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FUTURE EXPLOSIVE PULSE-POWER TECHNOLOGY FOR HIGH-ENERGY PLASMA PHYSICS EXPERIMENTS*

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A variety of high-performance pulse-power systems in the 10 to 20-MJ class have been built in the last ten years or are planned in the next 3-5 years. Such systems, using capacitive energy storage, are employed in particle beam fusion, x-ray effects, x-ray physics, and plasma physics experiments. Advances in the technology of high-energy-density capacitors over the same time period has substantially decreased the cost per joule of the basic capacitor and kept the total parts count in large systems within reason. Overall, the savings in capacitor costs has about balanced the generally increasing system costs keeping the total cost of large, high-performance systems at $1-2 per joule over the period. The next step, to 100-MJ class systems, will profit from the improvements of the last decade, but there seems little reason to project a lowering of the cost per joule. In contrast, there is every reason to expect the continuously growing system costs to outstrip any savings to be realized from improvements in capacitor technology. Thus, 100-MJ systems promise to cost $100 M or more.

Over the same period, explosive pulse power systems in the 10 to 20-MJ class have been employed, routinely, in plasma physics experiments. These one-shot systems currently cost about $100 K for the generator and switching and deliver energy to a plasma physics experiment in a few microseconds. Comparing only hardware costs, such systems are competitive with capacitor systems for developmental activities involving 100–200 shots — but not for repetitive applications involving 1000's of shots. For the next generation, hardware for 100-MJ systems is expected to cost $200-500 K At this rate, explosive systems are competitive with capacitive systems for applications involving up to 200–500 shots. In this paper, we discuss general concepts for generators and power-conditioning systems appropriate for high-energy applications. We scope two such applications and show how explosive pulse power can address those applications. And we describe one example of an explosively powered generator suitable for 100-MJ operation.

Large-Scale Flux-Compression Generators

Magnetic flux-compression generators represent a relatively simple, cost-effective technique for producing large amounts of energy at high current. Flux compressors use the energy released from a detonating chemical explosive to perform work on a magnetic field. The work increases the electrical energy in the circuit at the expense of hydrodynamic energy in the assembly. Flux compressors have the advantage of enabling very high energy experiments without the need for very large, costly pulse-power systems that take years to construct. They have the disadvantage that they are single-use systems and much of the hardware must be replaced for each experiment.

Concepts for large-scale flux-compression systems grow naturally from the configurations that have been used for many years for smaller scale systems. Figure 1 shows three of the most common flux compressor configurations. The "Plate" system consists of rectangular conductors in a box-like configuration. Explosive on the larger sides of the box is simultaneously initiated over its area and propels the sides of the box together. The typical plate configuration is capable of 10 to 12-MA currents, and 15-μs run times. Its inductance is relatively low and its energy gain is modest. The "Helical" configuration consists of a hollow metal pipe containing explosive located inside a coil of conductor. The explosive is initiated at one end, the metal pipe expands outward and contacts the coil at a point that follows the coil from initiation end to load end. The typical small helical configuration is limited to 1 to 3-MA currents because the conductors comprising the coil have limited cross section. Its run-time (50 μs) is controlled by the detonation velocity of the explosive. It produces the largest current and energy gain of any flux-compressor configuration. The "Strip" or "Bellows" configuration consists of flat conductors like the plate configuration, but the explosive is initiated at one end, like the helical. Unlike the plate, its shape is not constrained to be generally rectangular and large spacing and narrow conductor widths at the initiation end sometimes taper to wide conductors and narrow spacings at the output end. The strip configuration can produce 5 to 10-MA currents but is limited to run times of 50 μs, somewhat like the helical. Its gain is intermediate between the plate and the helical, but it is by far the simplest and least-expensive system to build and operate.

For very high energy applications, these basic configurations can be transformed into more-complicated systems. By revolving the plate around an axis of symmetry, a coaxial system is formed. The explosive occupies the inside of a cylindrical pipe but the areal initiation system can be reduced to a (simultaneous) line initiation system on the axis. In principle, the outer explosive charge becomes an areally initiated annulus of explosive, but practically it disappears all together. Such coaxial systems are capable of currents of 150 MA. But their inductance, and hence their gain is relatively low. To make high energies they become quite long. And practicality dictates that there be a small angle between the inner and the outer conductors where they contact. The sweeping of this contact point is a significant contributor to the generator's total operating time, which is typically 40–50 μs.

By rotating the strip configuration around an axis of symmetry, a disk-shaped system is formed. In this system, the explosive is initiated on or near the axis and the output current is taken from the outer radius. The disk configuration is modular. Additional assemblies can be placed next to each other and connected in series at the outer radius. The disk system, like the coax, is capable of very high currents, 150-250 MA. While the inductance of each individual unit is relatively low, the modularity of the configuration allows substantial gains to be achieved with several units. The total run time as the contact point sweeps from axis to outer radius, can be substantially less than the run time of a coaxial configuration of comparable inductance.

The helical configuration is fundamentally cylindrical and can be scaled to relatively large sizes directly. For large systems, the output currents are 30-50 MA, lower than either coaxial or disk configurations. The current risetime increases with the size of the systems because it is initiated at one end, but the gain remains the highest of the collection.

Clearly the plate configuration can be rotated around a vertical axis producing a simultaneously initiated disk, the strip can be rotated around a horizontal axis producing an end-initiated coaxial configuration or the helical can be initiated simultaneously along the axis to produce a faster helical system.

Power-Conditioning Techniques

For most plasma-physics experiments, one or more stages of pulse compression are needed to meet the requirements of the load. In general, high-current opening switches represent the critical component in power-conditioning systems. Power conditioners can generally be characterized as inductor-to-inductor-transfer systems relying on direct opening switches, or commutation schemes relying on a moving contact to affect current transfer. Among the most-practical schemes for direct opening switches are those based on fusing techniques — either conven-

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tional fusing or augmented fusing. Similarly for microsecond time scales, the most practical commutation schemes employ a magnetically propelled plasma that transits a gap in a conductor to perform a commutation operation.

Figure 2 shows these three switching techniques in schematic form. In each case current is delivered from a coaxial source. For inductor to inductor-transfer systems, the storage inductor takes the form of a coaxial section whose dimensions are selected to provide the required inductance. The opening switch occupies one wall of the inductor (frequently the inner-coaxial conductor). For the commutation system, there may initially be no additional storage inductor, but the motion of the commutating element sweeps a volume that is subsequently filled with flux and this volume becomes a storage inductor. Output is taken in a coaxial section connected across the switching element (for direct-transfer schemes) or across the commutating gap (for commutation schemes).

Conventional fuses in which the conductor vaporizes under the influence of the current alone have been demonstrated for conditioning the output of large helical and large disk generators. For helical systems,[1] fuses carry currents for times in excess of 350 μs and interrupt peak currents of 20-22 MA in 5-6 μs. They sustain voltages of up to 60 kV at electric fields of up to 2 kV/cm. For much faster disk systems,[2] conventional fuses carry current for 20 μs, and interrupt currents of 60 MA in about 1 μs. They sustain voltages approaching 400 kV at almost 4 kV/cm. Since conventional fuses are scaled to the current and timescale of the generator, they do not have a substantial energy-dissipation limit.

Augmented fuses differ from conventional fuses in that some independently controllable process alters the geometry of some or all of the conductor during the time that current is flowing. For the explosively formed fuse shown in Fig. 2, hydrodynamic energy from an explosive is used to deform a conductor against a shaped die made of insulating material (Teflon). The thinning of the conductor in some regions leads to increased local accumulation of action, melting and vaporization. Explosively formed switches are particularly appropriate for conditioning the output of long-running helical generator and are routinely used to interrupt the 20 to 22-MA currents in 3-5 μs.[3] They sustain voltages around 100 kV. Since only a fraction of the conductor is believed to participate in the interruption process, there may be a limit to the energy dissipation of augmented fuses. Dissipation of 10 MJ has been achieved and is assumed to be scalable.

The plasma flow switch[4] is the most actively explored of the commutation switches. Currently used at Los Alamos[1,3] in conjunction with either a conventional or augmented fuse, the plasma-flow switch conducts 10-12 MA for times of 5 μs and switches energy into an implosion load in a fraction of a microsecond.

Applications-Soft X-Ray Production

One application of interest to the community is the production of large fluences of soft x-rays from 50 to above 500 eV. Such high-fluence x-ray sources are of interest for x-ray physics experiments and for the development of x-ray diagnostics. Fast plasma implosions represent the most promising source megajoule fluences of soft x-rays. For magnetically imploded plasma systems, energy is coupled from the magnetic field to kinetic energy of the collapsing plasma cylinder. When the plasma assembles on axis, its kinetic energy is converted to internal energy, heating the plasma and radiating x-rays in a complicated interplay of processes.

Simplistically, implosion velocity or kinetic energy can be calculated from circuit and kinematic considerations. Similarly, the thermalization process can be modeled by equating specific implosion kinetic energy ($v^2/2$) with internal energy in the pinch and then evaluating equations of state to estimate an upper bound on the temperature. Figure 3 shows results of such a simple estimate of plasma temperature for gold and aluminum plasmas as a function of internal energy (or implosion velocity) for pressures from 10^8 to 10^{12} Pa. For gold plasmas, velocities of 5 cm/μs are required to reach 50 eV and at velocities of 30 to 40 cm/μs, temperatures of 400-700 eV might be expected. For aluminum plasmas, velocities of 7-14 cm/μs are required to reach 50 eV (depending upon pressure) and velocities of 30 to 40 cm/μs could be expected to produce 300-800 eV plasmas. For comparison, capacitor-bank-driven implosion experiments[5] have achieved implosion velocities of 14-22 cm/μ in aluminum plasmas and radiation temperatures of 50-60 eV have been reported.

For scoping calculations, circuit models of fast flux-compression generators, fuse opening switches and cylindrical plasma implosions are used to evaluate the implosion velocities that could be expected from large-scale systems. A general, linearly decreasing $L_{(t)}$ model with compression times from 10 to 50 μs was used to model the flux compressor. Similarly, an elementary "zero-dimensional" model was used to model the implosion process. Since the performance of the opening switch is the critical element in the system, a considerably more detailed model of the fuse opening switch was used. The "CONFUSE" model[6] employs hydrodynamics and equation-of-state information to evaluate the resistance of a copper fuse during its melting vaporizing and to supply that information to the circuit calculation. The model uses one variable parameter which is referenced to experimental data[2].

Figure 4 shows the circuit employed in the scoping calculations. A flux compressor whose initial inductance was 225 nH was loaded with a 6.22-MA current (4.3 MJ, 1.4 Weber). The flux compressor operates (without losses) into a 14.83-nH storage inductor and a fuse opening switch. The implosion load includes a self-closing (voltage-activated) switch, a 10-nH vacuum inductance, and a 12-nH dynamic inductance. This inductance is characteristic of an typical fast plasma implosion which uses a cylinder initially 5 cm in radius and 2 cm high, radially compressed by a factor of 20. Depending upon the time of current interruption, the flux compressor could produces 100-MA current and 75 MJ of stored energy in the storage inductor. Simple flux conservation arguments show that the opening switch must dissipate 30 MJ of energy and that the ideal maximum kinetic energy that could be coupled to the implosion is 14.2 MJ.

For nominal values of fuse parameters (cross-sectional area and length)[7] the closing voltage of the load-isolating switch was first optimized to produce 40-cm/μs implosion velocities (500 to 600-nS implosions). For all cases, a switch voltage of around 400 KV resulted. The fuse parameters and implosion load mass were then adjusted to maximize the kinetic energy delivered to the load at 40-cm/μs. Finally, with fuse parameters and opening switch voltage, i.e., the system configuration, were held fixed, and the implosion mass was varied to explore the range of energies and velocities that could be expected.

Figure 5 shows the results of the scoping calculation employing three flux-compression times (50, 20, and 10 μs). For velocities of 40 cm/μs, the slower, 50-μs, system coupled just over 2 MJ of kinetic energy to the implosion while the fast, 10-μs, generator couples just over 7 MJ to the implosion or 50% of the ideal maximum. Peak currents were in the range of 50 MA.

Applications-Imploding Liner Fusion

Another interesting application of a magnetically driven implosion is that of compressing fuel to fusion conditions. Conventional practice[8] in inertial confinement fusion capsule design employs pusher-implosion velocities in the range of 30 cm/μs not dramatically different from those considered above. However, as we have discussed, such high velocities significantly reduce the efficiency of coupling electrical energy to kinetic energy.

The introduction of a moderate preheat (50 eV) and a modest magnetic field (40 T) into the capsule offers the possibility[9] of producing substantial thermonuclear yield in larger capsules with lower fill density while requiring pusher velocities as low as 1–5 cm/μs. The Magnetized Fuel Target (MFT) regime differs substantially from conventional inertial confinement fusion regimes and relies on the presence of the magnetic field to increase energy deposition in the fuel by inhibiting electron thermal conduction and by trapping fusion alphas. In addition, the lower initial fuel density reduces bremsstrahlung radiation losses. Thus, the magnetized fuel approach generally makes better use of the energy available from the pusher implosion.

For MFT scoping calculations, the same circuit shown in Fig. 4 was employed. However, the low initial fuel density and large amounts of energy available allow initial radius of the implosion to be increased to 10 cm, and the length of the imploding cylinder to increase to 10 cm. This increased size of the load increases the dynamic inductance to 60 nH and the ideal maximum kinetic energy to 31.7 MJ. The same optimization procedure was used with the objective of optimizing the implosion energy at 5 cm/μs. Figure 5 shows kinetic energy coupled to the implosion as a function of implosion velocity. At 5 cm/μ, kinetic energy ranges from 29.7 MJ to 28.2 MJ (90The peak current in all cases was 94–96 MA and the implosion time was about 5 μs. Interestingly, while the load-isolating switch is essential for the fast implosion systems, calculations with this switch closed for all time in the slower application show nearly the same coupled kinetic energy and the same time of implosion referenced from the beginning of flux compression. Clearly the imploding cylinder must carry current for a substantially longer time when the closing switch is eliminated, however. Finally the circuit parameters allow the opening switch to reach a higher resistance than has previously been observed. Limiting the resistance rise to a factor of 200 (consistent with several reported high-current experiments) reduces the coupled energy by about 10%.

Representative High Energy System

Generators for high-energy applications can be designed using any of the configurations in Fig. 1, and each configuration offers distinct advantages. The disk configuration has received attention in both the US and Soviet explosive pulse-power communities. Soviet scientists have reported combining relatively large, high-gain helical flux generators with very high current disk explosive magnetic generators (DEMGs), with remarkable results.[10,11] At Los Alamos, experiments have been performed using disk-like configurations,[12]. Because of the Soviet results, we have employed designs guided by their experience in our analysis.

The basic operation of a disk configuration employing sweeping detonation is shown in Fig. 6. The compression cavity is initially filled with magnetic flux from a 5-MA current flowing in the wall. Explosive (of perhaps complex shape) surrounds the compression cavity and is initiated on the axis so that the detonation wave sweeps radially outward collapsing the compression cavity from center line toward the outer radius. Current is taken at the outer radius of the system.

The contours in Fig. 6 describe the motion of the walls of the compression cavity as calculated by a phenomenological model created to analyze disk configurations. The model utilizes the elementary Gurney forumlation to calculate velocity of radial elements of the wall. An elementary acceleration profile based on shock transit time through the wall is used to modify the instantaneous acceleration derived from the Gurney formulation. From the time-varying shape of the cavity, an inductance is calculated. The inductance shown in Fig. 6 can be compared with the 20-μs linear inductance profile used in the scoping calculations. Using the time-varying inductance and an ad-hoc model for resistive losses, a circuit model calculates the current in the circuit, and from the current the magnetic field, which opposes the motion of the conductor, is calculated. The equations of motion are then integrated using both the Gurney velocity and the effects of magnetic pressure. Thus, the inductance is a function of not only geometry but current level as well.

The single biggest advantage of the disk configuration is its modular nature, which allows a number of elements to be connected in series[2]. With the output voltages added, very high currents at useful voltages can be realized. The drawback of many units is that the total quantity of explosive can become large. In Fig. 7, we explore ways to reduce the total explosive used in a representative system employing four modules. The left-most system is a baseline configuration with outer radius of 50 cm and run time of about 60 μs. It produces 100-MJ and 275-MA output current (into 2.7-nH load). The ad-hoc loss model suggests 86% flux efficiency and that 8% of the 1224 MJ of explosive energy is converted to electrical energy. In the middle configuration, the amount of explosive is approximately halved by thinning the intercavity spacing. The peak current is slightly reduced, and the efficiency almost doubles. However, the wall profiles begin to show evidence of flux pocketing, which will dramatically reduce performance. We conclude that we have reduced the explosive too much. In the right-most configuration, we have inserted an inert wedge in the explosive volume, removing almost 75% of the mass of explosive compared to the baseline configuration, but leaving enough explosive to smoothly compress the cavity walls. In this configuration, the current is reduced to 259 MA, the energy to 90 MJ, the run time slightly increased, and the efficiency increased to 30%. Most notably, the total explosive charge is only 60 KG — comparable to that currently used for 10 to 20-MJ helical systems.

Explosives with more modest performance have also been used in the calculational model, and replacing the high-performing PBX formulation discussed here with a much more modest explosive (nitromethane) resulted in a 10% degradation in energy, an 8% degradation in peak current, and a 40% increase in run time.

Complete hydrodynamic models (without magnetic pressure) have also been employed and the result of such a calculation is shown in Fig. 8. The phenomenological model and the hydromodel compare remarkably well.

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FIGURE I Configurations for High Energy Flux Compression Generators

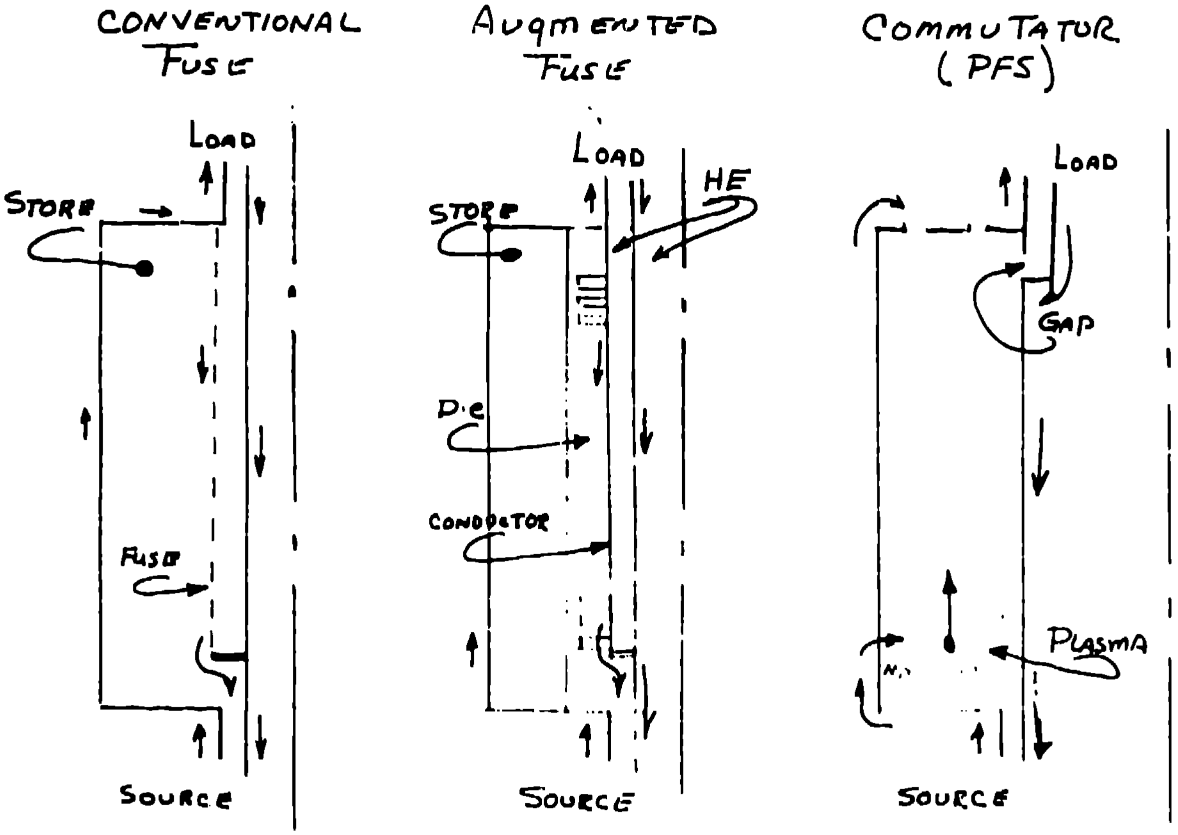


FIGURE 2 Configurations for High Current Opening Switches

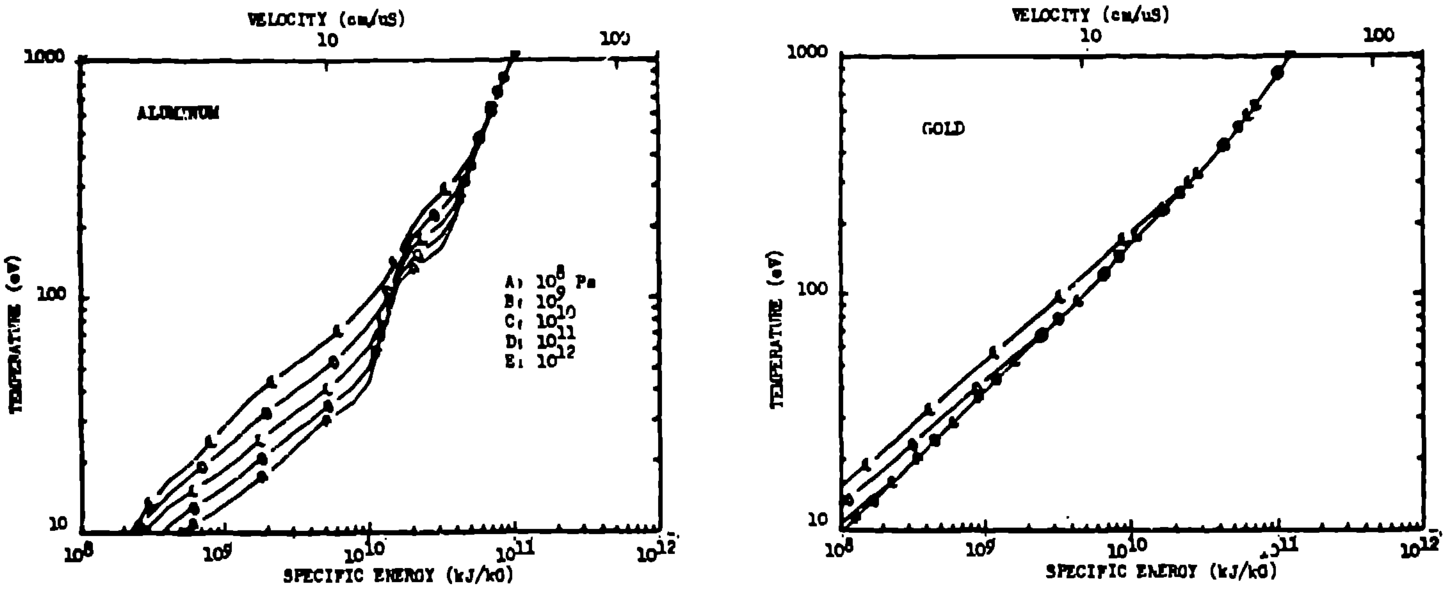


FIGURE 3 Plasma Temperature as a function of implosion velocity

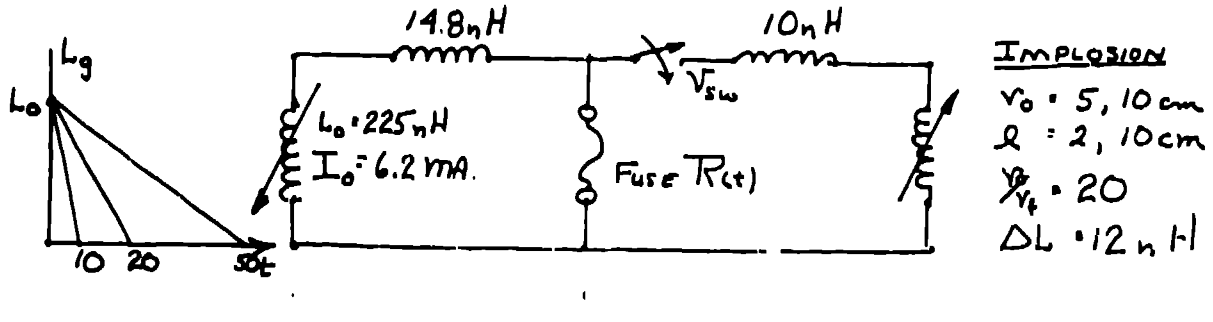


FIGURE 4 Circuit for Scoping Calculations

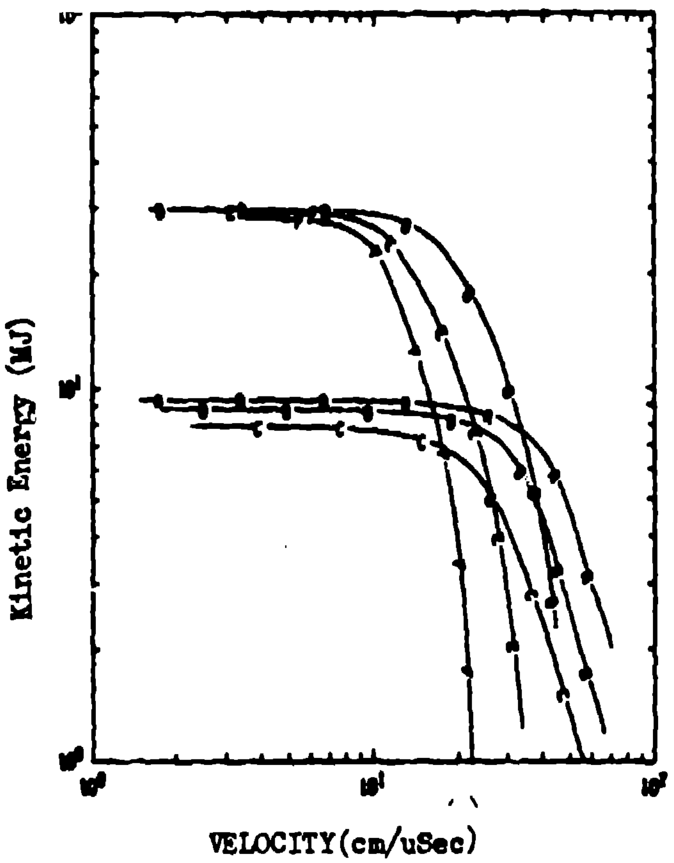


FIGURE 5 Kinetic energy coupled to implosions as a function of final implosion velocity.for generator run times of 10,20,50 uSec

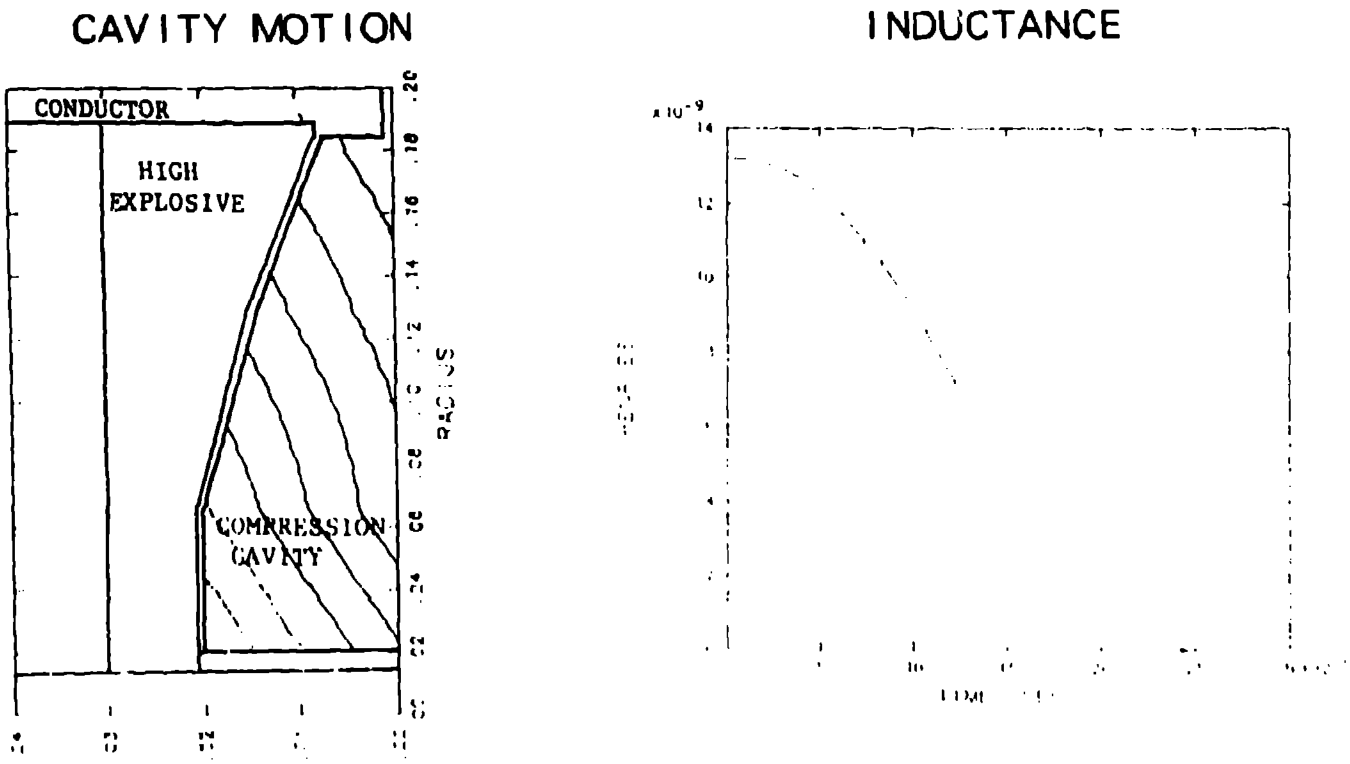
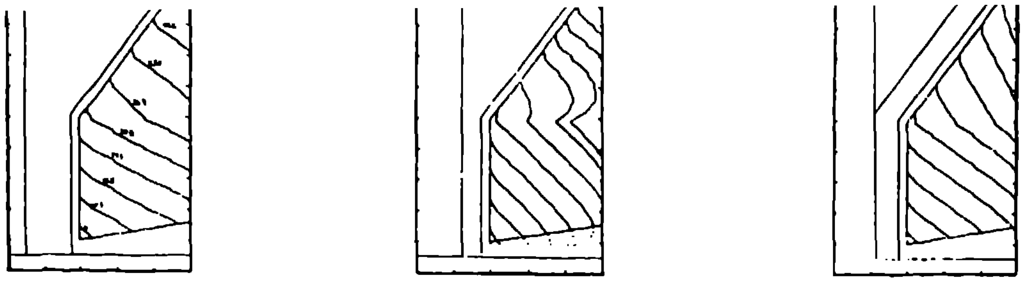


FIGURE 6 Disk Generator Operation



	NOMINAL	THINNED	SHAPED
EXPLOSIVE			
PER STAGE	61 KG	37 KG	14 KG
TOTAL, HE	245 KG	146 KG	59 KG
ENERGY, HE	1224 MJ	732 MJ	296 MJ
ELECTRICAL			
PEAK CURRENT	275 MA	267 MA	259 MA
PEAK ENERGY	101 MJ	96 MJ	90 MJ
TIME	58.8 μS	59.1 μS	59.7 μS
EFFICIENCY			
ELECT/HE	8%	13%	30%
FLUX	86%	83%	82%

FIGURE 7 Disk Generator/Explosive configurations

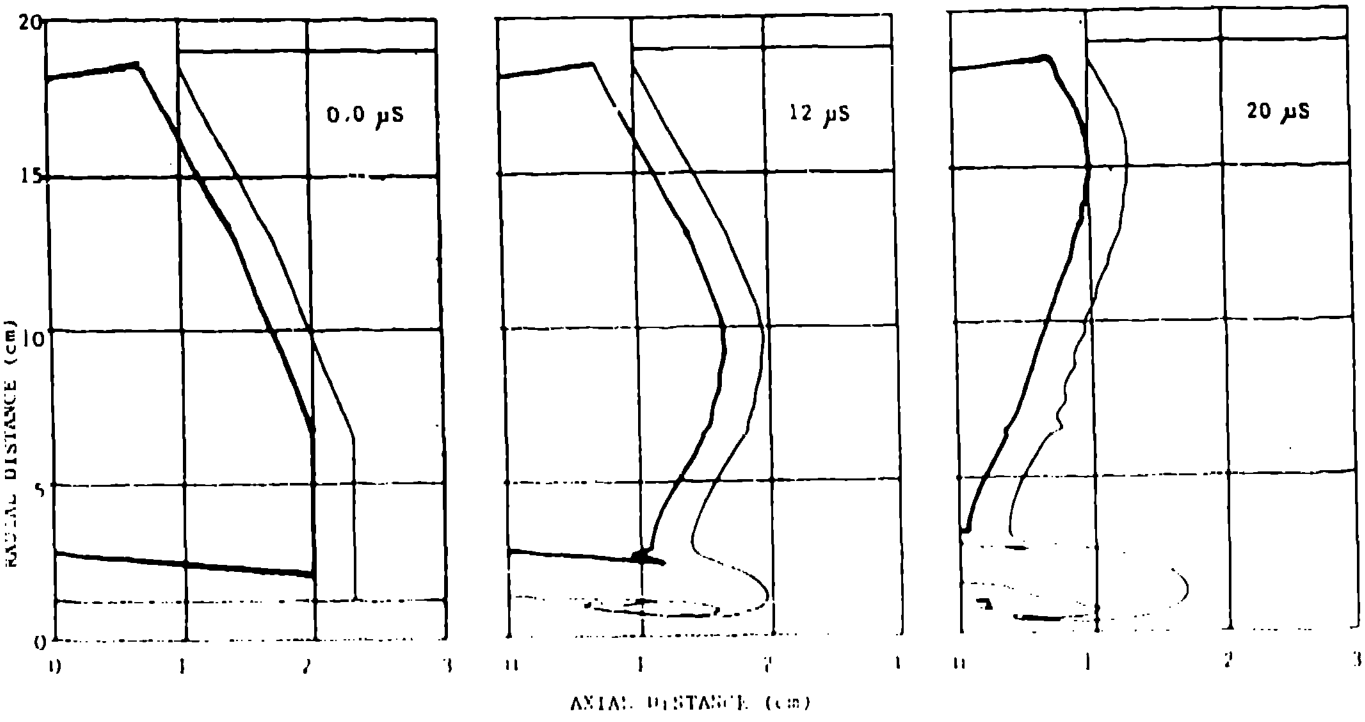


FIGURE3 Hydrodynamic Calculations of Generator Performance