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Submission Abstract

(not included in presentation)

By discharging a capacitor through a wire, it is possible to cause an explosion due to the resistive heating. The wire goes through two phase changes, first melting and then vaporizing. The timing of these phase changes depends sensitively on the equation of state and conductivity models of the wire material, providing a ripe opportunity for validation. I will present results from simulations of exploding copper wire experiments. I will compare these simulations to laboratory experiments performed by DeSilva and Vunni (Phys. Rev. E 83, 2011). I will also try to characterize the impact of the major sources of error for the simulations.

Validation of Copper Material Models in ALEGRA Through Exploding Wire Simulations

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Abstract

I ran simulations of exploding copper wires using the ALEGRA finite element code. I varied the wire diameter, wire length, and external resistance within uncertainties in order to judge the error in the simulation results. I then compared voltage and current as a function of time to data from recent experiments in order to validate the equation of state and conductivity models used for copper in ALEGRA, as as been done in the past for aluminum. I observed that ALEGRA matched the overall trends present in the experiments. However, the simulations show a steep rise in voltage when the copper melts while the experiments show a much smoother rise. In addition, the simulation did not accurately reproduce the depth of the local minimum in current.

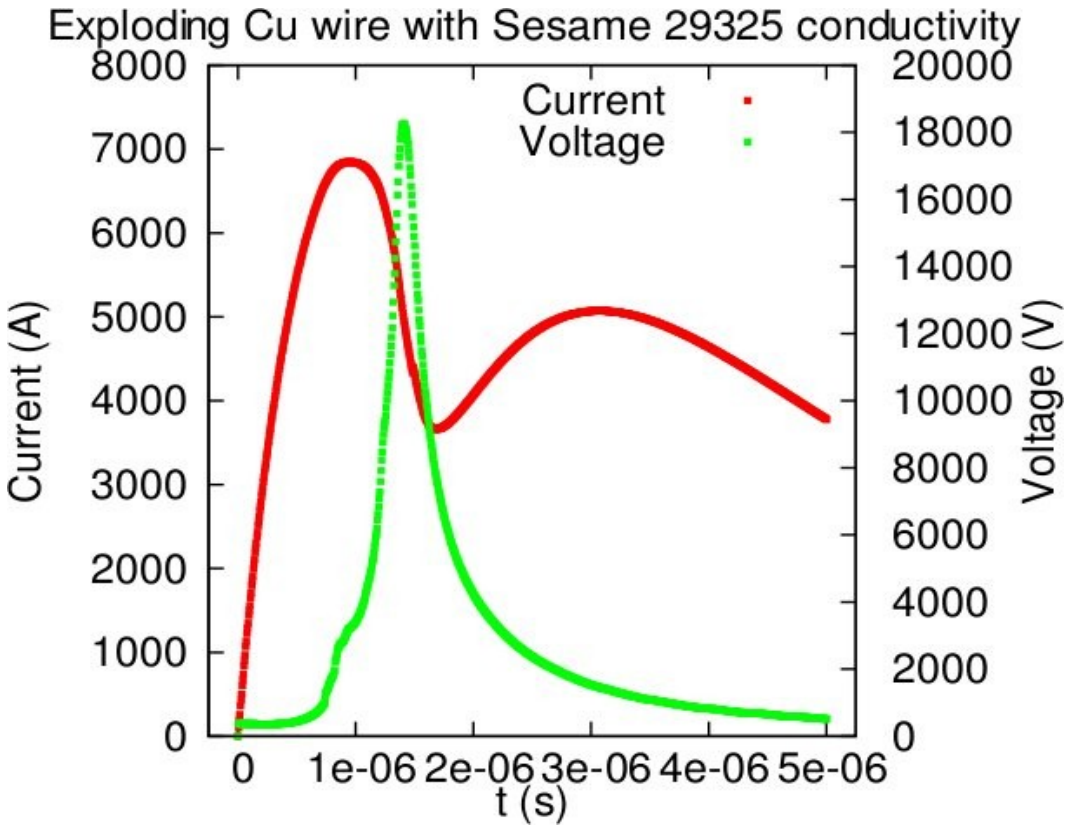
Introduction

By discharging a capacitor through a wire, it is possible to cause an explosion due to the resistive heating. The wire goes through two phase changes as its internal energy increases, first melting and then vaporizing. Fig. 1 shows the measured voltage and current as the wire explodes. The timings of the current and voltage peaks depend sensitively on the timing of the phase changes. Therefore they effectively test the equation of state and conductivity models for the wire material and provide an opportunity to validate these material models.

Recently, Vunni and DeSilva performed exploding wire experiments using several different materials in a water chamber [1]. Doney, Vunni, and Niederhaus used the results of the experiments performed on aluminum wires in order to validate aluminum models in ALEGRA [2]. I have performed a similar analysis on the copper wire experiments. It is important in validation to consider the uncertainty in the experimental parameters, as failure to do so could erroneously indicate a fault in the model [2]. It was observed for aluminum simulation that variations in the external resistance in series with the capacitor, the wire length, and the wire diameter had the most significant impact on the results.

In order to take the experimental uncertainties into account, I performed exploding copper wire simulations varying each of those three parameters by their uncertainties. I then compared the range of results from these simulations to the range given by the experimental data. I observed that the voltage and current peaks had comparable timings in the experiments and simulations, and that ALEGRA modeled the general trends correctly. However, I also observed a couple of flaws in the simulation similar to those seen in the aluminum analysis [2].

Figure 1



As the capacitor is discharged, first the current becomes very large due to the wire's low resistance. Resistive heating causes the wire to melt, and the voltage across the wire begins to rapidly rise [3]. The current peaks and falls sharply as the wire expands. Once the wire vaporizes, the voltage peaks and begins to fall off again. The current hits a local minimum before rising once again as current travels through the vaporized wire, and finally falling off as the voltage difference disappears.

Setup

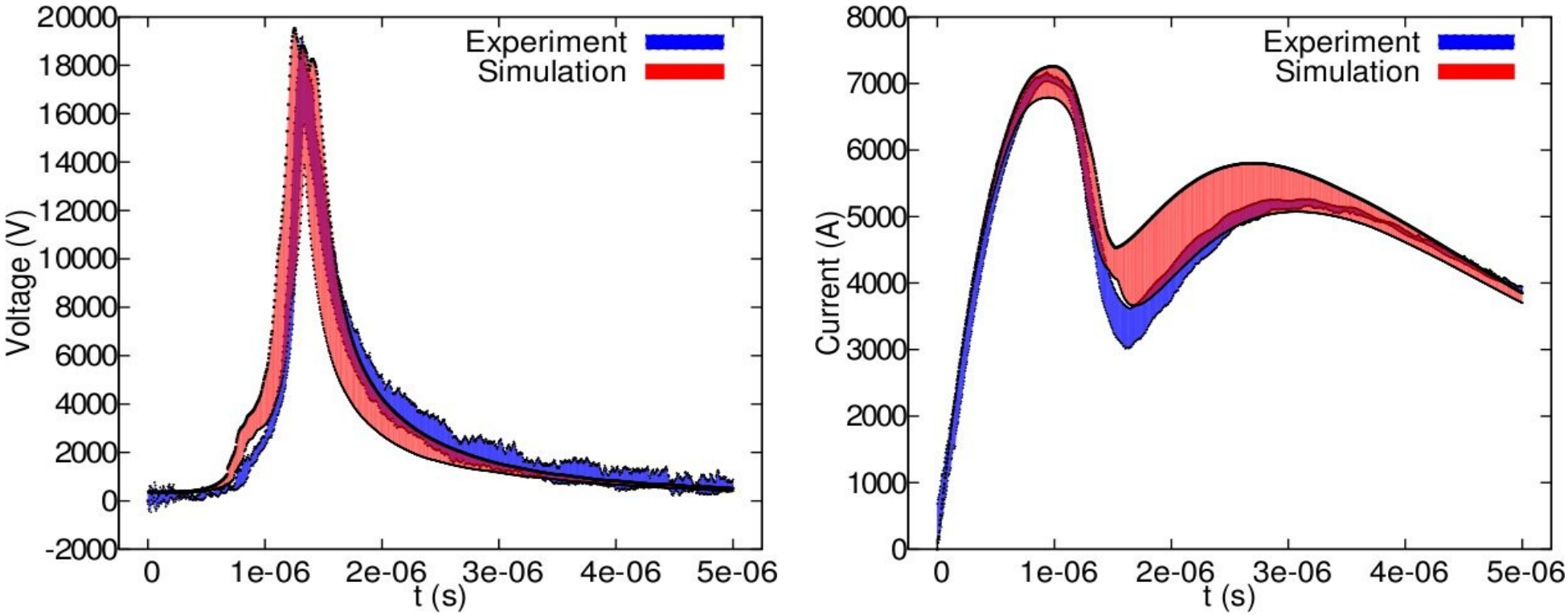
ALEGRA is a finite element code with the capability to model magneto-hydrodynamics (MHD) and shock waves [4]. In order to get accurate results it is important to have a sufficiently fine mesh. For exploding wire simulations, it is also important to have the mesh extend far enough radially that the boundary can be assumed to have no magnetic field. However, increasing resolution and size both increase the computing time.

Doney, Vunni, and Niederhaus demonstrated that for aluminum wire simulations, there was no significant difference between simulations with 3.8 elements per wire radius and those with 5.1 elements per wire radius [2]. They also showed that increasing the mesh beyond 400 wire radii in width had only a small impact on the current through the wire but a large effect on computing time. Therefore, for the copper exploding wire simulations I chose a two dimensional mesh with about 3.8 elements per wire radius and with a radial extent of 400 wire radii. The copper equation of state was modeled with the Sesame 3320 EOS table [5]. The conductivity was modeled with the Sesame 29325 electrical conductivity model for copper, which is a quantum-molecular-dynamics tuned LMD model for copper [6].

Results

The experiments were performed with an external resistance of 2.00 ± 0.10 Ω, a wire length of 16.5 ± .8 mm, and a wire diameter of 126.26 ± 1.89 μm. I set these values to the upper and lower limits of their uncertainty ranges, getting eight permutations. I recorded the lowest and highest value of Voltage and Current from each time step in order to get a range of uncertainty for the simulations. Figure 2 shows this range plotted along with the experimental results.

Figure 2



The blue band is the range between the lowest and highest values observed in the three experiments for each time step. The red band is the range between the lowest and highest values observed in eight simulations with the wire length, wire diameter, and external resistance varied by their uncertainties.

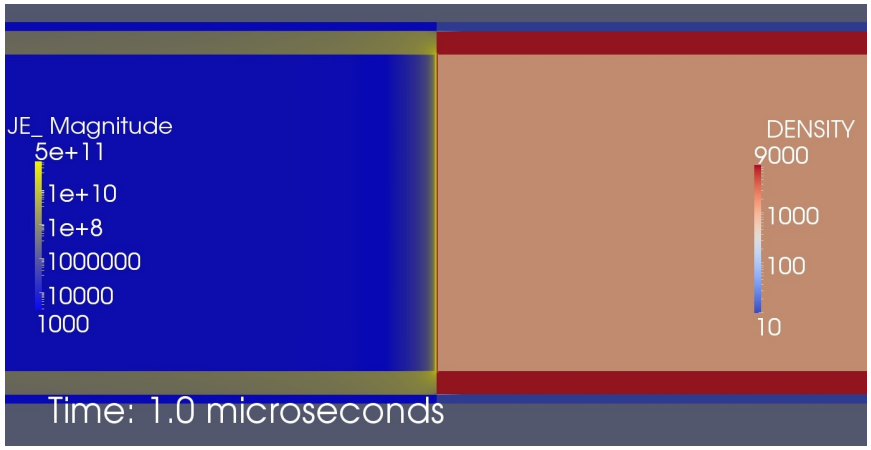
Discussion

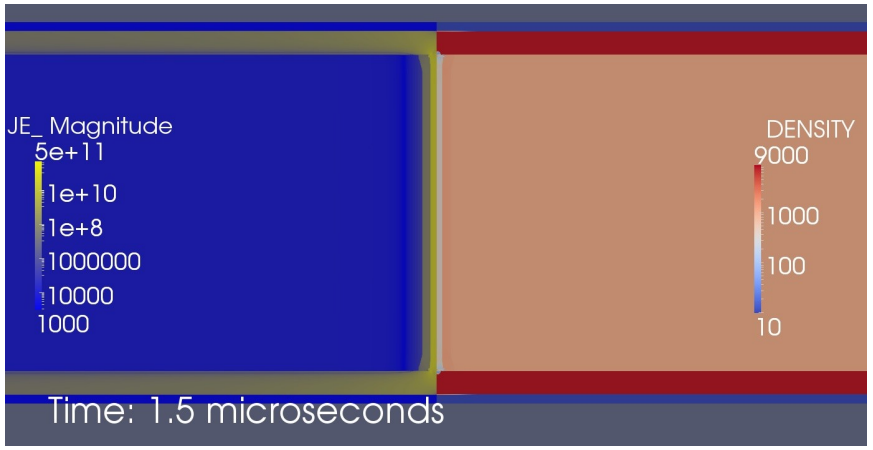
Although the simulation and experimental data are similar in form, there are two points that demonstrate modeling flaws. First, the simulation exhibits a sharp rise in voltage as the wire melts, while the experimental data demonstrate a much smoother transition. Also, he local minimum observed in the current after vaporization is lower in the experiment than in the simulation. These suggest deficiencies in the material model. Additionally, the multiple peaks in the simulation voltage band imply that the method of varying each value by its uncertainty underestimates error in the simulations. It would be interesting to compare simulations with parameters closer to the means to see how well they match the current simulation band.

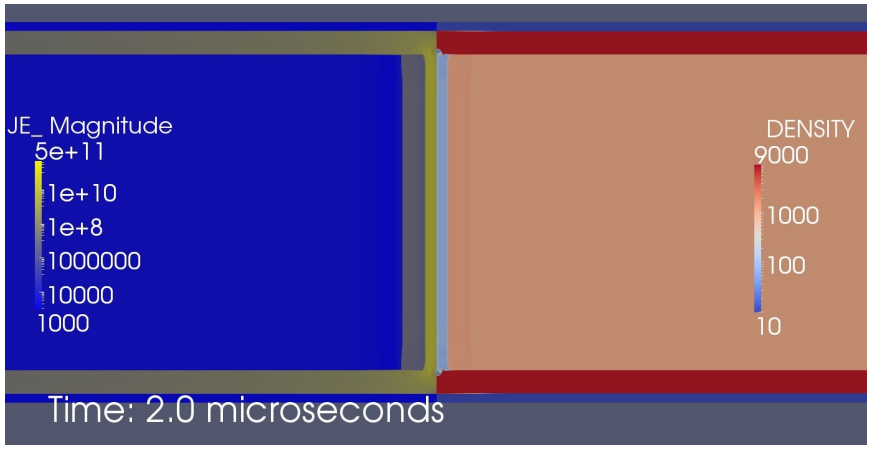
Future work should compare these results to simulations using the LMD conductivity model for copper. This would allow more detailed evaluation of the Sesame 29325 electrical conductivity model for copper. It would also be useful to double check that the assumptions for aluminum with regards to mesh size and resolution also hold for copper. Lastly, it would be interesting to test the ALEGRA code and material models for wires made of materials other than copper. Vunni and DeSilva performed experiments on other metals including Titanium and Iron [1]. More simulations could be performed to validate the conductivity models for those materials as well.

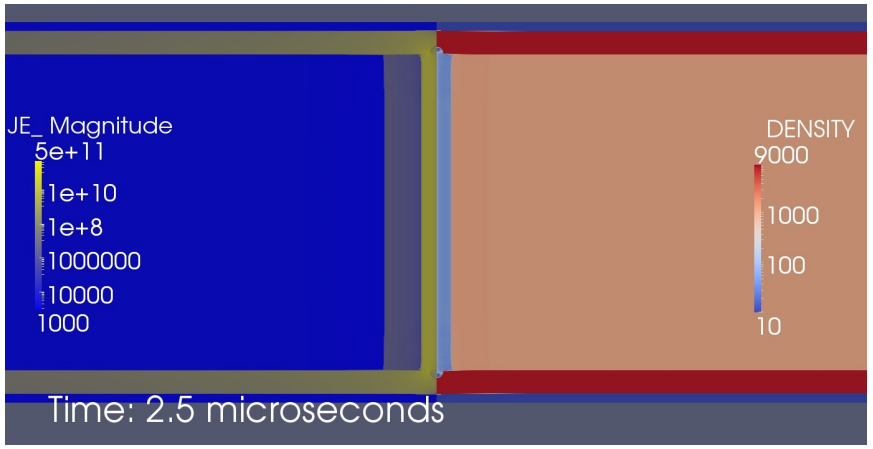
Figure 3

These images show the mass and current density of the exploding wire setup at several points of time. The wire can be seen in the center of each frame. The electrodes are at the top and bottom, red on the density scale. The beige area in the mass density plot (blue in the current density plot) is the water in the chamber. Current Density is in Amp/m^2 Density is in kg/m^3 Both are on a log scale

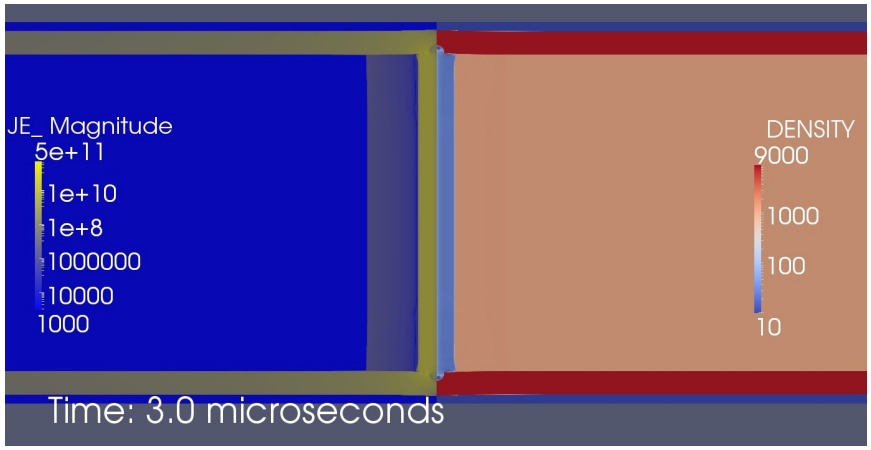


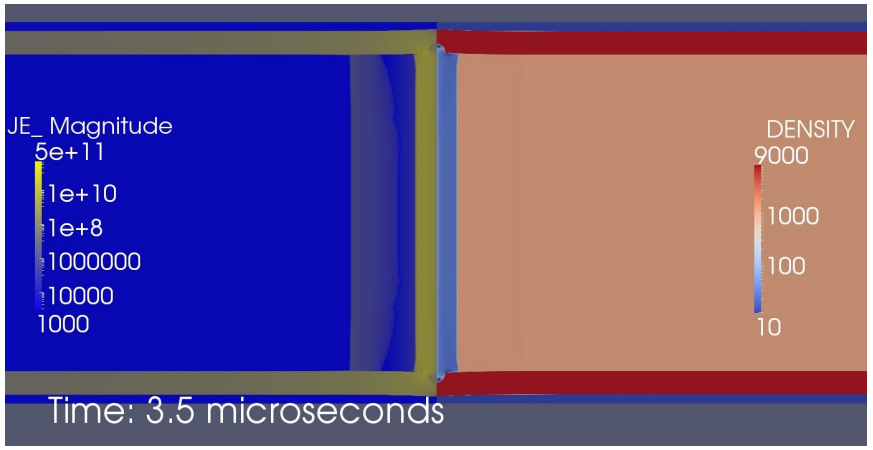


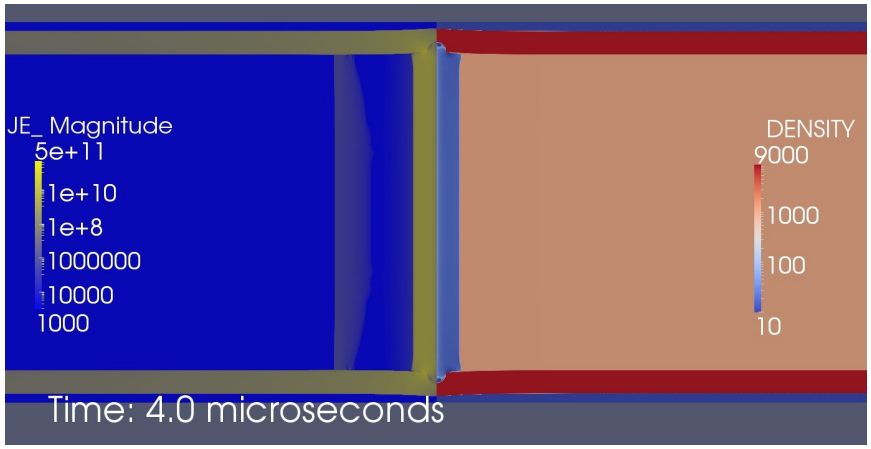


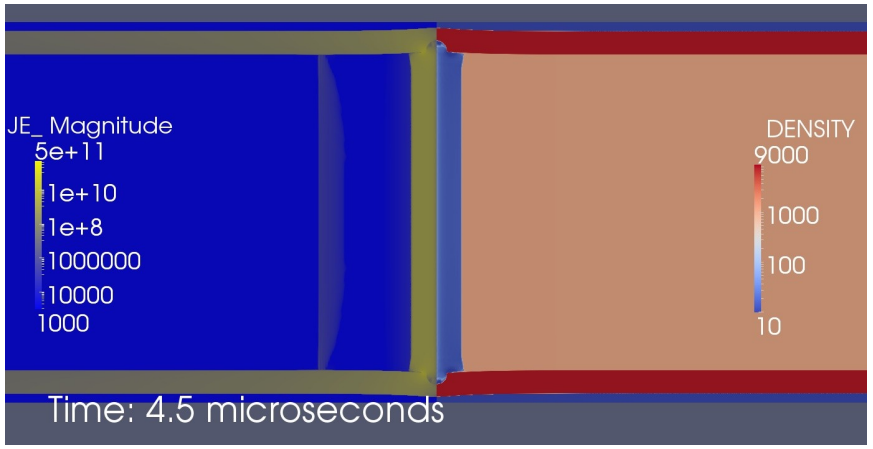


The electrodes can be seen at the top and bottom of these plots









References

[1] A. W. DeSilva and G. B. Vunni, “Electrical conductivity of dense Al, Ti, Fe, Ni, Cu, Mo, Ta, and W plasmas,” Phys. Rev. E 83 (2011), 037402.

[2] R. L. Doney, G. B. Vunni, and J. H. Niederhaus, “Experiments and simulations of exploding aluminum wires: validation of ALEGRA-MHD,” U.S. Army Research Laboratory Technical Report ARL-TR-5299 (2010).

[3] T. J. Tucker and R. P. Toth, “EBW1: A Computer Code for the Prediction of the Behavior of Electrical Circuits Containing Exploding Wire Elements,” Sandia Laboratories Technical Report SAND-75-0041

[4] A. C. Robinson et. al., “ALEGRA: an arbitrary Lagrangian-Eulerian multimaterial, multiphysics code,” Proceedings of the 46th AIAA Aerospace Sciences Meeting, Reno, NV, AIAA-2008-1235 (2008).

[5] G. I. Kerley, "Equations of State for Copper and Lead," Kerley Technical Services report KTS02-1 (2002).

[6] M. P. Desjarlais, “Practical improvements to the Lee-More conductivity near the metal-insulator transition,” Contrib. Plasma Phys. 41 2-3 (2008), 267-270.