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Title: ATLAS PERFORMANCE AND IMPLODING LINER PARAMETER SPACE

Author(s): R. E. Reinovsky, I. R. Lindemuth, W. L. Atchison, J. C. Cochrane, R. J. Faehl

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Atlas Performance and Imploding Liner Parameter Space

R.E. Reinovsky, I.R. Lindemuth, W.L. Atchison , J.C. Cochrane, R.J. Faehl

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Abstract

Ultra-high magnetic fields have many applications in the confining and controlling plasmas and in exploring electron physics as manifested in the magnetic properties of materials. Another application of high fields is the acceleration of metal conductors to velocities higher than that achievable with conventional high explosive drive or gas guns. The Atlas pulse power system is the world's first pulse power system specifically designed to implode solid and near-solid density metal liners for use in pulse power hydrodynamic experiments. This paper describes the Atlas system during the first year of its operational life at Los Alamos, (comprising 10-15 implosion experiments); describes circuit models that adequately predicted the bulk kinematic behavior of liner implosions; and shows how those (now validated) models can be used to describe the range of parameters accessible through Atlas implosions.

Introduction

Atlas is the world's newest, ultra-low impedance, high current capacitor bank facility. Storing 24 megajoules at full charge, Atlas, shown in Figure 1, is the first large scale pulse power system specifically designed for executing solid-density liner implosions. Atlas is the flagship facility for pulse-power driven hydrodynamics experimentation in the world at this time. Conceptual development for Atlas began in 1992. Component selection, development and testing continued through 1996 when the final configuration was selected and engineering design begun. Construction began in late 1999 and assembly was completed in August 2000. Atlas passed its pulse power acceptance tests in December 2000 and achieved operational status after a series of pulse power characterization tests in August 2001. Atlas will operate at Los Alamos until late 2002. It will then be disassembled and reassembled at the Department of Energy's Nevada Test site where it will continue its mission in powering a variety of pulse power hydrodynamics experiments.

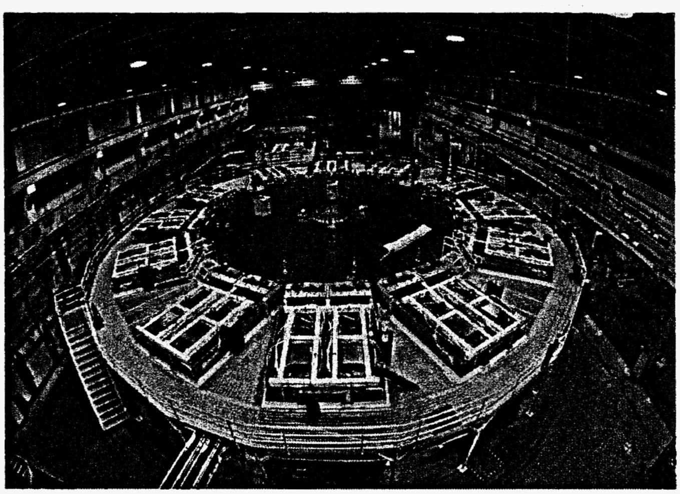
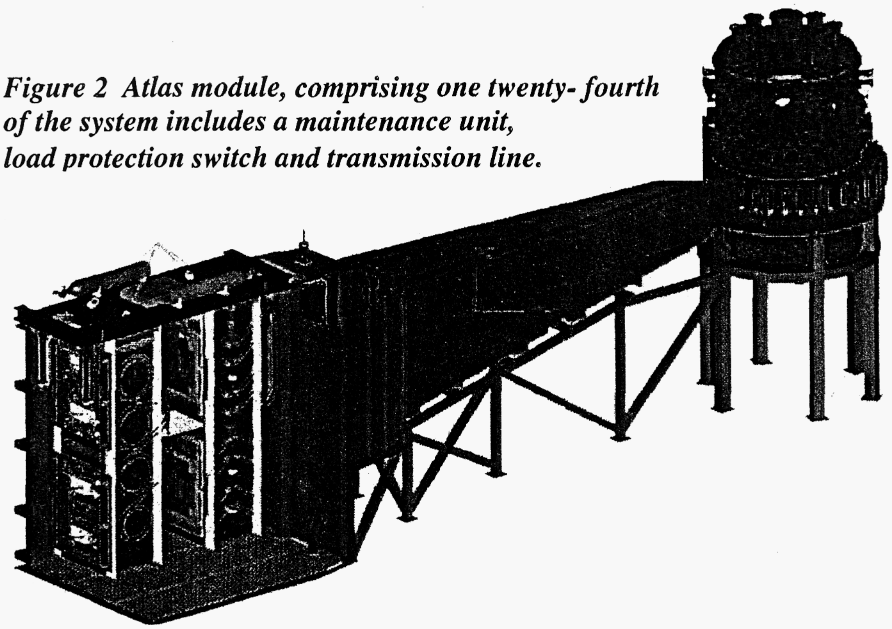


Figure 1 Atlas facility at Los Alamos.

The Atlas Pulse Power System

Modular design, based on a customized low inductance Marx generator configuration, and emphasizing reliability, fault tolerance and easy access for the experimental and diagnostic scientist make Atlas the highest performance, laboratory, microsecond pulsed power system in the world. The complete system stores 24 MJ at rated charging voltage of 240 kV and delivers more than 30 MA currents with rise time from 5-6 μs, depending on the inductance of the load. The 24-fold modularity of Atlas is shown schematically in Figure 2.

Figure 2 Atlas module, comprising one twenty-fourth of the system includes a maintenance unit, load protection switch and transmission line.



A custom designed Marx generator is the basic building block of the Atlas system. The individual Marx generator consists of four 35 µf / 60 kV capacitors each storing about 63 KJ. The custom capacitors are plastic cased, and specially configured with terminals on opposing sides to accommodate the low inductance, folded Marx configuration shown in Figure 3. The four capacitors are charged to opposite polarity (using separate, modular power supplies) and are switched in series by two low inductance, high current, 120 kV, rail-gap switches. These switches are the current step in the evolution of a low inductance rail switch introduced by Maxwell Laboratories Inc in 1974. Each switch is rated for >500 KA and xx coulombs total charge transport per discharge. Switches are trigged with a fast rising, 10 kV/ns, low impedance pulse to ensure multi-channel operation. Switches are insulated with a mixture of 14% sulfur-hexa-fluoride gas in argon. Switches can reliably operate over a voltage range of approximately two for any setting of the inter-electrode gap. Thus with the switch gap set for 240 KV operation, reliable operation between about 135 and 240 KV can be obtained. To operate at lower current, other machine configurations are employed as discussed below. Current output from the Marx module is delivered to an output header through 14 coaxial cables. Series and parallel resistors included in each Marx module limit current in the event of a fault, making Atlas extremely resistant to damage to the pulsed-power components. Each Marx stores approximately 250 KJ and is required to deliver about 300 KA for full machine performance

Four individual Marx modules are assembled, mechanically, into an easily handled "Maintenance Unit" (MU) which comprises the fundamental pulse power sub-system. The four Marx generators are electrically connected in parallel at a single cable-header in each maintenance unit from which current is extracted for the system. Each maintenance unit contains a complete control system that monitors and operates individual MU function using programmable logic controllers interfaced through a local area network to the master control system located in the control room. Each MU also contains an individual trigger system that accepts a single high voltage trigger signal and produces eight, simultaneous high voltage, low impedance trigger pulses that are delivered to each of the eight rail-gap switches in the four marx modules. Each MU is serviced by an individual pair of high voltage power supplies operated in opposite polarity and by individual

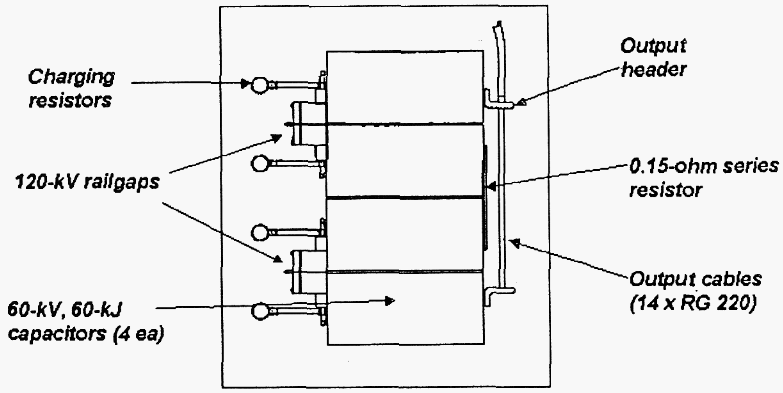


Figure 3. Atlas low impedance Marx configuration

pressurized gas systems. A schematic of a Maintenance Unit is shown in Figure 4. Two maintenance units are housed in each of the 12 rectangular oil tanks that comprise the Atlas system.

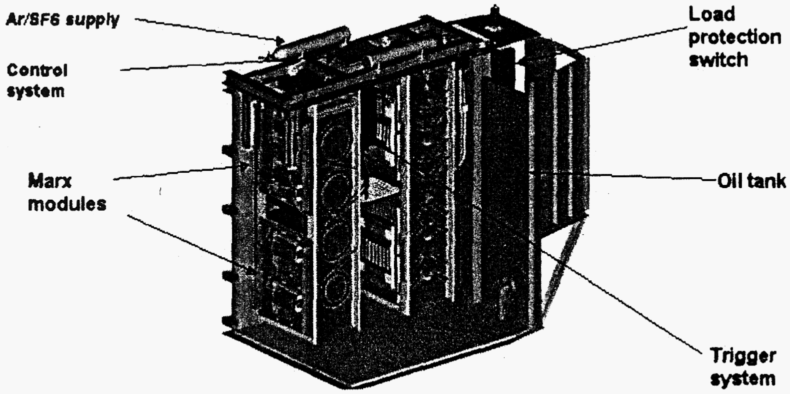


Figure 4 Atlas Maintenance Unit assembly.

A unique feature of Atlas is a specially designed mechanical switch, which provides additional isolation between the charged Marx generators and the complex, sophisticated, and expensive pulse power hydrodynamics load. The switch is shown in Figure 5. While the Atlas rail-gap switches were developed and tested to meet the stringent pre-fire specifications required to ensure that the overall reliability of Atlas, the "load protection switch" (LPS) provides additional protection for Atlas loads. The LPS is a normally closed mechanical switch that provides a low inductance short circuit at the output of the Marx generators. With the switch closed, a full current discharge from the Marx will deliver at most a few kA current downstream to the target. The switch remains closed until a fraction of a second before a machine discharge. The switch mechanically opens in about 250 ms and closes again about one second after the discharge. The LPS has conducted full Marx discharge current in tests without damage and can be mechanically operated indefinitely.

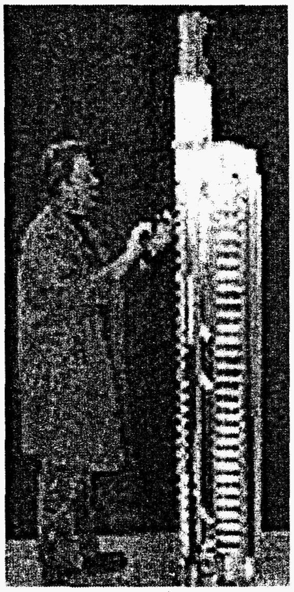


Figure 5 Load Protection Switch

Current from each MU/LPS assembly is delivered to the load region in the center of the machine through a flat, tri-plate transmission line. The transmission lines are about 16 ft long and four feet wide at the input end, narrowing to about one foot wide at the load end. The transmission lines, shown in Figure 6, are fabricated from aluminum plate with 2 cm spacing between the inner, 2.54 cm thick, high potential plate ant the outer 1.27 cm thick plates. In the system, the flat plate transmission lines are vertically arranged, oil insulated and converge to a diameter of about two meters at the center of the machine.

In total, the machine consists of 96 individual Marx generators, assembled into 24 maintenance units. The MUs are housed, in pairs, in 12 rectangular oil tanks in a symmetric arrangement of three tanks per quadrant or "segment" of the system. Diagnostic isles separate each quadrant and allow access to the center of the system. As shown in Figure 7, each oil tank is connected to two narrow oil troughs that contain the flat plate transmission lines and are in-turn connected to a common cylindrical oil tank in the center of the machine. At the center, current is collected from the 24 vertical transmission lines and directed into a horizontal, parallel plate feeds to deliver current to the load. Figure 8 shows how current is collected from

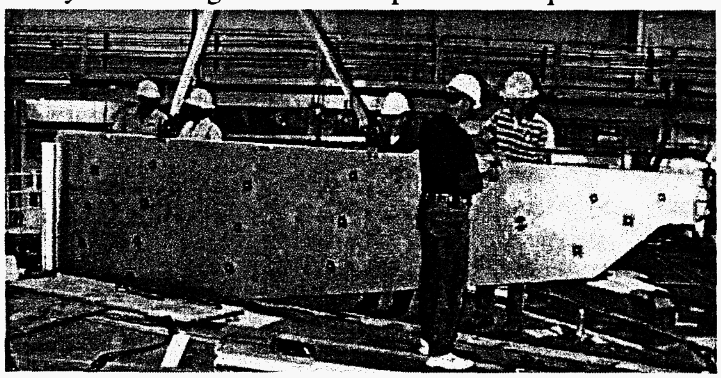


Figure 6 Transmission line tri-plate assembly

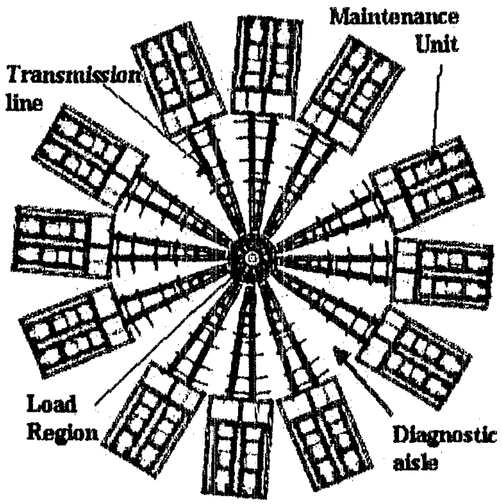


Figure 7 Atlas configuration

parallel plate lines and convoluted in an oil insulated coaxial transmission line section with a vertical axis. The outer conductors of the tri plates are terminated on the outer conductor of the coaxial section. The center-conductors of the tri-plates pass through oil insulated openings in the outer coaxial conductor and terminate on the inner conductor. The inner and outer coax sections are mechanically supported on a plastic insulator/oil interface with low electric stress (and no current flow) on the underside of the machine and with a low inductance plastic/oil power flow interface on the top. Radially inward from the interface the parallel plate transmission line is solid dielectric insulated. For pulse power acceptance testing, an approximately static load, approximately 9 nH, was installed at the oil/solid interface. The test load is later replaced by a custom, solid insulated transmission line connecting the machine to the liner load.

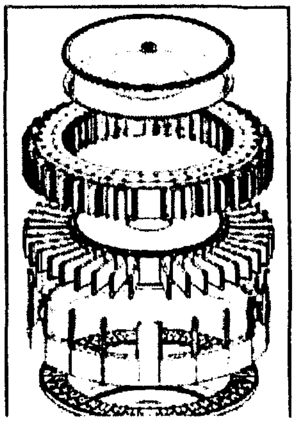


Figure 8 Load region convolute

Downstream of the oil/plastic interface the solid insulated transmission line is treated as part of the experimental load. The first generation transmission line geometry shown in Figure 9 was designed to elevate the load from the plane of the transmission line while keeping the inductance to a practical minimum. Insulation in the first generation line included a nominally permanent polyurethane cast insulator at larger radius and a replacable polyethylene insulator at smaller radius. This configuration served for ten consecutive experiments at currents ranging from 8 to 22 MA before failing and being replaced with an all polyethylene system.

Pulse Power Testing

As noted above, the Azimuthal, four-fold symmetric arrangement of pulse power component places three Marx tanks in each quadrant of the machine. This allows fractions of the system to be operated while maintaining comparable current symmetry at the load. Specifically one-third of the MUs can be operated (one tank in each quadrant), or two-thirds of the system (two tanks per quadrant) can be employed. Pulse power testing using a 9nH static load demonstrated operation of the system at 9 MA, 17 MA and 28 MA. Additionally, the system was tested into using a low inductance static load at reduced charged voltage and current. These tests confirmed the fundamental design parameters for the system and allowed formulation of a fixed –element circuit model of the system. Figure 10 shows the Atlas equivalent circuit and Table 1 gives parameters for the full and one-third system as used for the

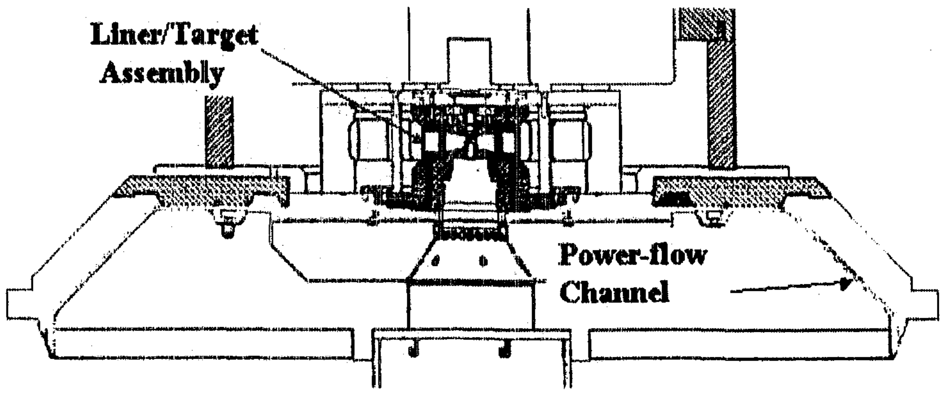


Figure 9 Load region first generation power-flow system.

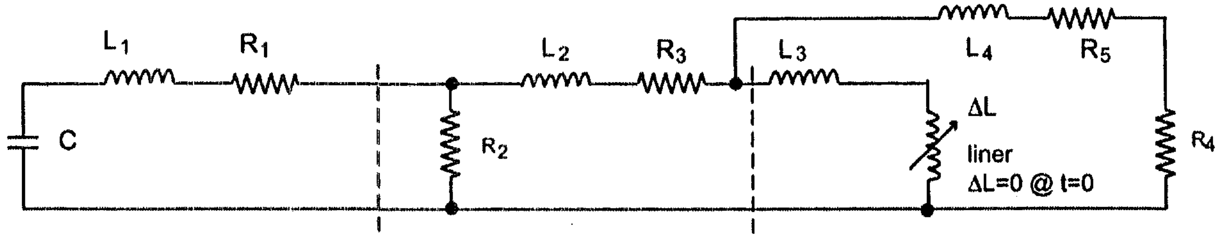


Figure 10 Atlas equivalent circuit. The right loop is used for one and two segment operation

first series of experiments conducted with the first generation power flow channel.

When operated in the one-third (or two-thirds) configuration, all vertical transmission lines and their associated parallel current limiting resistor remain in the circuit even though the capacitors in those branches remain uncharged and the switches do not conduct. Thus the circuit loop containing R4, R5 and L4 describes the transmission line and parallel damping resistors of the non-operating part of the machine in the one-third-system configuration.

	C (µF)	L1 (nH)	R1 (mΩ)	R2 (mΩ)	R3 (mΩ)	L2 (nH)	L3 (nH)	R4 (mΩ)	R5 (mΩ)	L4 (nH)
Full	816	2.6	1.875	50	0.01	6.2	15.41			
One Third	272	7.8	5.625	150	0.03	18.6	15.41	75	0.015	9.3

While machine discharges with fixed load inductance loads provide good characterization data, the most sensitive test of a circuit description is that using a dynamic (implosion) load. The first Atlas implosion experiments, designated Liner Demonstration (LD) experiments, were conducted to refine machine circuit parameters as well as to test liner implosion performance. The values of circuit parameters shown in Table 1 include fine adjustments resulting from analysis of the LD experiments. Subsequently, implosions experiments (the Spall series) were conducted using the one-segment (one-third system) configuration. The measured currents compared well with those predicted by the fixed element circuit model modified by the addition of an "zero dimensional", incompressible, kinematic description of the

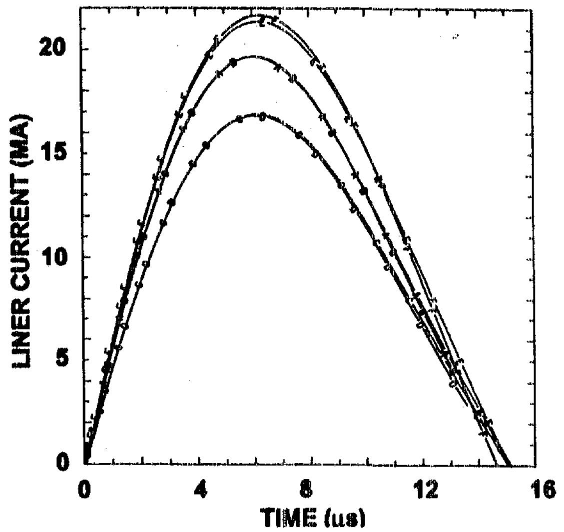


Figure 11 Current from full machine discharges. Curves A,C,E are measure current, curves B.D.F are model

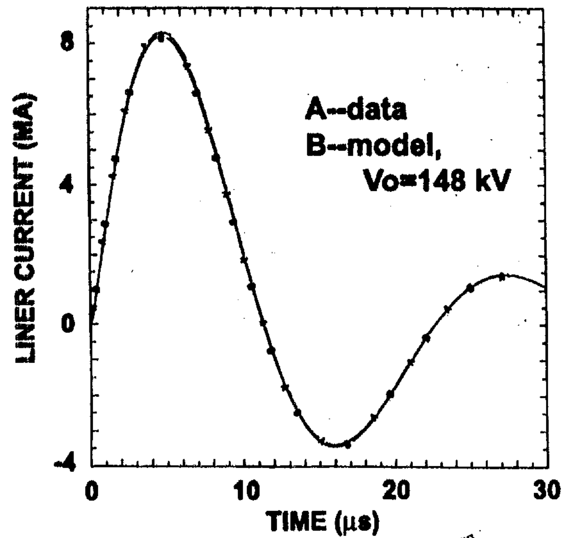


Figure 12 Current from one-third (one segment) discharges.

implosion, which imposes a time dependent load inductance on the circuit. Current profiles from three full-machine liner implosion experiments are shown in Figure 11 along with circuit model predictions of the current using the measured capacitor charge voltage, defined as the average of the (48) voltages measured on all MUs. Figure 12 shows the same comparison for a one segment, one-third machine, driven implosion experiment. For all implosion experiments shown, a constant 5 cm initial outer radius of the liner was maintained. However the liners were fabricated with different thicknesses to accommodate the needs of individual experiments. Specifically the LD-3 experiment used a much thicker liner (6 mm compared to 1-2 mm for other experiments) and some of the differences between measured and predicted currents (curves E,F) can be attributed to mechanical aspects of the thicker liner during the implosion. Figures 11 and 12 demonstrate the validity and high precision of the refined circuit model.

Atlas Parameter Space.

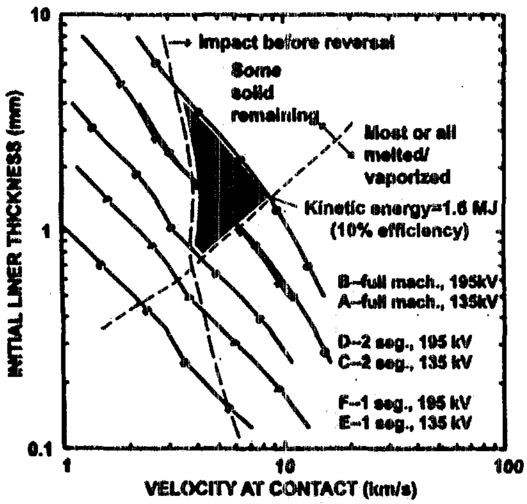


Figure 13 Parameter space accessible for 5 cm initial liner radii.

The circuit model can be directly applied to evaluate the range of liner parameters immediately available with the Atlas system. Pulse power hydrodynamic experiments are usually conducted in a configuration where a liner impacts an experimental "target", so the significant parameters describing the liner operation are liner initial radius, thickness and axial height and the radius at which the liner encounters the target. Figure 13 shows a map of parameter space for the set of initial conditions employed in the first (LD) series of implosion experiments: 5 cm outer radius and 4 cm initial height of the imploding liner. As the thickness of the liner is varied from 0.5 to 8 mm, the figure shows the range of final velocities available when the liner impacts a target at 1 cm radius as a function of liner thickness for three machine configurations and two different charge voltages. The lines on the figure show that by using the three machine configurations, and an appropriate choice of thicknesses, virtually continuous access to velocities from 1-10 km/sec can be achieved. However two other phenomena may further constrain the accessible parameter space. To invoke material strength to stabilize the growth of perturbation at the inherently magneto-Rayleigh-Taylor unstable outer surface of the liner, we require that at least some (>10%) of the liner thickness remain un-melted at the end of the implosion, and Figure 13 shows the part of the parameter space that satisfies those criteria. Additionally, experience suggests, but does not absolutely require, that the liner/target impact be completed during the first half cycle of current discharge – because of difficulties encountered when the magnetic pressure on the back of the liner goes through zero at the time of current reversal. This criteria imposes some further limits on the accessible parameter space.

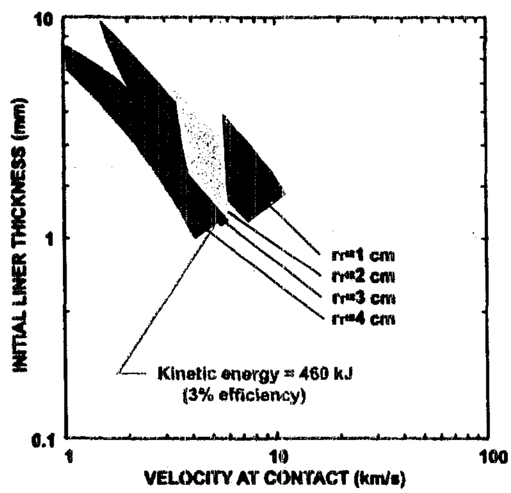


Figure 14 Impact velocities accessible for large target radii.

Interestingly, the high current capability of Atlas permits liners to be accelerated to very interesting velocities in short run distances, and this allows very large experimental targets to be driven by Atlas liners. Figure 14 shows the range of implosion velocities available for implosions impacting targets ranging from 1 to 4 cm in radius. While useful velocities can be achieved even with large targets, the efficiency of coupling stored energy to kinetic energy is reduced.

Figure 15 shows results of calculations of the parameter space accessible when the initial outer liner radius is decreased from 5 cm to 3 cm and the liner impacts a target at 2 cm radius. Again useful velocities are achieved and somewhat more energy is coupled to the liner for a 1 cm run distance as compared to the case of the 5 cm liner impacting a 4 cm target.

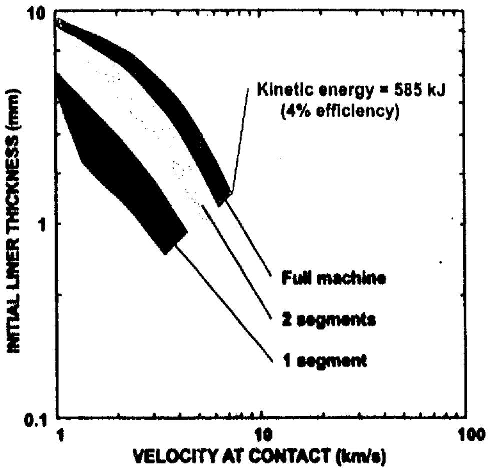


Figure 15. Impact velocities accessible for smaller initial liner radius: 3 cm.

On the other hand, Atlas is particularly well suited to driving the longer liners that may be useful in some pulse power hydrodynamics experiments. An especially interesting example is an experiment in which a magnetized plasma, such as a field reversed pinch configuration (FRC) is compressed by a relatively long liner to adiabatically heat the FRC plasma to fusion conditions, an embodiment of the approach known as Magnetized Target Fusion [1]. Another example is the compression of an axial magnetic field for high field generation. For a 30 cm long liner, similar application of the Atlas circuit model and the "zero dimensional" implosion, predict up to 50 % efficiency of stored energy conversion to liner kinetic energy.

Summary

The Atlas system has begun routine operation at Los Alamos. Without optimization, the routine experimental schedule allows one experiment every two weeks and reducing the cycle time to one week between experiments is straight forward. Initial, fixed inductance, pulse power tests coupled with the more sensitive liner implosion tests have resulted in a good characterization of the system using a fixed element circuit model. More complex circuit models including time varying resistances for switches and for the series and parallel resistors can be implemented, but appear to be unnecessary. Coupling the circuit model with a zero-dimensional, incompressible implosion model appears to also provide adequate kinematic description of elementary implosion characteristics. While it appears that operation beyond the first current zero may be possible in some circumstances, continuing analysis of liner stability issues may raise other constraints on achievable parameter spaces. It has also been suggested that fully vaporized and ionized (plasma) liners may be required to reach velocities above 12-15 km/second. Additional 1-D and 2-D modeling along with characterization experiments will be required to explore this range.

Initial pulse power hydrodynamics experiments on Atlas [2] will explore the constitutive properties of materials at extreme conditions of high strain and strain rate, material failure and interfacial dynamics at sliding surfaces. Perturbation growth in materials displaying strength and transition to turbulence are other topics of interest. More exploratory topics include exploring the properties of strongly-coupled plasmas, and the compression of magnetized plasmas and vacuum magnetic fields.

[1] Lindemuth, et al, Proceeding Megagauss VIII, Tallahassee, Florida, 1998

[2] Reinovsky, Proceedings Megagauss IX, Moscow-St Petersburgh, Russia 2002