# BENCHMARKING THE SPHINX AND CTH SHOCK PHYSICS CODES FOR THREE PROBLEMS IN BALLISTICS

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## ABSTRACT

The CTH Eulerian hydrocode, and the SPHINX smooth particle hydrodynamics (SPH) code were used to model a shock tube, two long rod penetrations into semi-infinite steel targets, and a long rod penetration into a spaced plate array. The results were then compared to experimental data. Both SPHINX and CTH modeled the one-dimensional shock tube problem well. Both codes did a reasonable job in modeling the outcome of the axisymmetric rod impact problem. Neither code correctly reproduced the depth of penetration in both experiments. In the 3-D problem, both codes reasonably replicated the penetration of the rod through the first plate. After this, however, the predictions of both codes began to diverge from the results seen in the experiment. In terms of computer resources, the run times are problem dependent, and are discussed in the text.

## INTRODUCTION

The shock physics code- commonly referred to as a hydrocode- allows an engineer to model experiments by numerically solving the conservation equations of mass, momentum, and energy. The insight gained from this approach is invaluable to understanding the phenomena observed during testing. While several types of codes are available to the engineer, two of the more significant ones are the Eulerian and smooth particle hydrocodes. Eulerian hydrocodes are relatively mature tools that have been available for over 10 years. Probably the best known and most widely used is CTH [1]. CTH was developed by Sandia National Laboratories and solves the conservation equations using a leap-frog method finite volume scheme. A significant amount of benchmark data is available for CTH. In contrast, the smooth particle hydrodynamics (SPH) codes are relatively new techniques that are rapidly evolving [2]. An SPH code solves the conservation equations using analytical interpolation functions that estimate the field variables at each point in space. The SPH technique holds great promise for many types of problems, but relatively little benchmarking data has been published. Presently, the SPHINX code has one of the larger user bases for SPH codes [3]. Hence, comparisons between the SPHINX and CTH codes and experimental data are beneficial to a great number of users.

In this paper we discuss the ability of the SPHINX and CTH shock physics codes to replicate the results of 3 problems of interest to the ballistics community: a shock tube, a long rod penetration into a semi-infinite steel target, and a long rod penetration into a spaced plate array.

These cases were selected for two reasons. First, they show an increasing level of complexity. The shock tube problem is one-dimensional and uses only an ideal gas equation of state. The long rod penetration into the semi-infinite steel target is an axisymmetric problem where material strength is treated. The spaced plate case requires a three dimensional treatment and includes fracture. The second reason for their selection is that these cases highlight the differences in the two approaches. The first case should be easier to calculate using a Lagrangian technique. The second case favors an Eulerian treatment. Finally, the third case should highlight key advantages of the SPH treatment, the ability to simulate the impact of a projectile into a target with large void space and the projecitle's fracture. Our comparison will focus on the ability of the two codes to replicate the results of the cases, the run time for each of the problems, and the computer resources required.



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## DISCLAIMER

## THE SHOCK TUBE PROBLEM

This problem- also known as the "Sod" problem- is shown below in Figure 1 [4]. It was selected because it exhibits shock phenomena and has an exact analytical solution as long as the waves do not interact with the boundaries. It contains a contact discontinuity, a shock wave, and a rarefaction wave, all of which are fundamental to any treatment of shock phenomena.

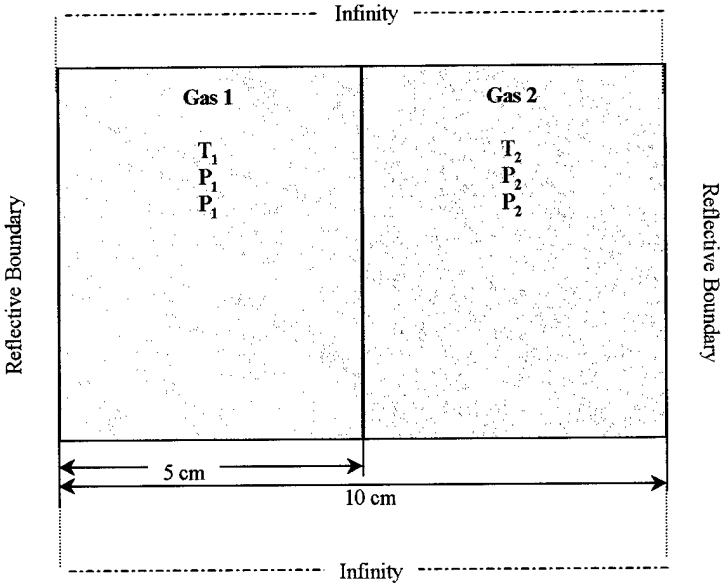


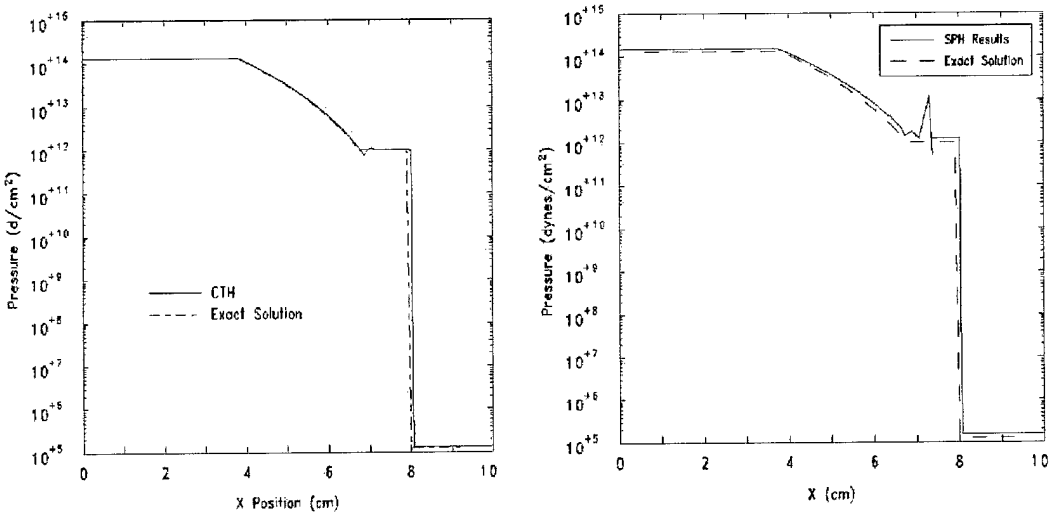

Figure 1. Shock Tube Problem Definition

Here, the problem consists of two gases in contact. The first gas is at densities and temperatures much greater than the second one. Table 1 summarizes the parameters used in the analyses. Note that an ideal gas equation of state (EOS) has been used. Cell size for the CTH calculation was .01 cm. The smoothing length for the SPHINX calculation was .01 cm as well.

Table 1. Shock Tube Problem Parameters

| *PARAMETER* | *GAS 1* | *GAS 2* |
|---|---|---|
| $\gamma$ | $1.666\overline{}$ | $1.666\overline{}$ |
| Molecular Weight | 1.0 | 1.0 |
| $C_V$ ergs/gr • eV | 2.0e11 | 2.0e11 |
| Temperature eV | 100 | .01 |
| Density $g/cm^3$ | 1 | .001 |

Figure 2 shows the results of the CTH and SPHINX calculations 80 nanoseconds after the start of the calculation. As can be seen, both codes correctly calculate the pressure at most X locations.




2a. CTH Results

2b. SPHINX Results

Figure 2. Shock Tube Problem Results for CTH and SPHINX

The CTH calculation matches the result almost perfectly, but suffers from a small overshoot at the interface between the two gases. SPHINX does almost as well. There is a slight difference in the location of the relief fan in the SPH solution. A more serious concern, however, is the instability observed at the interface between the two gases. This is due to the large density discontinuity between the two materials and is endemic to the classical SPH treatment. The Moving Least Squares (MLS) method being researched by Dilts, and the Normalized SPH method of Libersky, have the potential to solve many of the shortcomings of the SPH technique [5,6]. Figure 3 shows a normalized SPH solution [6] of a similar problem with slightly different initial conditions provided to us by Dr. Libersky. As can be seen, a considerable improvement has been made using this technique. The instability has disappeared.

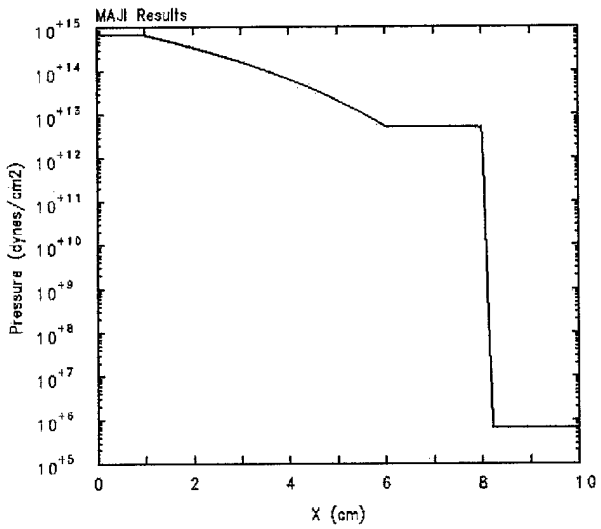
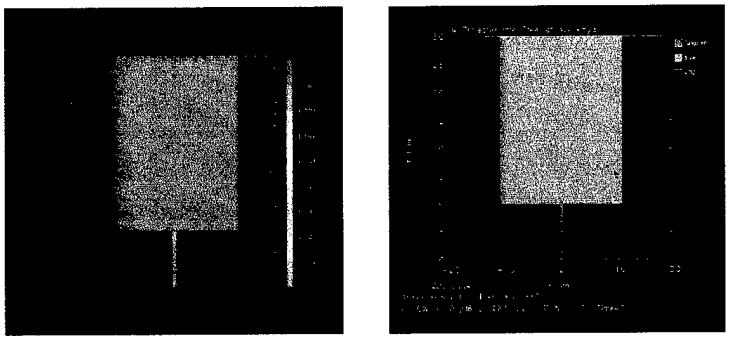



Figure 3. Shock Tube Problem Results Using a Normalized SPH Approach.

Thus, the conclusions we have drawn are that both CTH and SPHINX are capable of modeling the shock tube problem, in terms of replicating the shock and rarefaction waves and, that the spurious results at the gas's interface shortcomings of the classical SPH method treatment may be overcome using evolving numerical approaches.

## LONG ROD IMPACT INTO A SEMI-INFINITE TARGET

Figure 4 shows the problem set-up for a .68 cm diameter by 15.96-cm long tungsten rod impacting a semi-infinite steel target.



4a. SPHINX Calculation 4b. CTH Calculation

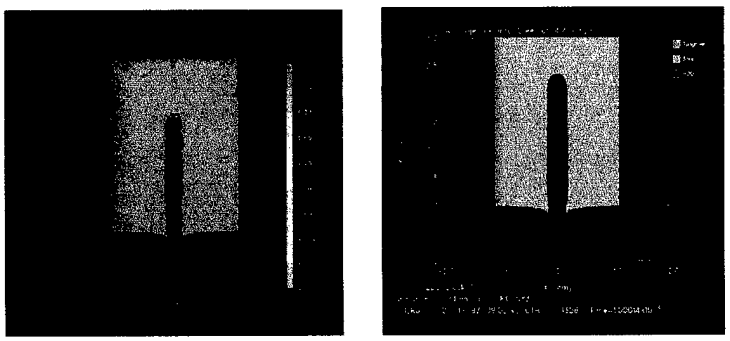
Figure 4. Problem Set-up for Long Rod Impact into a Semi-infinite Target

This problem was selected because the data is well characterized, making it ideal for benchmarking [7]. It includes all of the features of the shock tube problem and adds the complexities of material strength and material erosion. The experiments were modeled using an axisymmetric assumption. Material strength was treated assuming an elastic perfectly plastic constitutive response. The Mie Gruneisen EOS was used for modeling the volumetric response of the materials. Table 2 summarizes the problem parameters. Cell size was .2 cm for the CTH calculation. The smoothing length in the SPH calculation was .2 cm as well.

Table 2. Problem Parameters for the Axisymmetric Long Rod Impact

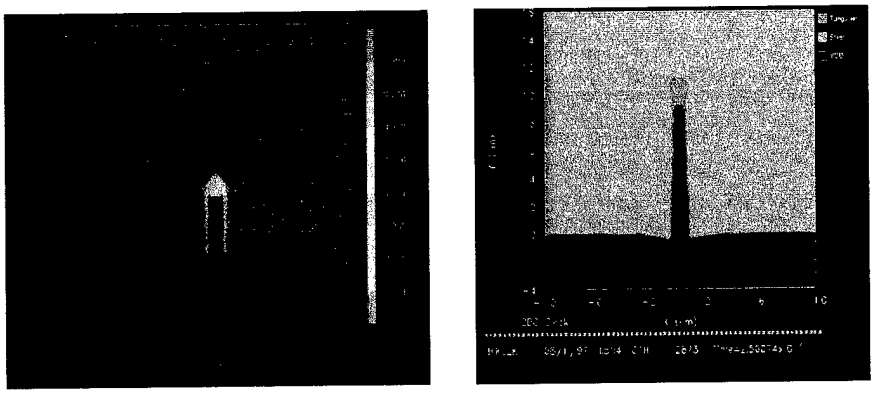
| *PARAMETER* | *TUNGSTEN* | *STEEL* |
|---|---|---|
| Flow Stress dynes/cm$^2$ | 10.e$^9$ | 7.1e$^9$ |
| Density g/cm$^3$ | 17.35 | 7.84 |
| Poisson's Ratio | .30 | .279 |

Two experiments were modeled. In the first, the impact velocity was 4.40 km/s. In the second experiment, the rod impact velocity was 1.29 km/s. The graphical results of the calculations are summarized in Figures 5 and 6. A quantitative comparison is shown in Figure 7. As can be seen, neither CTH nor SPHINX produces results that match the experiments exactly.



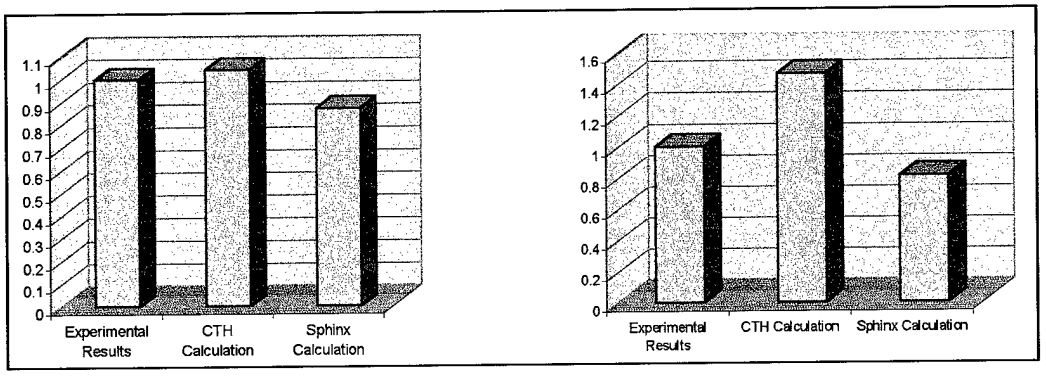
5a. SPHINX Calculation 5b. CTH Calculation

Figure 5. Results of the 4.40 km/s Impact Experiment



6a. SPHINX Calcualtion 6b. CTH Calculation

Figure 6. Results of the 1.29 km/s Impact Experiment




7a. 4.40 km/s Impact 7b. 1.29 km/s Impact

Figure 7. A Comparison of Experimental and Calculated Results for the Depth of Penetration

In the first experiment, CTH overpredicts the depth of penetration by 5%. The SPHINX calculation under predicts the results by 15%. In the second experiment, the CTH over predicts the depth of penetration by 46%, while SPHINX again under predicts the penetration, this time by 20%. It is believed that the differences are due to the manner in which the material strength is handled, since recent benchmarking using the ALEGRA Arbitrary Lagrangian Eulerian (ALE) code has shown results that match to within 10% for both cases using the same problem parameters [7].

Both the CTH and SPHINX calculations were performed using a Silicon Graphics workstation with an R10000 processor. Run time for the CTH calculation was 15 minutes. The run time for the SPHINX calculation was 25 minutes. The CTH model contained 15,000 cells, while the SPH model used 20,000 particles.

The conclusion we have drawn is that neither code predicts exactly the depth of penetration of the rod in these cases. While both CTH and SPHINX have predicted the depth of penetration to within 15 percent for the 4.40 km/s impact, perhaps neither a pure Eulerian or SPH approach is warranted for the 1.29 km/s impact velocity. An ALE code may be the best tool for this low velocity problem.

## THREE DIMENSIONAL SPACED PLATE IMPACT

The final problem discussed is the three dimensional plate impact experiment shown below in Figure 8. This problem incorporates all of the features of the first two cases, but adds the additional feature of fracture. Like the second experiment, the data available makes this problem ideal for benchmarking.

In this experiment a tungsten rod with a diameter of .406 cm., and a length of 15.08 cm. is launched into three .644 cm thick 4140 steel plates at 2.25 km/s. The distance between the plates is 25.4 cm. The rod has 3.4° of pitch and .4° of yaw when it impacts. This orientation necessitates a three dimensional treatment. Note that tungsten was modeled using the Johnson-Cook constitutive model using parameters found in reference 8. The steel plates were modeled using an elastic perfectly plastic constitutive relation (Table 2). Like the second case, the Mie-Gruneissen EOS was used. The SPHINX calculation used a smoothing length of .049 cm, and the CTH calculation had a cell size of .05 cm.

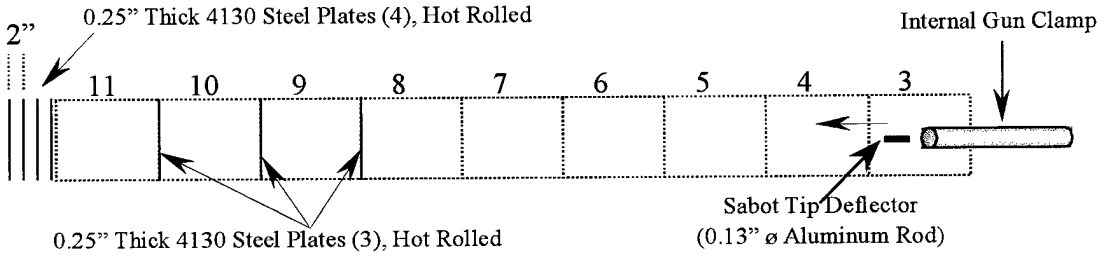
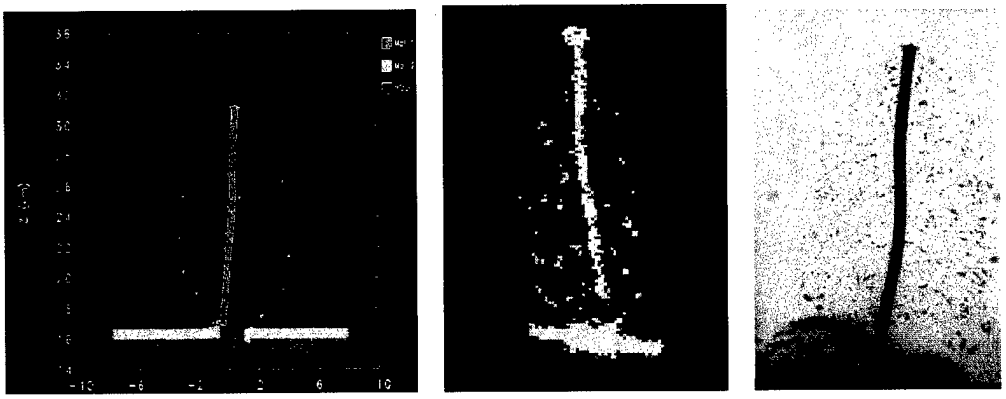


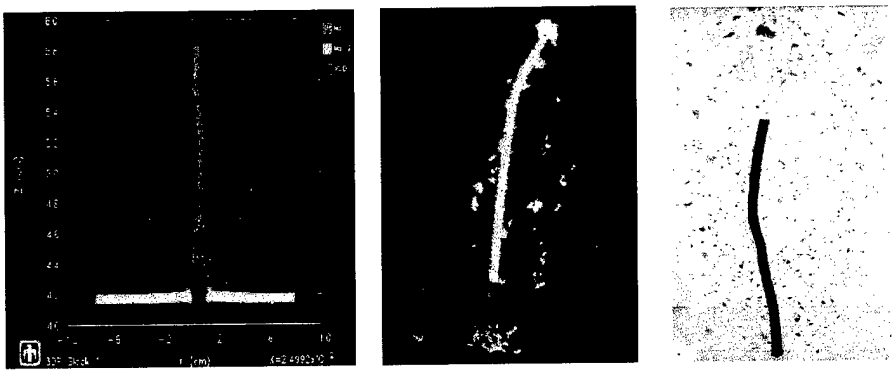

Figure 8. A Spaced Plate Experiment

Figures 9 through 11 summarize the results of the calculations. Radiographs from the experiments are included for comparison purposes. As can be seen, both codes match the data qualitatively for the first plate impact. However, as the rod progresses through the plates, the agreement lessens. It is obvious that, after the third plate impact, SPHINX is not replicating the experimental results. CTH is doing only marginally better.



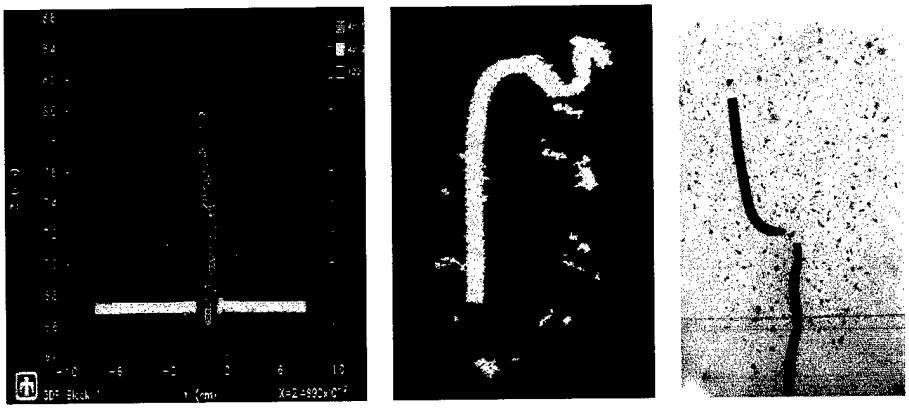
9. CTH 9b. SPHINX 9c. Radiograph

Figure 9. Rod after First Plate Impact



10a. CTH 10b. SPHINX 10c. Radiograph

Figure 10. Rod after Second Plate Impact



11a. CTH 11b. SPHINX 11c. Radiograph

Figure 11. Rod after Third Plate Impact

Some of the disagreement may be due to the tungsten becoming more brittle as it progresses through the plates [9]. The answer may also be that the Johnson-Cook constitutive and damage models are not appropriate in this instance. However, these explanations probably do not account for all of the discrepancies seen. If they did, the code results would be in better agreement despite their disagreement with the experimental results.

Let's turn now to the computational resources used in the problem. The SPHINX calculation was performed using 256 processors on the Los Alamos National Laboratory's Cray T3D computer. The run time was approximately 12 hours. The CTH calculation was performed on the Sandia National Laboratories' computer. Run time was approximately 60 hours when 304 processors were used. Processing speed on the SNL computer is about three times slower than the T3D, so run times are comparable between the two codes.

The conclusion drawn from this discussion is that both CTH and SPHINX do a good job calculating the rod impact with the first plate. However, their solutions begin to diverge as the rod exits the second plate. By the time the rod exits the third plate, neither code has accurately predicted the outcome of the experiment.

## CONCLUSIONS

Having discussed the results of the three benchmarking problems, let us now summarize our conclusions. First, both SPHINX and CTH can model the one-dimensional shock tube problem well. Discrepancies in the SPH results should be eliminated by better numerical techniques. Second, both codes do a reasonable job in modeling the outcome of the axisymmetric rod impact problem. Neither code correctly reproduces the depth of penetration in both experiments. However, the results are reasonable for the 4.40km/s impact. An ALE code may be the tool of choice for the low velocity experiment. Finally, in the 3-D problem, both codes reasonably replicate the penetration of the rod through the first plate. After this, however, the predictions of both codes begin to diverge from the results seen in the experiment. In terms of computer resources, the run times are similar for both codes however, they were run on different machines with SPHINX using 256 processors, and CTH using 304 processors. Precise comparisons will have to wait until both codes can be run on the same machine.

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