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EVOLUTION OF SOME LOS ALAMOS FLUX COMPRESSION PROGRAMS

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Introduction

When we were approached to give a general discussion of some aspects of the Los Alamos flux compression program, we decided to present historical backgrounds of a few topics that have some relevance to programs that are very much in the forefront of activities going on today. Of some thirty abstracts collected at Los Alamos for this conference, ten of them dealt with electromagnetic acceleration of materials, notably the compression of heavy liners, and five dealt with plasma compression. Both of these topics have been under investigation, off and on, from the time a formal flux compression program was organized at Los Alamos. We decided that a short overview of work done in these areas would be of some interest. Some of the work described below has been discussed in Laboratory reports that, while referenced and available, are not readily accessible. For completeness, some previously published, accessible work is also discussed but much more briefly.

Perhaps the most striking thing about the early work in these two areas is how primitive much of it was when compared to the far more sophisticated, related activities of today. Another feature of these programs, actually for most programs, is their cyclic nature. Their relevance and/or funding seems to come and go. At certain times they are worked on intensely, but then they sink to a low level of activity or none at all as different, more pertinent, programs arise that require the funding. Eventually, many of the older programs come back into favor. Activities involving the dense plasma focus (DPF), about which some discussions will be given later, furnish a classic example of this kind, coming into and then out of periods of heightened interest.

We devote the next two sections of this paper to a review of our work in magnetic acceleration of solids and of plasma compression. A final section gives a survey of our work in which thin foils are imploded to produce intense quantities of soft x-rays. The authors are well aware of much excellent work done elsewhere in all of these topics, but partly because of space limitations, have confined this discussion to work done at Los Alamos.

2. Magnetic Acceleration

Interest in this subject really started in our efforts to understand better the cause of a number of lost shots. These lost shots came about because of premature firing or breakdown of the capacitor bank switches. Most of the assemblies used in those days, and many today, were designed to hold together mainly during the initial flux loading, after which time the explosive would dominate the dynamics of the system. However, these systems usually did not survive destruction from magnetic forces during the complete ringdown of the capacitor bank, as generally occurred when the switches fired prematurely. In our efforts to understand this premature destruction of assemblies, various calculations were made of the motion of components under magnetic forces. Some experiments were done, in part, to confirm the calculations. These are described in the following subsection, 2.1, "Plate Acceleration." In section 2.2, "Pipe Closure," some results are given of our efforts to close relatively thick-walled pipes magnetically. Finally, in subsection 2.3, "Railguns," some of our work in magnetic launching of materials is summarized.

2.1. Plate Acceleration

In two sets of experiments, thin dural plates were magnetically accelerated as noted in Ref. 1. The experimental arrangement is shown in Fig 1. Projectile plate motion was observed by a framing camera. The plate was backlit by an electronic flash. A transparent plastic plate, with calibrated grid marks, was placed between the flash and projectile plate, allowing observation of the plate position as a function of time.

(i) Source inductance dominated experiments. Several microhenrys were put into the circuit, partly to limit the current. Since base-projectile plate inductances were much smaller than this, the circuit analysis was made using constant inductance. Since projectile plate heating was small, the circuit resistance was also taken as constant. These experiments are described in Ref. 2*, where it will be noted that a different method was used to maintain contact with the projectile plate as it moved.

Dural plates, 26-cm long, were accelerated, with widths, w, of 25 and 50 mm; and thicknesses, τ, of 0.8 and 0.24 mm. The heavy brass base plates were made the same widths as the projectile plates.

Figure 2 shows experimental results for one of the shots together with two calculated curves. As noted, the terminal velocity of ~ 0.21 mm/µs was reached in about 350 µs after the plate had traveled about 50 mm, which happens to about coincide with the plate width. With the wider plates, terminal velocities occurred in travel distances much smaller than the plate widths.

For the upper calculated curve, the magnetic drive field was taken as uniform and equal to µI/w – the value that would be obtained with uniform current density and no edge effects. The second calculated curve partially allowed for edge effects. The terminal velocities for these calculated curves, as taken from the plots of Fig 2, were 0.32 and 0.24 mm/µs, respectively, as compared to the experimental value of 0.21 mm/µs.

A terminal velocity was derived under the assumptions used for the upper curve:

$$v_T = \frac{\mu_o}{2\,\rho w^2 \tau R}\,(1/2\,\mathrm{CV}_o^2) \qquad (1)$$

Here, ρ is the density of the projectile plate and μ is the free space permeability. V_o is the initial voltage of the capacitor bank of capacitance, C. It is interesting to note that the terminal velocity varies with the initial bank energy and not with the square root. The terminal velocities obtained were in qualitative agreement with Eq. (1) (to within less than a factor of 2). As might be expected, the agreement was closer when approximate terminal velocities were reached when the projectile plates had moved less than their widths; thus indicating less influence of end effects.

(ii) Base-projectile plate inductance significant. A second set of experiments is described in Ref. 3. Here, a capacitor bank of considerably greater energy was used. Further, it was tightly coupled to the plate acceleration assembly. In this case, since the circuit inductance of Fig. 1 varies, there is no simple solution for the current as there was in case (i). The projectile plate motion and circuit equations are linked in a non-linear way. However, a solution can be obtained for the terminal velocity if the base-projectile plate edge effects are ignored and the circuit resistance, R, is constant.

$$v_T = -\frac{2\,\mathrm{Rw}}{\mu L} + \sqrt{\frac{2E_o}{M} + \left(\frac{2Rw}{\mu L}\right)^2}\;\mathrm{v} \qquad (2)$$

Here, M is the mass of the projectile plate of length, L, and E_o is the initial bank energy. As before, R is the constant circuit resistance.

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*Several references given in this paper bear designations such as GMX-6-385 or Office Memorandum. These refer to internal reports. Copies of these reports are available upon request, but they have not been reproduced in significant quantities.

The experiments performed and described in Ref. 3 used Eq. (2) as a guide. The bank energy and dural plate dimensions were set so that Eq. (3) gave terminal velocities of about 1.0, 3.0, and 8 mm/µs. In the first experiment, the plate went as expected, reaching a velocity of about 1 mm/µs. In the second experiment, a velocity of nearly 3 mm/µs was obtained, but the plate vaporized shortly thereafter. The third experiment produced only a high-speed cloud of vapor before any significant motion could be observed. The experiments were subsequently explained when heating of the projectile plate was taken into account. (III) Projectile plate heating. An analysis of the heating effects on projectile plate acceleration was published later when it appeared that magnetically accelerated plates might be useful in some simulated shock effects.(4) The analysis that includes plate heating effects is most easily carried out with use of two thermodynamic functions defined below, where the specific heat, C(T), and electrical resistivity, r(T), depend upon the temperature.

$$G(T) = \int^{T} \frac{C(T)}{r(T)} dT \qquad (3)$$

$$H(T) = \int^{T} C(T)\, dT \qquad (4)$$

With the assumptions of uniform plate current density, no edge effects, and constant plate dimensions there is a one-to-one correspondence of plate velocity and temperature.

$$v(T) = \frac{\mu\tau}{2} [G(T) - G(T_0)] \qquad (5)$$

Values of functions G(T) and H(T), known as a form of the "action" and heat integral respectively, are plotted for aluminum and copper in Ref. 4. It is found from the aluminum curve, with samples 0.25-mm thick, that the temperature reached by the plate at a velocity of 1 mm/µs is only a few hundred degrees, but (with some mental extrapolation of the curves) that the temperature would exceed the melting temperature at a velocity of 3 mm/µs, and would most likely vaporize at 8 mm/µs.

An expression for the terminal velocity is also given in Ref. 4. If E_0 is the initial capacitor bank energy divided by the projectile plate mass then the terminal velocity v_T is included in Eq (6).

$$E_0 = 1/2\, v_T^2 + \frac{R_0 W \tau}{L} [G(T) - G(T_0)] + H(T) - H(T_0) \qquad (6)$$

The right-hand terms are the plate kinetic energy, the joule energy dissipated in the external resistance, and the joule energy dissipated in the plate, per unit plate mass.

The explanation of why the plate motion is not greatly affected by heating can be obtained from Eq (6) and plots of the functions G(T) and H(T). As it turns out, for typical circuit resistances of a few milliohms, the plate thermal energy required to melt or vaporize the plate is generally smaller (less than half) than the sum of the plate kinetic energy and the thermal energy lost to the external resistance. Thus, the plate velocity may be nearly that calculated without allowance for plate heating, even though the plate may be vaporized.

2.2 Pipe Closure

Fairly large diameter pipes with relatively thick walls can be closed explosively. This is effected by wrapping a layer of high explosive circumferentially around the pipe, and then detonating the explosive simultaneously at several point around the circumference. Some years ago, we were asked if it would be possible to close such pipes magnetically. The pipes suggested were rather large – 90-100-cm diameter with walls 10-15-mm thick.

The closure mechanism would have to be a theta pinch, since there was no way to pass current through a portion of the pipe itself. Consequently, a header system was constructed as shown in Fig. 3. As noted, the current could be crowbarred by firing the detonators near peak current. The detonators would break down the insulation separating the plates shortly after firing. Small "jet" holes were drilled through the top plate under the detonators. These small plates were easily replaced after a shot.

Figure 4 shows the type of closure obtained with aluminum pipes, 76-mm diameter and 1.6-mm wall thickness. About 200 kJ of a 600 kJ bank were used in the tests. The two cylinders on the left, marked UC, were tested without crowbarring the current. For the third test, the current was crowbarred. This procedure evidently transferred too much energy to the pipe since there was a partial "bounce back" of the material after closure. This phenomenon has also been observed in explosive pipe closure when too much explosive is used.

A preliminary series of tests was made using a smaller bank and pipes with dimensions about half of those shown here. From those results and those shown here, it was roughly estimated that energies in the 10 MJ range would be required to close the large pipes suggested, an easily accessible value for flux compression generators (FCG) powered by a relatively small capacitor bank.

2.3 Railguns

Work was started on railguns at Los Alamos in 1979 and continued for several years with FCG's as power sources. Under a separate program, work continued for a few more years with capacitor bank power sources. This report will be confined to a short discussion of the FCG powered guns.

Two types of generators were used: strip generators and helical generators. Details of the strip generator are given in Ref. 6, while the helical generator is described in Ref. 7. Those experiments employing the strip generator were done jointly with people from Lawrence Livermore National Laboratory. Projectile masses were typically about 3 g except for one shot in which a large (165 g) lexan projectile was accelerated. The results of these tests are summarized by Hawks et al.[8,9] Flash x-ray photographs are shown in Ref. 8 for several lexan projectiles in free flight in air, usually 10-25 cm beyond the gun muzzles. At lower velocities, the projectiles remained intact. At a velocity of 5.4 km/s, an originally cubic projectile had assumed a very symmetric "mushroom" shape. It is probable that it fractured sometime later. All projectiles accelerated to higher velocities, after free flight in air, were fractured into two or more pieces.

Table 2 of Ref. 8 gives a summary of data taken for a number of shots. Very incomplete data were obtained for the last five shots listed, and the velocities listed, for the most part, were calculated from the current records. In view of the difficulties met by several investigators in achieving such velocities, it is unlikely that they are correct. One exception could be the last shot under column 5D. Here, the railgun was about 5-m long and the projectile consisted of a thin tantalum disk mounted in a cylindrical lexan sabot. A flash x-radiograph showed that the tantalum disk had moved a total of 8.7 m in a time set at 1130 μs. A page is devoted to a discussion of this shot in Ref. 10, where it was suggested that a velocity of ~10 km/s matched the limited data available. However, since the shot was never repeated, we cannot consider this a firm result.

A helical generator was used to power railguns in which very large projectiles were launched. The generator output went to an inductive store in series with the railgun. The inductive store was crowbarred at the end of the generator run to prevent loss of flux through the remains of the generator circuit. The first two projectiles were lexan, 0.6 and 0.7 kg, respectively, and were driven with a plasma armature, while the last shot used a projectile, mainly aluminum, 1.05 kg, which was in direct contact with the rails. Results of the tests are discussed in Ref. 7 together with some conclusions reached. Only in the second shot, did the projectile remain intact, but its launch velocity was only three quarters of that predicted by our best code. No more than 10% of the energy supplied to the inductive store (4-5 MJ) ultimately appeared as kinetic energy in the projectiles. Work was started on this program when it appeared that we would be asked to launch projectiles of this size at a remote location, where no other energy sources were available. In view of the expense of these shots, the program was terminated when the need for remote firing went away.

3. Plasma Compression

Although a limited amount of work was done considerably earlier, the Los Alamos Flux Compression Program was formalized in 1957 with the primary aims of developing and using large magnetic fields to compress D-T plasmas. A short history of this development is given in the later 1965 paper, Ref. 1. In these earlier days, work at the DOE (then called the AEC or Atomic Energy Commission) laboratories was essentially born "classified" and remained so until properly reviewed. If warranted, the work was then declassified. Although these program concepts and progress were discussed freely with appropriate people, such as people at the various AEC laboratories, public disclosure was not authorized until 1959, to permit a talk on the production of implosion produced magnetic fields,[11] that was published a year later.[12] A brief description of the uses of the large implosion systems to compress DT plasma and various other applications was also published in 1960.[13]

In the following, we summarize briefly the results obtained with liner implosions, FCG driven systems with fixed load coils, and some highly speculative calculations based upon FCG powered plasma focus experiments.

3.1 Liner implosion.

Most of the Los Alamos liner implosion work was summarized by Thomson et al.[14] In spite of great theoretical promise, the liner implosion experiments done here were not particularly successful. Much of the difficulty was traced to the inability to create a suitable plasma to be imploded. In the first method tried, the plasma was to be produced by intersecting two high-speed, explosively produced deuterium jets. As noted in Ref. 1, these jets wee found to be contaminated with far too many impurities.

In most of the work reported by Thomson, et al., the initial plasma was produced *in situ* by means of a θ pinch. As was pointed out, however, when closed, resistive liners were used to contain the plasma and initial fields, the implosion fields obtained were quite high – multi-megagauss – but with the θ pinch it was impossible to get the initial plasma temperatures more than 10-15 eV – too low to produce neutrons in the subsequent implosion. With the more conventional slotted liners, suitable initial plasma temperatures (200-800 eV) were obtained, but the ultimate implosion fields obtained were greatly reduced owing to the need for a plasma confining envelop inside the liner – such as thin-walled Pyrex tubing. It was discovered later that loss of plasma out of the ends of the discharge tubes further limited the ultimate D-D neutron yields to less than 10^4 in the best shots. To offset the plasma end-loss, Caird et al.[15] developed an implosion system that retained a magnetic mirror from the initial field to a peak mirror field of 4 MG. The liner implosion program was terminated, however, before the mirror configuration was employed in a plasma compression shot.

As noted earlier, one of the stumbling blocks to successful liner implosions is that of creating the initial plasma. One of the recent exciting approaches involves creating an appropriate magnetized plasma, which, theoretically, has properties that make it very suitable for implosion. Aspects of this topic are considered in a number of papers given at this conference under the acronyms MAGO/MTF (magnetized target fusion). The status of the program most recently published is given by I. R. Lindemuth, V. K. Chernyshev, et al.[16]

3.2 FCG powered θ pinch

The last explosive powered θ pinch shots fired at Los Alamos were done in collaboration with Sandia National Laboratories' personnel. Two types of Sandia FCG's were used in the experiments, the Model 105 and the larger Model 169 helical generators.[17]

The θ pinches were operated in the first half-cycle mode, as were the liner shots discussed above. The requirements for this mode of operation are an initial, fully ionized plasma, a reversed or bias magnetic field, and a relatively fast rising main field pulse. As is well-known, most of these plasma devices also require a preliminary "warm-up" series of shots to properly precondition the plasma region before firing the main shot.

Thomson et al.[18] give details of the overall system. The initial plasma was created in a Pyrex or quartz discharge tube by means of a 40 kA linear discharge between two electrodes about 60 cm apart, that spanned the main high-field coil. A separate coil pair supplied the bias fields, typically, 0.1 to 0.2 T. Separate, small capacitor banks supplied the energy for both axial current discharge and bias fields. The high-field header system was designed so that a fairly large, fast capacitor bank could be used to precondition the discharge tube, followed by a rapid disconnect of the bank and then a quick connection of the FCG to the header.

The generator output pulses were suitably shaped by using a Sandia designed fuse assembly with a voltage breakdown package. The generator load consisted first of only the fuse package. The θ-pinch load was in parallel with the fuse package, but isolated from it with dielectric sheets pretested to break down and switch in the plasma load at a predetermined voltage. These features can be seen very clearly in sketches and photographs of Ref. 18.

Damerow et al.[19] present the final results of the series. They give a comparison of the performance of this system with that of other θ pinches then in operation. In spite of the small size and relative simplicity of these systems, D-D neutron yields obtained were comparable to those of all but the very largest pinches, and the neutron yields per unit length of plasma column were comparable to these of the large pinches.

While the results obtained were interesting, extending them to really interesting levels appeared to be very difficult and costly, so the program was not continued.

3.3 Z-Pinches

Two programs, the Birdseed and the Dense Plasma Focus Programs, very briefly described below, conclude this section. Z-pinches are featured in these programs as opposed to the θ-pinch lenses described above.

i) Birdseed. In this program, rocket launched FCG powered plasma guns injected neon plasma into the ionosphere. Three rockets were launched from the Barking Sands Facility on the island of Kauai, Hawaii, two in the summer of 1970 and one in 1971. In all shots several hundred kilojoules (up to 350 kJ) of plasma were injected into the ionosphere at an altitude of about 200 km. Efforts were made in separate shots to inject plasma as closely as possible, both parallel and perpendicular to the earth's magnetic field lines.

The basic systems, including two FCGs and a plasma gun were developed and fired many times at Los Alamos. The systems were packaged into Sandia National Laboratories rockets and launched by Sandia personnel. Details of the experiments may be obtained from Ref. 20.

(ii) Dense Plasma Focus. The dense plasma focus (DPF) is a simple, efficient device for producing very large neutron bursts from a relatively small plasma volume in very short times. With yields already obtained (10^{12} D-D neutrons) the short burst time and small emission volume made it attractive to develop it for an expendable flash neutron radiography source – to complement already existing x-radiography sources.

A small program was started to see if we could successfully power a dense plasma focus with an FCG and, if so, to increase the neutron yields above those previously obtained. Freeman, et al.[21] summarize the results obtained up to the time when the program was stopped pending further development of a suitable opening switch.

The plasma focus was conditioned by firing several shots using a small indoor capacitor bank. The entire assembly consisting of the DPF and its containment vessel, after loading it with deuterium to the precalculated pressure, was rapidly disconnected from the capacitor bank, transferred to the firing site and rapidly connected to the FCG system.

Plate generators were used to power the focus. Current was carried by a "ballast" load for most of the generator run time. The DPF was then switched into the system at the appropriate time. In a series of tests with increasing energy supplied by the FCGs, we obtained a maximum yield of about 3×10^{11} D-D neutrons at a DPF current of about 2.4 MA. Up to this level we saw no significant deviation from the semi-empirical law that yields scaled as the fourth or fifth power of the peak focus current.

As we increased the current level developed by the FCG, the DPF matching conditions required higher initial deuterium pressures. The higher pressures required higher initial $\dot{I}$ values to get good plasma lift-off. Increasing the initial $\dot{I}$ became increasingly difficult with the generator system in use. However, many calculations suggested that we could obtain good plasma lift-off at greatly increased peak DPF current by putting an opening fuse in the ballast load circuit. If the neutron scaling law persisted, very large neutron yields might be obtained, $10^{18\text{-}19}$ DT neutrons per shot. To date, work embodying these ideas, has not been resumed.

4. Soft X-Ray Source Development Projects

In our flux compression program, we have also conducted a foil-plasma z-pinch project with the goal of producing soft x-rays. This effort commenced in the mid 1970's in cooperation with the Air Force Weapons Laboratory[22], and continued as a Los Alamos project from 1980 until 1995. Our goal from the outset was to generate Megajoule quantities of soft x-rays from a plasma z-pinch driven either directly by a fast flux compression generator, or by the energy stored in an inductive store powered by a flux compression generator. Early tests were powered by a set of one, two, or three plate generators[22] in parallel. In these tests, we provided initial field to the plate generators from an energy storage capacitor bank without the implosion load in the circuit. To complete the circuit, we attached relatively high inductance static loads to the output of each generator, and isolated the foil z-pinch load with explosively actuated closing switches. By timing the closing switches appropriately, we could use the fast rising part of the plate generator waveform to drive the z-pinch, while sharing the current with the parallel static load. This scheme was simple, but in order to achieve a short pulse for the z-pinch, we had to leave very large currents in the static load. In the early 1980's, we began a program to develop opening switches for use in similar circuits. Our first attempts were to adapt the plasma compression technique published by Pavlovskii[23] for our own purposes. A version of this switch was developed that used an annular plasma cavity with a plane wave explosive lens to perform the plasma compression. This switch yielded fast rising current pulses, and a series of experiments, named Pioneer[24], was conducted between 1984 and 1986 that used single plate generators and two annular plasma compression switches. Good implosions were achieved, but the current levels were limited to ~2 MA by the ~20 nH load of the system, and the fact that our switch was limited to ~1TW energy dissipation rate[25]. Subsequently, we developed explosively formed fuse[26] (EFF) opening switches, that were capable of carrying large currents for long times, and still operating reasonably fast. We conducted the Laguna series of tests[27] using MK-IX generators[28] to deliver ~12 MA to 140 nH storage inductors, then diverted current to the load using the EFF opening switch. This system was capable of producing implosions with kinetic energy of order 200 KJ[28], but by the time we had the system working well enough to perform systematic z-pinch implosion tests, we realized that we could build a better system using the same basic building blocks. The final system in this effort was called Procyon, and has been the object of many publications[29,30]. Using Procyon, we were able to perform z-pinch experiments with plasma flow opening switches as a second pulse compression stage, at ~14 MA, and direct drive experiments at 12-13 MA. Figure 5 shows a cross section of the Procyon system, and Figure 6 shows waveforms from a typical test. It was with this system that we achieved our best radiation producing results. On our best test we produced 1.5 MJ of radiation with a full width at half maximum of 250 ns and a temperature of ~ 60eV[31]. We have now turned our attention to driving heavy liners with our explosive pulsed power systems, and have fired one Procyon test with such a load[30]. We are further developing more energetic systems for future high energy applications, as are described in another paper in this conference[32].

SUMMARY

We have presented some of the early Los Alamos history in three areas that are under intensive study today: magnetic acceleration of dense matter, plasma compression, and the generation of large quantities of soft x-rays. Some of the material discussed goes back nearly forty years. During the intervening time dozens of people have worked on these programs in varying degrees. It would be a monumental task to identify all of them We, therefore, call the readers' attention to the references which, collectively, list most of these people as authors. Unfortunately, not all the contributors to these programs are so listed, and to them we offer our sincere apologies.

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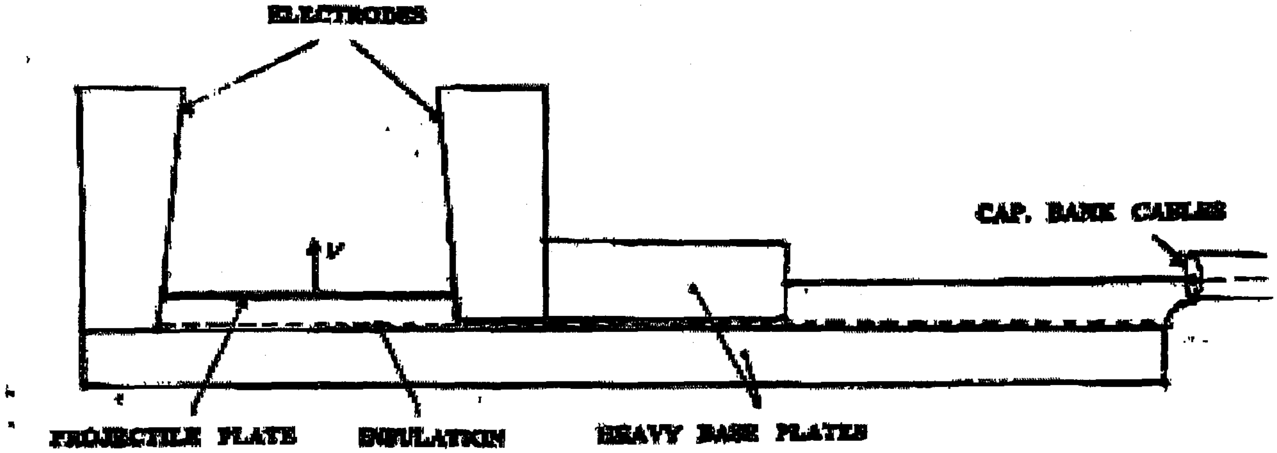

Figure 1. Experimental setup for accelerating "projectile plate". The electrodes, which required frequent

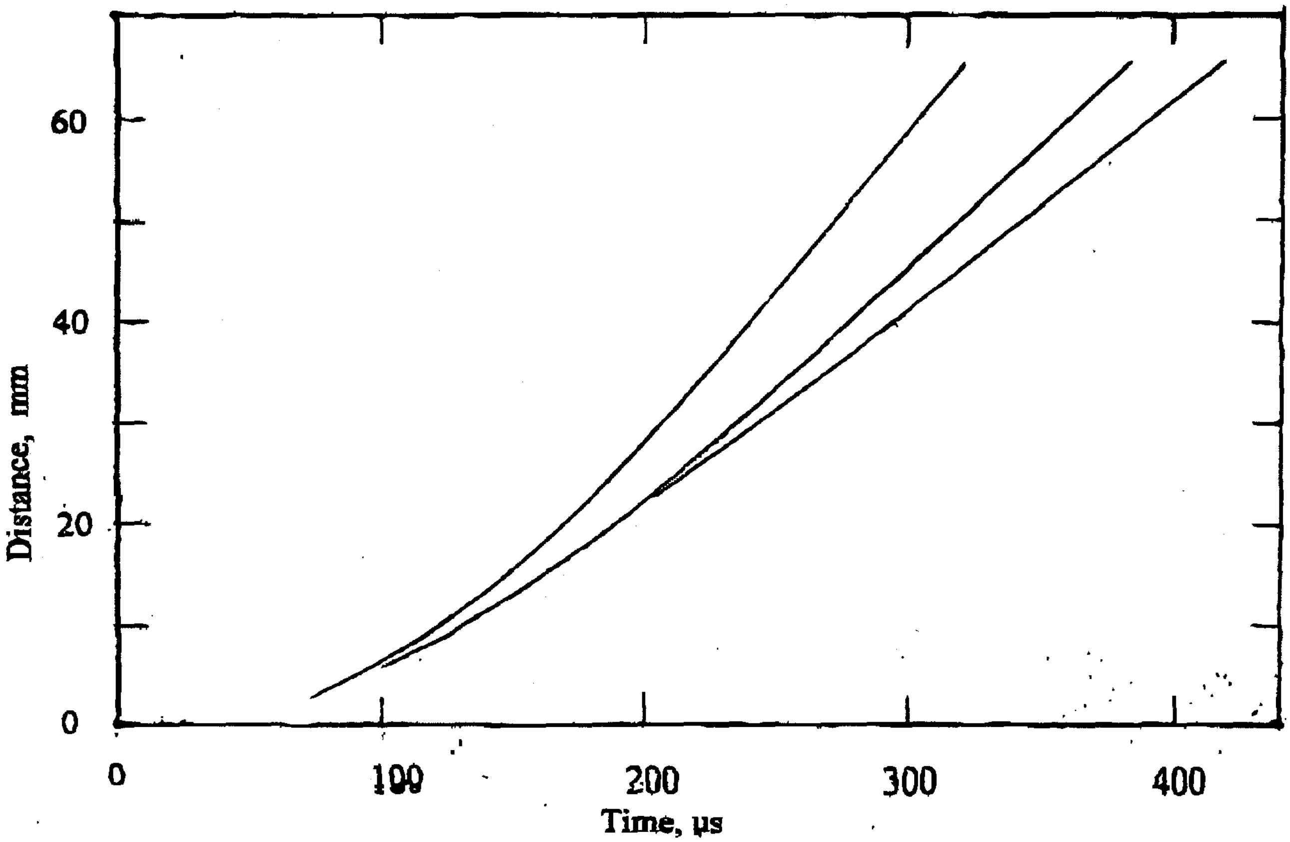

Figure 2. Motion of a magnetically accelerated dural projectile plate, 28-cm long, 5-cm wide, and 0.24-mm thick.

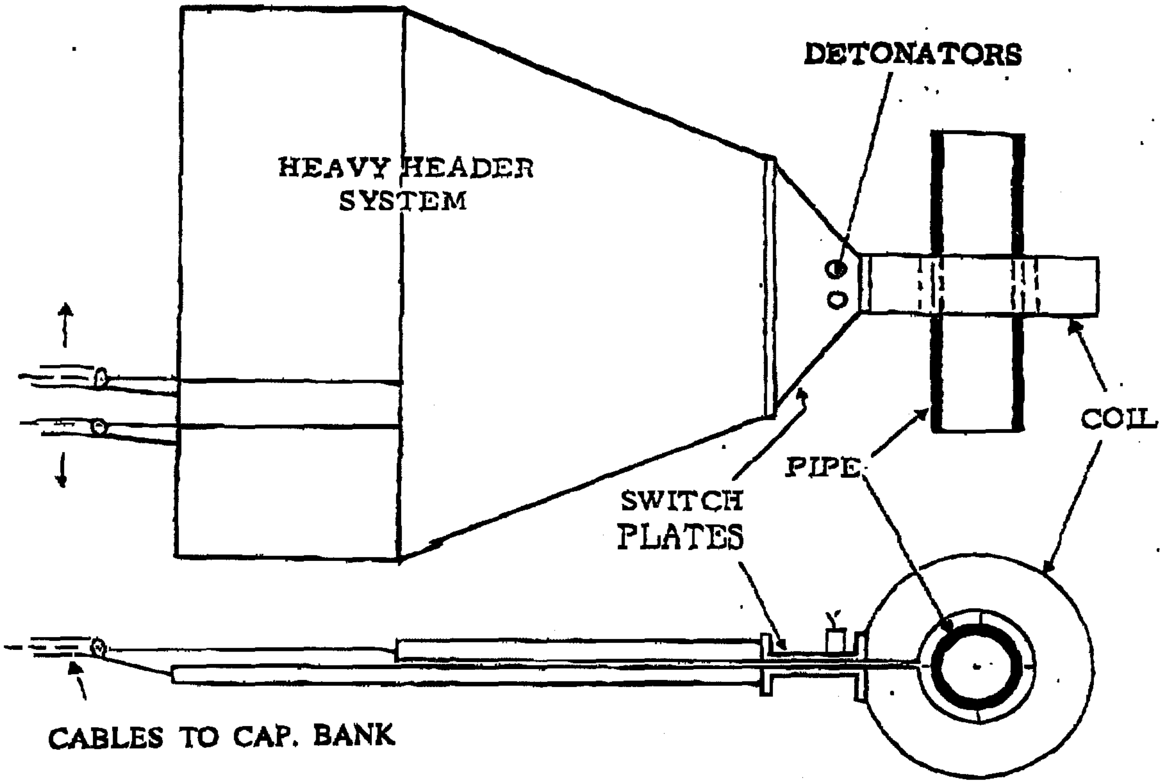

Figure 3. Header-coil systems for pipe closure tests. A small, easily replaced section has provisions for crowbarring the load coil current, using detonators.

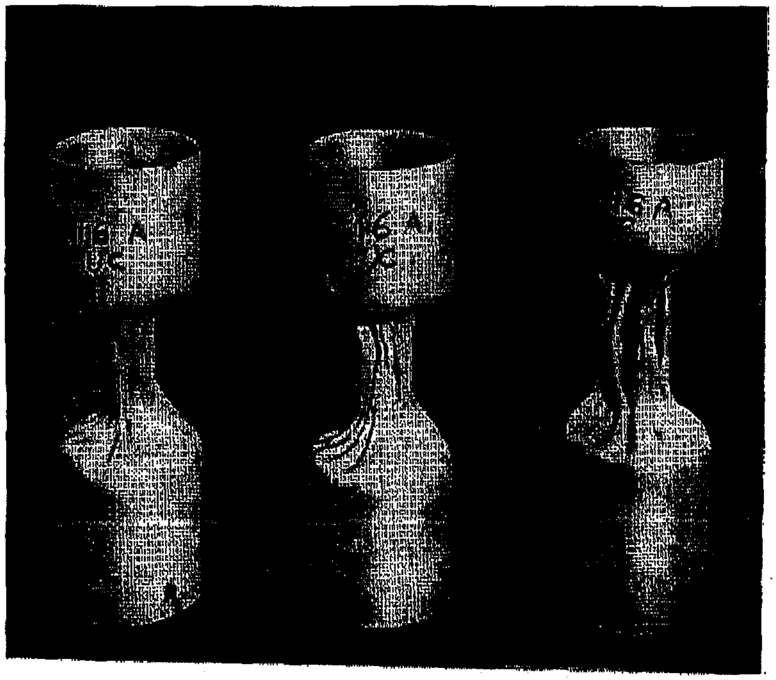

Figure 4. Photographs of magnetically closed dural pipes. The pipes were 76 mm in diameter with 1.6-mm-thick walls.

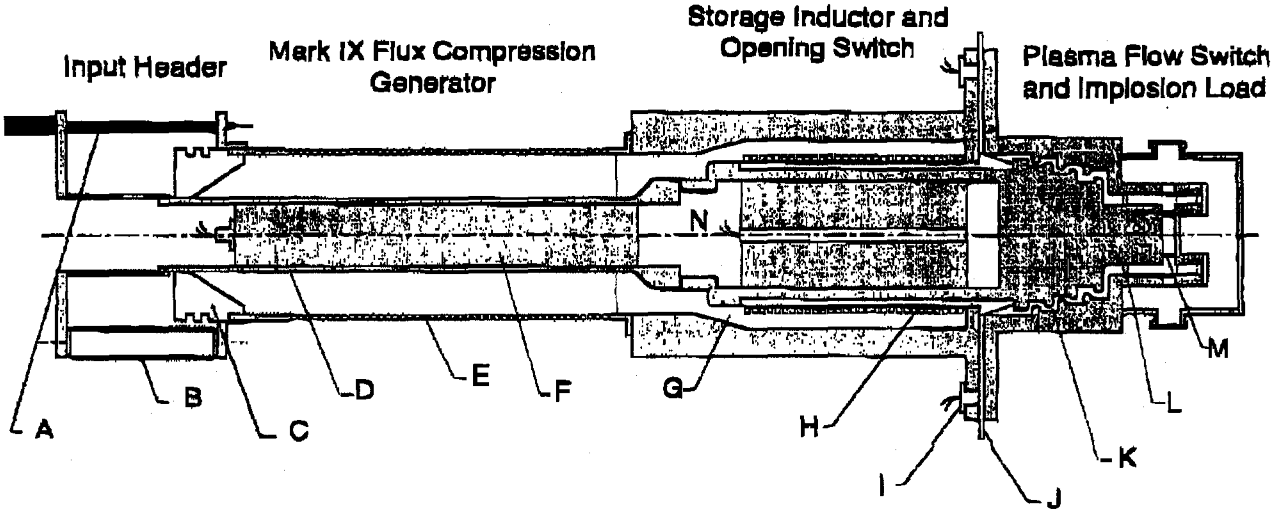

Figure 5. Procyon assembly with a PFS load. Current flows through A, E, H, and D with insulators C and G and termination resistor B (4Ω). MK-IX explosive, F, shorts out across C, then sweeps flux out of helix (E) into storage inductance, G. Explosive, N, is initiated simultaneously on axis and drives EFF conductor, H, into forming die of G. As EFF resistance rises, closing switches, I, are actuated and current flows through PFS, L, that subsequently switches into implosion load, M.

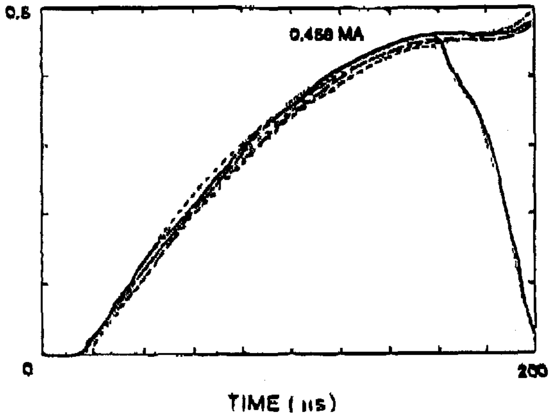

Figure 6a. Initial current from capacitor bank on typical test. A - Outside generator after crowbar. B - Remains in generator circuit.

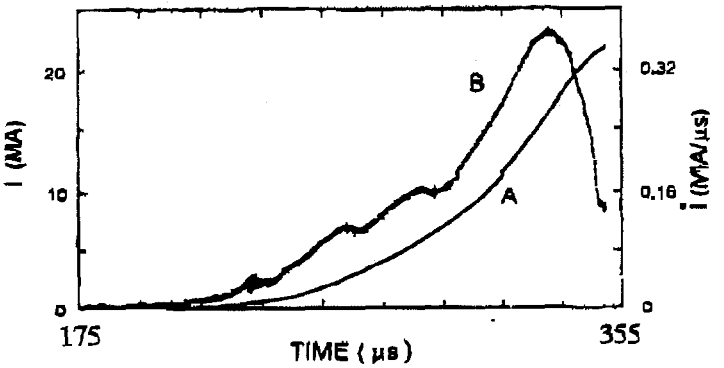

Figure 6b. I(A) and $\dot{I}$ (B) during flux compression phase. B is a Rogowski coil output, and A comes either from Faraday probes or a machine integration of B. Notches on B are where MK-IX stator bifurcates.

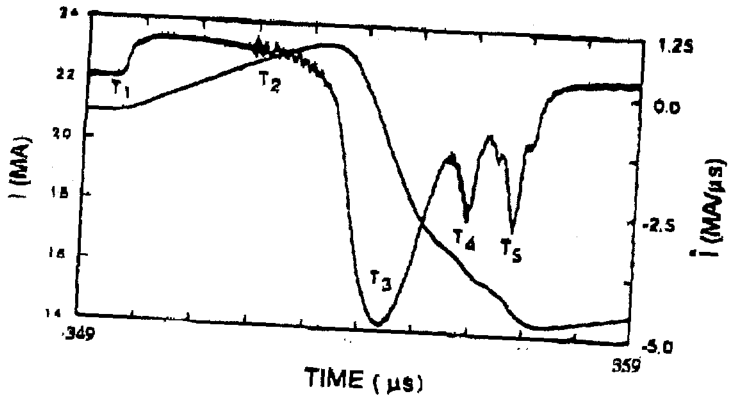

Figure 6c. I(A) and I (B) during switching and transfer phae. t_1 is initial motion of EFF, t_2 is closing switch time, t_3 is peak transfer time, and t_4 and t_5 are PFS switching and implosion times.