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MODELING OF HIGH-EXPLOSIVE DRIVEN PLASMA COMPRESSION OPENING SWITCHES*

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I. INTRODUCTION

In 1977 Pavlovskii et al.,[1] reported on a high-explosive (HE) driven opening switch with which they achieved a resistance increase of 0.2 Ω in 0.45 μs, interrupting a current of 7.3 MA and switching 4 MA into a 30 nH load. The geometry, as pictured by Pavlovskii et al., is shown in Fig. 1. From the dimensions cited in Ref. 1 we calculated a linear current density of 0.12 MA/cm for the Pavlovskii switch. The channel that is labeled Foil/Plasma is a current carrying channel that starts as a metallic foil. This foil is quickly vaporized by the high electrical current and a plasma channel is formed. This plasma channel is the current path until the high explosive is detonated. The high explosive expands to close off the plasma channel and blow through the dielectric at the bottom to make an alternate current path available. In their article, Pavlovskii et al., suggest that it is the compression of the plasma channel by the explosion products that causes the resistance increase.

There have been several experimental efforts in the United States with systems that are comparable to Pavlovskii's but thus far they have not achieved results that are as good. Turman and Tucker[2] report that with a cylindrical system 4.5 cm in diameter and 3 cm in length they achieved resistance increases of as much as 30 to 40 mΩ with currents of as much as 2 MA (or linear current densities of 0.15 MA/cm). More recently Turman, Tucker, and Skogmo[3] have reported resistance increases of nearly 90 mΩ in a cylindrical switch that is 20 cm in diameter, 10 cm in length, and carrying a current density of 0.06 MA/cm.

Goforth et al.,[4,5] have developed a donut shaped, planar geometry version of the plasma compression switch. With this donut switch they have achieved resistance increases of 50 mΩ in 300 ns with a linear current density of the order of 0.13 MA/cm. This switch has been successfully used in the recently completed series of experiments in the Los Alamos Foil Implosion Project, "Trailmaster."

The computational modeling work of Greene et al.,[6,7] suggests that most of the early time resistance increase in these switches, at least the levels achieved in the United States, can, indeed be explained by compression of the plasma. This, coupled with recent advances in the computational modeling of the electrical resistivities of

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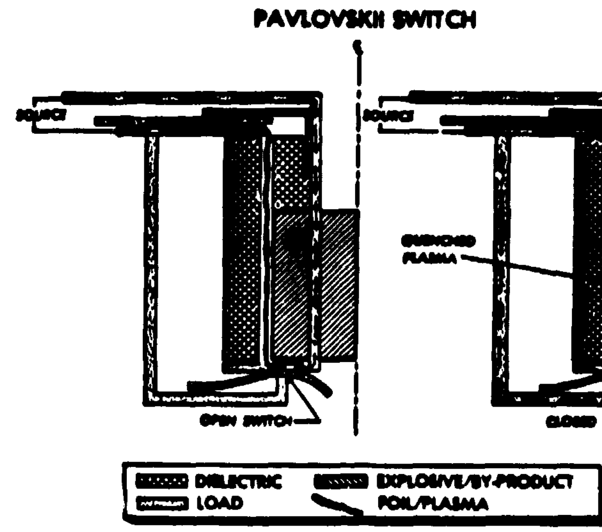

Fig. 1. Qualitative depiction of the Pavlovskii switch before and during switching. The high explosive expands to close off the plasma channel and blow through the dielectric at the bottom to make an alternate current path available.

metals,[8,9] has made it possible to create a relatively simple, zero-dimensional, model that explains much of the behavior of these switches. Such a model is particularly useful in exploring the possibilities of scaling these switches to higher current levels. In the present work we describe this model and compare its predictions with results from both planar and cylindrical geometry experiments.

II. THE MODEL

The initial path of the current through a plasma compression switch is through a thin (500-nm thick) metal foil. The current explodes the foil to form the seed for the conducting plasma. The behavior of the foil at this point is the same as an exploding metal fuse for which we have a simple model.[10] We have, therefore, chosen this model as our starting point. The fuse model assumes that the foil material is homogeneous and is characterized by a single temperature and density. The thickness of the foil is assumed to be much less than the magnetic diffusion skin depth so that the magnetic field varies linearly across the foil. For the present application we assume that the side of the foil away from the channel is fixed in space while the side by the channel is untamped. The foil/plasma will, therefore, cross the channel at the expansion velocity as the foil explodes. Equations for the electrical resistance of the foil, the magnetic fields, the motion of the foil, and the kinetic and internal energies are all solved selfconsistantly. The electrical resistivity, the pressure, and the specific energy of aluminium are taken from the Los Alamos SESAME EOS library.[11] In the case of aluminum we have created a SESAME-style table based on the theory of More and Lee[8,9] which we have modified to agree with experiment where possible. Details are provided in Ref. 10 and, therefore, are not repeated here.

As the aluminum expands across the channel the background gas, typically oxygen in our calculations, is added to it. The amount of the background gas is based on the initial density and the volume swept out by the expanding mixture during a timestep. The mixing is assumed to achieve instantaneous equilibrium so the background gas that is added each timestep is given the temperature that has already been achieved by the mixture. Once the expansion begins the total mass in the mixture is the sum of the mass of the aluminum and the gas accreted. The mass of the aluminium is, of course, fixed, whereas the mass of the gas increases until the volume of the channel is filled. The total gas pressure is the sum of the two partial pressures.

Once the mixing has begun in the channel, the electrical resistivity is taken to be the sum of the resistivity of the aluminum and the gas (cf. Frost[12]). That is:

$$R = R_{al} + R_g = \frac{(\rho_{al} + \rho_g)}{w_e \delta_e} l_e$$

where l_e, w_e and δ_e are the length, width, and the thickness respectively of the conducting plasma. To obtain the resistivities, ρ_{al} and ρ_g, we call the SESAME tables separately with the density of the aluminium and the density of the gas.

Once the conducting plasma has expanded to fill the entire channel the expansion is stopped by setting the expansion velocity to zero. From this point on the resistance of the switch drops as the plasma heats due to Ohmic heating. We found that in comparison to experiment our model switch reached too low a resistance during this plasma conductivity phase. This suggested that some piece of physics which we had ignored in our fuse model was playing an important role here. The most likely candidate to provide significant cooling would seem to be radiation. To allow for radiation cooling we have included a very simple radiation cooling model.

$$\frac{dE}{dt} = -\kappa d a c T^4 (V_r f_w)$$

where κ is the Planck opacity, and d is the density. The product κd is taken to be the larger of either the aluminium or gas values. The V_r term is a radiating volume:

$$V_r = w_e l_e \delta_r$$

where δ_r is the smaller of δ_e and the radiation mean free path which we take to be $(\kappa d)^{-1}$. The f_w term is an adjustable factor that mocks up the fraction of the radiation that is transmitted by the walls. The temperature in the plasma is very sensitive to this factor. By comparing model results with the measured conduction phase resistance of switches we have tested, we have set f_w to only 0.04.

To open the switch we compress the plasma at the detonation velocity of the high explosive, a quantity that depends on the type of high explosive. In the present case, we are using 0.88 cm/μs. The resistance goes up because we have a smaller δ_e in

$$R = \rho \frac{l_e}{w_e \delta_e} \quad .$$

However, the temperature also goes up rapidly. In part, this occurs because the increase in R drives up the Ohmic heating. Primarily, however, the decrease in the volume rapidly drives up the internal energy. The increase in the temperature, of course, reduces R because

$$\rho \propto T^{-3/2}$$

for an ionized plasma.

A simple, ideal gas, analysis of this compression phase indicated that the resistivity decrease due to the temperature increase would off set the resistance rise due to compression.[6] Our model, relying on the SESAME tables, does predict a rapid resistance increase during compression. Our previous work[6,7] indicates that this increase can occur because much of the increase in internal energy in the plasma goes into repeated ionizations, increasing the z, rather than just increasing the temperature.

In our model we terminate the compression phase when the pressure in the plasma reaches a predetermined value. We freeze the resistance at the value it has achieved at this point. This is a very considerable simplification in the model in that it permits us to avoid the inclusion of a high explosive equation-of-state. The behavior of the actual switches after the initial resistance rise has not been consistent. In many cases there has been observed a small reduction in resistance followed by a considerable increase. We have interpreted this second increase to be the result of mixing between the hot plasma and relatively cool HE detonation products.[7] We have, however, had shots in which this second resistance rise did not occur. In our model we have set the cutoff pressure to $3 \times 10^9 Nt/m^2$ for planar geometry and $2 \times 10^9 Nt/m^2$ for cylindrical geometry to match the resistance increases observed in our experiments.

This entire model has been included as a part of the electrical circuit in the 1-D MHD code RAVEN.[13]

III. RESULTS AND CONCLUSIONS

The time dependent behavior of the plasma compression opening switch used in the most successful experiment to date in the Los Alamos Foil Implosion Project is shown as solid lines in Figs. 2 and 3. Details of the switch are available in Ref. 5. We have modeled this switch as having a 16 cm length and ;. 67 cm width. Since the actual switch is a donut geometry this width is an average of the inner and outer circumferences. The thickness of the plasma channel is 0.3 cm. Our model results are shown as dashed lines in these figures.

The modified More-Lee resistivity table clearly overestimates the resistivity of the aluminium in the fusing phase, but we do reach this phase and recover from it at about the right times. The model resistivity drops from the fusing phase somewhat faster than the actual switch. We attribute this discrepancy to the inadequacy of our very simple mixing model. A more realistic model would delay the time for the background gas to come to equilibrium and, hence, the resistance would fall more slowly.

The experimental results shown in Figs. 2 and 3 are the ones used to adjust the wall transmission factor for our radiation cooling model. With this factor properly adjusted our model clearly does quite well during the long conduction phase. This phase is extremely important in our project. We are evaluating these switches for use with larger high-explosive generators, some of which have very long (>100 μs) run times and relatively low dL/dt values. Furthermore, we are hoping to reach currents in excess of 10 MA in our next series of experiments and at that level any resistance can represent a considerable energy loss. Indeed, our preliminary analysis using this model indicates that these switches may not work as well as some other candidates in this next experimental series.

Figure 3 shows the agreement that our model achieves during the opening of the switch. The onset time of the compression has been set to the time of the minimum resistance in the experimental curve. Considering the simplicity of our model we consider this agreement to be quite remarkable. It would seem to eliminate any question that the opening resistance rise of the switch is due to compression of the plasma.

In Fig. 4 we show the comparison between our model and another experiment during the opening phase. This switch was a cylindrical model, 12.7 cm in length, with the plasma channel having a 12.7 cm inner diameter and a 0.3 cm thickness. Again the onset of the compression phase in the model was set to agree with the time of the resistance minimum in the actual switch. In this case the model predicts the resistance rise to occur slightly ahead of the experiment. The rate of rise shows good agreement. It seems likely that the slight discrepancy in the resistance rise between the model and experiment is due to the cylindrical geometry which our model does not take into account in any way. We used the experimental results shown in Fig. 3 to set the maximum pressure cutoff in planar geometry so it is not surprizing that the theory and experiment agree quite well in that data set. For cylindrical geometry we used a very rough average of the resistance peak from several experiments to get the pressure cutoff so the match is not as good for the particular experiment shown in Fig. 4.

We conclude that our simple model explains the essential features of these switches.

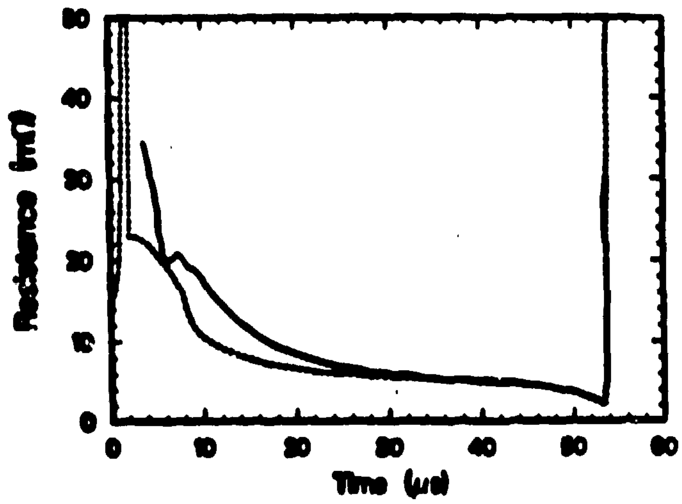

Fig. 2. Comparison of the experimental results (solid line) and model results (dashed line) for the conduction phase of the planar geometry switch used in the recent "Trailmaster" experiments.

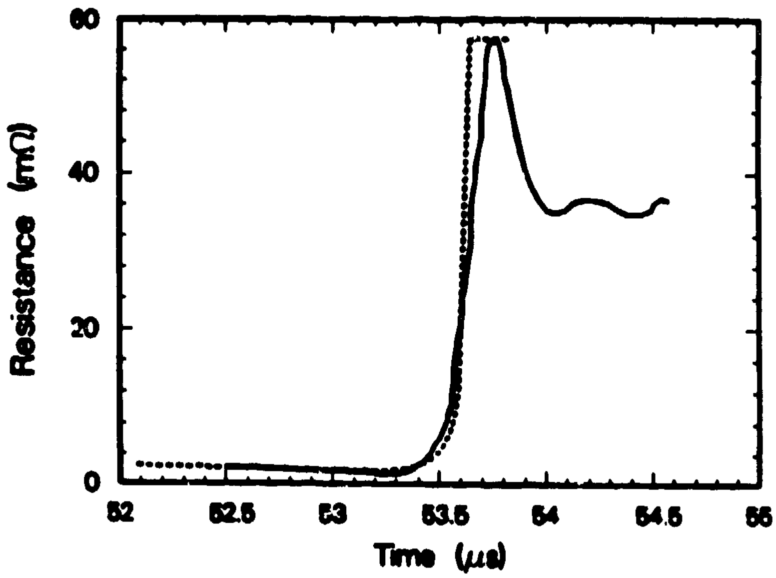

Fig. 3. Comparison of the experimental results (solid line) and model results (dashed line) for the opening phase of the planar geometry switch used in the recent "Trailmaster" experiments.

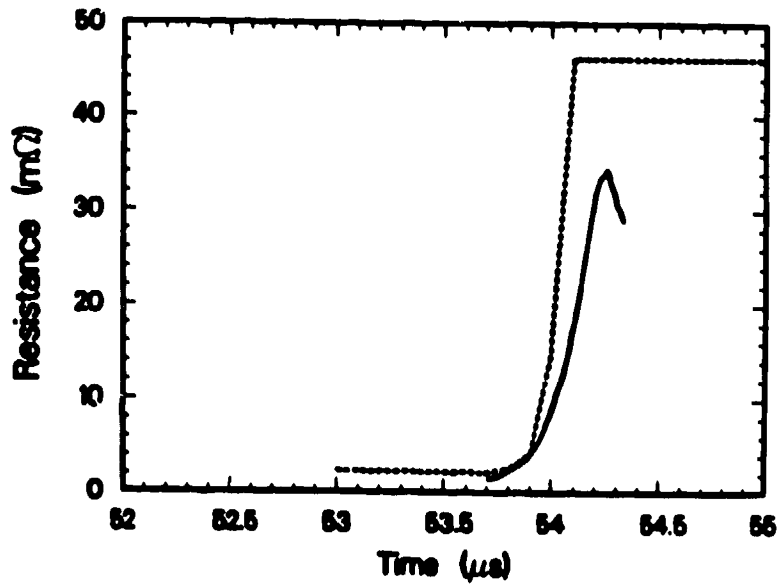

Fig. 4. Comparison of the experimental results (solid line) and model results (dashed line) for the opening phase of a cylindrical geometry switch.

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