

# MODELING AND ANALYSIS OF THE RANCHERO COAXIAL EXPLOSIVE PULSE POWER GENERATOR SYSTEM

W.L. Atchison, J.H. Goforth, I.R. Lindemuth, R.E. Reinovsky  
Los Alamos National Laboratory, New Mexico, USA

## Abstract

A key element in the design of a coaxial generator system is the simplicity of the geometry. The clean cylindrical geometry allows us a reasonable chance at modeling RANCHERO performance using our 1D and 2D MHD modeling codes. The results of numerical simulations have been compared to several tests of the RANCHERO system in a variety of configurations. Recent comparisons of 1D calculations with the REOT-2 data have been extremely good and suggest that the generator is behaving in a very 1D like nature until reaching 90-95% of peak current. Differences between calculated current and measured performance during the last 3 mm (out of 70 mm) of flux compression may be a consequence of either the EOS for SF<sub>6</sub>, 2D effects, or both. This study will examine the existing models and attempt to provide a robust integrated model which can then be used to drive design studies, pre- and post-shot analysis, and predict performance parameters for slight variations of the base design of RANCHERO.

## I. INTRODUCTION

The RANCHERO explosive pulse power system is a coaxial flux compression generator designed to produce 25-50 mega-amps of current from a single module into a low inductance load. The design discussed in this effort was developed primarily to drive high current in heavy metal liners for Z-pinch experiments. The fundamental design is very similar to the CN-III [1] generator tested at Los Alamos a number of years ago. However, RANCHERO incorporates several design variations to reduce cost and difficulty of fielding it as a pulse power source.

The use of RANCHERO as a power source for Z-pinch experiments requires the system to be reliable, reproducible, and predictable. A reasonable goal would be for the system to perform to within at least 5 % of the desired output specifications into a specified load. The results of this effort indicate the nature and simplicity of the RANCHERO design combined with the maturity of present day MHD modeling capabilities may provide for this kind of accuracy.

## II. SYSTEM DESCRIPTION

The physical geometry of RANCHERO is very similar to that of the CN-III system. (See Figure 1) Three design features, two of which were not available

for the CN-III, are key to the low cost and simplicity of the RANCHERO design. The first and possibly most important is the development of a relatively inexpensive and reliable line detonation system for lengths on the order of a meter. Second is the use of an explosive mixture (PBX-N110) which can be easily cast into a cylindrical geometry and still produce a uniform radial burn. Coupled with a simple smoothing layer, this combination of detonators (on axis) and explosive appear to be able to produce a 1D like cylindrical burn wave front to drive the armature very uniformly. The third important design change is the use of aluminum (6061-T6) for both the armature and stator. These design features drastically reduce the cost and difficulty of fabricating each module.

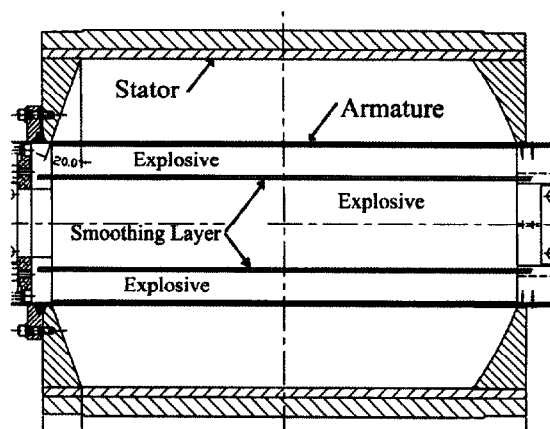


Figure 1. Sample RANCHERO Drawing

The outer radius of the armature is 7.62 cm (3.0 in.) and the inside radius of the stator is 15.24 cm (6.0 in.). The length from glide plane to glide plane at the armature for this study was 43.0 cm; however, a 1.4 m armature has been built and fired. Not shown in figure 1 is a thin insulating layer of polyethylene located on the inside surface of the stator to protect the surface from low density material presumed to be released from the outside surface of the armature. A number of tests using this basic geometry have been fired. Each separate test has had slight differences with figure 1 such as location of gaps for coupling current to loads, armature thickness, etc. as the design and purpose of the system evolved.

Figure 2 shows the schematic diagram used to represent the total system including the charging bank,

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1. REPORT DATE <b>JUN 1999</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Modeling And Analysis Of The Rancher0 Coaxial Explosive Pulse Power Generator System</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Los Alamos National Laboratory, New Mexico, USA</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.</b>					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>SAR</b>	18. NUMBER OF PAGES <b>4</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

coupling cables, generator module, and inductive load. Those elements of the system external to the generator are represented as circuit elements. The one exception is the "Crowbar switch". Between the outer surface of the armature and the glide plane on one side is a gap. The charging bank and cables are connected across this gap which allows the armature/stator gap and the load circuit to be seeded with current as the charging bank discharges into the total system. The movement of the armature outward closes this gap and removes the charging circuit from the system. This "Crowbar switch" is represented in the models used here by a variable resistor with an initial value of  $10^4$  ohms that switches to  $10^{-9}$  ohms at the prescribed time corresponding to first armature motion.

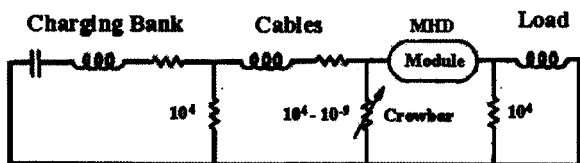


Figure 2. Schematic diagram of complete system

### III. MODELING TOOLS

The bulk of the calculations conducted in this study employed the 1D-lagrangian code RAVEN. A 2D-eulerian MHD code was also used for a limited number of calculations. The focus of this effort is on the results and conclusions drawn from the 1D modeling. However, some supporting 2D calculations were able to corroborate specific elements of the 1D findings. One such fact was the over prediction of peak current when a vacuum condition is assumed for the armature/stator gap.

Both simulation codes include extensive models that treat the constitutive properties and behavior of the materials employed in these experiments. These calculations use a modified Steinberg-Guinan [2] treatment of strength. This strength model also employs the Lindemann melt model that treats the pressure dependence of melt temperature. The equation of state information was obtained from a standard set of SESAME EOS [3] tables used at Los Alamos National Laboratory. In addition, a model of the elastic-plastic deformation and the resulting work heating is included.

An important part of these calculations is the treatment of the explosive. In these simulations a constant velocity cylindrical detonation wave is assumed. The location as a function of time of the detonation wave is programmed into the calculation and the detonation energy is released at the location of the wavefront. The JWL EOS model [4] is then used to simulate the properties of the detonation gases. For the simple geometry used in RANCHERO this "Programmed burn" model should be sufficient to treat the high explosive dynamics.

The numerical MHD model of the generator is used to simulate the dynamic behavior of the module. In this

manner the impact of physical changes within the generator can be predicted based on first principles alone. The MHD simulation is calculated self-consistent with a numeric circuit model. Static elements such as the capacitor bank and coupling cables are treated as simple circuit elements. The combined MHD/Circuit model allows us to apply physical variations to the generator module and predict currents and voltages at locations that are accessible.

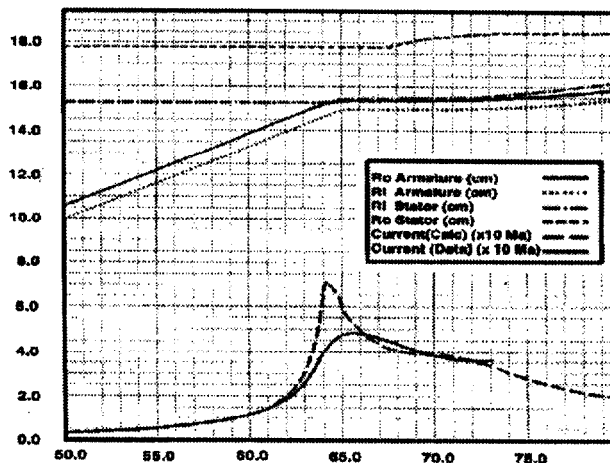


Figure 3. Initial prediction of RANCHERO performance

### IV. INITIAL MODELING EFFORTS

Figure 3 is an example of the first attempts at modeling the performance of RANCHERO. The curves in the upper half of the graph show the inner and outer surfaces of the armature and stator. Though difficult to see at this scale there is also a 3-mm thick layer of polyethylene as described earlier. The region between the armature and the stator was originally assumed to be a vacuum. However, unknown at the time of the original analysis was that the operations crew back-filled the vacuum with 20 psia of SF<sub>6</sub> to provide additional prevention against electrical breakdown in the generator. The two lower curves are the predicted and measured current.

The comparison of measured current to predicted current shows a drastic over prediction of peak current as well as a faster rise-time. The faster rise time could indicate that the actual performance of the explosive was less energetic than was claimed. Variations of the explosive parameters (JWL) could slow the rise-time, but then shape of the curve could not be matched very well. This suggested that some additional physical phenomenon was present in the experiment that was not included in the simulation.

The manner in which the predicted current overshoots the maximum measured value and peaks sharply is the direct consequence of a hard collision between the armature and stator in the simulation. The force of impact during this collision is so hard as to compress the polyethylene density a factor of three. The impact also causes compression of the inside

surface of the stator. The result is an extremely narrow distance of closest approach between the armature and stator and subsequent flux compression of the magnetic field to values much greater than would be inferred from the actual measured current.

A large number of phenomena were originally postulated which would explain this significant difference. In general 2D effects were believed the most likely problem. Figure 3 indicates the predicted curve departs from the measured current when the armature is still more than 1 cm from the stator. This would require any surface structure capable of trapping flux to be about 1 cm in amplitude. The suspected phenomenon included armature bending, material jetting possibly at the glide planes, and Magneto-Raleigh-Taylor instabilities. 2D calculations were conducted to explore several of these possibilities. Surprisingly, the 2D simulations all indicated the system should be well behaved and did not indicate any of these 2D effects were plausible answers. In fact the 2D predicted current was even more extreme than the 1d result.

## V. IMPROVEMENTS AND RESULTS

If 2D effects and flux trapping are assumed not to be present, the lower and broader peak in the measured current trace suggests the collision behavior in reality is much softer than in the simulation. This is the first indication that treating the armature/stator gap as a vacuum is inappropriate. Eventually the presence of gas in the armature/stator gap does explain the bulk of the difference between simulations and data. However, the first step at this point is to examine the treatment used to model the collision and indirectly the method used to model the vacuum.

RAVEN treats a vacuum using a Yukawa vacuum pressure [5]. The Yukawa vacuum pressure models the pressure in the vacuum cell as a function of the width of the cell. The functional form of the pressure is shown in equation 1.

$$p = p_o \frac{\exp \left[ -\frac{\Delta r}{dr} \right]}{\frac{\Delta r}{dr}} \quad (1)$$

Where:

$P_o$  = reference pressure

$dr$  = scale length

This vacuum model allows for the transmission of force across the vacuum cell when the width of the cell ( $\Delta r$ ) becomes small relative to the parameter  $dr$ . One approach to arriving at an appropriate value of  $P_o$  and  $dr$  is to initially set  $dr$  to a large value and  $P_o$  to a small value. Then the value of  $dr$  is adjusted down and the value of  $P_o$  is adjusted upward until the vacuum cell becomes small compared to the adjacent material cells

and the value of the pressure peaks at an appropriate value during the collision. This process was used to produce the best possible 1D results when the armature/stator gap was assumed to be a vacuum.

During the process of finding the best values of  $dr$  and  $P_o$  we discovered the results obtained when  $P_o$  was small and  $dr$  was large compared more favorably with the data. While the calculated results under these conditions are not really physical, it does suggest something was cushioning the collision between the armature and stator. Consultation with the operations crew identified the use of  $SF_6$  as a buffer gas in the armature/stator gap.

Two approaches were used to model the presence of gas in the armature/stator gap. The first was to use an ideal gamma law EOS for the buffer gas with the atomic mass set to that of  $SF_6$  and initial pressure and temperature set to those used in the experiment. The first observation made was that the armature velocity was faster than the sound speed in the gas. Consequently, condensed gas was snow plowed up in a bow shock on the surface of the armature. This additional mass modified the velocity profile of the armature. This effect combined with variations of the JWL parameters of the explosive produce excellent agreement in time scale and shape when comparing the simulation to the data. The results of parametric variations of gamma and JWL parameters indicate the best fit to the data occurs with about a 6% degradation of the JWL parameters in the explosive and a gamma value of 1.6.

The 6% degradation of the explosive is plausible, since measured variations in the density of the PBX-N110 have been observed in the final casting. However, the gamma value of 1.6 is inconsistent with complex molecular structure of  $SF_6$ . A more appropriate value for  $SF_6$  in the gas phase is 1.1. The calculated peak value of current did, however, agree favorable with the data to within a fraction of a percent. Of course the accuracy in the measured current is no better than 3%. The deviation of the predicted current from measured value now occurred very near the peak value when the  $SF_6$  had been compressed a factor of 10,000. This rapid compression could cause the  $SF_6$  to be condensed into a liquid phase. In which case the effective gamma of the material could approach a much higher value. This led the second approach to simulating the behavior of the buffer gas.

The second approach was to use a Van derWaal's EOS to model the gas. This equation of state had the desirable effect of having a rapid decrease in compressibility as the liquid density is approached. The results are shown in figure 4 and 5. As expected the resulting simulation compares favorably with the data. While there is still a small amount of overshoot and the current still falls away slightly after peak the compressibility factor results in limiting the peak and sustaining the high value of current for a period comparable to the measured current. Figure 5 shows

the derivative of the current with time. This comparison is helpful in discerning fine details in the current waveform. In this case even detail associated with the first motion, the action of the crowbar, and current amplification can be observed. Identification of this detail allows us to even check specific timings in the generator and verify portions of the simulation.

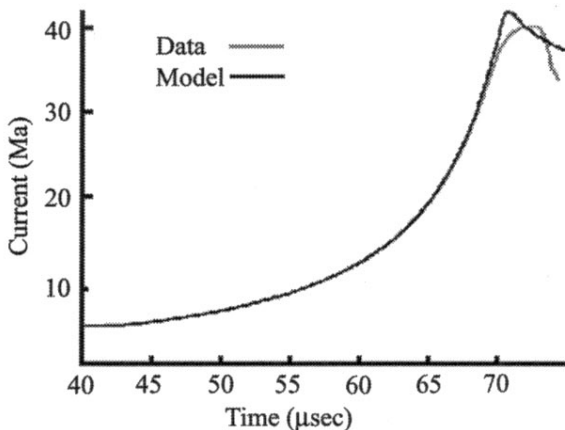


Figure 4. Simulation (1D) vs. Data comparison of current waveform

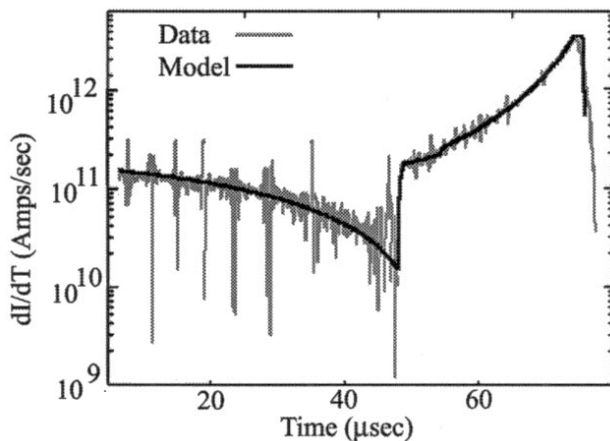


Figure 5. Simulation (1D) vs. Data comparison of current derivative

## VI. SUMMARY

The results shown in figures 4 and five represent the best 1D simulations to date. There remain some issues relating to the behavior of the SF<sub>6</sub> such as the relative amount of shock heating of the gas by the bow shock in front of the armature, as well as corrections to the Van derWaal's EOS at high compression ratios. However, the authors believe at this point we have exhausted the ability of this 1D model to simulated the RANCHERO generator. The agreement is good now up until the armature is with 0.5 mm of the stator resulting in a peak current that appears to be approximately 5% high. At this point it begins to be feasible that 2D effects

may explain the remaining differences. These results identify several important sensitivities that must be addressed to accurately simulate RANCHERO. These sensitivities include accurate values for the JWL parameters of the explosive, appropriate treatment of the buffer gas in the armature/stator gap, and while not addressed in this paper attention to detail in identifying the values of the external circuit elements in the total system. (I.e. Charging bank, coupling cables, and load inductance's)

Future activities for this work in progress will address two things. First we will expand the simulations to include a more complete 2D simulation in an attempt to explain the remaining differences. Again the suspected phenomenon are surface instabilities and perturbations on the armature surface, possible jetting at the glide planes, and in general other physics which could result in flux trapping and limitation of the output current from the generator. Second we will expand the analysis effort to include additional experiments which have already been executed and are planned for the future. Hopefully the result will be an affirmation of the predictability of generator performance.

## VII. REFERENCES

- [1] Bruce L. Freeman, Maurice G. Sheppard, and C. Max Fowler, "Advanced High-Explosive Flux Compression Generator Development: The CN-III Series", Los Alamos National Laboratory, Los Alamos, NM, LA12348, Aug. 1992.
- [2] Daniel J. Steinberg, "Equation of State and Strength Properties of Selected material", Lawrence Livermore National Laboratory, Livermore, CA, UCRL-MA-106439, Feb. 1991.
- [3] Stanford P. Lyon and James D. Johnson (ed.), "SESAME: The Los Alamos National Laboratory Equation of State Data Base", Los Alamos National Laboratory, Los Alamos, NM, LA-UR-92-3407, 1992.
- [4] B.M. Dobratz, "LLNL Explosives Handbook: Properties of Chemical Explosives and Explosive Simulants", Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52997, Mar. 1981, page 8-21.