LA-UR-97-2411
CONF-9706113--

THE RANCHERO EXPLOSIVE PULSED POWER SYSTEM

James H. Goforth, Walter L. Atchison, Donald E. Bartram, C. Maxwell Fowler, Jeffrey D. Goettee, Dennis H. Herrera, James C. King, Emmanuel A. Lopez, Ernesto C. Martinez, Henn Oona, Robert E. Reinovsky, Maurice Sheppard, John Stokes, Leonard J. Tabaka, David T. Torres,
University of California, Los Alamos National Laboratory,
Los Alamos, New Mexico 87545

11th IEEE International Pulsed Power Conference
Hyatt Regency, Baltimore, MD

June 29 - July 2, 1997

Photograph: by Chris J. Lindberg

DISCLAIMER

THE RANCHERO EXPLOSIVE PULSED POWER SYSTEM

James H. Goforth, Walter L. Atchison, Donald E. Bartram, C. Maxwell Fowler,
Jeffrey D. Goettee, Dennis H. Herrera, James C. King, Emmanuel A. Lopez,
Ernesto C. Martinez, Henn Oona, Robert E. Reinovsky, Maurice Sheppard, John Stokes,
Leonard J. Tabaka, David T. Torres,
University of California, Los Alamos National Laboratory,
Los Alamos, New Mexico 87545

Introduction

We are currently developing a high explosive pulsed power system concept that we call Ranchero. Ranchero systems consist of series-parallel combinations of simultaneously initiated coaxial magnetic flux compression generators, and are intended to operate in the range from 50 MA to a few hundred MA currents. One example of a Ranchero system is shown in Fig. 1. The coaxial modules lend themselves to extracting the current output either from one end or along the generator midplane. We have previously published design considerations related to the different module configurations,[1] and in this paper we concentrate on the system that we will use for our first imploding liner tests, a single module with end output. The module is 1.4-m long and expands the armature by a factor of two to reach the 30-cm OD stator. Our first heavy liner implosion experiments will be conducted in the range of 40-50 MA currents. Electrical tests, to date, have employed high explosive (HE) charges 43-cm long. We have performed tests and related 1D MHD calculations at the 45-MA current level with small loads. From these results, we determine that we can deliver currents of approximately 50 MA to loads of 8 nH.

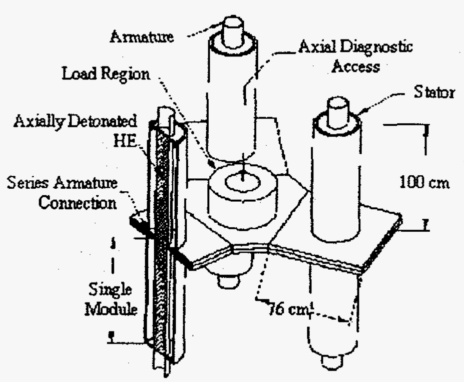

Figure 1. Ranchero system concept. This system has two series generators in each of three parallel branches. As shown, the system requires ~180 kg explosive and needs a helical booster generator with an additional 50 kg explosive for very high current operation. The module currently under development is 140-cm long, which would increase the total explosive to 250 kg + 50 kg.

Single Module Configuration

Figure 2 shows a single Ranchero module with a load similar to one that will be used for our first liner tests. These tests will provide similar conditions to those available for experiments with our Atlas capacitor bank facility, which is under construction; and as a result, we are designing loads of ~8 nH to approximate Atlas loads. Opening and closing switches will be located on the parallel plates at the generator output for experiments in which the load cannot tolerate the long low-level current pulse that occurs while feeding initial current to the generator.

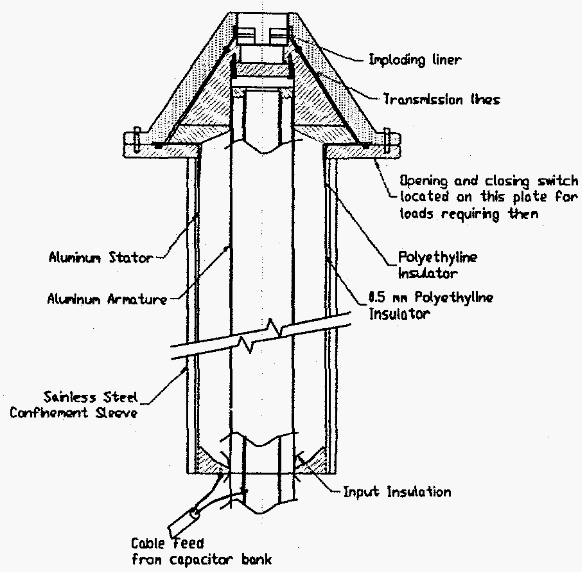

Figure 2. Single 1.4 m Ranchero Module with Atlas-like load attached. The explosive is detonated 56 places along the 1.4 m axis.

The armature for this module will be the same as we have used in small-scale experiments (6-mm-thick aluminum wall with an OD of 15.2 cm) except for length and detonation point spacing. The total length is 140 cm versus 43 cm. The detonation system for these armature chargesconsists of two Slapper detonator cables placed back to back, each with 56 discrete points (total of 112 points) placed 24.5 mm apart. The points on our 43-cm system are 18 mm apart, and there are small differences in the ripple inherent in the armature because of the different point spacing. Using a 2D hydrodynamic (2D hydro) code to help adjust the thickness of an acrylic smoothing layer, we can achieve a smooth enough armature for adequate generator performance.

Skin Depth and Armature Heating Issues

One of the most important issues in the design of this module relates to current diffusion. We have examined the issue with our 1D MHD code, RAVEN which treats the diffusion of the magnetic field and, hence, the current into both the armature and the stator. RAVEN is a 1D Lagrangian code, which uses the SESAME tabular equations of state. Included is a Steinberg-Guinan strength model, a Lindemann melt model, and temperature-dependent electrical conductivity. Figure 3 shows the density, magnetic field, and yield strength profiles calculated by RAVEN at a time just prior to impact of the armature with the stator. Although this is an idealized 1D result, since 2D effects will have dominated before the stator actually gets this close, these results do identify issues relating to flux loss that limits generator performance. The density contour shows the location of the outer armature surface (~15.225 cm) and the inner stator surface (~15.26 cm). The magnetic field contour clearly shows the field has diffused moderately deep into both the armature and the stator. Note the field has penetrated further into the armature (~ 0.5 mm) than the stator (~0.3 mm). The density plot also shows the polyethylene insulator and the armature/stator gap has been compressed to approximately 0.35 mm. Thus, the effective flux region when the field diffusion is considered is about 1.15 mm instead of the physical gap of 0.35. The flux that has diffused into the armature and stator represents a temporary loss of field energy that cannot be recovered on the time scale necessary to be useful for any practical load. A convenient approximation we have used in the past suggests that the diffusion would be ~0.8 mm in both armature and stator. Much of our analysis is based on that estimate, and we will comment on the resulting differences. Also shown in Fig. 3 is the yield strength profile at the same time. The significance of this is that it is zero for a small layer (~0.07 mm). This indicates that the stator outer surface is just beginning to melt. The elevated temperature of the armature is caused by the shock heating done by the explosive as well as the plastic work done on the armature as it is driven to a larger radius. This also explains the increased diffusion of the magnetic field in the armature, since the resistivity increases as the temperature in the stator increases, but the stator remains relatively cool allowing for a slightly lower resistivity.

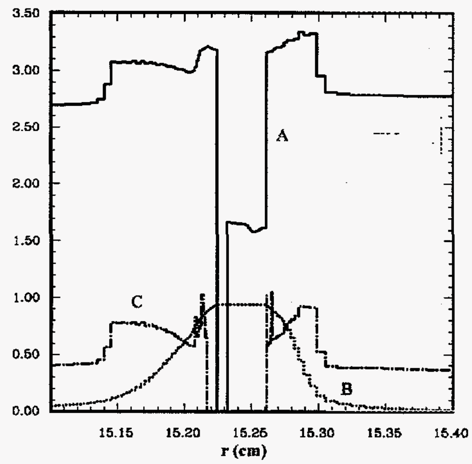

Figure 3. RAVEN calculations of density (A), magnetic field (B), and yield strength (C) for the Ranchero armature and stator at a time near collision.

Full Current Experiments

We have conducted two experiments in the 45-50 MA range, which have provided valuable insight to our module performance and design. One experiment ("A") tested a module with parallel stator and armature and essentially no load. The second experiment ("B") tested a module with a four-degree taper on the stator and an end output load. The test configurations are shown in Figs. 4 and 5. Probe grooves in Test A resulted in an inductance of 0.3 nH, in addition to the generator cavity, and the load for Test B was initially 0.62 nH in addition to the same 0.3 nH probe grooves. The purpose for these tests was to determine the residual terminal inductance for our generators, and both experiments had an initial current of 1.8 MA from a four mF capacitor bank charged to ~14 KV. The resulting current waveforms are shown in Fig. 6. The two curves are seen to be extremely consistent until the effect of the tapered stator (and slightly bigger load) become important. Faraday rotation current data are shown from the two tests for consistency, although the probe in Test A, which is subjected to a shock wave in the generator body, failed before current peak. Test A had ground shifts on the electrical data, so we are less confident of those values. However, a dB/dt probe fitted to the Faraday probe during early times shows that the generator continued for several hundred nanoseconds after the Faraday probe failed and achieved a peak current of 48 MA. To examine the question of residual inductance, we performed the following analysis on both tests. We first calculated the total initial inductance assuming no flux diffusion into the walls. We then used the measured current gain along with the initial inductance to compute a final inductance, assuming no losses. To obtain further insight to the sources of the residual inductance, we calculated cavity dimensions implied by the

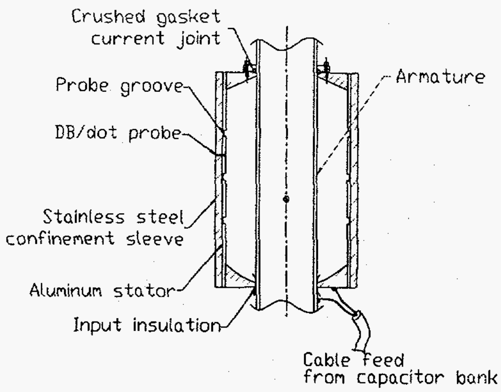

Figure 4. Test configuration (A") with parallel armature and stator. Faraday rotation probes in the indicated groves failed early, but dB/dt probes survive to well past current peak. The armature is initially 43 cm in length.

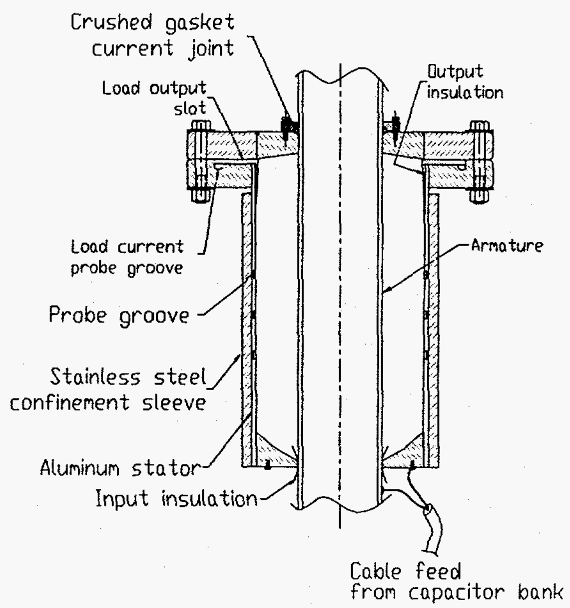

Figure 5. Test configuration B with end output load. Faraday probes in the load current probe groves survive past peak current. The armature is 43 cm in length.

resulting inductance, assuming full length generators. Using a skin depth of 0.8 mm, as we originally estimated, we could then prescribe what effective gap was left between the stator armature at peak current. The results are shown in Table I. Test A achieved peak current with a gap of 1.6 mm remaining. The insulation on the stator was 0.5 mm, leading us to conclude that the generator peak occurred with ~1.1 mm bigger gap than we could account for. Using the RAVEN result above, an even larger gap of 2.4 mm (1.9 mm larger than we can account for) is calculated. This result led us to conduct Test B with a tapered stator. Using the original skin depth estimate, Test B results indicate that the effective gap was 0.4 mm, even though the insulation was still 0.5-mm thick. This is consistent with the hydro in the RAVEN calculation, but the complete RAVEN result suggests that we still have a 0.7 mm air gap at peak current. We conclude that the slight taper allows flux pocketing to be reduced, if not eliminated, and that this was the reason for the larger estimated gap on Test A (rather than, for instance, having a larger skin depth than we calculate). We will attempt to optimize the generator design for speed versus flux pocketing in future experiments, but we believe that some taper will be beneficial for designs using thin insulation. If the new MHD calculations are more accurate, the implication is that we will have a larger final gap than that shown in Table I. However, the trend is unchanged,

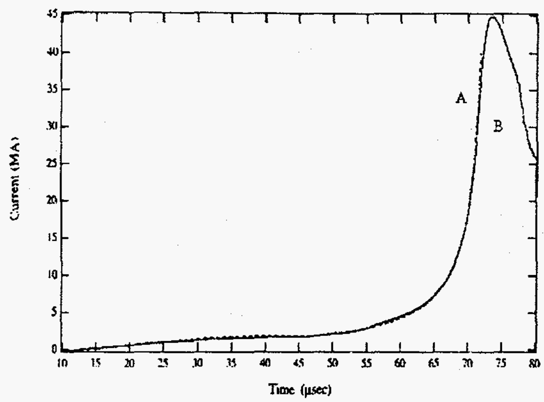

Figure 6. Current waveforms from two test. For consistency, we show the two Faraday rotation probes even though the fiber in Test A failed because of shockwave in its location. A dB/dt probe fitted to the early Test A curve yields a peak current of 48 MA on that test. Consistency between the two curves is very good until the effects of the tapered stator become important. The taper gives rise to ~ 1 μs longer operation with reduced dI/dt during the last 1 μs.

and if true, the reduced skin depth benefits us in two ways. First, we can explore ways of further reducing our residual inductance. Second, we will not experience as much increase in our total load inductance because of diffusion.

Table I. Results from Test A and B. The final gap does not include the part of the residual inductance caused by the 0.8-mm calculated skin depth.

Test	L_0 Gen (nH)	L_0 Ext (nH)	L_{final} Ext (nH)	I_0 (MA)	I_{final} (MA)	$L_{residual}$ (nH)	Final Gap (mm)	Insulation (mm)
A	55.5	0.3	0.4	1.8	48	1.7	1.1	0.5
B	55.9	0.92	1.17	1.8	45	1.1	0.4	0.5

Extrapolations to Liner Experiments

We have made extrapolations based on the results of Test B to determine the currents available in a load of ~ 8 nH using a 1.4-m Ranchero module. The results are shown in Table II. The initial current will be provided by our 12 mF capacitor bank at ~18.5 KV, and the stator insulation will remain the same as in small-scale tests. The residual inductance is scaled by the ratio of generator lengths, and we might see as much as 1 nH additional load inductance because of the skin depth in the load.

Table II. Test B data scaled to a full-scale Atlas simulation.

Test	L_0 Gen (nH)	L_0 Ext (nH)	L_{final} Ext (nH)	I_0 (MA)	I_{final} (MA)	$L_{residual}$ (nH)	Insulation (mm)
Atlas Scale Test	195	8.0	~9	3.3	53	3.6	0.5

Pulse Conditioning With Ranchero Waveforms

Some loads will not be able to tolerate the long foot seen on the current waveforms given in Fig. 6. For these tests, an opening switch can be used to carry the early current pulse, while a load isolation switch prevents current from reaching the load. For heavy liner loads, we will subsequently close the load isolation switch and actuate the opening switch to transfer current to the liner. Figure 7 shows a calculation of such a test using an opening switch profile scaled from previous opening switch explosive. Several candidates for this opening switch exist, and we are considering the most cost effective versus performance required. The switch does not have to be a high-performance switch as long as we switch while most flux is still in the generator. The switch used in the calculation must absorb ~ 1 MJ energy, and achieve a resistance of 50 mΩ in 3 μs. Switching the same switch 4 μs earlier, delivers 5% more current to the load, and requires absorbing only 0.4 MJ. Switches will be tailored to the needs of the load, with the tradeoffs being between energy lost to the switch and complexity of the switch versus liner design difficulty and early time performance of liner loads.

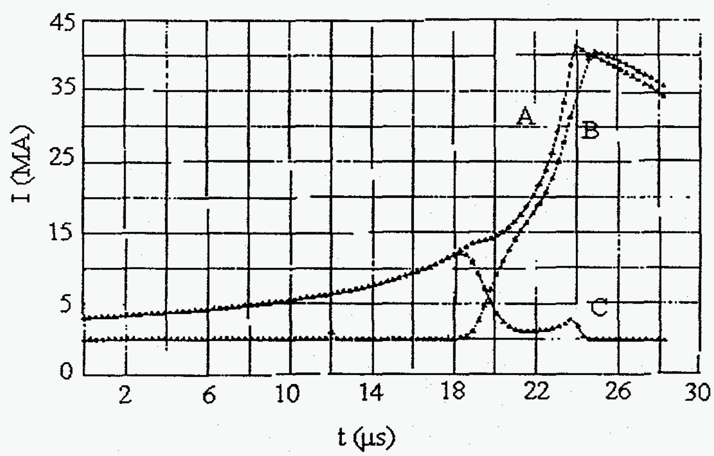

Figure 7. Circuit model calculation of a Ranchero module with an opening switch and load isolation switch to protect the liner load from the early current foot. Curve A is the model current, curve B is the load current, and curve C is the opening switch current. The opening switch is the calculation in a resistance profile that is plausible from experience, and requires no extension of technology to create.

Conclusion

Thus far we have demonstrated that we can operate 30-cm OD coaxial generators with a slight taper on the stator with very good flux efficiency. With no further power conditioning, we can deliver over 50 MA to an 8 nH load that increases to 9 nH because of the flux diffusion in the load. Calculations using representative values for opening switch resistance profiles indicate that we can operate the same load at currents over 40 MA with pulses as short as 5 μs. The switch required for this test would have to reach only modest resistance, but would have to absorb ~ 1 MJ energy in the switching process. Allowing pulses as long as 10 μs reduces the energy lost in the switch substantially.

References

1. J. H. Goforth, et al., "Ranchero: A High Current Flux Compression Generator System For Heavy Liner Experiments," *Seventh Conference on the Generation of Megagauss Magnetic Fields*, 1996, to be published.

Acknowledgment

The authors wish to thank Martha McKinney for her tireless efforts in preparing this manuscript and the Vugraphs for the accompany talk.