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I. INTRODUCTION

Massive, cylindrical liners imploding at velocities of 10 to 50 km/s are useful scientific tools with many applications. For example, such liners can compress a hot, clean, pre-magnetized plasma to reach thermonuclear ignition, MAGO/MTF. Magnetically driven imploding liners can also be used to explore the physics of plasmas compressed to near solid density, as impactors (drivers) for shock physics experiments and for experiments exploring the equation of state of material at very high pressures. For imploding a magnetized target plasma, the liner must be 6–10-cm long and moving with a velocity of 10–20 km/s when it arrives at a radius of 6 cm. For shock wave physics and EOS experiments the target can be substantially smaller, about 1-cm radius, but liner velocities above 20 km/s are required to reach the most interesting conditions.

Driving imploding liners to velocities above 10 km/sec and to energies above 20 MJ/cm of length using magnetic drive requires high current, high energy electrical sources in the >100 MJ class. Realistic, if approximate, assessments of the stability of the liner to Raleigh Taylor instability suggest that the total liner run distance should not exceed 25-50 cm, and much shorter runs may be required. These conditions imply implosion times not exceeding 25-35 μs and since current rise times substantially exceeding the implosion time offer even more opportunity for the birth and growth of disruptive instabilities the rise time should likewise be not greater than about 50 μs. While capacitor banks in the 100 MJ class with appropriate rise time are conceivable, explosive pulse power systems patterned after those already demonstrated by researchers at VNIIEF offer virtually immediate access to the required driver parameter space. Combining VNIIEF generator technology[1] with VNIIEF and US theoretical and computational techniques, diagnostics and experience with liner systems has led to the conceptual design of an experiment in which an aluminum liner of approximately 1 kg mass is imploded from an initial radius of 24 cm to a final radius of 6 cm. At 6 cm radius, the velocity of the liner is >15 km/sec. The pulse power system for the experiment is a 100 cm diameter disk explosive magnetic generator of VNIIEF design delivering 100-200MA.

II. PHENOMENOLOGICAL MODELING OF DEMG OPERATION

A phenomenological model of DEMG operation has been described and comparisons of the model results with experimental performance reported[2,3] The model uses a series of one-dimensional calculations of the axial motion of the generator wall to approximately describe the two-dimensional compression of flux in the DEMG cavity. Motion of the wall driven by high explosive is calculated by a Gurney model[4] where the explosive performance is described by a detonation velocity and a detonation energy density. Wall motion is opposed by magnetic pressure produced by the time dependent currents flowing in the walls of the generator cavity. Flux loss axially into the wall is calculated using magnetic diffusion into the finite conductivity of the copper wall. The current flowing in the wall heats the wall non-uniformly in the axial direction, and the diffusion calculation tracks flux penetration into a wall of varying conductivity, permitting an approximate evaluation of the non-linear diffusion losses. Cavity motion and wall losses are expressed as time dependent generator inductance and resistance, and a self-consistent circuit calculation couples generator behavior with that of a dynamic (imploding liner) load.

Applying the phenomenological model to a set of cavity parameters characteristic of a 100 cm diameter DEMG produces the inductance and resistance functions of time shown in Figure 1.

III. INITIAL SYSTEM CONCEPT

Initial flux for the DEMG is provided by a helical flux compressor operating for about 200 μs to load the DEMG to an initial current of about 10 MA. Since this modest but long time-scale, early current flows through the liner as well, it could adversely affect the liner. Conceptually, a shunt fuse opening switch of only modest performance can be used to protect the liner from the early current in a manner similar to that used in Reference 3 – but without the added complexity of a series closing switch. Behavior of such a system is calculated in Figure 2. where we see that such a fuse suppresses the early current in the liner. However, the impedance of the liner path downstream of the fuse is low and even a modest increase in fuse resistance, for example to only 0.1 mΩ, can divert 10-20 MA downstream to the liner in 20-30 μs. Since subsequent calculations showed no adverse effects upon the liner from the early current, design calculations were conducted without the benefit, or complexity, of a shunt fuse.

IV. SLUG MODEL IMPLOSION LOAD PERFORMANCE

To calculate the general behavior of the DEMG/liner system, the time varying circuit elements ($L_{(t)}$ and $R_{(t)}$) from Fig 1 were combined with a point mass model of the liner implosion and other fixed circuit elements representing, for example, the 2.5 nH inductance of the transmission line connecting the liner to the generator in a circuit model. Simple approximations for the capacitor bank and a helical flux compressor are added to include the effects of the early, long time-scale currents on the imploding load.

The circuit model, shown in Figure 3, was used to self consistently calculate the interaction of liner and generator resulting in a description of system performance in terms of liner velocity and energy.

Parametric calculations were conducted using a circuit-survey code (CONFUSE)[5] to explore a range of system parameters including liner length, mass, and initial radius. A simplified version of the inductance and resistance profiles from the phenomenological model was used in the CONFUSE computations. In this simplified version the resistance profile is independent of the current, but nevertheless, gives performance very similar to that described in Section II

The parameter survey is conducted around a design point in which the initial radius of the liner is 25 cm, the length is 8 cm, the thickness is 3 mm, and the initial generator current of 10 MA. Figures 4a and 4b show the effects, in velocity/kinetic energy space, of varying various liner parameters when the liner arrives at 6 cm radius. Figure 4a shows the effect of varying liner length, thickness and initial current in the DEMG. Figure 4b shows the effect of varying liner initial radius. In general, we see that the velocity range of 10–20 mm/μs is readily achievable and kinetic energies around 100 MJ can be expected for judicious choice of parameters.

V. HYDRODYNAMIC PERFORMANCE OF A HIGH ENERGY

The CONFUSE survey provides insight into the general behavior of DEMG/liner systems in response to parameter variations. But because it treats the liner implosion as a point mass, CONFUSE does not, provide detailed information about the condition of the liner material. To assess, the condition of a liner that is thick, compressible, of near solid density and several magnetic diffusion depths in thickness, we turn to an elementary, one-dimensional MHD code, CRUNCH[6]. The code uses a simple one-dimensional, Lagrangian formulation. It uses the SESAME equation-of-state library, and a prescribed current history to drive the MHD calculation. While inclusion of a self-consistent circuit model is planned for the future, a specified current waveform consisting of experimental helical flux compressor data and a self-consistent circuit calculation (CONFUSE) using the inductance/resistance information from phenomenological DEMG code is used for calculations presented here. The driving current waveform from the beginning of the operation of the helical preamplifier through the time of the collision of the liner with a shock wave physics target at a radius of 1 cm. is shown in Figure 5. For reference, the initial current in the DEMG is taken to be 10 MA at about 175μs and the peak current is 183 MA occurring at 233μs or about 58 μs from the start of the DEMG operation.

The liner is aluminum with an initial radius of 240 mm and thickness of 4mm. While not significant in the CRUNCH calculation driven with a specified current waveform, the planned initial height of the liner is 80 mm and the total liner mass is1.02 kg.

Figure 6 shows a plot of the inner and outer radius of the liner as a function of time from 140 μs until the time of collision. While Crunch currently does not treat strength of the liner material, simple estimates suggest that the initial strength of the 4-mm-thick liner at 24-cm radius is overcome by the magnetic pressure when the current is 2–3 MA (compared with 10-MA current from the helical preamplifier). The inertial 1-D MHD calculation shows that the first appreciable motion (ΔR = 1 mm, or about 25% of the liner thickness) occurs at about 178 μs, and reference to Fig. 5 shows that the current in the liner is just 10 MA at this time. At 204 μs the liner has moved 4mm (one liner thickness) and the current is about 26 MA. At the time of peak current, 233 μs, the liner has moved about 72 mm or 30% of its initial radius. . For a long (8-cm) liner, even minimal motion at early time contributes significant inductance to the circuit, and this in turn is responsible for limiting the peak current delivered by the DEMG. For example, starting at 24-cm radius, the first 5 mm (2%) of liner motion, increases the inductance in the circuit downstream of the generator by 0.33 nH or almost 16% of the initial downstream inductance! Figure 6 shows that the inner surface of the liner crosses 6-cm radius at about 240.8 μs. At this time, the current has dropped to about 115.7 MA and at about 243.1 μs, the liner crosses the 1-cm radius and impacts a sample shockwave target. At this time the current has dropped to about 98 MA.

Figure 7 shows the velocity of the inner and outer surface of the liner plotted as a function of radius. At radius of 6 cm, the inner surface velocity is about 16 km/s and the outer surface velocity is about 13 km/s. As the imploding liner compresses to the 1-cm radius, the inner surface velocity climbs to about 35 km/s, while the outer surface velocity actually falls to just over 10 km/s. The deceleration of the outer surface is a consequence of both the decreasing magnetic force as the current drops and the inertial force resulting from the transfer of kinetic energy to the inner parts of the liner material as they accelerate. The total liner kinetic energy at 6 cm is about 145 MJ and at 1 cm about 186 MJ.

Simple analytic estimates[6] based on uniform current density can establish the velocity of a (planar) magnetically accelerated plate of thickness Δ as a function of action, Q.

$$V_{max} = (\mu\, Q/2\rho)\, \Delta$$

Because values of Q can be associated with melt and vaporization of a specific material, it is possible to make a quick estimate of the velocity of the 4-mm liner when the material is beginning to melt (23.2 km/s) and when it has completely melted (29.5 km/s).. To further complicate the picture, it is clear that the melting temperature in aluminum is a function of pressure. For reference, Fig.8 shows the shape of the melt curve of aluminum for pressures of 1 to 150 Gpa.[8] These simple analytic estimates seem to place relatively severe limitations on liner velocity, suggesting that the liner is fully melted before it could be compressed to 1 cm inner radius. If true, this would place significant limitations upon the performance of a magnetically driven system for either compression of a plasma or for production of shocks in a target. On the other hand, an implosion situation is neither one in which the current is uniformly distributed over the entire cross-section of the liner during the period of acceleration, nor is the liner even of constant thickness during the acceleration (Fig.6), and the simple estimates may be too limiting.

Figures 9 and 10 describe the condition of the liner at about 6-cm radius (for compressing a magnetized plasma) and later when the inner surface is about to impact a target cylinder of radius 1 mm. Figure 9 shows the density, velocity, pressure, temperature and conductivity of the liner as a function of radius at a time of 240.8 μs from the beginning of the operation of the helical preamplifier. The liner is about 14-mm thick. The maximum density is moderately over normal (3.3 g/cm^3) but the outer part of the liner has clearly vaporized and expanded to densities of about 0.5 g/cm^3. The inner surface of the liner is moving at 19 km/s while the outer surface is imploding at about 17 km/s. The pressure in the liner peaks at about 29 GPa. The temperature of the liner varies significantly through its thickness and the melting temperature (933 K) and vaporization temperature (2740 K) for aluminum at ambient pressure are indicated on the plot.. The plot suggests that, at this time, the temperature of a layer about 8-mm thick on the inner surface of the liner is below ambient melt—and most of that solid material is barely above room temperature. Another 3-mm-thick layer in the middle of the liner is between ambient melt and ambient vaporization temperature and the last 4-mm-thick layer is vaporized. The peak temperature on the outside zone of the liner is about 3 eV (not shown). Fig 8 shows that at 29 GPa, the melting temperature of aluminum would increase to about 2200 K. The temperature profile shows a feature at radius of 7.1 cm (at about 2200 K). This plateau represents the inner part of the melted layer and suggests that even more of the inner part of the liner is actually solid. The figure also shows the conductivity of the liner as a function of radius. The room temperature conductivity (corresponding to a resistivity of about 2.8 μΩ-cm) is marked for reference. The 29 GPa pressures in the liner depress the conductivity, even when the liner is well below melt temperature. The conductivity decreases relatively smoothly through the unheated inner layer, then more rapidly through the heated, solid material and then displays a plateau around 7 cm where the temperature curve suggests the liner melts.

Figure 10 presents the same kind of information for the liner after it has traveled to an inner radius of 1 cm at a time of 243.1 μs.. The peak density is almost 5 g/cm^3 and the inner surface velocity is about 26 km/s, while the outer surface velocity has dropped to 17 km/s. The figure also shows the temperature and pressure at this time with the ambient melting and boiling temperatures are indicated. The peak pressure is about 150 GP The inner 13 mm of the liner is at a temperature below 800 K. However, at pressures of 150 GPa the melting temperature of aluminum has risen to almost 5000 K. Though not seen in the figure, the temperature profile contains a modest plateau around 5000 K, not unlike that seen in Fig 9. While the temperature of the outer layer is about 6 eV the calculations suggest that the inner 18 mm of the liner may be in the solid state.

VI. VELOCITY AND SPECIFIC ACTION

The preceding section has shown that the material at the inner surface of an imploding liner may remain solid even when the surface velocity is more than 2 km/s. A fundamental question in liner applications is identifying the highest velocity that can be obtained while at least the inner surface remains solid, or liquid, etc. Although, this a rather complicated question, it can be speculated that the condition of the liner is related, at least approximately, to the specific action $Q=\int I^2 dt / A_o^2$, where A_o is the initial cross-sectional area of the liner.

Fig. 11 summarizes a series of CONFUSE computations for two different initial radii. Each curve shows the action and velocity as the liner thickness is changed. Standard parameters for the computations are the same as in section IV (10 MA initial DEMG current, 8-cm long) except that the transmission inductance is 2 nH. The values of velocity and action are the values when the liner has reached a radius of 6 cm. At 50-cm initial radius, significantly higher velocities can be obtained, albeit at much higher action values. However, if an action value below melt is considered, e.g., 5 x 10^{16} A^{2}s/m^4, the larger initial radius results in a measurably higher velocity even at the same action. Furthermore, since the mass of the liner is higher in the 50-cm case, the energy of the liner is much higher, 186 MJ, compared to only 40 MJ in the 25-cm case.

VII. SUMMARY

We have summarized some of the motivation behind high energy liner experiments. We have identified the 100-cm-diameter DEMG as a promising candidate for powering such experiments and described a phenomenological modeling approach used to understand the limits of DEMG operation. We have explored the liner implosion parameter space that can be addressed by such systems and have selected a design point from which to develop a conceptual experiment. We have applied the phenomenological model to the point design parameters and used 1D MHD tools to assess the behavior of the liner for parameters at the design point. We have not to optimized the choice of pulse power or liner parameters.

We conclude that operating in the velocity range of 10–20 km/s, kinetic energies around 100 MJ are practical with currents approaching 200 MA in the liner. Higher velocities (up to almost 40 km/s) are achieved on the inner surface of a thick liner when the liner collapses to 1-cm radius. At 6-cm radius the non-optimized liners explored here are attractive drivers for experiments exploring the compression of magnetized plasmas and at 1 cm they are equally attractive drivers for shock wave experiments in the pressure range of 30–100 Mbar. An experiment based on this design concept is scheduled to be conducted in VNIIEF in August 1996.

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FIGURE CAPTIONS

Fig 1 Disk inductance. (a) and Disk dL/dt + R_{wall} (b) from phenomenological model

Figure 2 Showing that a simple fuse without a series load isolating switch is only marginally successful in protecting the liner from early current.

Fig. 3 Circuit used to conduct parametric calculations. C, L_c and R_c refer to the capacitor bank providing initial flux to the system. L_H and R_H to the helical current amplifier, L_o and R_o to the DEMG , L_T to transmission line inductance and L_L to the liner.

Fig. 4 Results of Parametric Calculations.

Fig. 5 Current waveform used for Crunch Calculations. Waveform is composed of measured data from helical preamplifier experiments and self-consistent calculation of DEMG driving a liner..

Fig. 6. Liner (inner and outer) radius vs. time

Fig. 7 Liner velocity (inner and outervs. radius.

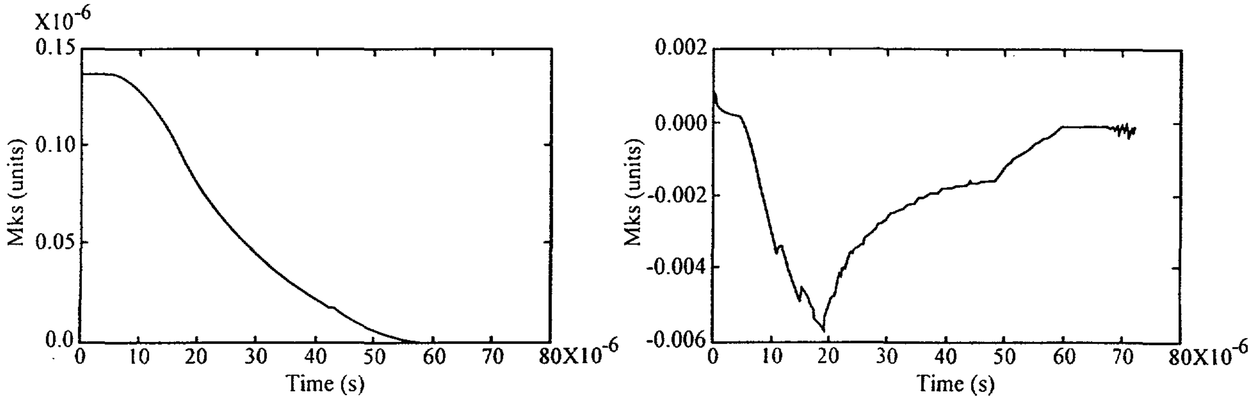
Fig. 8. (a) The phase diagram of aluminum at low pressure. (b) The theoretical melting curve of aluminum at high pressure. The points are low-pressure experiments and the cross is the predicted shock-Hugoniot melting point.

Fig. 9 Density, pressure, temperature, velocity and conductivity in the liner when the inner surface is at about 6 cm.

Fig. 10 Density, pressure, temperature, velocity and conductivity in the liner when the inner surface is about to impact a target at 1 cm radius.

Fig. 11 Specific action/velocity parameter space

Fig 1



(a)

(b)

Fig 2

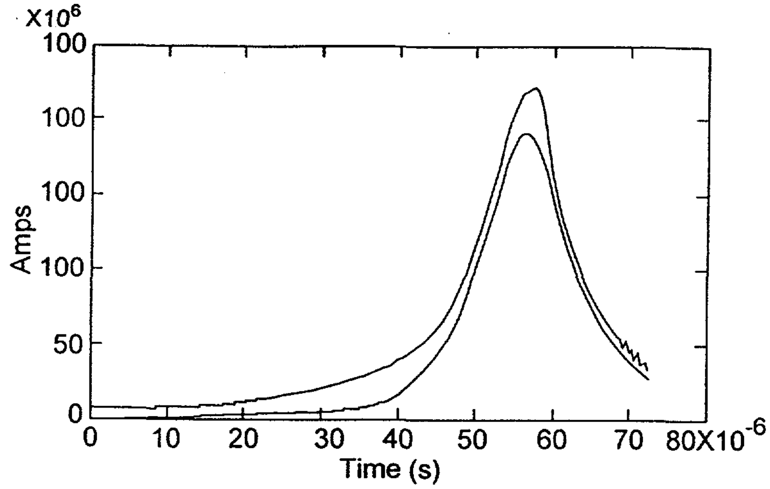


Fig 3

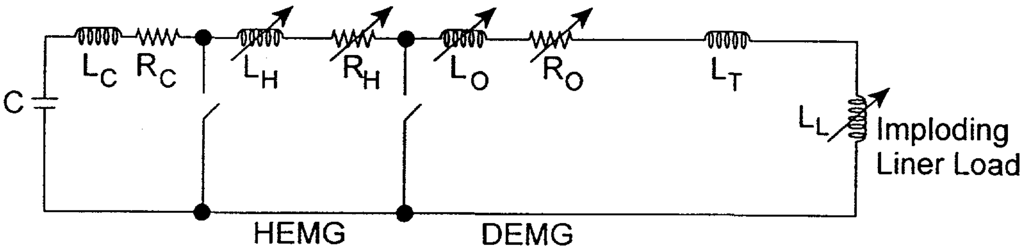


Fig 4

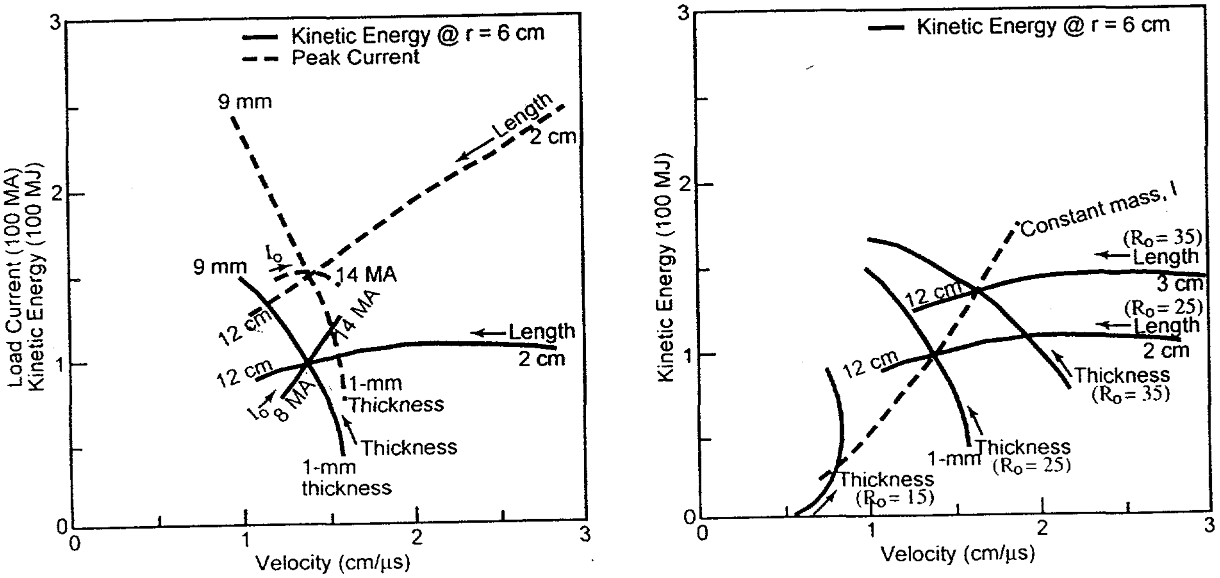


Fig 5

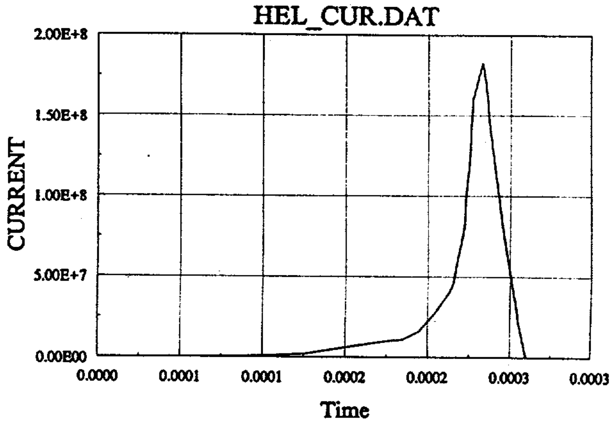


Fig 6

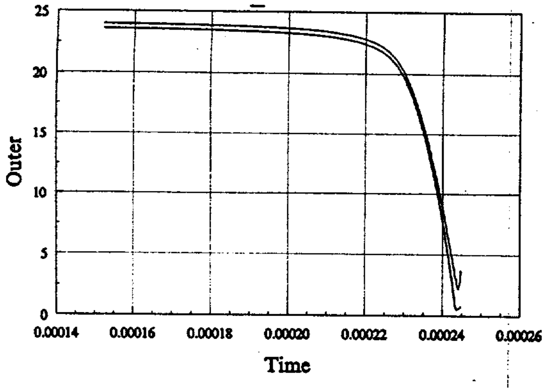


Fig 7

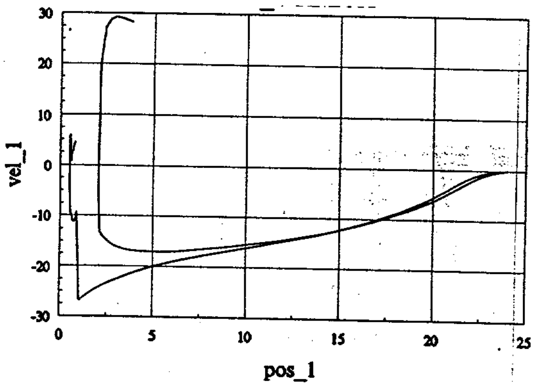


Fig 8

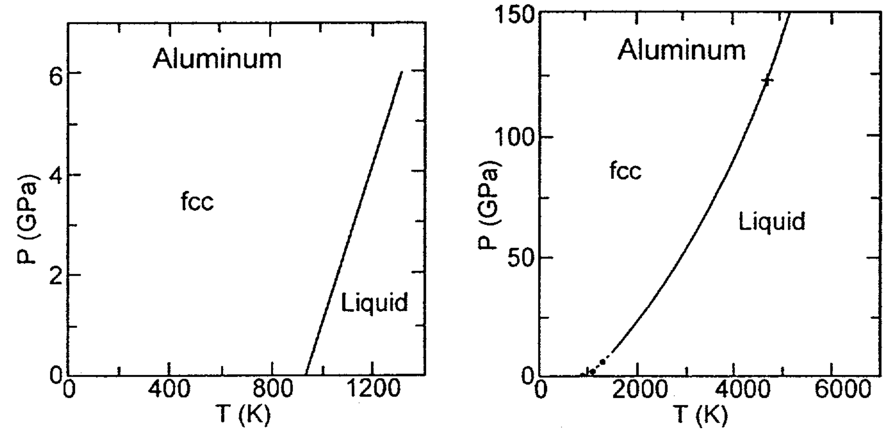


Fig 9

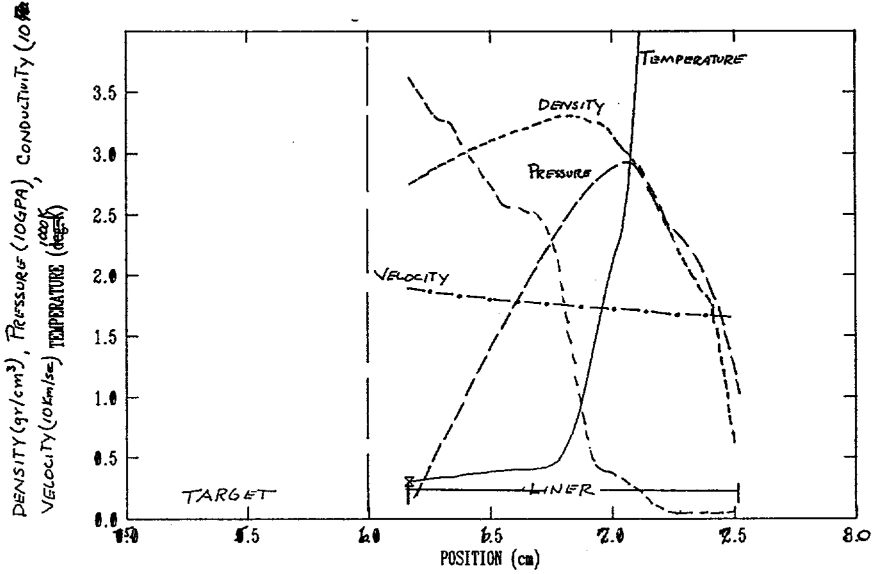


Fig 10

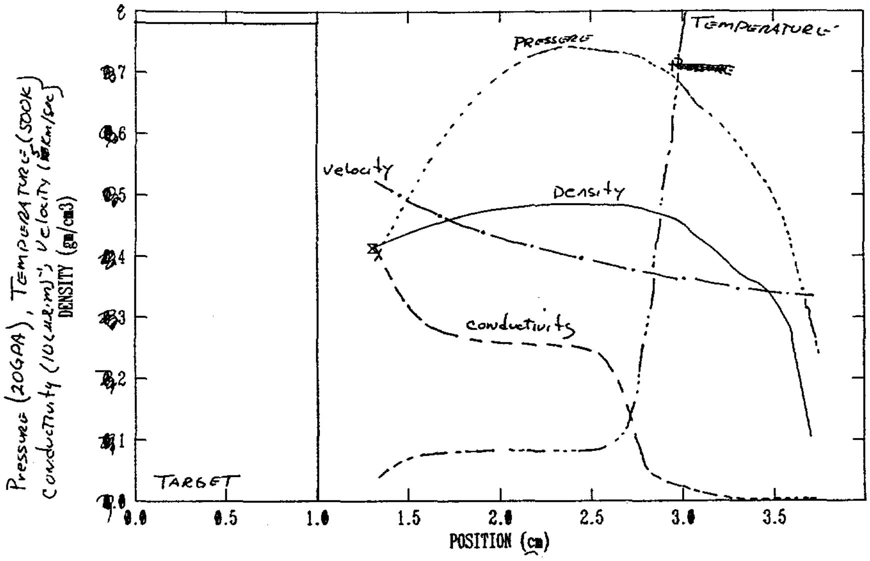
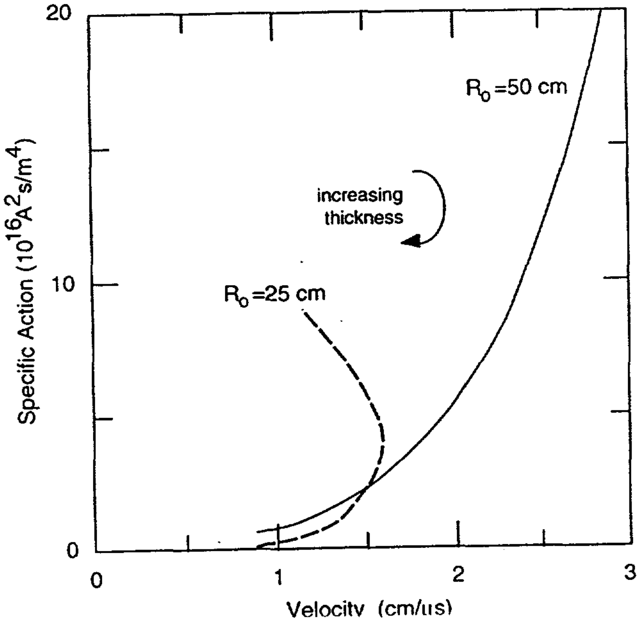

Pressure (20GPA), Temperature (500K)
Conductivity (10 ucu.m)^-1, Velocity (km/sec)
DENSITY (gm/cm3)
8
7
6
5
4
3
2
1
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
POSITION (cm)
TARGET
Temperature
Pressure
~~Pressure~~
Velocity
Density
conductivity

Fig 11


20
10
0
0
1
2
3
Specific Action ($10^{16}A^2s/m^4$)
Velocity (cm/μs)
R_o=50 cm
R_o=25 cm
increasing thickness