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TITLE: **STABILITY OF MAGNETICALLY IMPLODE LINERS FOR HIGH ENERGY DENSITY EXPERIMENTS**

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STABILITY OF MAGNETICALLY IMPLODE LINERS FOR HIGH ENERGY DENSITY EXPERIMENTS

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ABSTRACT

Magnetically imploded cylindrical metal shells (z-pinch liners) are attractive drivers for a wide variety of hydrodynamics and material properties experiments. The ultimate utility of liners depends on the acceleration of near-solid density shells to velocities exceeding 20 km/sec with good azimuthal symmetry and axial uniformity. Two pulse power systems (Ranchero and Atlas) currently operational or under development at Los Alamos provide electrical energy adequate to accelerate ~50 gr. liners to 1-2 MJ/cm kinetic energy.

As in all z-pinches, the outer surface of a magnetically imploded liner is unstable to magneto-Rayleigh-Taylor (RT) modes during acceleration. Large-scale distortion in the liners from RT modes growing from glide plane interactions or initial imperfections could make liners unusable for man experiments. On the other hand, material strength in the liner should, from first principles, reduce the growth rate of RT modes – and can render some combinations of wavelength and amplitude analytically stable. The growth of instabilities in both soft aluminum liners and in high strength aluminum alloy liners has been studied analytically, computationally and experimentally at liner kinetic energies up to 100 KJ/cm on the Pegasus capacitor bank using driving currents up to 12 MA.

Introduction:

Magnetically imploded cylindrical metal shells (z-pinch liners) are attractive drivers for a wide variety of hydrodynamics and material properties experiments. Perhaps the most challenging application of high velocity imploding liners is the delivery of strong shocks (up to 100 Mbar) to a central target and such applications require both high velocity (>20 km/sec) and large kinetic energies (1-50 MJ/cm). Furthermore they also require that the liner arrive at the central target at near solid density, retaining good azimuthal symmetry and axial uniformity. This is clearly a demanding set of criteria. Previously, [1] the authors have discussed some of the aspects of accelerating liners to appropriate conditions, concluding that while overall dynamics are tractable, and appropriate power systems have been demonstrated, it is the behavior of the liner under extreme acceleration that may ultimately limit their usefulness. During the compression of such a cylindrical liner, a variety of dynamic processes can result in distortion of the liner. The inner free surface of the liner can wrinkle as a result of the compressive motion – a phenomenon sometimes described as the Bell-Plesset effect[2]. Interactions between the liner and the electrodes (glide-planes) which deliver current from the driver to the liner can initiate perturbations that propagate into the all important central region of the liner at (or above) the sound speed in the liner material. And, perhaps most significantly, the outer surface of the liner (the interface between the liner and the driving magnetic field) is magneto-hydrodynamically unstable in the same way that an interface between fluids of differing density is subject to unstable growth of a small perturbation when the light fluid is accelerated into (or supports) the heavy fluid -- the classic Rayleigh-Taylor(RT) case.

Material Strength in Solid Liners:

While the growth of the MHD RT instability in a plasma shell or column has been explored extensively, and is relatively well understood, the detailed behavior of a solid or near-solid liner is relatively unexplored. The behavior of an imploding solid liner is complicated because, unlike plasma columns, the solid liner initially retains material strength. Analytically it is known that material strength, like surface tension, reduces the growth rate of perturbations. For sufficiently short wavelength perturbations the growth rate is zero for a given acceleration and this results in a "stable" implosion. The material parameters of yield strength (Y_o) and sheer modulus (G) are indicative of the effects of material strength and it is convenient to compare both with the magnetic drive pressure. For cases where the drive pressure exceeds both yield strength and sheer modulus for most of the duration of the event, material strength effects are likely to be insignificant. For practical cases, as for example the case of a high purity aluminum liner approximately 1 mm thick imploded with 5-30 MA currents, the drive pressure is larger than Y_o and smaller than G for most of the period of a 10 μs implosion.

The situation is further complicated in two respects. First, ohmic heating resulting from the multi megampere drive current (up to 100 MA in reference 1) raises the temperature of the liner, modifying its material strength. In the extreme, ohmic-heating can melt the liner resulting in virtually complete loss of material strength and returning the situation to the more familiar fluid case. Second, in a cylindrical liner, the drive current flows initially on the outer (unstable) surface of the liner and magnetically diffuses toward the inner surface, resulting in non-uniform heating through the thickness of the liner. Non-uniform heating results in non-uniform variations in strength through the thickness of the liner. In general the strongly accelerated, magnetically imploded solid density liner presents a complicated situation.

Conceptually, we can approach the investigation of the stability of a magnetically imploded liner in several cases. In the first case the driving conditions are limited so that the driving current does not significantly heat the liner. The liner does not melt during its implosion and retains much of its ambient strength for all times of interest. In the second case, the drive is increased to the point where the outer surface of the liner melts relatively early in the implosion process. With melting, the liner conductivity decreases significantly, allowing the current to move rapidly into the bulk of the liner. Thus, for much of the time of interest the liner consists of an unmelted, inner layer, which retains material strength, and a melted, strengthless, outer layer. Furthermore, the proportion of solid to liquid liner is constantly changing. An extreme of the second case is where the driving current density is sufficiently high that the entire thickness of the liner melts at some point during the implosion. After melting, the classic fluid instability analysis provides a good description of the liner's behavior. The third case is intermediate between the first two. In the third case, the melting of the outer layer is delayed so that a significant fraction thickness of the liner is unmelted and displaying material strength during much of the implosion duration. However, the effect of strength is steadily decreasing as more of the liner heats and the entire liner melts before the end of the event

Experimental Observations:

To compare the three cases a series of experiments were conducted using a high purity aluminum liner, whose axial height was 20 mm and whose inner radius was 24-25 mm. The liner was imploded with currents ranging from 4 to 12 MA delivered by a 860 μF laboratory capacitor bank with a short circuit quarter period of about 8 μs. In each case, multi-view radiographs taken transverse to the cylindrical axis are the primary diagnostic. For some experiments, exterior, transverse visible light imaging, and magnetic and contact probe measurements inside the liner augmented the radiographs. On a few experiments VISAR measurements of inner surface velocity were taken.

For the first case, the liner initial wall thickness is 0.4 mm and the peak drive current is 4.2 MA. The implosion time was about 16 μs for the inner surface to converge to the axis. Figure 1 a series of radiographs taken from two consecutive experiments showing the liner imploding smoothly with little evidence of unstable perturbation growth on the outer surface. The inner surface of the liner reaches 3-4 km/sec and one-dimensional MHD calculations show the liner to be largely unmelted through the entire course of the implosion.

For the second case, the liner wall thickness was increased to 1.15 mm and the peak drive current increased to 12 MA. The implosion takes just over 8 μs . Figure 2 shows a sequence of radiographs timed to look at the last microsecond of the implosion. One-dimensional MHD calculations show that the outer surface of the liner melts at about 4 μs. By the time the last radiograph was taken (at 7.7 μs) the outer 45% of the liner material had melted. Because of convergence effects, this 45% of the line material would form a 1-D layer about 1.3 mm thick. The radiographs show, strikingly, that after the outer surface melts, small wavelength perturbations with 0.5 -1.0 mm wavelength appear and grow to amplitude of 1-2 mm. The perturbations appear to be limited to the outer (melted) part of the liner and do not appear to distort the solid inner part.

For the third case, a 0.4-mm liner was imploded with an intermediate value of drive current, 6.4 MA. The implosion time was just over 10 μs. The peak acceleration was about 10^9 m/s/s and the peak drive pressure was just over 10 GPa. 1-D MHD calculations show that the outer surface of the liner melts at just under 7.0 μs and the inner surface melts just after 7.5 μs. The overall character of the liner is intermediate between the behavior shown in Fig 1 and Fig2

The parameters for this case are chosen such that the liner remains unmelted for much of the implosion and then melts throughout its thickness in a relatively short time. This case presents perhaps the most challenging set of parameters to simulate. Experiments were conducted in which a set of small amplitude perturbations was machined into the outer surface of the liner and the growth of those perturbations was monitored radiographically. For the radiographs shown in Figure 3, the initial perturbation was 50 μ in peak to peak amplitude with wavelengths of 0.75 mm and 2.0 mm. The radiographs show the perturbation during the linear growth phase (when the perturbation retains its sinusoidal shape), the non-liner spike-and-bubble phase and when the perturbation has grown to such amplitude that the magnetic field is breaking through and completely disrupting the liner. The growth of the perturbation was simulated with a 2-D Eulerian MHD code using analytic fits to material strength properties [3]. The results are shown in Figure 4

Several analytic treatments of perturbation growth have been published. Recently Rayevski[4] has offered an analytic formulation that predicts a threshold acceleration for instability growth for particular choices of initial amplitude and wavelength. Since the acceleration of the interface changes as a function of time, a time dependent amplitude threshold can be calculated for each initial perturbation wavelength. In Figure 5 we have plotted (1) the time dependent amplitude of the (growing) perturbation from a 2-D MHD calculation (2) the amplitude measured from radiographs at two times and (3) the time (acceleration) dependent amplitude threshold for perturbation growth for each of the two wavelengths present. The figure shows that the radiographically measured perturbation amplitude is in very good agreement with the calculation. Furthermore when the amplitude in the calculation (and presumably in the experiment as well) is below the threshold, as is the case for several microseconds after the beginning of the current pulse the perturbation does not grow. As the critical amplitude threshold drops below the initially imposed value,(because the acceleration is increasing), the perturbation begins to grow. The figure also shows the time of outer surface melt and inner surface melt. When the entire liner is melted the perturbation appears to grow at the rate predicted by fluid models.

Liner Fabrication Criteria

The existence of a critical amplitude/wavelength threshold provides a useful specification on the criteria to which a liner must be fabricated to provide a stable implosion at a given acceleration. We recognize several kinds of departures from perfectly cylindrical liners that must be addressed in the fabrication process. The liner has a practical surface finish. The short wavelength, small amplitude variations resulting from tooling on the inner and outer surfaces can be reduced to a fraction of a micro-inch ($<0.02\ \mu$) through costly, high precision processes using single crystal diamond tooling, but, if acceptable, conventional processes are much more economical. The liner also has a larger amplitude, long wavelength variation in overall wall thickness. This "waviness" is governed more by machine tolerances than by tooling processes. In figure 6, we plot the threshold perturbation parameters in amplitude/wavelength space for one material (high conductivity aluminum) for several (fixed) values of acceleration typical of the current experiments (Pegasus) and of the future higher acceleration experiments (Atlas). The figure clearly shows that increasing the acceleration reduces the permitted area of perturbation space where stable operation can be expected. More significantly, the plots show that for accelerations considered, the short wavelength, small amplitude perturbations characteristic of surface finish is likely not to be a limiting criteria – as long as the outer surface retains material strength. On the other hand, the long wavelength "waviness" may lead to significant perturbation growth and material strength characteristic of 1100 aluminum will not be adequate to stabilize this effect.

Figure 7 shows the radiographic results of an experiment conducted to directly compare two surface finishes – one made by very high quality diamond tooling, and one using conventional technique representing almost the extreme of poor quality (~1μ rms.). Imploded with almost 8 MA driving currents, the outer surface of the liner is calculated to melt at about 7 μs. The first radiograph – about two microseconds later shows little evidence of growth of the small wavelength perturbations for either the fine or course surface finish. This result is consistent with the predictions on Figure 6. After melting, the short wavelengths begin to grow with a rate characteristic of fluid instabilities ultimately becoming discernable at 9.6 μs and by 10.8μs the substantially larger initial amplitude of the course surface has manifested itself in substantially larger perturbations late in the implosion.

Conclusion:

The behavior of solid density liner may be significantly affected by material strength when the liner material is unmelted. Simulations are capable to tracking that unstable growth through a broad range of linear and non linear amplitudes and compare favorably with analytic formulations for perturbation growth.

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[1] "Development of Imploding Liners with Kinetic Energies Above 100 MJ and Their Applications", R. Reinovsky, C Ekdahl, *Proceeding Megagauss VII*, Sarov, Russian Republic, VNIIEF (1998)

[2] "On the Stability of Fluid Flows with Spherical Symmetry", M.S. Plesset, J Applied Phys., 25, 96-98 (1954).

[3] "A Constitutive Model for Metals Applicable at High Strain Rate", D.J. Steinberg, S.G. Cochran, M.W. Guinan, *J. Appl Phys* 51, (1980).

[4] "Hydrodynamic Instability in Strong Media", V. Rayevsky et al, VNIIEF, 1997, published by Univ of California UCRL-CR-126710.

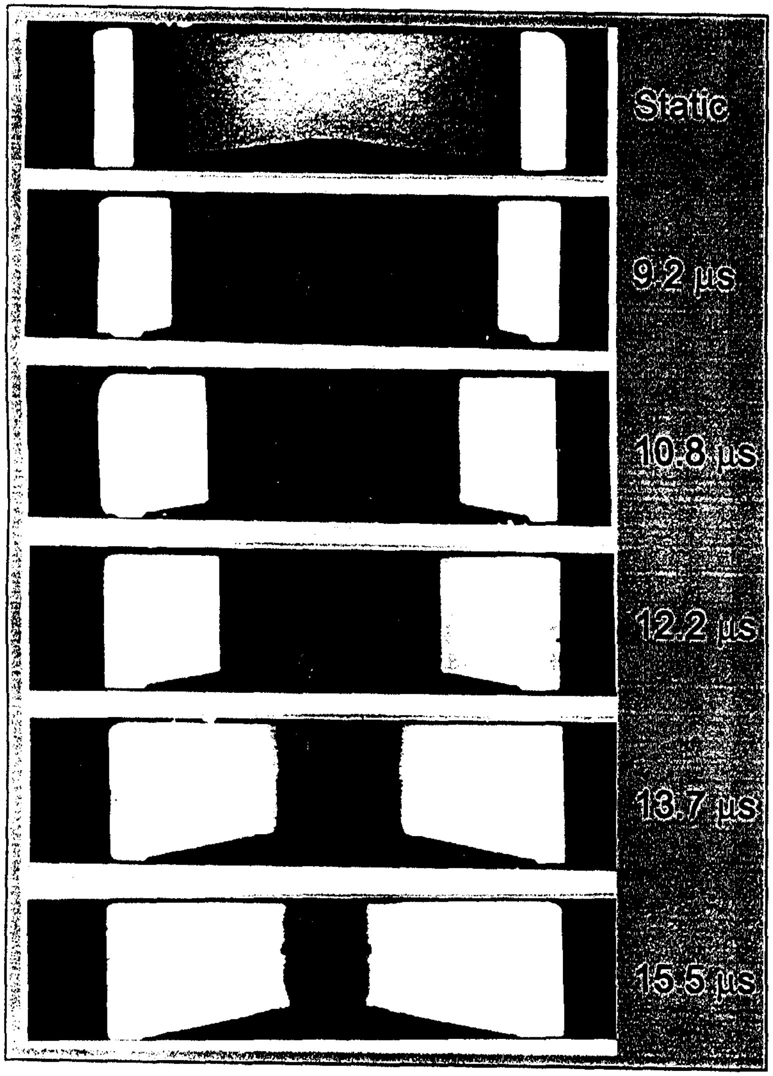

Static
9.2 µs
10.8 µs
12.2 µs
13.7 µs
15.5 µs

Fig 1

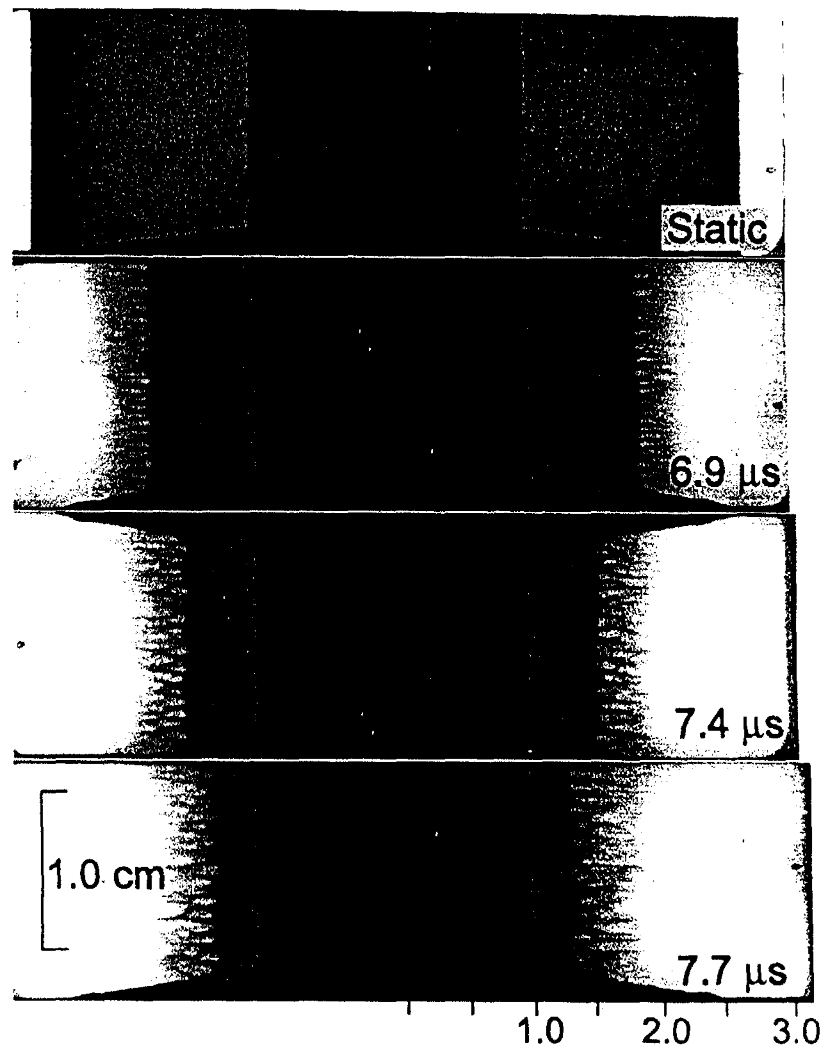

Static
6.9 µs
7.4 µs
1.0 cm
7.7 µs
1.0
2.0
3.0

Fig 2

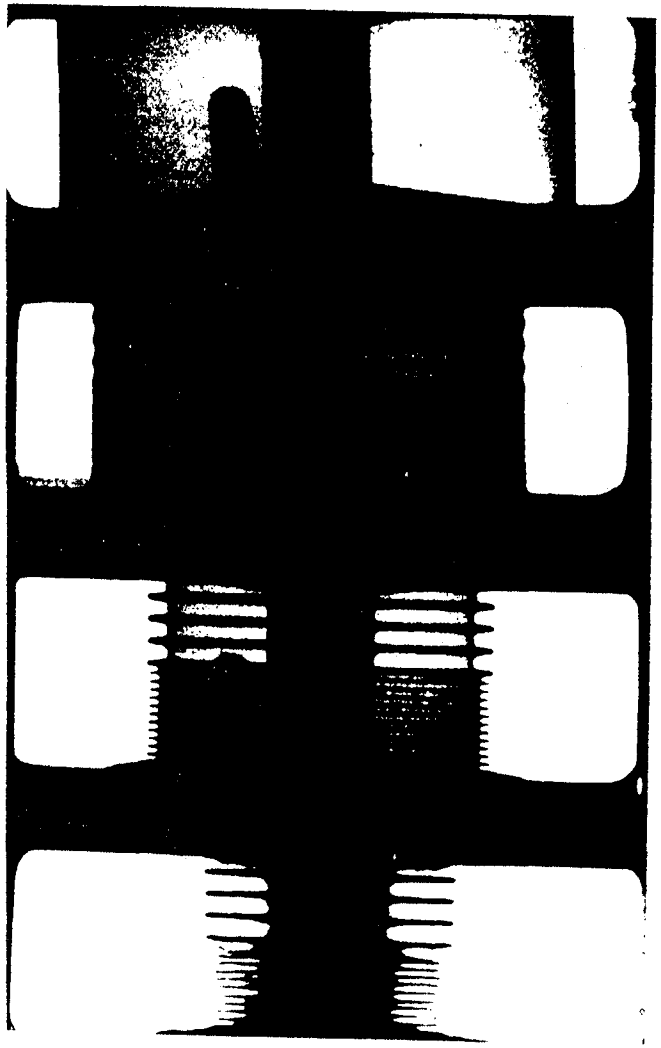
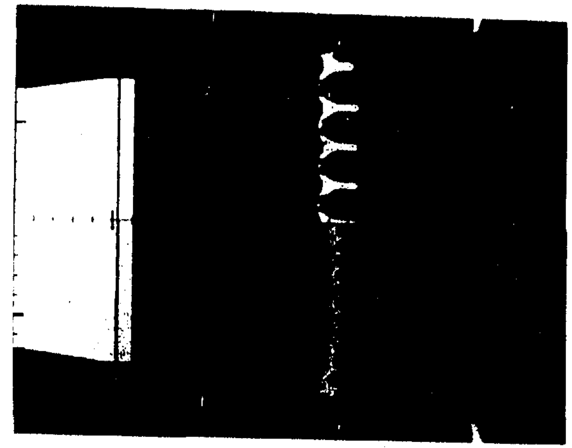
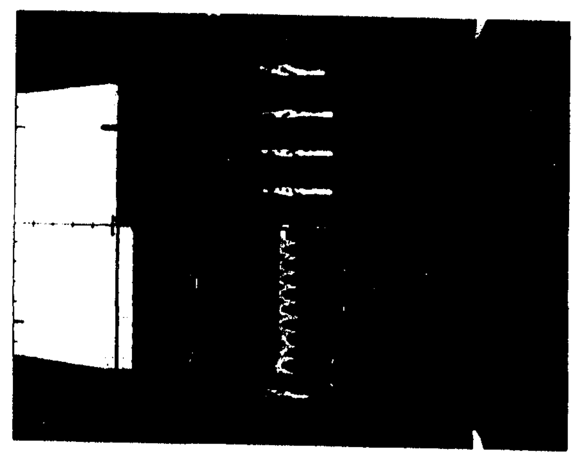


Fig 3

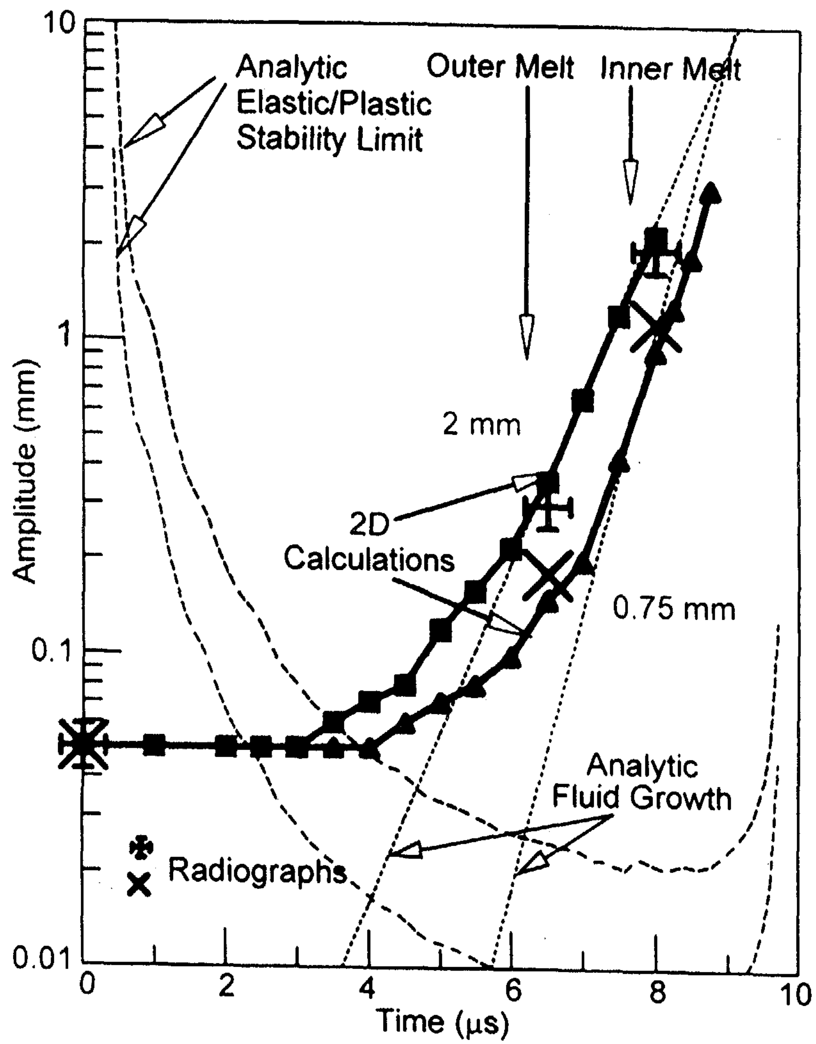


Time = 8.0 μs



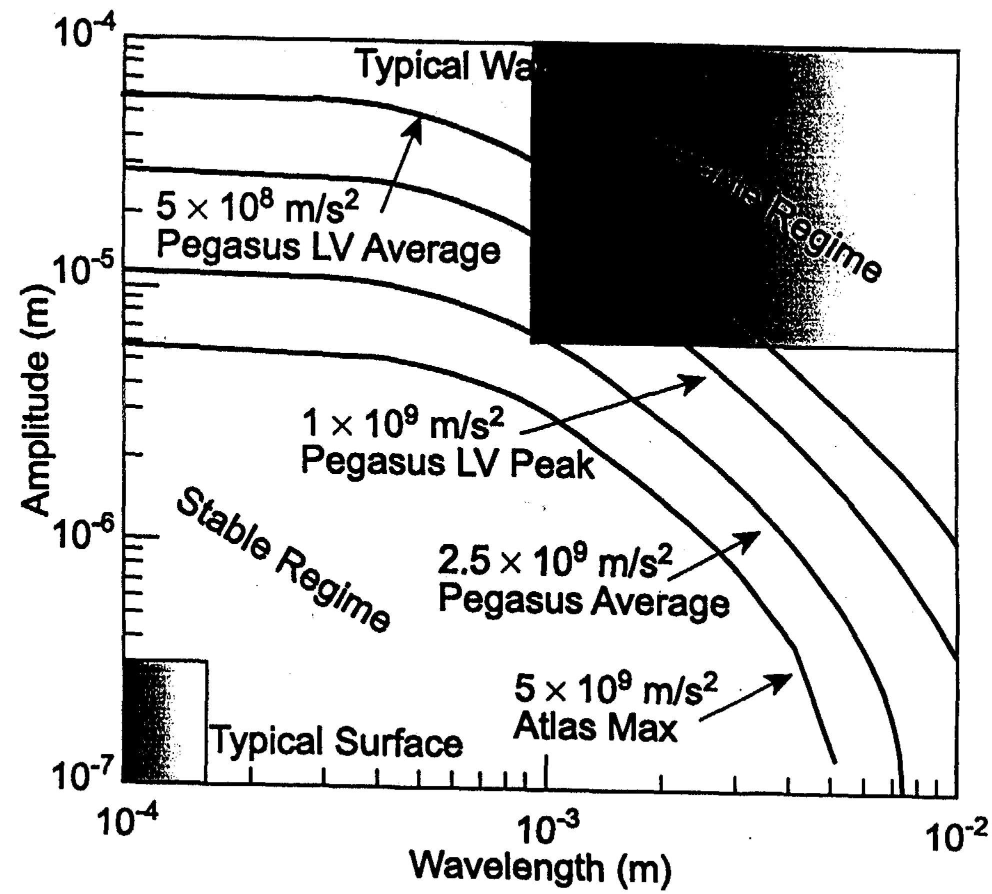
Time = 8.6 μs

Fig 4



Analytic
Elastic/Plastic
Stability Limit
Outer Melt
Inner Melt
2 mm
2D
Calculations
0.75 mm
Analytic
Fluid Growth
Radiographs
Amplitude (mm)
Time (μs)
10
1
0.1
0.01
0
2
4
6
8
10

Fig 5



Typical Wa
Regime
5 × 10⁸ m/s²
Pegasus LV Average
1 × 10⁹ m/s²
Pegasus LV Peak
Stable Regime
2.5 × 10⁹ m/s²
Pegasus Average
5 × 10⁹ m/s²
Atlas Max
Typical Surface
Amplitude (m)
Wavelength (m)
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻³
10⁻²

Fig 6

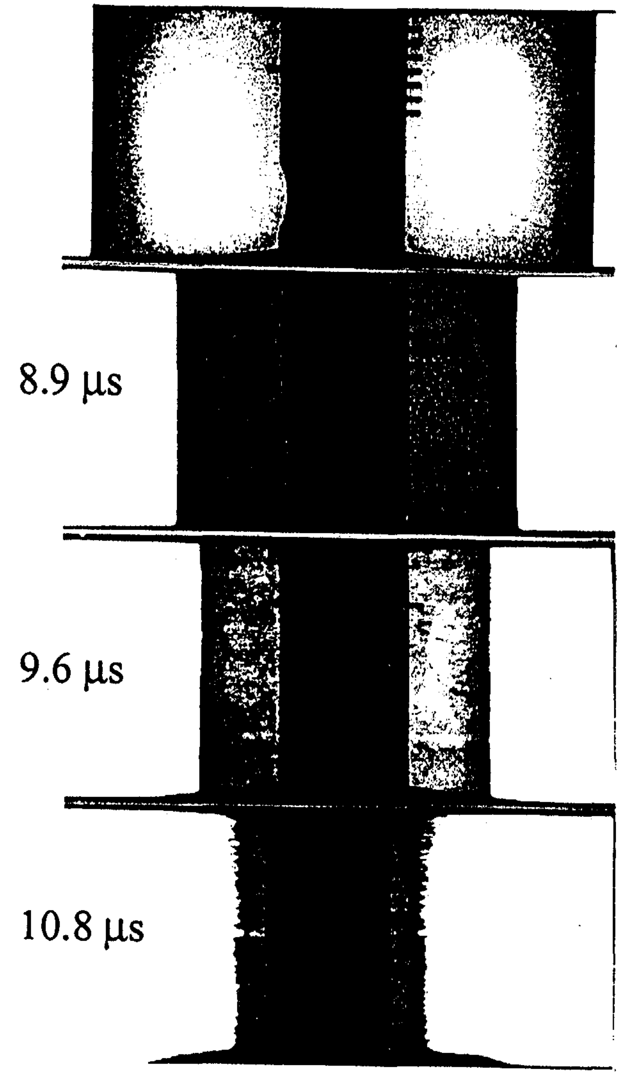


Fig 7