LA-UR-80-3190

CONF-801138--3

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MASTER

SUBMITTED TO: Conference on Electromagnetic Guns and Launchers, 4-6 November 1980, San Diego, CA

University of California

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EXPLOSIVE FLUX COMPRESSION GENERATORS FOR RAIL GUN POWER SOURCES*

by

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ABSTRACT

A class of explosive magnetic flux compression generators is described that has been used successfully to power rail guns. A program to increase current magnitudes and pulse lengths is outlined. Various generator loss terms are defined and plans to overcome some of them are discussed. Included are various modifications of the conventional strip generators that are more resistant to undesirable expansion of generator components from magnetic forces. Finally, an integral rail gun is discussed that has coaxial geometry. Integral rail guns utilize the rails themselves as flux compression generator elements and, under ideal conditions, are theoretically capable of driving projectiles to arbitrarily high velocities. Integral coaxial rail guns should be superior in some regards to their square bore counterparts.

I. Introduction

We describe a class of explosive magnetic flux compression generators that has been used successfully to power rail guns in a joint LLNL-LASL rail gun program. This report is one of five presented at this conference that, collectively, attempt to survey the present and near-term future status of this joint laboratory program.[1-4]

There are a number of types of explosive flux compression generators, each possessing some particular advantage for the particular application at hand.[5] The generators used for the rail gun power supplies belong to the strip generator class, first described in 1965 although in use several years earlier.[6] Strip generators were selected for this work because they can deliver large currents for long times - prerequisites for many rail gun applications.

In Section II, we describe the construction and operating principles of strip generators, testing procedures, and present some typical current-time wave forms obtained with both static and actual rail gun loads. Plans for near term future generator developments, that include methods for increasing currents and pulse lengths, are given in Section III. It is pointed out that minimizing various loss terms is important.

II. The Strip Generator

We describe here the strip generator presently used in this program, some of its pre-testing before use with the rail guns, and some of the current wave forms generated by it. This generator is the simplest and cheapest generator used at Los Alamos. A variant of this generator will be used in some future shots. It will be described in Section III.

(a) Description

Basically, the conventional strip generator consists of long parallel strips of copper, one of which is overlaid with explosive sheets, together with input and output blocks for capacitor bank cable input leads and for connections to the load respectively. Figure 1 gives a sketch of the generators tested and used to date. The copper strips are about 57 mm wide, 1.6 mm thick, and 2.45 m long, although higher current tests have been made using shorter lengths. The copper strips are separated by 51 mm. The long edges of the upper copper strip are bent up to add structural rigidity. This strip then assumes the form of a shallow U-shaped channel as noted by the sectional sketch of Fig. 1. Two layers of C-8 Detasheet explosive, 45 mm wide, are placed over the upper copper plate. To minimize expansion of generator components from magnetic forces steel ballast bars, 51 mm wide and 12.7 to 25 mm thick are laid on top of the Detasheet explosive and directly under the bottom copper strip. The input and output wedges are cut from 51 mm square brass bar stock, and then drilled and tapped individually to accommodate cable input header attachments and to make output connections to the various loads tested.

Initial flux is supplied to the generators by a large capacitor bank located at the firing site. The bank is presently being upgraded to some 900 kJ, but at the time the results reported here were obtained its nominal rating was 600 (3000 μF, 20 kV). The bank is so arranged that only half of it may also be used. This is frequently done, especially when new systems are being developed. The detonator is fired after flux is introduced into the generator and load. The resultant detonation of the explosive strips first results in closing the current input slot, thus trapping the magnetic flux. As detonation proceeds the top plate is driven into the bottom plate, thereby pushing the flux into the load.

(b) Pre-testing

Several preliminary test shots are normally carried out with particular types of generators before they are used in rail gun shots. These tests furnish information on shot timing, current carrying capability, the amount of ballasting required, and give some idea of the current limits expected in the actual rail gun tests. Current carrying capability is usually established by firing the generators into nearly short circuit loads.

Figure 2 gives a sketch of a test load used to roughly pre-assess the generator performance when used to power a 0.9 meter rail gun. The test load, designed to simulate a 1/2" bore gun, was formed from two parallel brass bars, each 19.1 mm square and 0.91 m long, and separated from each other by 12.7 mm. Steel ballast bars, 12.7 mm wide and 51 mm high, were then placed on top of the upper brass bar and beneath the lower bar. The entire 0.91 m long load was in the circuit at all times. Thus, the generator had to power the complete simulated rail gun load, instead of the gradually increasing load a projectile travelling down the bore would generate. In this sense the test would represent a lower limit on the current-time profile an actual projectile would experience.

Other tests were made on this shot. One was a study of the separation of the rails from the magnetic forces developed during the test. Results of this study will be described in Section III. Another test was designed to detect an electrical breakdown between the rails, (uninsulated in actual guns) should it occur. Electrical insulation was therefore extended only 0.45 m between the rails or half-way down the "bore". B_z magnetic field measuring probes were placed in the bore. One was placed in the insulated section, as was a current measuring (Rogowski) probe. The other B_z probe was placed at the end of the bore. If an electrical breakdown occurred between rails in the uninsulated section, the probe signals would reflect the breakdown. In the actual shot the two B_z probe signals were essentially identical showing that no electrical breakdown occurred over the uninsulated section. The current record obtained for this shot is shown in Fig. 3. During generator burn the current gradually increased to nearly 700 kA at generator burnout. After burnout the current decayed from flux penetration into the rails and from expansion of the bore. Tests of this nature are useful but, as it turns out, are only qualitative. As will be note' in Section III, the load inductance increased substantially from rail separation thus reducing the current from that which a well-designed rail gun would allow. On the other hand, in our actual rail guns it appears that an appreciable fraction of the flux can be lost through the current arc behind the projectile. In this sense, the test would overestimate the current.

(c) Rail gun current profiles

Current vs. time plots are given on Fig. 4 for three different rail gun shots.[1,2] Identical strip generators were used on all shots, and the 3000 μF capacitor bank supplying the initial flux was charged to about 16 kV on each shot. The two lower curves were obtained from shots with essentially identical rail guns (1.83 m long) and projectiles (12.7 x 12.7 mm bore, lexan cubes). The upper record was obtained with a large bore gun (50 x 50 mm bore; lexan cube) of length 0.3 m.

In all shots the current arc is established during the initial capacitor bank current rise, during which time the copper fuse located behind the projectile is vaporized. The energy required to vaporize the fuses is small, and the time at which vaporization takes place can only be readily detected from current time derivative signals. The strip generator detonation times are chosen to occur near the maximum current produced by the capacitor bank. In all cases this occurred at about 80--85 μs after capacitor bank trigger, at which times the currents were of order 630-640 kA.

The lower two curves show the extremes we have encountered in supposedly identical shots. At present we have not isolated the causes for this variation. The current profiles are intimately related to the projectile dynamics, and some difference in projectile behavior could be involved. However, greater attention was paid to ballasting potential weak spots for the higher current shot of this pair, particularly at the connection of the generator output to the rail gun input. This factor could account for some of the higher current.

The current profile obtained from the short, large bore gun exhibits the highest current we have obtained to date with this system, 1.95 MA.

III. Future Developments

The major generator development effort in the next year or so will be to increase the current carrying capability and the pulse lengths delivered by the generators. As will be discussed below success in achieving these goals is strongly dependent upon minimizing losses.

We will confine this discussion to considerations of single, practical generators. It may be possible to connect and consecutively fire several such generator modules in series. This would multiply the individual generator pulse length, but would compound the loss terms that are usually strongly time dependent. Use of several individual modules to power segmented rail guns remains to be demonstrated, as in the case for other proposed power sources. However, in this case the modules would be isolated. The fractional loss terms would then be the same as those of a single module but the pulse lengths would be multiplied. There is little doubt that significantly better performance can be expected if this can be done, or if related techniques can be employed such as use of suitable opening switches or, in some situations, high current capacity diodes.

(a) Losses

It is generally assumed that the generator explosives contain far more energy than any electromagnetic energy terms involved in their operation. Thus total energy balance, which would involve that contained in the explosive, is usually not particularly useful. Instead, electrical quantities of interest are deduced from mechanical and electrical properties of the generator and load and by invoking the conservation of flux. Implicit in these solutions are various work and kinetic energy terms that might occur from motion of various components of the generator and load.

There are some rail gun systems we are studying where limitations may arise from lack of sufficient explosive energy, because it may be difficult to use much explosive in a practical way. These situations could arise in various hybrid or integral rail guns, such as those described by Peterson and Fowler.[7] Here, one or both of the gun rails may be overlaid with explosive. Thus, the rail gun itself serves as a strip generator. An interesting, particularly sturdy, variation of this hybrid generator, utilizing a coaxial arrangement, is shown in Fig. 5. Either the central cylinder could be loaded with explosive, which might also be explosive energy limited, (configuration A), or the outer cylinder could be encased with cylindrical explosive charges (configuration B). In the latter case, phased detonation of the explosives could lead to very high projectile velocities as, theoretically, is the case with the square bore integral rail gun.[7] However, in both cases the projectile would be annular in shape. It might prove difficult to form and maintain a radially symmetric current arc. Even with a symmetric arc, the pressure on the projectile would decrease with increasing projectile radius, and this could also be troublesome. Consequently, no experimental work has been done with these configurations as yet.

With no energy limitations on the explosives the losses, in the flux diffusion approximation, are thereby limited to those of the magnetic flux originally resident in the system. Some of these losses occur in the rail gun itself - diffusion into the rails and losses associated with the current arc between the rails. These losses can be very significant but, since they are not directly assciated with the generators, will not be considered further in this report.

Flux losses associated with the generator itself include that which has diffused into the copper strips, flux trapped at the moving contact region between the strips, and that trapped in the stray inductance at the conducting joints that attach the generator output to the rail gun input. Very roughly the fractional flux losses associated with the first two processes vary respectively as the square root of the pulse length, and directly with the pulse length. In both cases, the fractional flux losses are smaller when the generator inductance per unit length is larger. We intend to study these loss terms in more detail as time progresses.

Possible loss terms associated with the generator output-rail gun input are graphically illustrated in Fig. 6. This figure shows two x-ray photographs of this junction for the simulated rail gun load sketched in Fig. 2. The upper view is a pre-shot view of the junction while the lower view was taken near generator burnout. The initial inductance of the connecting junctions was reasonably low. A more significant fraction of the initial flux was later lost at the junction owing to the great increase in inductance brought about by displacement of the junction components from magnetic forces. Proper support for such regions, either by ballasting or clamping, is important for efficient generator operation. As noted earlier, a higher current was obtained in a series of otherwise identical rail gun shots when more care was taken to strengthen this junction.

Mechanical displacement of the strip generator plates from magnetic forces also occurs during the explosive generation stage. Although the explosive finally does wipe out all of the initial inductance originally in the strip generators, these displacements produce time variations in the generator inductance that depend upon the current-time profile seen by the generator strips. Proper modelling of the generator-rail gun should account for these displacements as noted by Deadrick et al.[4]

(b) Increasing the current pulse

We intend to increase the pulse lengths by increasing the length of the generators, and by using slower detonating explosives. Practical construction considerations set an uppen length limit of about 3.7 m (12 feet) for a module. Additionally, Baratol explosive strips are now being processed for testing. This explosive detonates at a velocity somewhat less than three-quarter of that of Detasheet. Finally, special explosives have been developed at Los Alamos for this work that detonate at velocities of order half that of Detasheet.[8] If these explosives are not too severely limited in energy their use, in conjunction with the larger generator lengths, should allow construction of generators that are capable of producing useful pulses in excess of a millisecond long.

Increase in current magnitudes will be accomplished first by discharging the capacitor bank at higher voltages. Later, we anticipate the need for more initial generator energy than is available in the capacitor bank. We are therefore starting development of a spiral-type booster generator. It should be capable of supplying the strip generators with several megajoules of initial energy.

There are several ways to make the strip generator sturdier, a necessity to combat mechanical displacements brought about by larger currents and pulse lengths. The present generator cross-section may be sealed linearly, and various clamping arrangements can be used to assist the inertial ballasting presently in use. Both of these are cumbersome, however, so we have started construction of "inside out" strip generators, similar to those reported by Herlach et al.[9] A schematic of this generator is shown in Fig. 7. The magnetic stresses are disposed more favorably for this class of generator since they tend to push the lighter, explosive driven plates inwards. On the other hand, the outer plates can be quite massive and, further, they are also subject to simple clamping arrangements. Although these generators are more complicated, and therefore more costly, than the conventional ones presently used, the costs are still small compared to those of the rail guns. They usually use the explosives more efficiently and, for a given width, they can be constructed to have more inductance per unit length.

Finally, some thought has been given to using coaxial generators instead of strip generators for prime power sources.[5] These generators are similar to the coaxial rail guns shown in Fig. 5, without the annular projectile, of course. They are exceptionally sturdy generators. Explosive machining costs could be eliminated by using liquid explosives, such as nitromethane, for the A configuration. However these generators normally have less specific inductance than strip generators, and they are more difficult to make in long lengths. It is also usually more difficult to make connections to the loads. An exception would be if the load itself is coaxial, such as the coaxial rail gun of Fig. 5.

*Work performed under the auspices of the U. S. Department of Energy.

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Figure Captions

Fig. 1. Side view of a conventional strip generator. The cross-section is shown at plane AA.

Fig. 2. Simulated rail gun load powered by a strip generator, showing the heavy ballasting used to resist expansion by magnetic forces.

Fig. 3. Current-time record obtained from the generator powered simulated rail gun load shown in Fig. 2.

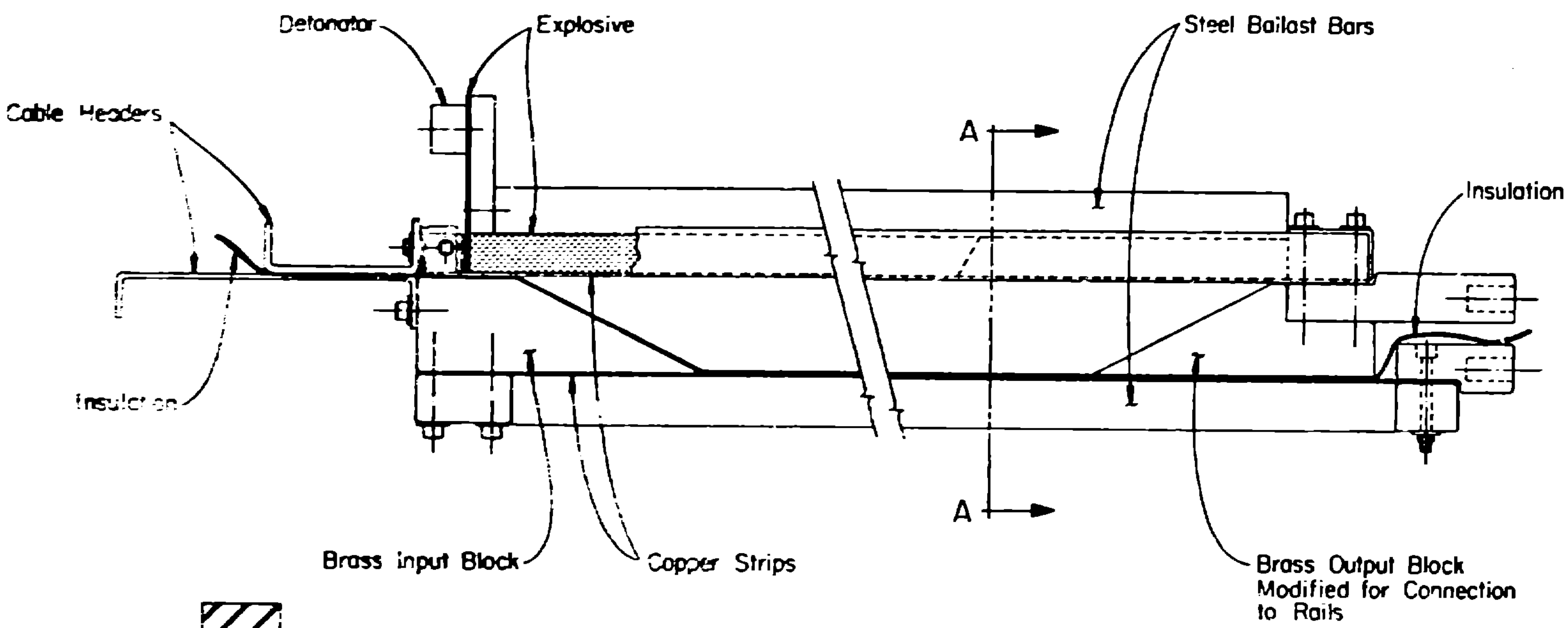
Fig. 4. Current-time records obtained from three different rail gun shots with cubical lexan projectiles. 1.8 meter long rail guns with 12.7 mmm square bores were used for two of the shots. In the third shot, the rail gun was only 0.3 m long, but the bore was 50 mm square. The highest current obtained to date was recorded on this shot.

Fig. 5. Integral coaxial rail guns, showing annular projectile. Explosive is loaded in the inner cylinder for configuration A and around the outer cylinder for configuration B. Without the projectile, both configurations become coaxial flux compression generators that have some advantages as external power sources for rail guns.

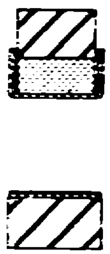
Fig. 6. a) Flash x-ray of shot setup at load-generator connection for the simulated railgun of Fig. 2.

b) Flash x-ray taken near generator burnout at same region as the setup shot (Fig. 6a).

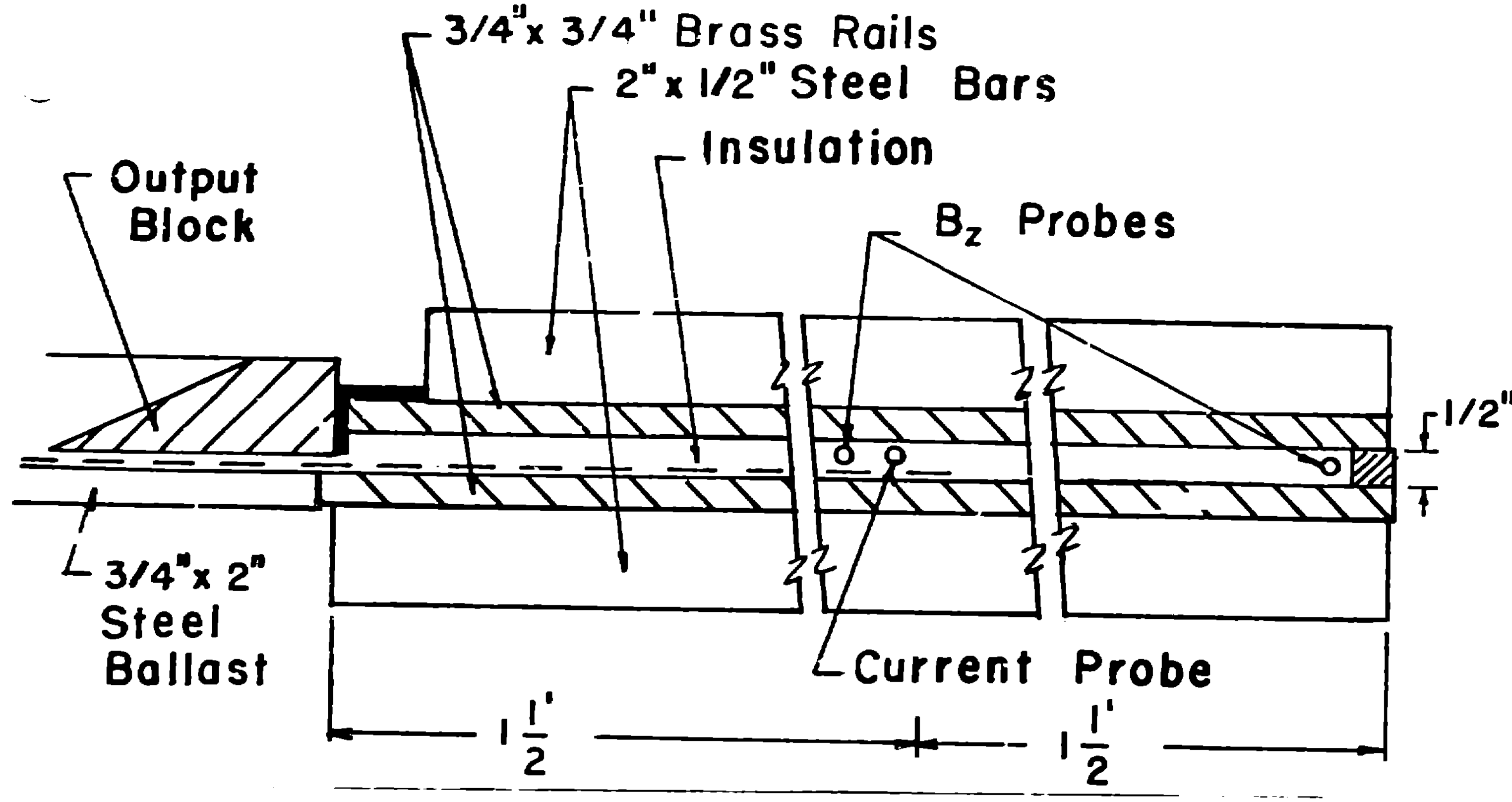
Fig. 7. Side view of "inside-out" strip generator. Although more complicated to fabricate than conventional strip generators, they can be more readily adapted to withstand magnetic stresses.



Detonator
Explosive
Steel Ballast Bars
Cable Headers
A
Insulation
Insulation
A
Brass Input Block
Copper Strips
Brass Output Block Modified for Connection to Rails



Section A-A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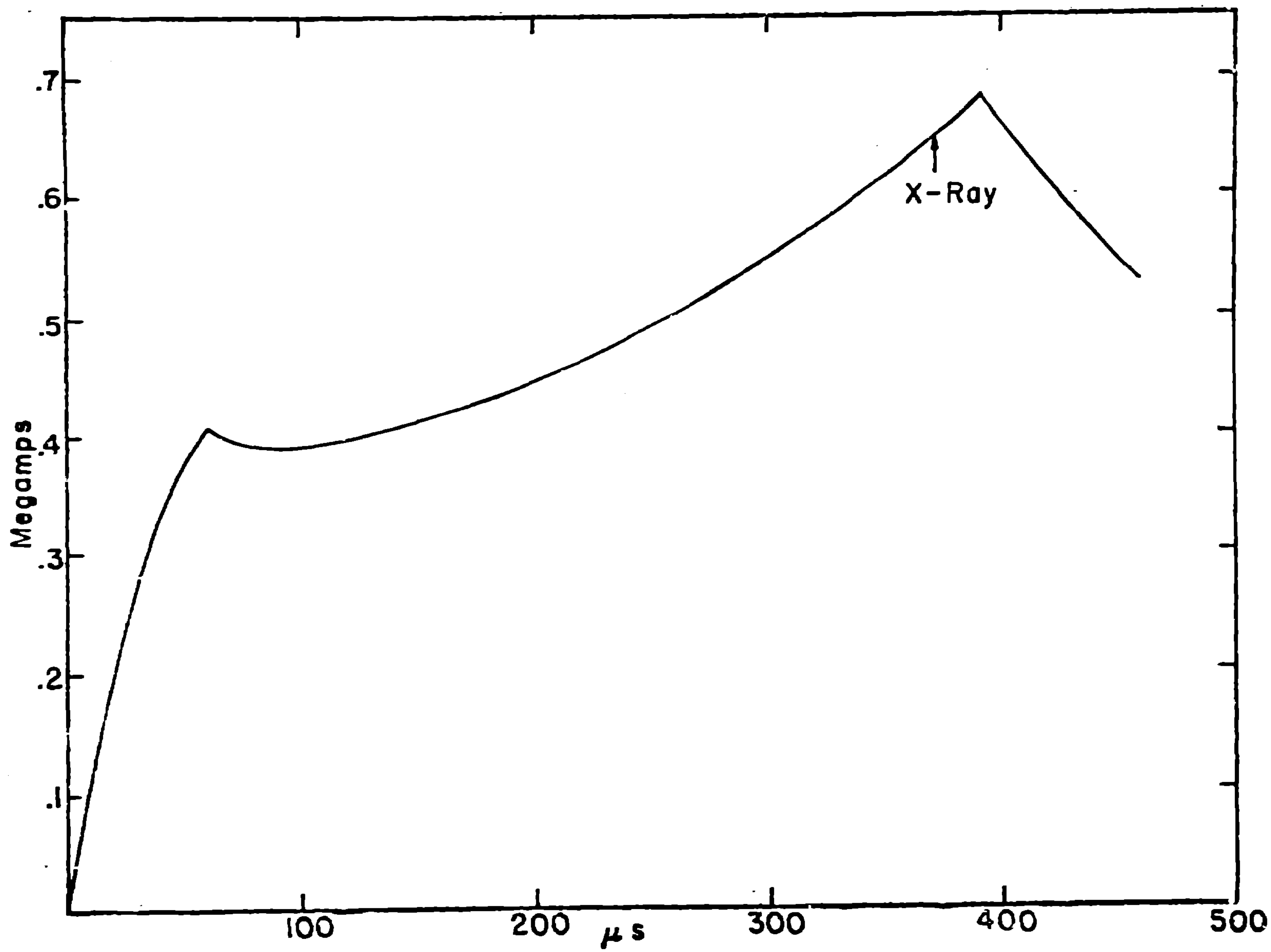
2" x 1/2" Steel Bars
Insulation
Output Block
B_z Probes
1/2"
3/4" x 2" Steel Ballast
Current Probe
$1\frac{1}{2}'$
$1\frac{1}{2}'$



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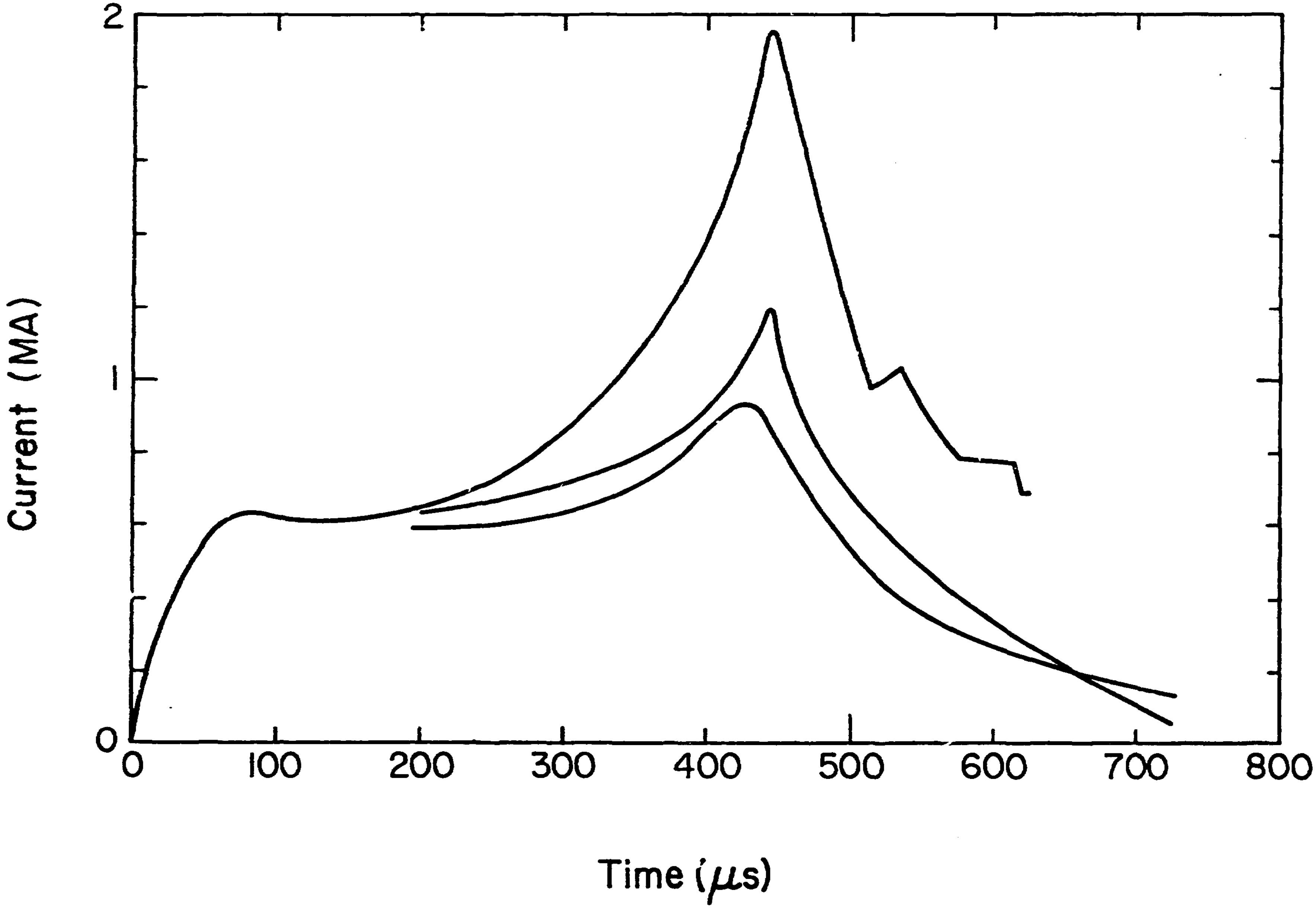
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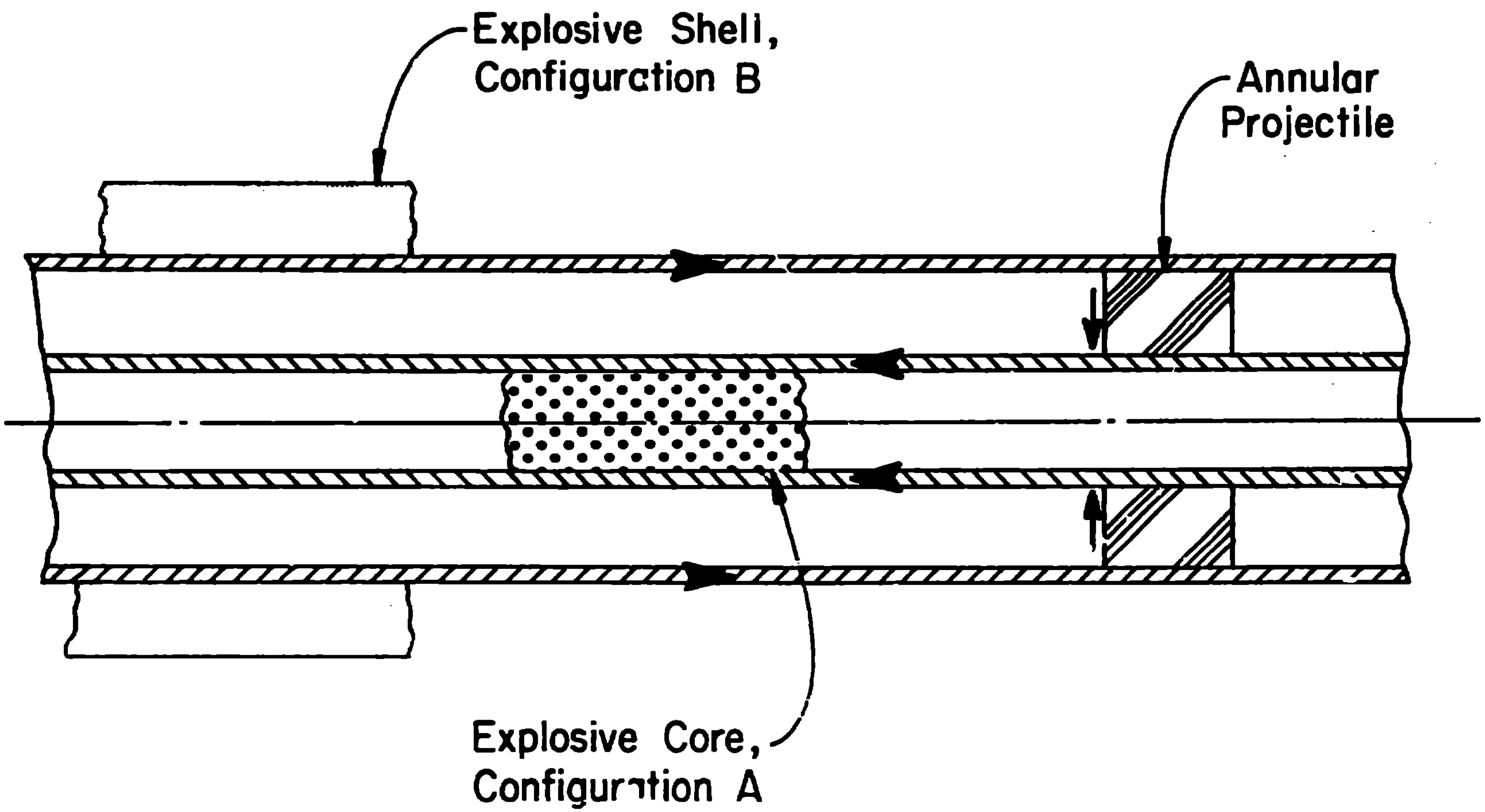
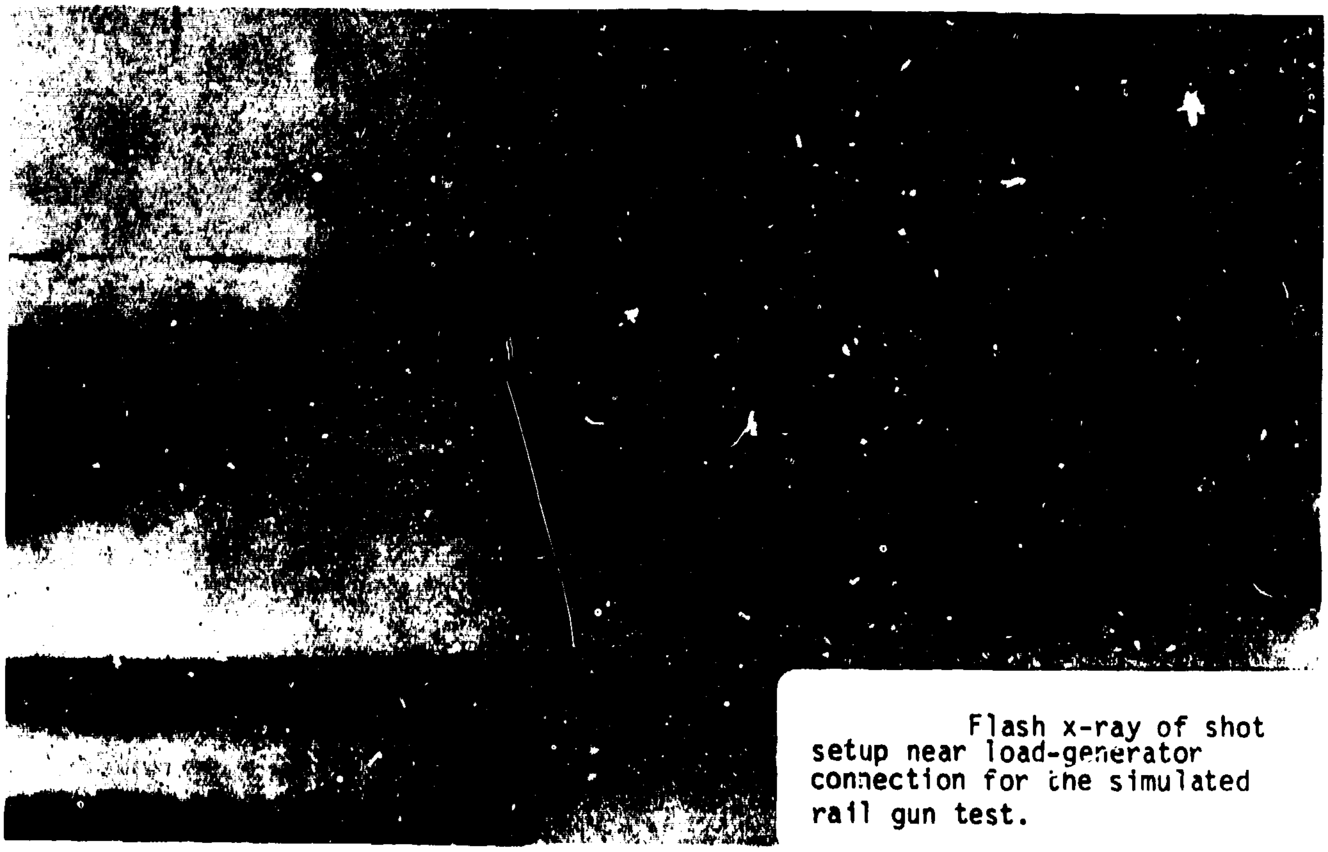
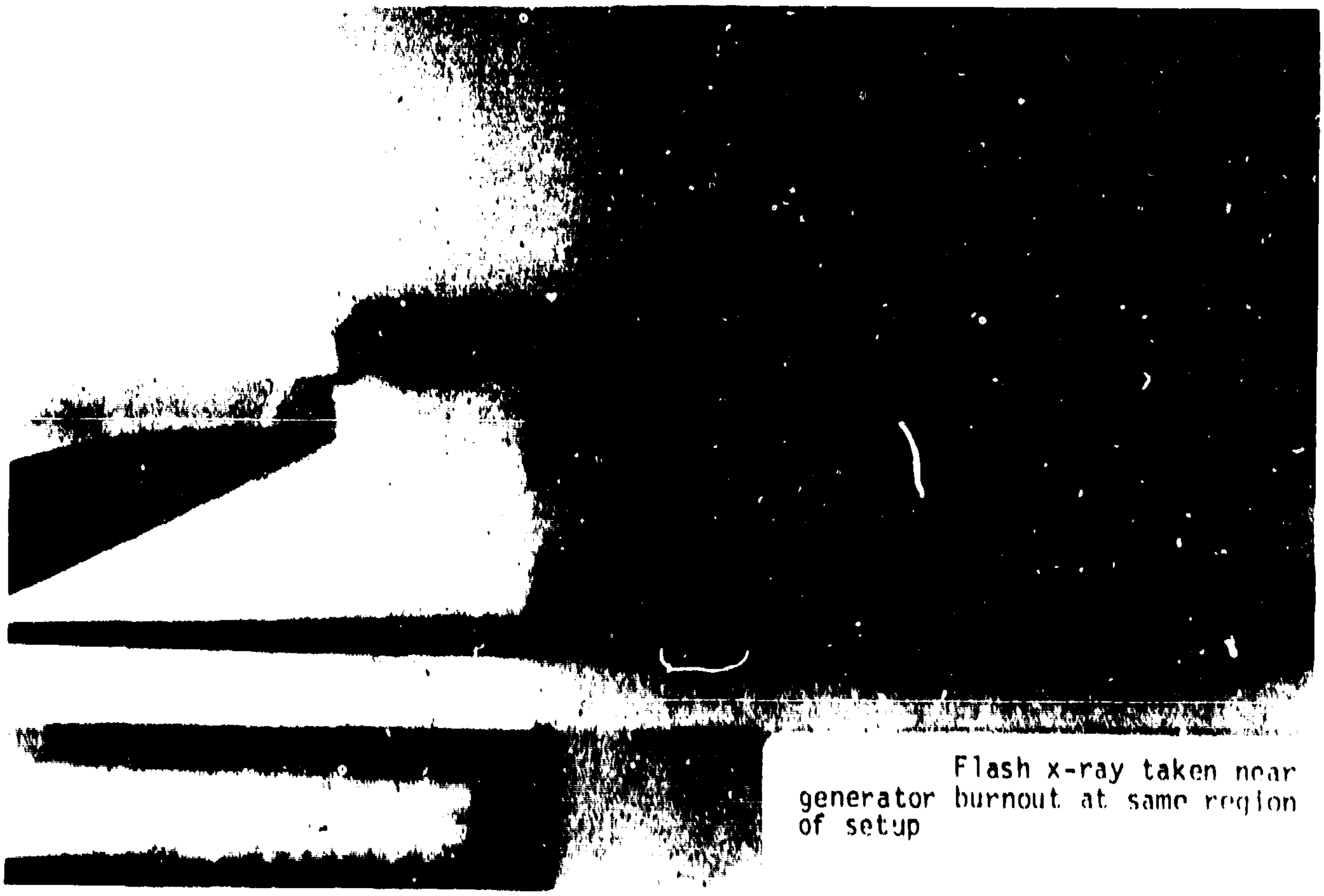
700
800
Time (μs)

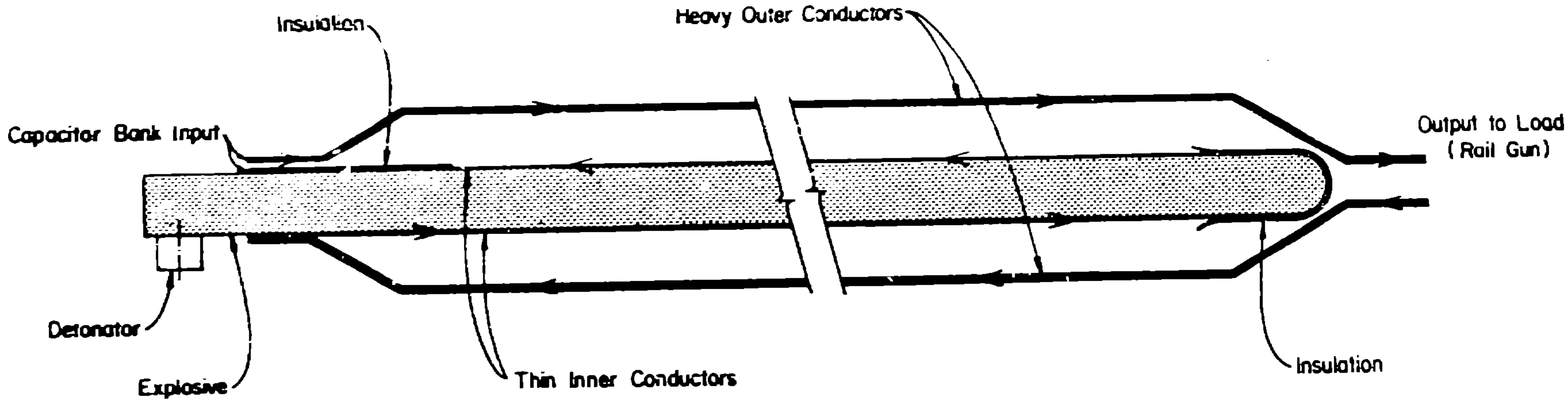

Explosive Shell, Configurction B
Annular Projectile
Explosive Core, Configurction A



Flash x-ray of shot setup near load-generator connection for the simulated rail gun test.



Flash x-ray taken near generator burnout at same region of setup



Insulation
Heavy Outer Conductors
Capacitor Bank Input
Output to Load
(Rail Gun)
Detonator
Explosive
Thin Inner Conductors
Insulation