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ACCELERATING THICK ALUMINUM LINERS USING PULSED POWER

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Abstract

We have investigated the acceleration of very thick cylindrical aluminum liners using the Pegasus II capacitor bank. These accelerated solid liners will be used to impact other objects at velocities below 1.5 km/sec, allowing us to generate and sustain shocks of a few 100 kilobar for a few microseconds. A cylindrical shell of 1100 series aluminum with an initial inner radius of 23.61 mm, an initial thickness of 3.0 mm, and a height of 20 mm, was accelerated using a current pulse of 7.15 MA peak current and a 7.4 microsecond quarter cycle time. The aluminum shell was imploded within confining copper glide planes with decreasing separation with an inward slope of 8 degrees. At impact with a cylindrical target of diameter 3-cm, the liner was moving at 1.4 km/sec and its thickness increased to 4.5 mm. Radial X-ray radiograms of the liner showed both the liner and the glide plane interface. The curvature of the inner surface of the liner was measured before impact with the 15-mm radius target. The radiograms also showed that the copper glide planes distorted as the liner radius decreased and that some axial stress is induced in the liner. The axial stresses did not affect the inner curvature significantly. Post-shot calculations of the liner behavior indicated that the thickness of the glide plane played a significant role in the distortion of the interface between the liner and the glide plane.

I. INTRODUCTION

Cylindrical liners have been used for a long time to accelerate a thin piece of conductive metal to high velocities, and then use those liners to perform a variety of experiments [1]. The most common use of those liners dictate that they are accelerated to the highest possible velocities, provided they are stable. These requirements are satisfied provided the liners are thin, to reduce the accelerated mass, and implode with a large aspect ratio, to increase the acceleration times. However, there is a need for thick slow liners that will be used to generate shocks for sustained periods of time, times of the order of many microseconds, that allow a material to strain for a long time, or allow the distortions in the material to adiabatically develop. Many experiments, such as the study of friction at interfaces, require sustained pressure for a long period of time allowing the distortions and perturbations at the surfaces to develop long enough for their effect to propagate and manifest itself as distortions within the materials as well. These requirements motivated us to develop a thick liner on Pegasus, and to investigate the distortions in the liner and the the glide plane that supplies its driving currents.

We use the approach of designing the liner using simple 1-D codes to get the to the correct regime of operations, then used 2-D MHD codes to study the details of the distortion of the liner and the system. In what follows we will present the approach, and show some of the results of the measurements.

II. LINERS

The liners were used on the Pegasus facility they are usually made of aluminum and their size depends on the geometry allowed in the power flow channel. 1100 series aluminum was used because of its high plasticity, high action figure of merit, and ease of fabrication.

A. *Facility*

Pegasus is a pulsed power facility consisting of a 4.3 MJ capacitor bank , with a capacitance of 850 μF fired with initial bank voltages of up to 100 kV. The bank's series resistance is about 0.5 mΩ, and the inductance of the bank and the fuses of about 8-9 nH. There is an

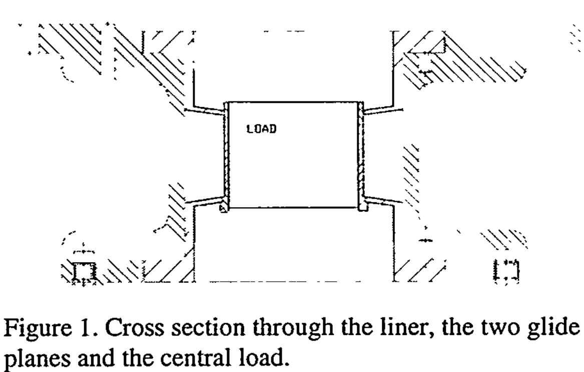

Figure 1. Cross section through the liner, the two glide planes and the central load.

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additional 24 nH inductance associated with the power flow channel. The detail of the bank and the machine is described elsewhere [2]. In the present set of experiments we used a slight variation of the normal liner, our liner was typically bolted to the power flow channel. As the liner imploded, it slid across a copper glide plane that was inclined at 8 degrees to the direction of implosion, see fig. 1 for a cross section of the liner and load.

B. 1-D calculations

We used a 1-D MHD code [3] to make a parametric study of the liner properties and the bank characteristics. The code required a circuit model for the capacitor bank and a tabular entry for the fuse. The parameters of the fuse were not modeled correctly by this code, but an approximate behaviour was included. The liner we used was 2 cm high, and had an internal radius of 23.6 mm, and a height of 20 mm, limited by the geometry of the machine, and the availability of boules of aluminum for machining. One of the criteria used for the design was the availability of an impact velocity of about 1.5 km/sec at a radius of 15 mm where it impacts a load. The results of the calculation for the velocity are sensitive to the charging voltage, and differ from the simple thin liner approximation, see Figs 1. And 2 for the results. The impact velocity is found to depend on V^2 [log ($t^{-3/2}$)] where t is the thickness of the load, and V is the voltage across the bank. The results of the calculations show that we could achieve our goal with a liner that is 3 mm thick, if use a charging voltage of 50 kV [100 kV across the bank], and that the liner does not melt before impact. We emphasize that these calculations are guides for design and that a detailed fuse model is required.

C. 2-D calculations

We now consider the results using an axisymmetric Eulerian 2D MHD code [4]. The code was used with an externally derived time dependent current derived from the circuit model for the liner-generator-coupled system. No attempt has been made to model the perturbations in the manufacturing process. We wanted to find if the use of a knife edge cookie cutter, as was done for thin liner, [4] was necessary. The initial calculations without account for the glide plane's finite thickness are shown in Fig. 4, 5, and 6 for different times. We found that very little stress exists in the liner, and that the velocity is consistent with the 1D calculations. We also found that the liner stayed solid up to impact, and that a small amount of axial curvature was present.

Later modeling, that included the actual thickness of the glide plane, showed that the liner ploughs into the glide plane, without a lot of jetting at that corner. The distortion of the glide plane sends a weak acoustic wave through the liner, but does not perturb the liner much. The liner seems to implode with a reasonably large radius of curvature

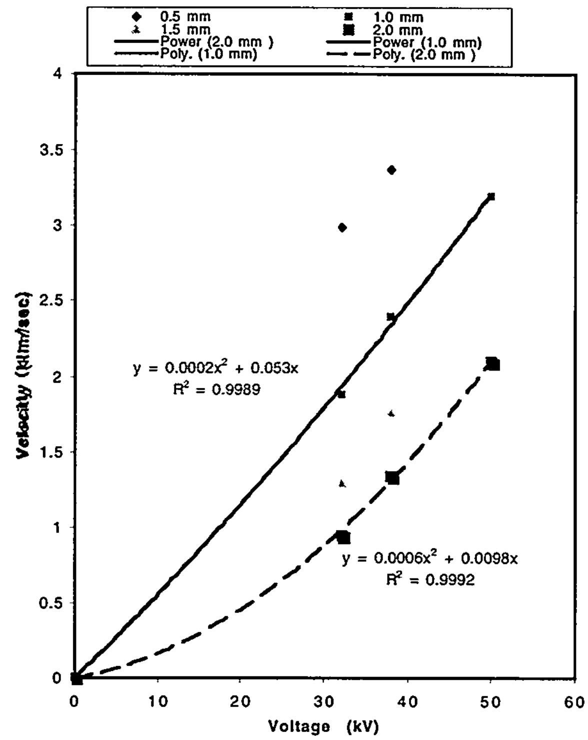

Figure 2. Impact velocity for the 2-cm high liner as a function of charge voltage, for different thicknesses

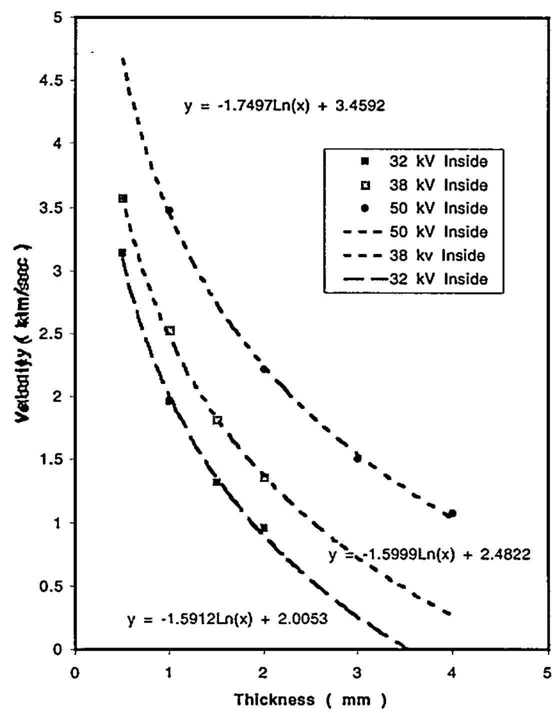

Figure 2. Impact velocity for the 2-cm high liner as a function of thickness, for different voltages.

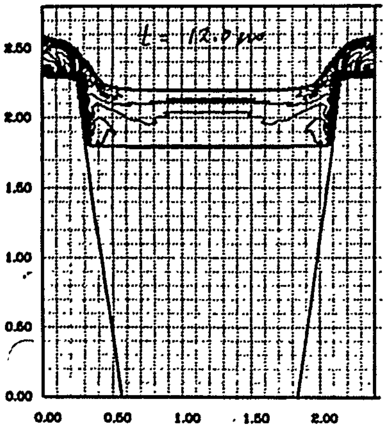

Figure 4. Stress profile and location for the 2-cm high liner at 12.0 μs.

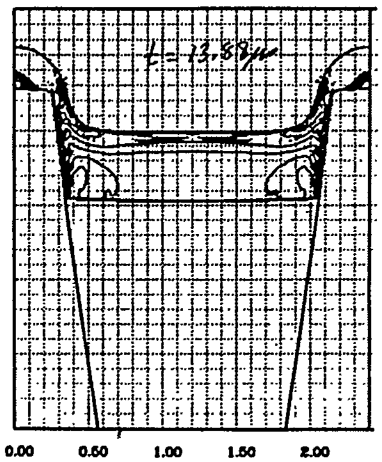

Figure 5 Stress profile and location for the 2-cm high liner at 13.88 μs just before impact at 15-mm radius.

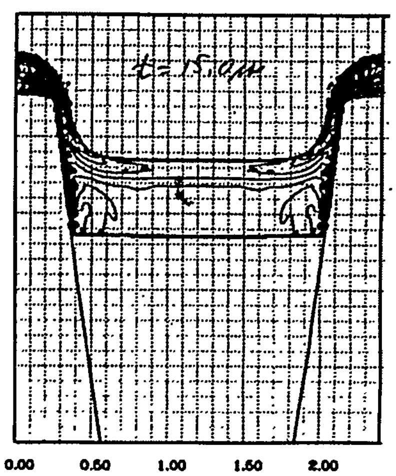

Figure 6. Stress profile and location for the 2-cm high liner at 15.0 μs past impact time.

III. EXPERIMENTAL DATA

Two experiments were carried out at Pegasus, DF-1 and DF-2. Both used a 3-mm thick liner with an inner radius of 23.61 mm, a height of 20 mm, and 1100 series aluminum. The initial surface was surface finished to a measured 10 μ inch rms. surface roughness using diamond turning. A diagram of the liner is shown in fig. 6. Pulsed radial x-ray sources were used to observe the liner. Using the Tungsten 64 keV line. The current drive was monitored using 6 PFC B-dot loops set at 60° azimuthal intervals, 4 high pass filtered B-dot loops for load symmetry measurement and five Faraday probes for bank diagnostics. The charge voltage in each case was set at 50 kV, but we recorded 49.6 kV on the first shot, DF-1, and 50.6 kV on the second shot, DF-2. The shots differed only in the using a rail gap switch on DF-1 and a detonator switch on DF-2. The peak currents were measured at 7.14 and 7.45 MA and the times of peak current were 7.4 and 7.4 μs respectively. A summary of the data is shown in Table 1, where the calculations used the measured currents. Had the predicted currents been used errors of up to .5 microseconds would have been observed. Most of the error in predicting the current occurs because of the inadequate treatment of the fuse in the 1-D code. For DF-2 we expected a velocity of 1.2 km./ sec and measured 1.19 km / sec.

Table 1. Radial Position Data

Shot/X-ray	Time (μs)	Calculation (mm)	Measurement (mm)
DF-1/P-13	13.7	16.76	16.74
DF-2/P13-1	13.05	16.94	16.91
DF-2/P17-1	15.205	14.29	14.35

A. Radial Data DF-1

The radial x-ray image [P13-1] of the liner at 13.7 μs is shown in Fig. 7. The radiogram clearly shows the bending of the copper glide-plane and the curvature of the liner, 1-mm before impact. The top part of the image shows the static image of the target showing a core 130 mm in diameter, a 2 mm aluminum cylinder that holds the inner load together, and a 3mm thick liner. The center of the liner is 1/3 mm closer to the axis than the outer edge. The measured radius of curvature of the surface is 1110 mm, similar to that of figure 5. Since the surface is moving at 1.2 km/sec, this corresponds to a difference in impact time of 0.28 μs, across the full liner

B. Radial Data for DF-2

Three radial images for DF-2 were taken. One time before impact [t=13.05 μs] a second just after impact [14.35 μs] and a third after impact [17.6 μs]. While the first data shows a curvature similar to that of DF1, the other show an inversion of the curvature indicating a yield failure in the aluminum liner! or a bouncing of the liner from the inner aluminum cylinder!.

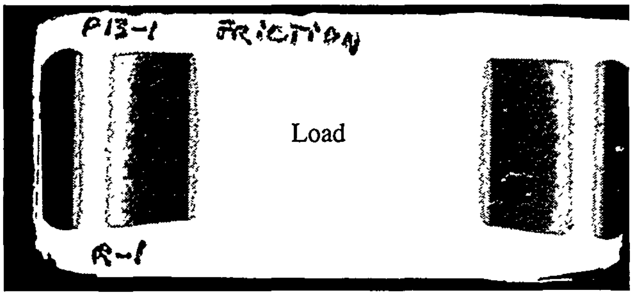

Figure 7. Static radiogram, DF1_P13-1s_300dpi.tif, of the load and liner.

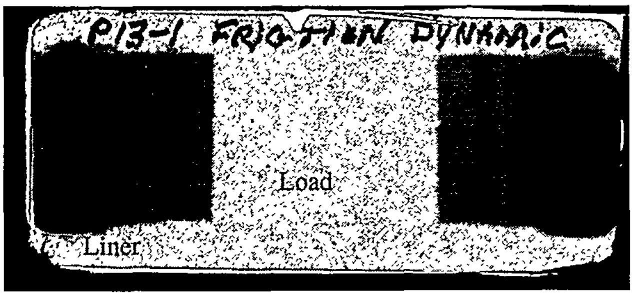

Figure 8. Dynamic radiogram, DF1_P13-1D_300dpi.tif, of the liner at 13.7 μs. The inner cylinder is the load; the first dark band is the gap.

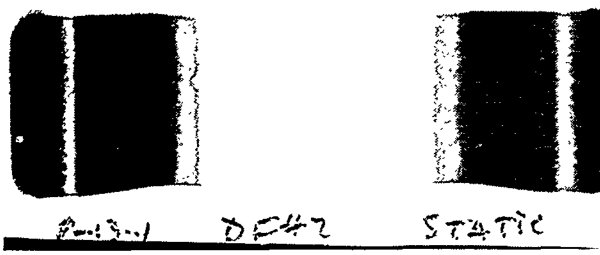

Figure 8. Static of the second liner, DF2_P13_1s_m.tif.

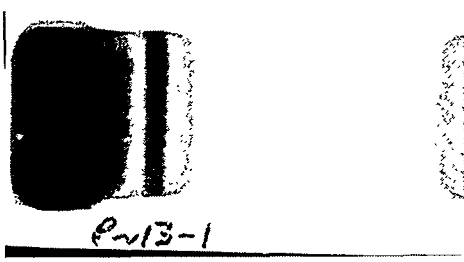

Figure 9. Dynamic radiogram, DF2_P13_1D_m.tif, of the second liner at 13.05 μs.

III. SUMMARY

We have described our effort in the design of slow, thick liners, and showed how 1-D calculations can give us an accurate description of the velocity and position of the liner, given a measured driving current. Prediction of the current is dependent on accurate knowledge of the fuse behaviour and machine conditions. The liner velocity changes by 5% for each 10 % change in voltage or current. 2D calculations are also useful in describing in detail the stress, temperature and pressure distribution in the liner, as well as in describing the distortion in the liner. We also found that these 2-D codes predict accurately the shape of the glide plane, and the material left behind at the glide-plane-liner interface. The radial x-ray radiography has been also found to give an excellent tool for performing these studies.

We conclude that for future work the glide plane should be made of thicker copper, so as not to significantly affect the motion of the liner. This allows us to generate shocks fronts that are more uniform in the axial direction

We would like to acknowledge the expert help of Bernhard Carpenter with the x-ray development, and R. Richard Bartsch and Irvin R. Lindemuth for discussions regarding liners. The expert help of the Pegasus operation crew is also acknowledged

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