# IMPROVED MODELING OF ELECTRICALLY EXPLODED FUSE OPENING SWITCHES IN FLUX COMPRESSION GENERATOR EXPERIMENTS

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*Abstract*

In previously reported computational studies of fuse opening switches and other exploding metallic foils, apparent inaccuracies in the constitutive relations for the fuse material limited the accuracy of the modeling. In this paper, we use recently developed constitutive property models to re-examine experiments that used flux compression generators to deliver 25-35 MA to a copper fuse. Based upon this preliminary study, it is difficult to conclude that the newly developed models offer substantial improvement. For some considerations, models developed more than 15 years ago remain the most accurate.

## I. Introduction and Approach

A computational model of exploding metallic foil behavior [1] was developed at Los Alamos to design and analyze a wide range of experiments in which exploding metallic foils and fuse opening switches were driven by the output current of capacitor banks and magnetic flux compression generators. With some caveats, the original model successfully predicted and postdicted observations in experiments where the peak foil current ranged from 1 kA to 16 MA and foil conduction times ranged from 200 ns to 300 μs [2].

In contrast to empirical models available at the time, the model coupled hydrodynamics with Ohmic heating and electrical circuit equations and computed the foil material trajectory through density-temperature space. To determine the foil material's temperature- and density-dependent pressure, specific energy, and electrical resistivity, the model accessed tabulated atomic data base computer files having the format of the Los Alamos SESAME library. The model predicted from more-or-less "first principles" experimentally observed behavior that could not be explained by traditional empirical models, such as the variation of the specific action at "burst," the variation of resistance multiplication with thickness at fixed cross-sectional area, and a double-peaked current derivative [2]. The model predicted that significant hydrodynamic expansion of the foil material was required before the peak resistance was achieved, a prediction that was subsequently experimentally confirmed [3].

In anticipation of the Atlas capacitor bank (see Atlas papers, these proceedings), a series of experiments were conducted at Los Alamos and at the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) to emulate Atlas and to begin to acquire a database on the performance of liners at the high current levels to be made possible by Atlas. The experiments used magnetic flux compression generators (FCG) to provide the prime power. Because flux compression generators in general have a much slower rise time than Atlas and have an exponential waveform in contrast to Atlas' approximately sinusoidal waveform, a fuse opening switch and an explosively operated closing switch were used to shape the current waveform delivered to a fixed inductance or liner load.

The electrical circuit representation of the experiments is shown in Fig. 1. The experimental parameters are summarized in Table 1. Experiments ROS1 and RL2 used the Los Alamos Ranchero 43-cm-long coaxial generator, the RL3 experiment used the Ranchero 1.4-m-long generator, and the Advanced Liner technology experiment (ALT1) used a VNIIEF 10-module, 40-cm-diameter Disk Explosive Magnetic Generator (see ALT1 papers, these proceedings). All experiments used a copper fuse.

As suggested by Fig. 1, FCG/fuse/line systems are very complex and non-linear. To represent the FCG, we use either a phenomenological model or one-dimensional magnetohydrodynamics (MHD) to predict the generator inductance, Lg(t). This Lg(t) is used with electrical current data from generator characterization experiments (no fuse, no liner, only fixed inductance loading) to infer Rg(t). Although there is no guarantee that the Lg and Rg so determined will apply to fuse experiments, our past experience has shown that this is a valid procedure with acceptable accuracy, although in some instances it is necessary to slightly modify the model.

In our computations, the liner is treated as incompressible aluminum. The liner is accelerated by the magnetic pressure, and the inductance change, ΔL, due to liner motion is calculated self-consistently with circuit equations.

The purpose of this paper is to compare several different equation-of-state (pressure, specific energy as a function of density and temperature) and resistivity (also a function of density and temperature) models that are available in SESAME-format computer libraries. A similar evaluation for aluminum foils and liners using a

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14. ABSTRACT
**In previously reported computational studies of fuse opening switches and other exploding metallic foils, apparent inaccuracies in the constitutive relations for the fuse material limited the accuracy of the modeling. In this paper, we use recently developed constitutive property models to re-examine experiments that used flux compression generators to deliver 25-35 MA to a copper fuse. Based upon this preliminary study, it is difficult to conclude that the newly developed models offer substantial improvement. For some considerations, models developed more than 15 years ago remain the most accurate.**

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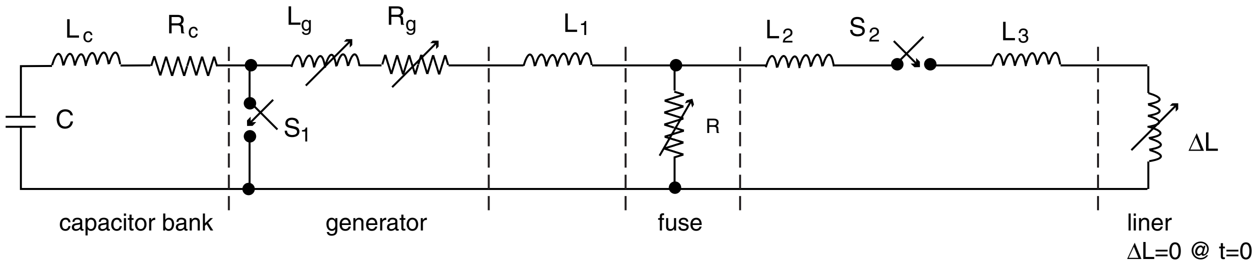


**Figure 1.** Fixed-element circuit representation of flux-compression-generator experiments to emulate Atlas.

**Table 1.** Experimental parameters.

| Experiment | Date | Fuse area (cm2) | Fuse length (cm) | Liner thickness (mm) | Liner outer radius (cm) | Liner height (cm) |
|---|---|---|---|---|---|---|
| ROS1 | 6/11/98 | 1.46 | 30 | none | none | none |
| RL2 | 4/15/99 | 1.46 | 30 | 1.6 | 3.66 | 4 |
| RL3 | 9/30/99 | 1.09 | 45 | 2 | 3.8 | 4 |
| ALT1 | 11/3/99 | 1.51 | 72 | 2 | 4 | 4 |

**Table 2.** Models used in the computations

| | Equation-of-state (table 301) | | Resistivity (table 602) | |
|---|---|---|---|---|
| Model | Library | Identification | Library | Identification |
| A | SESAME | 3333 | SESCU | 23333 |
| B | SESVNIF | 3330 | SESVNIF | 23330 |
| C | SESAME | 3333 | SESROSEN | 29333 |
| D | SESAME | 3333 | SESCU9 | 23339 |
| E | SESAME | 3333 | ANEOS | 23335 |

one-dimensional MHD model is reported in a companion paper (see W. L. Atchison, *et al*., these proceedings).

The five models evaluated are tabulated in Table 2. Model A is a more-or-less "standard" combination that has been used in our previously reported computations. Model B is based upon an analytic model that has been developed at VNIIEF [4]. Model C is uses one version of the recently developed DesJarlais/Rosenthal resistivity formulation (see DesJarlais *et al*., these proceedings). Model D uses a Burgess form of the resistivity. The resistivity used in model E is based upon fuse experiments conducted at Los Alamos in the 1970's and is constructed so that the resistivity is a function only of the specific energy deposited, independent of the density-temperature trajectory. In essence, model E is a SESAME-format implementation of a traditional empirical approach. The resistivity models used in Model B, C, and D were not available when previously reported computations were conducted.

We emphasize that, as illustrated by Table 2, whenever SESAME-format libraries are involved, there can be many different equation-of-state and resistivity versions for a given material, and different versions of equations-of-state can be combined with different resistivities. Therefore, whenever "SESAME" is being used, it is very important to specify which library, which identification, etc. We also emphasize that, in any computations using SESAME-format libraries, the accuracy depends not only on the basic model incorporated into a table but also on the table resolution and interpolation method.

It is beyond the scope of this paper to analyze the similarities and differences of the five models. Suffice it to say that each model predicts high resistivity at increased temperature and reduced density, but the high resistivity region occurs at different locations in temperature-density space. As shown in [1], the key function for fuse applications is the resistance multiplication

$$\mathrm{X}(t) = \frac{R}{R_o} = \frac{\eta\rho}{\eta_o\rho_o} = \mathrm{X}(\rho(t), T(t)) = \mathrm{X}(\varepsilon(t), p(t))$$

where $\eta$ is the resistivity, $\rho$ is the density, $T$ is the temperature, $\varepsilon$ is the specific energy, and $p$ is the pressure. In general, each model will result in a different $\varepsilon$—$p$ trajectory and a different $X(t)$.

## II. RESULTS

Space limitations prohibit us from reporting all of our computational results. Figures 2-5 illustrate typical results for the RL3 and ALT-1 experiments. As shown in Fig. 2, our generator model for the Ranchero generator is

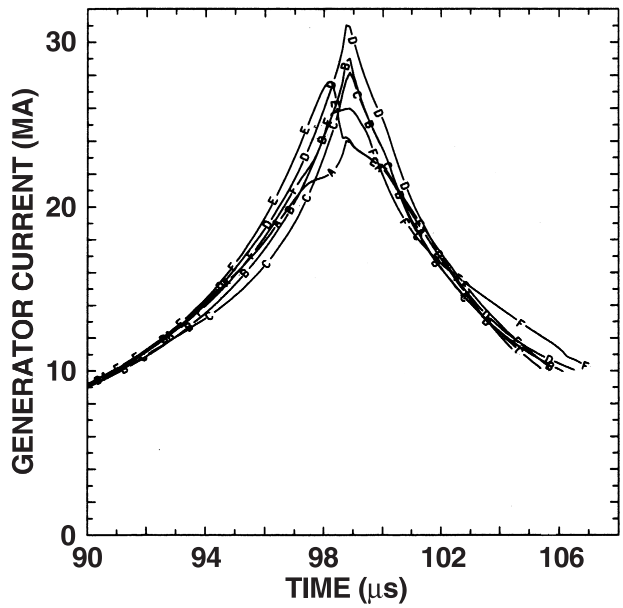


**Figure 2.** The RL3 generator current (model computations--curves A, B, C, D, E, data—curve F)

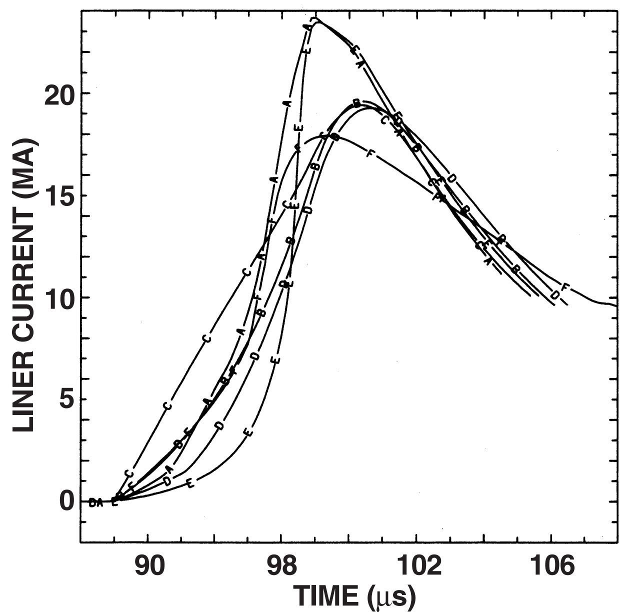


**Figure 3.** The RL3 liner current (model computations--curves A, B, C, D, E, data—curve F)

quite accurate up until about 65 μs, when fuse resistance effects begin to be important. On the other hand, our DEMG model used for ALT-1, which is based upon VNIIEF data reported at the Megagauss-III and IV conferences, is not entirely satisfactory and significant differences appear early, before fuse resistance comes in to play. Presumably, this shortcoming is due in part to recent improvements by VNIIEF.

The two equations-of-state used in this study give substantially different trajectories through $\rho$--$T$ space. Figures 6 and 7 show the trajectories for models A and B. The "standard" equation-of-state used with models A, C,

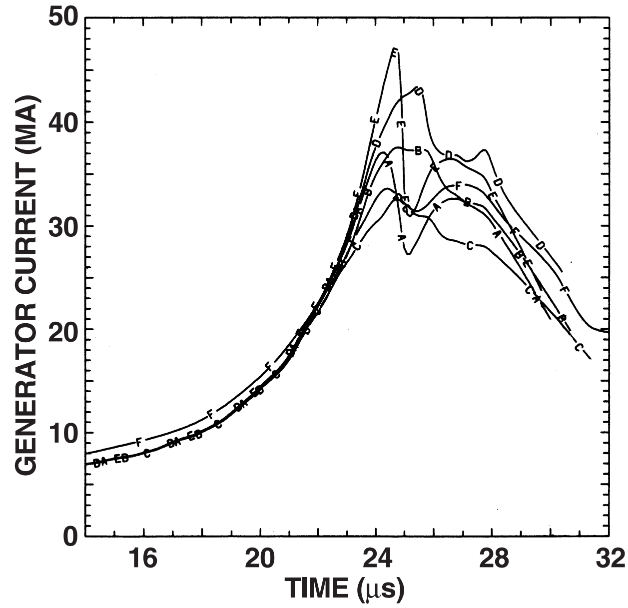


**Figure 4.** The ALT1 generator current (model computations--curves A, B, C, D, E, data—curve F)

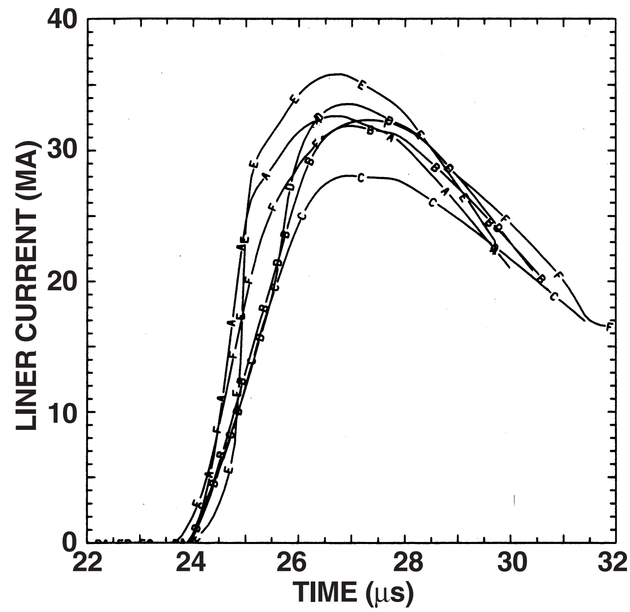


**Figure 5.** The ALT1 generator current (model computations--curves A, B, C, D, E, data—curve F)

D, and E leads to a rapid pressure increase early in the current rise and results in an earlier and more rapid expansion than predicted by model B.

Fuse performance is traditionally characterized by the specific action integral, $\Gamma = \frac{1}{A_o^2}\int_0^t I^2 dt$, and the specific energy dissipated by the fuse. Tables 3 and 4 summarize the results of the computations.

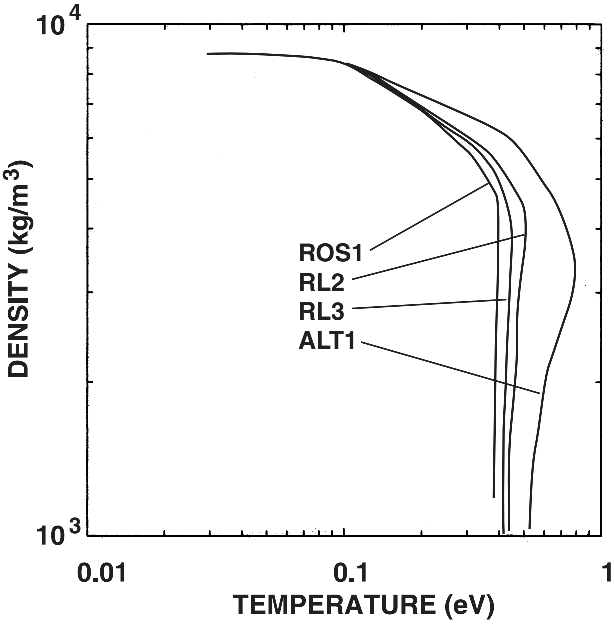


**Figure 6.** The density-temperature trajectories for model A. Time increases in the clockwise direction.

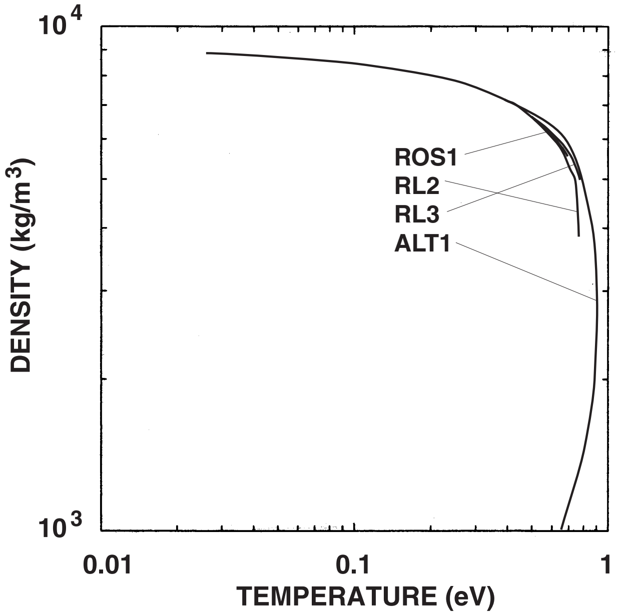


**Figure 7.** The density-temperature trajectories for model B. Time increases in the clockwise direction.

**Table 3.** The specific action integral ($10^{17}$ $A^2s/m^4$)

| | A | B | C | D | E | data |
|---|---|---|---|---|---|---|
| ROS1 | 1.64 | 1.67 | 1.29 | 2.04 | 2.31 | 1.56 |
| RL2 | 1.71 | 1.78 | 1.45 | 2.16 | 2.34 | 1.67 |
| RL3 | 1.64 | 1.84 | 1.49 | 2.26 | 2.35 | 1.66 |
| ALT1 | 1.88 | 2.06 | 1.81 | 2.40 | 2.35 | 1.81 |

**Table 4.** The computed specific energy deposited in the fuse (MJ/kg)

| | A | B | C | D | E |
|---|---|---|---|---|---|
| ROS1 | 2.71 | 3.03 | 2.35 | 3.37 | 3.67 |
| RL2 | 3.73 | 3.79 | 3.32 | 4.18 | 4.44 |
| RL3 | 3.35 | 4.35 | 3.63 | 4.73 | 4.92 |
| ALT1 | 5.98 | 7.20 | 7.07 | 8.02 | 6.66 |

## III. CONCLUDING REMARKS

We can make several general statements. Model A gives the most accurate specific action (Table 3) but predicts a resistance increase and dI/dt that are too high (e.g., Fig. 5). Model B gives an acceptable action (Table 3) and most closely matches the early rise in liner I, but does not always reach the peak observed dI/dt (e.g., ROS1). Model C consistently underpredicts the observed action, except for ALT1, whereas models D and E consistently overpredict the action (Table 3). Model C gives a very nearly constant dI/dt for the liner load, a waveform that differs significantly from the observations (Figs. 3, 5). For RL3, model A matches the observed peark dI/dt, but overpredicts the duration of the peak dI/dt, and hence I. Based upon this preliminary study, it is difficult to conclude which $\eta(\rho,T)$ model—actually, which $\eta$, $p$, $\varepsilon$ combination--is "better." Fuses may, in fact, be the best test of new resistivity models because of their density—temperature trajectories.

## IV. REFERENCES


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