Computational Investigation of In-Flight Temperature in Shaped Charge Jets and Explosively Formed Penetrators

Peter Sable[1, a)], Nathaniel Helminiak[1], Arne Gullerud[2], Eric Harstad[2], Jeromy Hollenshead[2], and Eugene S. Hertel[2]

[1] Marquette University, Milwaukee, WI 53233
[2] Sandia National Laboratories, Albuquerque, NM 87123

[a)] Corresponding author: peter.sable@marquette.edu

Abstract. With the increasing use of hydrocodes in modeling and system design, experimental benchmarking of software has never been more important. While this has been a large area of focus since the inception of computational design, comparisons with temperature data are sparse due to experimental limitations. A novel temperature measurement technique, magnetic diffusion analysis, has enabled the acquisition of in-flight temperature measurements of hyper velocity projectiles. Using this, an AC-14 bare shaped charge and an LX-14 EFP, both with copper linings, were simulated using CTH to benchmark temperature against experimental results. Particular attention was given to the slug temperature profiles after separation, and the effect of varying equation-of-state and strength models. Simulations are in agreement with experimental, attaining better than 2% error between observed shaped charge temperatures. This varied notably depending on the strength model used. Similar observations were made simulating the EFP case, with a minimum 4% deviation. Jet structures compare well with radiographic images and are consistent with ALEGRA simulations previously conducted. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

INTRODUCTION

Computational approaches are becoming more and more prevalent in system modeling and design. As such, significant effort has been given to the validation and benchmarking of software against experimental data, to ensure the fidelity of calculations. While there is an abundance of data over a range of experimental conditions, small time scale (micro to millisecond) temperature data has remained elusive due to the limited resolution of measurement instrumentation. However, recent developments in experimental techniques have enabled the measurement of in-situ temperature within dynamic events, specifically hypervelocity projectiles such as shaped charge jets (SCJs) and explosively formed projectiles (EFPs).

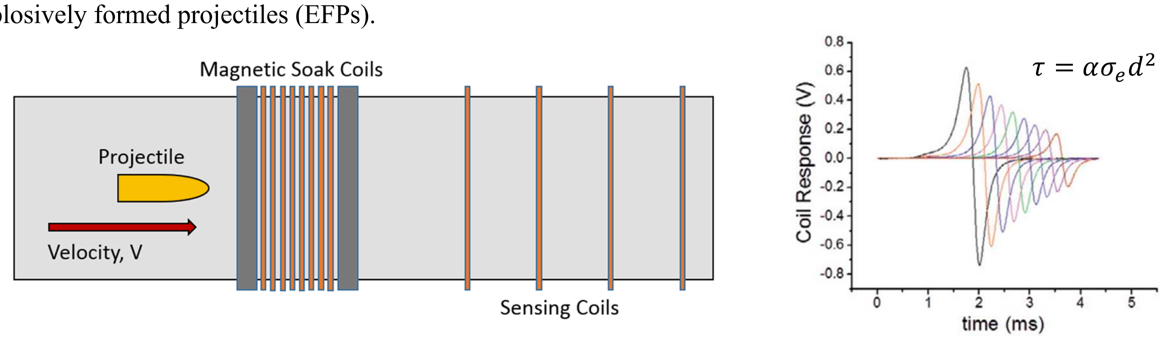

FIGURE 1. (Left) A representative schematic of the temperature diagnostic used by Uhlig [1]. (Right) The projectile of interest is saturated with a magnetic field via soak coil, the decay time of which is measured via inductance down range. This decay time is related to copper conductivity and therefore temperature.

This technique, developed by Uhlig and colleagues at the Army Research Laboratory (ARL), experiments are designed such that the projectiles of interested pass through a series of inductance coils and are therefore saturated with a detectable, material dependent, magnetic field. Downrange, the decay of the field is tracked via passive sensing coils [1-4]. The decay time of the projectile's magnetic field is directly proportional to the material conductivity, which can be further correlated to in-situ temperature [5]. A schematic setup can be seen in Figure 1.

Reported here, SCJ and EFP experiments conducted at ARL were modeled using CTH, in an effort to benchmark calculated projectile temperatures against experimental measurements [6, 7]. A particular interest was taken in temperature sensitivity to strength model, given the intrinsic link between the high-strain-rate deformation occurring and projectile heating. Four, more common, models were examined consisting of Johnson-Cook (JO) [8], Steinberg-Guinan-Lund (SGL) [9], Preston-Tonks-Wallace (PTW) [10], and Mechanical Threshold Stress (MTS) [11]. Other factors of interested including the effects of air versus vacuum conditions, and the inclusion of fracture. While experiment temperatures were indirectly calculated based on magnetic field decay and related conductivity, simulations will extract temperature calculations directly for comparison, in contrast to previously done studies using ALEGRA [4].

COMPUTATIONAL SETUP

To model both experimental configurations, a two-dimensional cylindrical domain was selected, given the axial symmetry of the problem, which allowed for greater computational efficiency. In both cases, throughout the initial detonation, projectile formation, and motion, the copper liner experience drastic change in temperature and pressure, and as such the chosen equation-of-state (EOS) must be robust enough to incorporate such variations up to and including melting. For this reason, a Sesame table was chosen over alternatives such as a Mie-Grüneisen EOS.

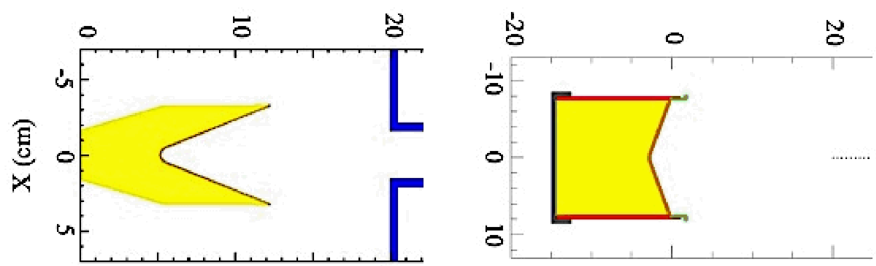

FIGURE 2. Initial CTH domain for both SCJ (left) and EFP (right) experiments. Both utilize an LX-14 explosive driver with a copper liner. The SCJ is bare and the EFP enclosed.

An AC-14 bare shaped charge was modeled, reflecting the experimental study, with a copper liner diameter of 6.5 cm, liner thickness of 1.2 mm, giving an overall shaped angle of 22 degrees. The jet is formed via an LX-14 explosive simulated using the Jones-Wilkins-Lee (JWL) model for reactive EOS and programmed burn for a rate law. As mentioned previously, the implications of constitutive modeling was a key concern and so the copper liner viscoplastic model was varied. Parameters are more concisely outlined in Table 1. It should be noted the table includes casing components only relevant to the EFP configuration. That being said, the EFP setup was modeled in a similar fashion, though with the additional casing components being assigned a Mie-Grüneisen EOS and elastic-perfectly-plastic von-Mises (EPPVM) strength models.

TABLE 1. Parameters used to computationally model both SCJ and EFP configurations. *Components only seen in the EFP case.

Material	**Copper Liner**	**LX-14**	**304SS Casing***	**6061Al Collar***	**Polycarbonate Base/Tubing***
Equation of State	Sesame Table	Jones-Wilkins-Lee	Mie-Grüneisen	Mie-Grüneisen	Mie-Grüneisen
Strength Model(s)	JO, SGL, PTW, MTS	--	EPPVM	EPPVM	EPPVM

Experiments were conducted in a near vacuum (~4 Pa, contained by polycarbonate tubing), in order to isolate jet temperature behavior from atmospheric effects, however this was noted to cause inconsistencies in experiments. Keeping this in mind, simulations were conducted with both atmospheric air (Sesame EOS) and vacuum conditions with any effects noted. In later simulations, the polycarbonate housing was added and fracture models included to determine any additional projectile temperature sensitivity. Overall, these effects had a minimal effect on bulk projectile temperature, changing the calculation by an order of one percent.

Mesh resolution was considered for both scenarios, to ensure proper convergence of temperature calculations. Using, projectile velocity and temperature as metrics, a flat mesh of 0.1 cm/cell was incrementally decreased by 0.01 cm, until convergence was observed. Cell sizes of less than 0.0125 cm/cell were considered adequate for the SCJ case, with the EFP converging slightly faster at 0.03 cm/cell. This corresponds well with the differences in liner thickness between the two experiments, with the SCJ liner being 1.2 mm thick as opposed to the EFP's 6 mm.

COMPUTATIONAL RESULTS

Shaped Charge Jet

The bare shaped charge initiated by an LX-14 explosive was simulated in CTH using the aforementioned parameters (Table 1). As would be expected, the blast wave propagating through the explosive, impinges the copper liner onto itself forcing a jet penetrator outward at 9.02 km/s in good agreement with the measured ~9.15 km/s seen in tests. While the time and location of jet separation varied with the constitutive model used, due to direct implications in plastic deformation, overall jet structure was more or less consistent, despite evident variations in temperature (Figure 3).

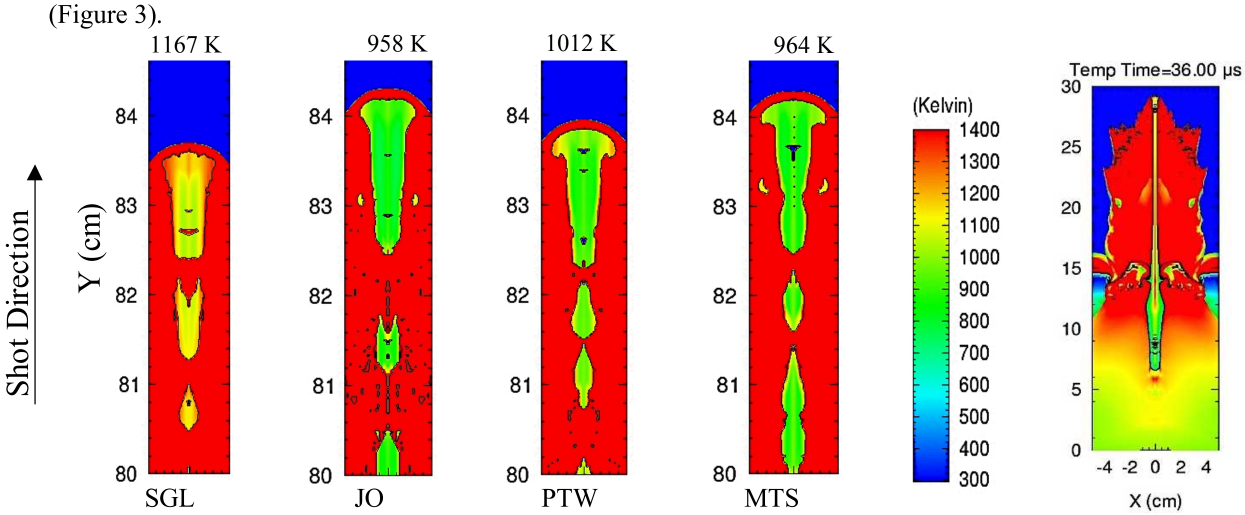

FIGURE 3. (Left) Shaped charge jet structure and temperature contours at approximately 80 cm standoff from initiation, bulk temperature results by strength model shown above, compared to observed 1190 K. (Right) Macroscale view of the SCJ.

To compare the spatially varying temperature field calculated by CTH to experiment, a radial temperature profiles of the front most slug were extracted. At least fifty (radial) profiles were taken spaced evenly along the y-axis. The average of each profile was further averaged among each of those collected resulting in a single bulk temperature calculation for each simulation. Taken at a standoff of about 80 cm, these were compared to an experimentally observed 1190±60 K [1, 2]. Values were 1167, 958, 1012, and 964 K for SGJ, JO, PTW, and MTS strength models respectively. Overall, all models used in simulations make a reasonable prediction of experimental temperature, and depending on application each model could be acceptable. However, each model treats plastic deformation differently, and, as this changes the energy contribution to material heating, there is a corresponding variation in calculated temperature. Observed in these simulations, the Steinberg-Guinan-Lund model best approximated experiment with about 1.9% error, compared to the furthest error of 22% by the Johnson-Cook model. This trend corresponds with previous simulations done in ALEGRA by Uhlig and Niederhaus [4]. It should be noted that Johnson-Cook (as well as other models) have a range of acceptable parameters. The effect of changing these was not explored, with only default values used.

Explosively Formed Projectile

Similarly, EFP simulations were run with the same LX-14 explosive and listed parameters, with strength model varying. Radial profiles were again extracted from CTH temperature contours and bulk temperature values were calculated. By design, EFP's undergo lesser strain-rate loading (10^3 instead of 10^5 s^{-1} seen by an SCJ) and therefore lesser overall temperatures as has been observed experimentally.

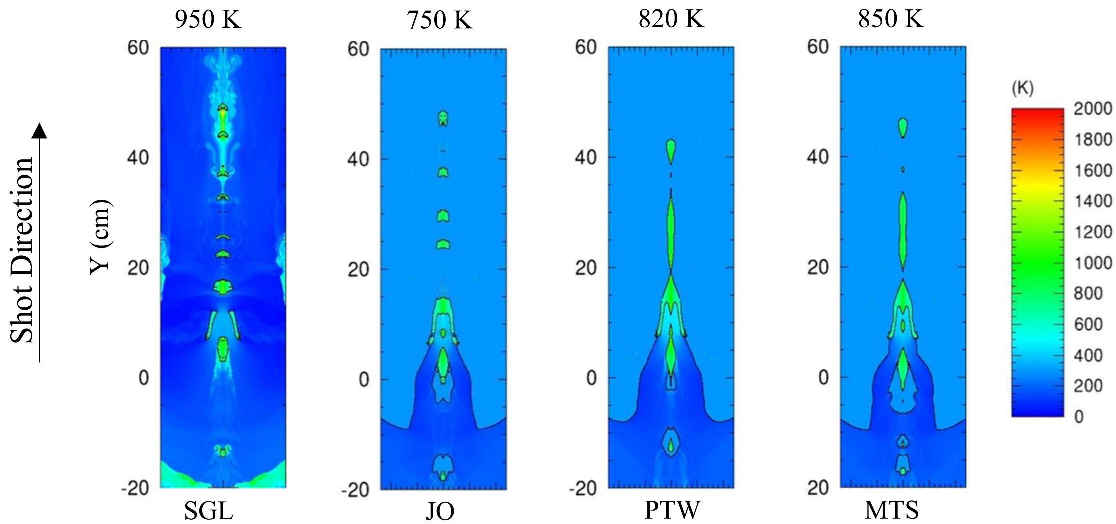

FIGURE 4. Explosively formed projectile simulations done with varying strength model. Results shown as temperature contours with front most slug bulk temperature displayed above, compared to the experimentally measured 725 K.

Experiments done at ARL measured in-flight EFP temperatures to be 725±60 K. Again, all simulations seemed to provide a reasonable approximation of this ranging from 750 to 950 K. In all cases, CTH over predicted temperature, with the Johnson-Cook model matching closest with experiment at 750 K (3.4% error). This contrasts with SCJ simulations, in that the Steinberg-Guinan-Lund model is actually the worst fit. However, given the differences in deformation between the two scenarios this makes sense. In general, SGL was made for higher strain-rate scenarios (>10^5 s^{-1}) while JO parameters were fit for lower (~10^3 or 10^4 s^{-1}) [8, 9]. More so, this observation confirms that despite most models giving a reasonable estimate, a more precise calculation must capture to the appropriate plasticity and so the appropriate model depends on the loading conditions and strain-rates involved. As an additional check, these results were also comparable to previous studies done in ALEGRA [3], with the same trends between models observed.

Radiographs

While the primary interest of this study was in-flight projectile temperature, an additional source of experimental data is radiographs taken of both the SCJ and EFP experiments. This provides an additional computational benchmark as the more accurately liner deformation is portrayed, the more accurately liner heating (and therefore temperature) should be approximated.

Pictured in Figure 5, the "best" CTH simulations are compared to ARL radiographs. Done using CTH's *radiograph* capability [6], it should be noted that this is a 3D tool, therefore numerical artifacts can be seen due to the toroidal nature of the 2D cylindrical domain. For the SCJ simulations, just as temperature was reasonably well predicted with all models, the jet structure was also consistent with radiographs, with SGL being most accurate in a qualitative sense. The EFP case is less straightforward. The JO model best approximated experimental temperature, however EFP structure shows significantly more projectile break up than radiographs. In fact, structure seems to be best captured by the PTW model, though calculating a slightly higher temperature. This could suggest the need to better tune model parameters, or rather that PTW should be the preference to capture EFP deformation and other factors such as equation-of-state should be examined.

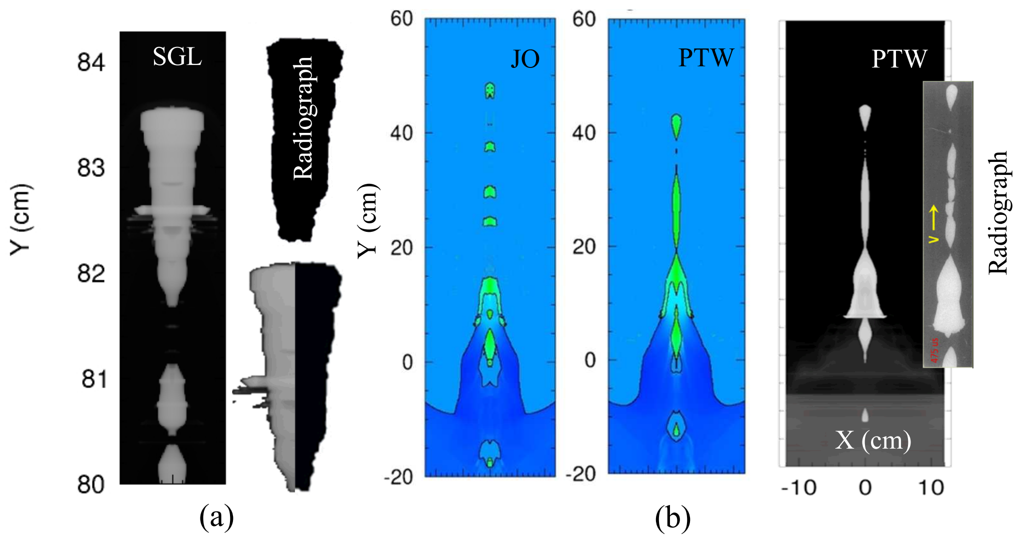

FIGURE 5. (a) SCJ simulated using the SGL model compared to an ARL radiograph. (b) EFP simulations (using JO and PTW) compared to experimental radiographs. Note, JO had a more accurate temperature calculation, however projectile structure is better captured by PTW.

CONCLUDING REMARKS

Shaped charge jets and explosively formed projectiles are critical applications in which proper modeling of both strength and thermodynamic characteristics are vital to accurately predicting formation and impact behavior. As such, it's imperative that approaches used to model such behavior are validated against experimental data to ensure fidelity. Temperature has remained one of the more elusive characteristics against which to benchmark, despite being among the most important, due to limitations in measurement technology. Here, CTH simulations are used to model novel SCJ and EFP experiments in which in-flight projectile temperature was measured [1, 2], enabling CTH temperature calculations to be benchmarked.

Looking at temperature calculations, a key concern is variations between strength models, given the unique behaviors observed at these strain-rates of about 10^3 and 10^5 s^{-1} seen for EFP and SCJ's respectively. Assuming equivalent system conditions at detonation, blast energy (primarily) goes to plastic deformation and PdV work on the copper liner, governed by the strength model and equation of state respectively. Changing the strength model alters how the energy is budgeted between the two and therefore directly effects temperature calculation. In this study, Johnson-Cook, Steinberg-Guinan-Lund, Preston-Tonks-Wallace, and Mechanical-Threshold-Stress models were examined, being among the more common models used in CTH, with only default parameters used.

For both sets of experiments, all models gave reasonable predictions within about 100 K of the experiment including uncertainty. The SCJ case was best captured by the SGL model with less than 2% error in temperature, and jet structure agreeing well with experiment radiographs. In contrast, the EFP experiments were best matched in temperature using JO with 3.4% error. Radiograph structure, however, was better approximated with a PTW, a discrepancy which suggests model parameters should be further tuned to the range applicable to the strain-rates of concern. Additional factors were considered such as vacuum conditions versus open air, and fracture included in strength modeling. Overall, the effects of these were minimal, not changing the overall trends between models.

In summary, CTH was shown to adequately simulate the described shaped charge jet and explosively formed projectile experiments, corresponding well with experimental observations. Strength model, as expected, was shown to have large implications on calculated temperature. No one model was shown to "best" match experiment for all scenarios, inferring as in most cases that the chosen strength model for simulations should be carefully considered for each application.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Casey Uhlig of the U.S. Army Research Laboratory, who performed the experimental basis of this work, for answering our many questions to ensure an accurate computational model. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

REFERENCES

1. Uhlig, W. C. and Hummer, C. R., 2013. In-Flight Conductivity and Temperature Measurements of Hypervelocity Projectiles. Procedia Engineering, 58 (2013), pp 48-57.
2. Uhlig, W. C. and Hummer, C. R., 2011. In-Flight Measurement of Shaped Charge Jet Conductivity and Temperature. ARL Report ARL-TR-5609.
3. Nierderhaus, J. H. and Uhlig, W. C., 2011. Analysis and validation for shaped charge jet simulations using ALEGRA. Technical Report SAND2011-2819.
4. Uhlig, W. C. and Heine, A., 2015. Electromagnetic diagnostic techniques for hypervelocity projectile detection, velocity measurement, and size characterization: Theoretical concept and first experimental test. Journal of Appl. Phys., 118, 184901 (2015).
5. Domenicali, C. A. and Christenson, E. L., Effects of Transition Metal Solutes on the Electrical Resistivity of Copper and Gold Between 4 and 1200 K. Journal of Appl. Phys., 32, 2450 (1961).
6. McGlaun, J. M., Thompson, S. L., and Elrick, M. G., 1990. CTH – A Three-Dimensional Shock Wave Physics Code. International Journal of Impact Engineering, Vol. 10, pp. 351-360.
7. Hertel, E. S., et. al., 1995. CTH: A software family for multidimensional shock physics analysis. Shock Waves at Marseille I. Springer Berlin Heidelberg, 377-382.
8. Johnson, G. R. and Cook, W. H., 1983. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. In: Proc. 7^{th} International Symposium on Ballistics: pp. 541-547.
9. Steinberg, D. J., Cochran, S. G., and Guinan, M. W., 1980. A constitutive model for metals applicable at high strain rate. J. Appl. Phys. 51 (3), 1498-1504.
10. Preston, D. L., Tonks, D. L., and Wallace, D. C., 2003. Model of plastic deformation for extreme loading conditions. J. Appl. Phys. 93 (1), 211-220.
11. Follansbee, P. S., and Kocks, U. F., 1988. A constitutive description for the deformation of copper based on the use of the mechanical threshold stress as an internal state variable. Acta Metall. 36, 82-93.