Nose KE-BL-CO-S  
Sims vs. 5083 Aluminum Targets**

INTENTIONALLY LEFT BLANK.

```

* Run History
*
*eor* cgenin
*
nose shape tests: hemi v=1147 target=5083 al finite
*
control
ep
mmp
viscosity bl=.1 bq=2 bs=0.1
endcontrol
*
mesh
block 1 geom=2dc type=e
x0 0.00
x1 n 40 w 1.6891 rat 1.0
x2 n 45 dxf 0.0422275 rat 1.05
endx
y0 -10.219055
y1 n 832 dyf 0.0422275 rat 1.0
endy
xactive 0.0 0.4
yactive -10.219055 0.0
endblock
endmesh
*
insertion
block 1
package '5083 Al target'
material 1
numsub 50
insert box
p1=0.0 0.0
p2=7.6 7.62
endinsert
endpackage
package 'w alloy rod nose'
material 2
numsub 100
*
* NOTE: striking velocity (yvel) is changed below
*
yvel 1.147e5
insert circle
ce=0.0 -0.33782

```

```

    r= 0.33782
endinsert
endpackage
package 'w alloy rod body'
material 2
numsub 50
*
* NOTE: striking velocity (yvel) is changed below
*
    yvel 1.147e5
    insert box
    p1=0.0  -0.33782
    p2=0.33782 -10.1346
    endinsert
endpackage
endblock
endinsertion
*
epdata
    vpsave
*
* NOTE: poisson ratio from for Tungsten from Metals Handbook, that for 5083
* Aluminum from Forrestal, M.J., V. K. Luk, and N. S. Brar, "Perforation of
* aluminum with conical-nose projectiles", Mechanic and Materials 10 (1990)
* pp. 97-105.
*
* NOTE: properties for 5083 aluminum from Silling, S. A., "CTH Reference Manual:
* Boundary Layer Algorithm for Sliding Interfaces in Two Dimensions", Sandia
* National Laboratories Report SAND93-2487, January 1994.
*
* NOTE: 5083 aluminum using undocumented power law
*
    matep 1
    johnson-cook='USER'
        ajo=-2.76e9 bjo=254.7  cjo=0.0
        mjo=1.0  njo=0.084  tjo=6.68e-2
        poisson 0.333
*
* NOTE: for strain failure at 150% all parameter for Johnson-Cook fracture model except
* the first are set to zero.
*
    jfrac='USER' jfd1=1.5 jfd2=0.0 jfd3=0.0 jfd4=0.0 jfd5=0.0
        jftm=0.0 jfpf0=-4.5e9
*
* NOTE: actual tungsten alloy was 95W-2.5Ni-1.0Fe-1.5Co (21% swaged) with r0=18.1.

```

\* 95W-3.5Ni-1.5Fe is being used to approximate the w alloy.

\*

matep 2

steinberg='TUNGSTEN\_NI\_FE'

r0st=18.16 tm0st=0.195002 atmst=1.3  
gm0st=1.67 ast=1.03e-12 bst=1.76396  
nst=0.13 c1st=0.0 c2st=0.0  
g0st=1.45e12 btst=7.7 eist=0.0  
ypst=0.0 ukst=0.0 ysmst=0.0  
yast=0.0 y0st=18.7e9 ymst=40.e9  
poisson=0.280

\*

\* NOTE: for strain failure at 150% all parameter for Johnson-Cook fracture model except the first are set to zero.

\*

\*

jfrac='USER' jfd1=1.5 jfd2=0.0 jfd3=0.0 jfd4=0.0 jfd5=0.0  
jftm=0.0 jfpf0=-35.e9

\*

\* NOTE: parameters for boundary layer algorithm taken similar to:

\* Kmetyk, L. N. and P. Yarrington, "CTH Analysis of Steel Rod Penetration  
\* Into Aluminum and Concrete Targets with Comparisons to Experimental Data",  
\* Sandia National Laboratories Report SAND94-1498, October 1994.

\*

\* NOTE: if no BLINT model, next line is commented out. If no yield strength correction factor 'corr' is omitted

\*

blint 1 soft 1 hard 2 wsl 0.084455 wbl 0.084455 fric=0.0 corr  
mix 3

endep

\*

tracer

block 1

add 0. 0. to 0. -10.134 n 10

endtracer

\*

edit

block 1

noexpanded

endblock

endedit

\*

eos

\*

\* NOTE: EOS properties from cth mgrun library

\*

```

* NOTE: 5083-H131 Aluminum eos approximated with 6061-t6 Aluminum
*       density reduced to reflect that for 5083 Aluminum from
*       Metal's Handbook.
*
mat1 mgrun eos=6061-t6_al r0=2.66 cs=0.534e6 s=1.4
          g0=1.97 cv=1.07e11
mat2 mgrun eos=tungsten_ni r0=18.16 cs=0.403e6 s=1.237
          g0=1.67 cv=1.66e10
endeos
*
*eor* cthin
*
nose shape tests: hemi v=1147 target=5083 al finite
*
control
  tstop 300.e-6
  rdumpf 3600
  cpshift 999.
endcontrol
*
restart
* file='rsct1'
  time=0.e-6
endr
*
cellthermo
  mmp
  ntbad=99999
endc
*
convct
*
* NOTE: if KE Sim convection=0, if MV Sim convection=1
*
  convection=0
  interface=high_resolution
endconvct
*
edit
  shortt
    time 0. dtfrequency 150.e-6
  ends
  longt
    time 0. dtfrequency 600.e-6
  endl

```

```
plott
  time 0. dtfrequency 50.e-6
endp
histt
  time 0. dtfrequency 0.3e-6
  htracer1
  htracer2
  htracer3
  htracer4
  htracer5
  htracer6
  htracer7
  htracer8
  htracer9
  htracer10
endh
ende
*
boundary
  bhydro
  block 1
  bxbot 0
  bxtop 2
  bybot 2
  bytop 2
  endb
endh
endb
*
fracts
  pressure
  pfrac1 -4.5e9
  pfrac2 -35.0e9
  pfmix -1.0e20
  pfvoid -1.0e20
endf
*
*eor* pltinp
*
```

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**Appendix F:**

**Input for Ogival-Nose KE-BL-CO-S  
Sims vs. 5083 Aluminum Targets**

**INTENTIONALLY LEFT BLANK.**

```

* Run History
*
*eor* cgenin
*
nose shape tests: ogive v=1286 target=5083 al finite
*
control
  ep
  mmp
  viscosity bl=.1 bq=2 bs=0.1
endcontrol
*
mesh
  block 1 geom=2dc type=e
    x0 0.00
      x1 n 40 w 1.6891 rat 1.0
      x2 n 45 dxf 0.0422275 rat 1.05
    endx
    y0 -10.219055
      y1 n 832 dyf 0.0422275 rat 1.0
    endy
    xactive 0.0 0.4
    yactive -10.219055 0.0
  endblock
endmesh
*
insertion
  block 1
    package '5083 Al target'
    material 1
    numsub 50
    insert box
      p1=0.0 0.0
      p2=7.6 7.62
    endinsert
  endpackage
  package 'w alloy ogive nose rod'
  material 2
  numsub 100
*
* NOTE: striking velocity (yvel) is changed below
*
  yvel 1.286e5
  insert uds
  point 0.0 0.0

```

point 0.050437038 -0.08003015622  
point 0.095867718 -0.1600603124  
point 0.136665799 -0.2400904687  
point 0.173135779 -0.3201206249  
point 0.205527612 -0.4001507811  
point 0.234047376 -0.4801809373  
point 0.258865148 -0.5602110935  
point 0.280120900 -0.6402412498  
point 0.297928948 -0.7202714060  
point 0.312381319 -0.8003015622  
point 0.323550306 -0.8803317184  
point 0.331490355 -0.9603618746  
point 0.336239443 -1.040392031  
point 0.337820 -1.120422187  
point 0.337820 -10.1346  
point 0.0 -10.1346  
point 0.0 0.0

endinsert

endpackage

endblock

endinsertion

\*

epdata

vpsave

\*

\* NOTE: poisson ratio from for Tungsten from Metals Handbook, that for 5083

\* Aluminum from Forrestal, M.J., V. K. Luk, and N. S. Brar, "Perforation of  
\* aluminum with conical-nose projectiles", Mechanic and Materials 10 (1990)  
\* pp. 97-105.

\*

\* NOTE: properties for 5083 aluminum from Silling, S. A., "CTH Reference Manual:

\* Boundary Layer Algorithm for Sliding Interfaces in Two Dimensions", Sandia  
\* National Laboratories Report SAND93-2487, January 1994.

\*

\* NOTE: 5083 aluminum using undocumented power law

\*

matep 1

johnson-cook='USER'

ajo=-2.76e9 bjo=254.7 cjo=0.0

mjo=1.0 njo=0.084 tjo=6.68e-2

poisson 0.333

\*

\* NOTE: for strain failure at 150% all parameter for Johnson-Cook fracture model except  
\* the first are set to zero.

\*

```
jfrac='USER' jfd1=1.5 jfd2=0.0 jfd3=0.0 jfd4=0.0 jfd5=0.0
jftm=0.0 jfpf0=-4.5e9
```

\*

\* NOTE: actual tungsten alloy was 95W-2.5Ni-1.0Fe-1.5Co (21% swaged) with r0=18.1.  
\* 95W-3.5Ni-1.5Fe is being used to approximate the w alloy.

\*

matep 2

steinberg='TUNGSTEN\_NI\_FE'

```
r0st=18.16 tm0st=0.195002 atmst=1.3
gm0st=1.67 ast=1.03e-12 bst=1.76396
nst=0.13 c1st=0.0 c2st=0.0
g0st=1.45e12 btst=7.7 eist=0.0
ypst=0.0 ukst=0.0 ysmst=0.0
yast=0.0 y0st=18.7e9 ymst=40.e9
poisson=0.280
```

\*

\* NOTE: for strain failure at 150% all parameter for Johnson-Cook fracture model except  
\* the first are set to zero.

\*

```
jfrac='USER' jfd1=1.5 jfd2=0.0 jfd3=0.0 jfd4=0.0 jfd5=0.0
jftm=0.0 jfpf0=-35.e9
```

\*

\* NOTE: parameters for boundary layer algorithm taken similar to:  
\* Kmetyk, L. N. and P. Yarrington, "CTH Analysis of Steel Rod Penetration  
\* Into Aluminum and Concrete Targets with Comparisons to Experimental Data",  
\* Sandia National Laboratories Report SAND94-1498, October 1994.

\*

\* NOTE: if no BLINT model, next line is commented out. If no yield strength correction  
\* factor 'corr' is omitted

\*

```
blint 1 soft 1 hard 2 wsl 0.084455 wbl 0.084455 fric=0.0 corr
mix 3
```

endep

\*

tracer

```
block 1
```

```
add 0. 0. to 0. -10.1345 n 10
```

endtracer

\*

edit

```
block 1
```

```
noexpanded
```

```
endblock
```

endedit

\*

```

eos
*
* NOTE: EOS properties from cth mgrun library
*
* NOTE: 5083-H131 Aluminum eos approximated with 6061-t6 Aluminum
*       density reduced to reflect that for 5083 Aluminum from
*       Metal's Handbook.
*
mat1 mgrun eos=6061-t6_al r0=2.66  cs=0.534e6  s=1.4
          g0=1.97  cv=1.07e11
mat2 mgrun eos=tungsten_ni r0=18.16  cs=0.403e6  s=1.237
          g0=1.67  cv=1.66e10

endeos
*
*eor* cthin
*
nose shape tests: ogive v=1286 target=5083 al finite
*
control
  tstop 300.e-6
  rdumpf 3600
  cpshift 999.
endcontrol
*
restart
* file='rsct1'
  time=0.e-6
endr
*
cellthermo
  mmp
  ntbad=99999
endc
*
convct
*
* NOTE: if KE Sim convection=0, if MV Sim convection=1
*
  convection=0
  interface=high_resolution
endconvct
*
edit
shortt
  time 0. dtfrequency 150.e-6

```

```
ends
longt
  time 0. dtfrequency 600.e-6
endl
plott
  time 0. dtfrequency 50.e-6
endp
histt
  time 0. dtfrequency 0.3e-6
  htracer1
  htracer2
  htracer3
  htracer4
  htracer5
  htracer6
  htracer7
  htracer8
  htracer9
  htracer10
endh
ende
*
boundary
  bhydro
    block 1
      bxbot 0
      bxtop 2
      bybot 2
      bytop 2
    endb
  endh
endb
*
fracts
  pressure
  pfrac1 -4.5e9
  pfrac2 -35.0e9
  pfmix -1.0e20
  pfvoid -1.0e20
endf
*
*eor* pltinp
*
```

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**Appendix G:**  
**Table of Simulation Results**

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KE-BL-CO-P Sims vs. 5083 Aluminum Targets					
65 g Hemi-Nose Rods (id=3)			63 g Ogival-Nose Rods (id=2)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1147	1026	rigid	1286	1145	rigid
1201	1027	eroded	1399	1296	rigid
1283	1090	eroded	1534	1432	rigid
			1600	1510	rigid
			1800	1730	rigid
			1900	1828	rigid
			2000	1909	deformed
			2100	1938	eroded
KE-BL-CO-P Sim vs. 7039 Aluminum Targets					
65 g Hemi-Nose Rods (id=3)			63 g Ogival-Nose Rods (id=2)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1038	737	rigid	1474	1344	rigid
1093	910	deformed	1595	1454	rigid
1198	915	eroded	1800	1697	rigid
			1900	1774	deformed
			2000	1820	eroded
MV-BL-CO-P Sims vs. 5083 Aluminum Targets					
65 g Hemi-Nose Rods (id=4)			63 g Ogival-Nose Rods (id=3)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1147	973	rigid	1286	1082	rigid
1201	1084	rigid	1399	1243	rigid
1283	1151	deformed	1534	1405	rigid
			1600	1460	rigid
MV-BL-CO-P Sims vs. 7039 Aluminum Targets					
65 g Hemi-Nose Rods (id=4)			63 g Ogival-Nose Rods (id=3)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1038	744	rigid	1474	1310	rigid
1093	796	rigid	1595	1399	rigid
1198	1007	deformed			

KE-NB-NC-P Sims vs. 5083 Aluminum Targets					
65 g Hemi-Nose Rods (id-5)			63 g Ogival-Nose Rods (id-4)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1147	726	eroded, excessively deformed	1600	1375	eroded
1283	930	eroded, excessively deformed			
KE-BL-CO-S Sims vs. 5083 Aluminum Targets					
65 g Hemi-Nose Rods (id-6)			63 g Ogival-Nose Rods (id-5)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1147	927	rigid	1286	1043	rigid
1201	1041	eroded	1399	1186	rigid
1283	1021	eroded	1534	1339	rigid
			1600	1439	rigid
KE-BL-NC-P Sims vs. 5083 Aluminum Targets					
65 g Hemi-Nose Rods (id-7)			63 g Ogival-Nose Rods (id-6)		
Striking Velocity (m/s)	Residual Velocity (m/s)	Comments	Striking Velocity (m/s)	Residual Velocity (m/s)	Comments
1147	828	eroded, excessively deformed	1286	1123	nose deformed slightly
1201	870	eroded, excessively deformed	1399	1292	nose deformed
1283	1007	eroded, excessively deformed	1534	1326	eroded
			1600	1420	eroded

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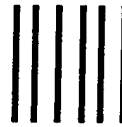
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