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SYSTEM EXPECTATIONS FOR PIONEER I FOIL IMPLOSION EXPERIMENTS*

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INTRODUCTION

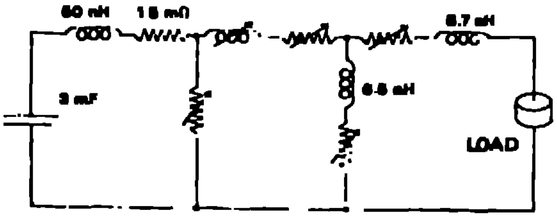
Prior to the beginning of the Pioneer I shot series of the Los Alamos National Laboratory TRAILMASTER project, numerous computational simulations were run to provide ball-park estimates for the electrical currents and voltages in the circuit, the timing of the implosion, the kinetic energy, temperature, and radiation output of the load. The purpose of these calculations was to provide guidance in setting the timings of the various switches within the circuit and to establish operating ranges for the various diagnostics.

In performing these calculations we have relied primarily on a fully implicit one-dimensional Lagrangian MHD code developed by Thomas Oliphant of the Thermonuclear Applications group at Los Alamos. This code provides us with a very sophisticated electrical circuit simulation capability as well as the ability to simulate the imploding plasma load as a zero dimensional slug and a one dimensional symmetric cylinder. To provide an estimate of the stability of the imploding plasma we have used a heuristic model of magnetically driven Rayleigh-Taylor instabilities in the zero dimensional slug simulations.

THE EQUIVALENT ELECTRICAL CIRCUIT

The equivalent electrical circuit used for the Pioneer I preshot calculations is shown in Fig. 1. The capacitance, resistance, and inductance that are shown on the first branch are all part of the capacitor bank at our Ancho Canyon firing facility and the cables that are required to connect the bank to the explosive driven plate generator. The time dependent resistor shown on vertical branch #1 represents a crowbar from the generator. In our calculation this resistor drops from a very high value to zero in 1 ns 40 μs after starting the discharge of the capacitor bank. At this time the seed current in the generator is 1.2 MA in good agreement with experiment.

The time dependent inductor in the second horizontal branch of the circuit is the 1 x 4 trapezoidal flux compression generator. To represent this, the code linearly interpolates between values in arrays of experimentally determined inductance and times. These values start at 300 nH and drop to 15 nH in 14 μs of flux compression. After 14 μs we assume that the inductance stays at 15 nH. Experiments indicate that the behavior of these generators is not very reproducible after 14 μs although some continue to produce out to 14.5 μs.



Equivalent circuit used for the Pioneer I pre-shot calculation.

FIGURE 1

The time varying resistor shown on the second horizontal branch represents the early time behavior of the plasma compression "donut" opening switch. These values also come from experimental data, in this case a rough average of several test shots.[1] The early and late behavior of the donut switch are separated in the calculation so that we can vary the time of onset of the late resistance rise to calculate how this time will affect the behavior of the total circuit. This opening is the opening of the switch caused by firing the high explosive to compress the plasma. This late rise is the time dependent resistor on the second vertical leg of the circuit. In the present calculations this resistance rise starts 14 μs after the start of the generator.

The 6.5 nH inductance on the second vertical branch is a calculated estimate of the inductance when the current is flowing from the generator through the opening switch. It is based on a formalism that was developed to predict values from an early Pioneer I mock-up. This same technique, together with detailed estimates from the engineering drawings of the vacuum diode, resulted in the 8.7 nH inductor on the third horizontal branch. The time dependent resistor on this branch is the closing switch that allows the load to see current. In the simulation presented here the switch is given 50 ns to close starting 14.175 μs into the generator run.

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The current predicted from the plate generator is shown in Fig. 2. The peak of 10.8 MA is probably somewhat higher than will occur in our experiments. However, experiments involving this generator and static loads have exceeded 9 MA. It should be noted that there is experimental evidence to suggest that this opening switch, when fired, places a voltage across the generator that can impact the generator performance. This is one reason that we have advocated firing the opening switch late in the generator run.

Figure 3 shows that this circuit should deliver nearly 3.5 MA to the foil load in less than 0.5 μs ($dI/dt = 7.0 \times 10^{12}$ A/s). The reason for firing the closing switch slightly after the opening switch is to allow the voltage to build up across the opening switch. This voltage markedly improves the time derivative of the current through the load when the closing switch closes.

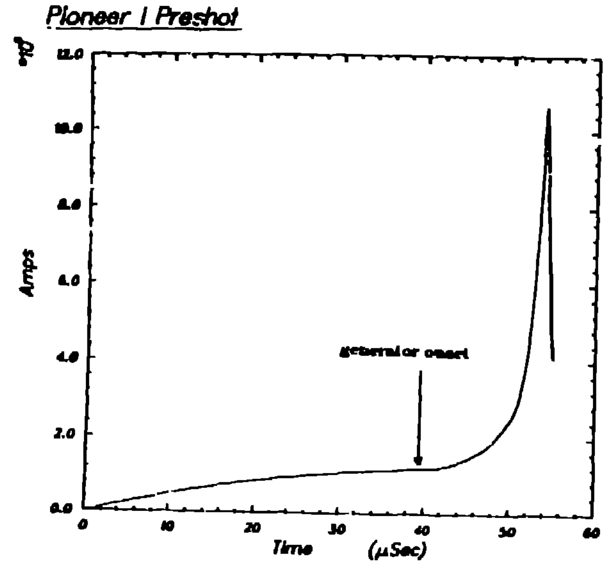
ZERO-DIMENSIONAL MODELING RESULTS

The zero-dimensional model treats the imploding plasma as a slug whose mass is equal to the total mass of the foil. This mass is accelerated by the force of the magnetic field caused by the current from the external circuit. We have found that this 0-D model gives velocities, and hence kinetic energies and inductances, that agree quite well with our 1-D model.

Figure 4 shows the kinetic energy of the imploding plasma calculated by this 0-D model. The calculation is terminated when the implosion reaches a 10:1 ratio (the radius reaches 0.3 cm). Similar modeling efforts at the Air Force Weapons Laboratory indicate that this 0-D simulation will probably predict too much kinetic energy, perhaps by as much as a factor of two. The principal reason for this discrepancy is the development of instabilities. To minimize these instabilities we have attempted to limit the time of implosion to less than 0.5 μs. This time dictated the choice of a 200 nm thick, 3 cm radius aluminum foil. We have used a heuristic model of magnetically driven Rayleigh-Taylor instabilities developed by Roderick and Hussey[5] to examine the effects of instability wavelength on the thermalization times for our plasma. These results are shown in Fig. 5. The lesson in this figure is to try to avoid 0.[illegible] cm wavelength perturbations in our load foil.

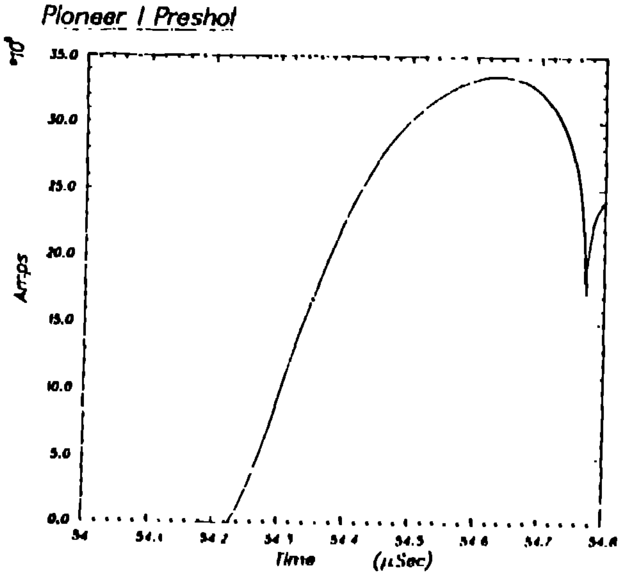
ONE DIMENSIONAL MODELING RESULTS

We have used our one dimensional simulations of the imploding plasma to get estimates of the plasma temperature, radiation output, and the extent to which the plasma is in thermodynamic equilibrium. The radiation transport package used in these calculations is a diffusion approximation.



Calculated current output from the 1 x 4 plate generator.

Figure 2



Calculated current delivered to the load in the Pioneer I experiments.

Figure 3

The zone set up and time rate of change of the zone boundary radii are shown in Fig. 6. The 10:1 implosion ratio is reached at 54.76 µs, 0.59 µs after the closing switch begins to close. Beyond this 10:1 point we don't trust 1-D simulations because we would expect instabilities to dominate.

Figure 7 shows the calculated temperatures. Rosseland mean opacity values indicate that the plasma is optically thin until the pinch occurs. Therefore, it is radiating energy nearly as fast as it is adding energy through Joule heating. This explains the relatively constant temperature until pinch.

PIONEER I-2

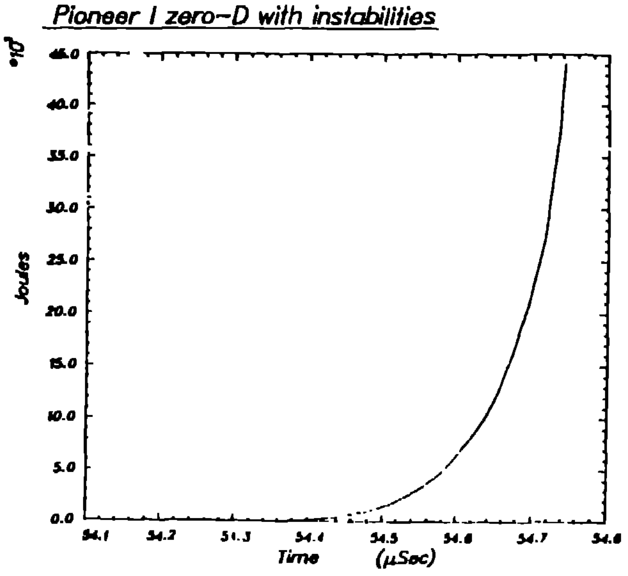
One-dimensional calculations have been made to compare with the results of the successful Pioneer I-2 experiment. These calculations used as input the measured current that reached the load in this experiment.[3] The calculated implosion is shown in Fig. 8. The timing of the implosion agrees with the observed time of the pinch and associated radiation pulse. Also interesting is the fact that the calculated maximum extension of the plasma during the expansion phase agrees quite closely in time with the early radiation peak seen by the x-ray detector that was set for the 3-12 eV plasma temperature range.

If it is assumed that there is no resistive component in the measured voltage across the load, then a time dependent inductance can be calculated by dividing the instantaneous measured current into the time integral of the measured voltage. From these inductance values we can determine an effective radius for the load

$$\left(\text{i.e. } L = \frac{\mu_0 \ell}{2\pi} \ln\left(\frac{R}{r_{eff}}\right) \right).$$

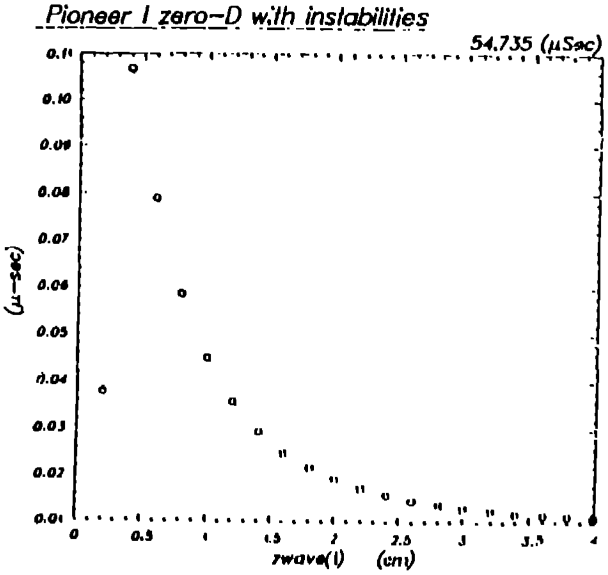
Values from these calculations are plotted as (x)'s on Fig. 8.

From our 1-D simulation we find peak implosion velocity of 12.5 cm/µs. This velocity translates to 17 kJ of kinetic energy if all of the foil mass participated in the implosion.



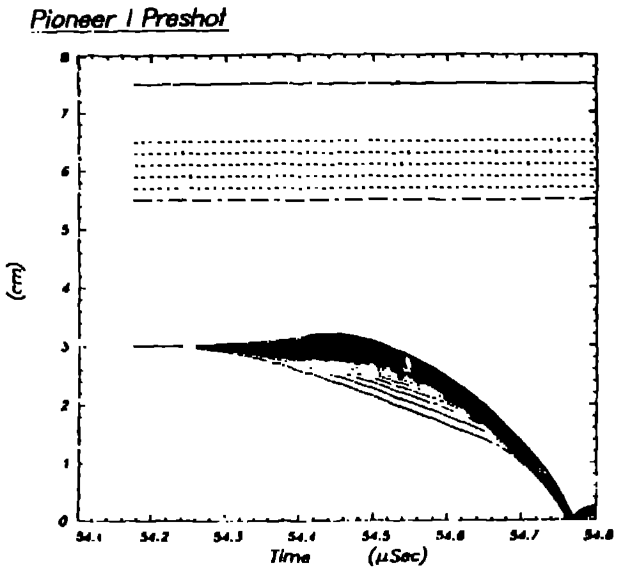
Kinetic energy of the imploding plasma calculated with a 0-D slug model.

Figure 4



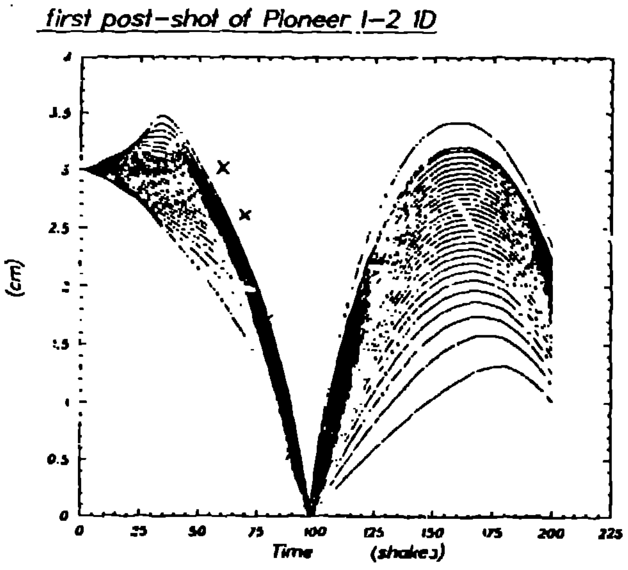
Thermalization time as a function of wavelength of R-Z perturbation calculated with a heuristic model of magnetically driven Rayleigh-Taylor instabilities.

Figure 5



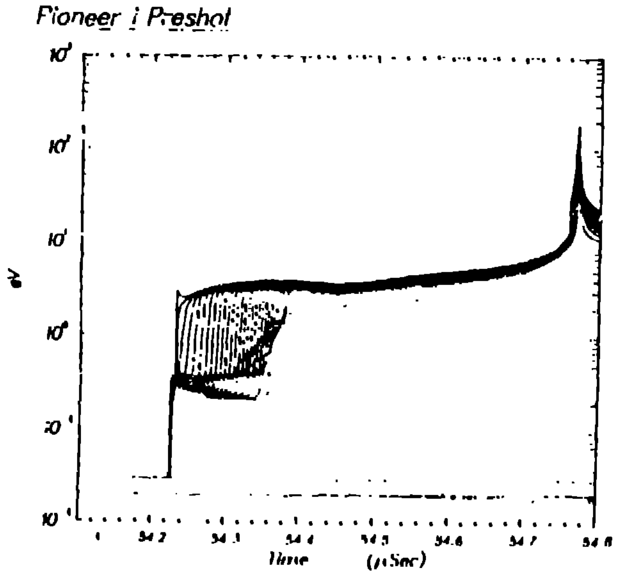
Calculated implosion of the plasma load using a 1-D MHD model.

Figure 6



Calculated implosion of the plasma load using the 1-D MHD model and the measured current from the Pioneer I-2 experiment. The (x)'s indicate the effective radius of the load determined from its inductance.

Figure 8



Temperature of the plasma load calculated by the 1-D MHD model.

Figure 7

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