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MULTI-MEGAMP, MULTI-TERAWATT INDUCTIVE PULSE COMPRESSION SYSTEM OPERATION

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ABSTRACT

Pulse power systems employing inductive store/opening switch technology represent attractive drivers for high energy, high power plasma experiments. Employing electrically exploding conductor (fuse) opening switches, an inductive pulse compression system has been built, tested and is in routine use as a power conditioning system charged by a 2 MJ capacitive primary store at the AFWL. The switch, interrupting 15-20 MA currents against 300-500 KV voltages decreases the risetime of the low impedence capacitor bank from 1.5 μS to 200 nS when operated into a 6 nH load. Detail measurement of resistivity of exploded foil fuses shows good agreement with resistivity data previously published for low energy, low power operation. The use of multiple staged fuses of different parameters offers the possiblility of further reduction in risetime, and/or increase in final resistivity of the "open" switch. The use of pulse shortening techniques permits conceptual and practical extension of simple, economical prime energy stores to larger energies without sacrifice of energy delivery time.

I. INTRODUCTION

Power sources capable of delivering large amounts of electrical energy at very high power levels are essential to many plasma physics experiments of interest in both energy and defense applications. Pulsed plasma loads typically display significant inductance in addition to the dissipative part of their impedence and circuits capable of delivering very high powers to inductive loads are of general interest to the plasma physics community. Conventional power systems, such as capacitive sources (including MARX and parallel banks) and pulse line sources all have fundamental constraints imposed by their circuit elements which limit the power they can deliver to an inductive load. For example, capacitive circuits are fundamentally limited in their energy delivery time, and hence in their power, by their characteristic $\sqrt{LC}$ time, while pulse line circuits are limited in the peak power which they can deliver by their characteristic line impedence.

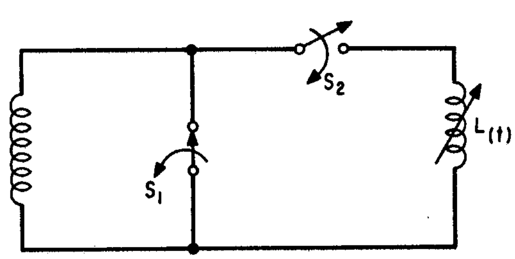

FIGURE 1. Inductive store/transfer circuit.

On the other hand, inductive sources in which energy transfer is effected by employing an opening switch, as in Figure 1, can, in principle, deliver very high powers to inductive loads with the power being limited by the performance; namely, the speed and the resistance, of the opening switch rather than by the fundamental circuit elements of the store and load.

In Figure 1, the opening switch may be considered to be a resistor rising instantaneously in resistance to a value of R_F. In this case, the current in the load is given by

$$I_L = \frac{L_s}{L_s+L_L} I_o \left(1 - e^{-\alpha t}\right)$$
$$\alpha = \frac{R_F(L_L+L_s)}{L_L L_s} \tag{1}$$

where I_o ,is the initially stored current. The power delivered to the load can be found from

$$P = L_L \dot{I} I = \frac{L_s}{(L_s+L_L)} R_F I_o^2 \left(e^{-\alpha t} - e^{-2\alpha t}\right) \tag{2}$$

And the power can be made arbitrarily large if the resistance of the switch, R_F , can be made sufficiently large independent of the initially stored energy, and the circuit elements of L_s and L_L. A similar analytic solution for the case of an opening switch which rises with a finite dR/dt (a ramp resistance) results in an expression for the power

$$P = \frac{L_s}{L_s+L_L} 2\dot{R} I_o^2 \, t\left(e^{-\beta t^2} - e^{-2\beta t^2}\right)$$
$$\beta = \frac{\dot{R}(L_L+L_s)}{L_L L_s} \tag{3}$$

In this expression the power can be seen to become arbitrarily large if sufficiently large values of dR/dt can be achieved. Thus inductive driving systems are seen to offer the possibility of delivering very high powers if opening switches of adequate performance can be developed.

At the Air Force Weapons Laboratory, electrically exploded conductor (fuse) opening switches have been investigated and have been shown to produce sufficiently large dR/dt and sufficiently high values of resistance, R, to allow the construction, test and operation of an inductive pulse compression system using a 2 MJ capacitor bank as the initial energy source. In the next section, we will describe the

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14. ABSTRACT
Pulse power systems employing inductive store/opening switch technology represent attractive drivers for high energy, high power plasma experiments. Employing electrically exploding conductor (fuse) opening switches, an inductive pulse compression system has been built, tested and is in routine use as a power conditioning system charged by a 2 MJ capacitive primary store at the AFWL. The switch, interrupting 15-20 MA currents against 300-500 KV voltages decreases the risetime of the low impedence capacitor bank from 1.5 wS to 200 nS when operated into a 6 nH load. Detail measurement of resistivity of exploded foil fuses shows good agreement with resistivity data previously published for low energy, low power operation. The use of multiple staged fuses of different parameters offers the possiblility of further reduction in risetime, and/or increase in final resistivity of the "open" switch. The use of pulse shortening techniques permits conceptual and practical extension of simple, economical prime energy stores to larger energies without sacrifice of energy delivery time.

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performance of the opening switch, and in the following section the design and performance of the inductive pulse compression system will be discussed. In the fourth section, a possible approach to improving switch and system performance will be described.

II. OPENING SWITCH

For single pulse operation driving very high energy density plasma loads, an electrically exploded conductor (fuse) opening switch is a simple and promising candidate. Using a series of 100 KV capacitor banks operating at energies between 100 KJ and 450 KJ, aluminum and copper foil fuses have been successfully operated. The results from low energy (100 KJ) operation have been previously reported (1). Using the circuit shown in Figure 2, fuse operation has been successfully extended to the 450 KJ level.

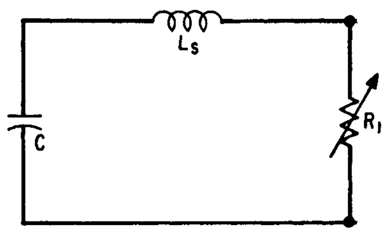

FIGURE 2. Capacitor bank fuse test circuit.

The fuse and storage inductor are packaged as shown in Figure 3. The primary insulation for the output voltage is a 0.125" polycarbonate sheet overlayed with 4 layers of .005" polyester film (Mylar). The fuse material is a .001" thick aluminum foil whose width, which is constant throughout its length, is adjusted according to the scaling principles outlined by Maisonnier in 1966 (2). The quench material surrounding the hairpin folded fuse foil is quartz sand (glass beads commercially available for "bead blasting") of nominally 60-100 microns diameter. Beads are contained in singly folded polyester film envelopes. Current connections to the ends of the foil are made by secure mechanical clamping. The entire fuse is assembled in place on the machine and confined by approximately 1" of moderate density polyurethane foam on each side to compress the package, absorb shock, and confine the beads. The entire assemble is situated between the output transmission lines of the system in a volume which also serves as the inductive store L_S.

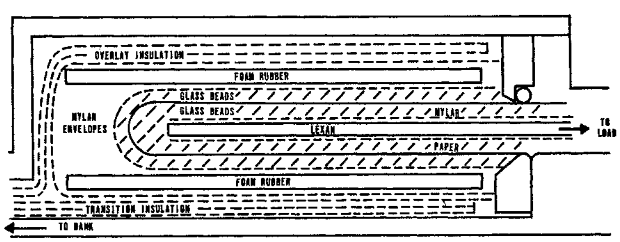

FIGURE 3. Fuse and storage inductor construction.

Fuses of length of 70 cm and width of 44 cm were operated at stored energies up to 300 KJ and discharge voltages of 90 KV, resulting in the interruption of 2.5 to 3 MA currents and the generating of nearly 0.5 MV output voltage, as shown in Figure 4. Using

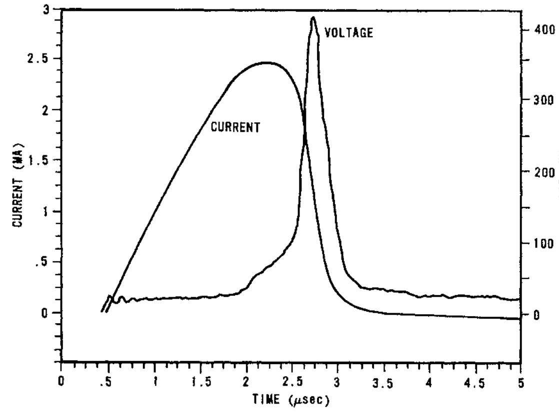

FIGURE 4. Current and voltage for aluminum foil fuse.

various fuse dimensions, electric fields in excess of 10 KV/cm were supported along the fuse during operation. Correcting for the inductive component of the voltage across L_F and careful time correlation of the data in Figure 4, allows determination of the resistance of the opening switch as a function of time. As shown in Figure 5, peak values of R of about 600 milliohms have been observed.

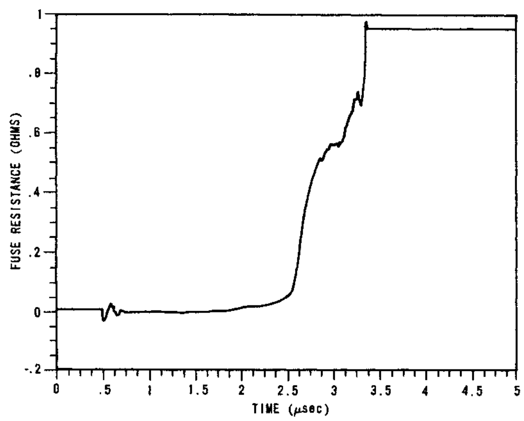

FIGURE 5. Fuse resistance for aluminum foil fuse.

Using Equation 2, an estimate can be made of the power which an inductive store system based on parallel scaling of such an opening switch could deliver to an inductive load. Observing that maximum energy transfer (but not maximum power) occurs when $L_S=L_L$, and that the time dependent exponential term in Equation 2 reaches a maximum value of 0.25, a factor of 4 scaling in current (to 12 MA) and resistance (to 150 milliohms) could give rise to powers of 2-3 TW.

III. HIGH ENERGY INDUCTIVE PULSE COMPRESSION SYSTEM

At the AFWL plasma implosion loads are under investigation as intense X-Ray sources (3). Because implosion loads display an initially inductive impedence followed by a rapid increase in both L and dL/dt, inductive store/opening switch drivers are ideally suited as power sources for such loads (4). An inductive store/ pulse compression system has been implemented on the 1.9 MJ SHIVA I' fast capacitor bank system using opening switches such as those described in Section II. The circuit shown in Figure 6 employes

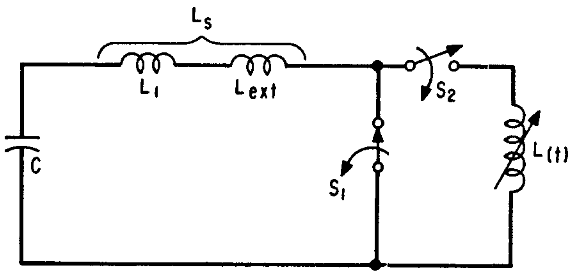

FIGURE 6. Inductive pulse compression system for driving imploding plasma loads.

the fuse as a low inductance switch initially shunting current past the SHIVA load (L(t)). The bank internal inductance L_1 is augmented by the addition of L_{ext} to meet the optimization criteria previously reported (4)

$$L_s^2 = L_o^2 + L_o \Delta L$$

where L_o is the initial inductance of the load and ΔL is the increase in the inductance of the load during the implosion. Four fuse assemblies similar to those described in Figure 2 are arranged around the central load region of the four armed SHIVA bank as shown schematically in Figure 7.

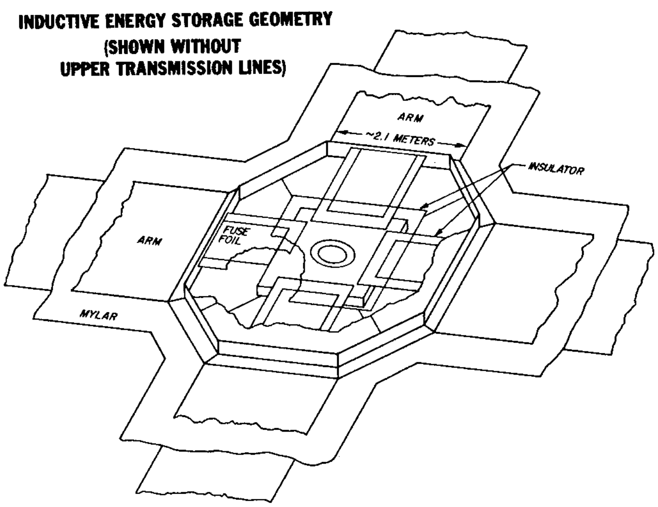

FIGURE 7. Schematic arrangement of fuses and load on SHIVA capacitor bank.

Low inductance solid dielectric switches shown in cross-section in Figure 8 are employed as S_2 to deliver energy to the plasma load. The dielectric switches, which operate in the self-breaking mode, consist of prestabbed layers of high density polyethylene with thicknesses from .060" to .090".

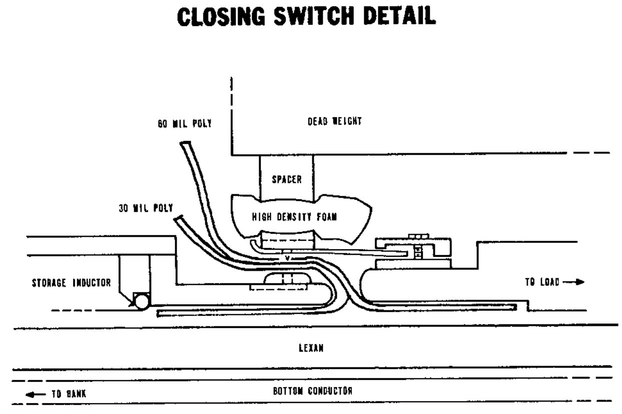

FIGURE 8. Low inductance closing switch construction.

The dielectric is stabbed .015" deep in circular patches with 6-8 sites on a 1 cm diameter per patch and 6-12 patches located along the 70 cm length of each of the 4 switches. The switches self break at 125-150 KV producing 5-10 current carrying channels per switch or a total of 20-40 channels around the circumference of the load region.

Experiments have been conducted in which current was delivered by the opening switch system to an aqueous dummy load characterized by an inductance of 5.8 nH and a resistance of 12 milliohms. As shown in Figure 9, voltages of approximately 300 KV were applied to the load as a result of the interruption of the 16 MA current by the fuse opening switch. Approximately 7.5 MA were delivered to the load with a 10% to 90% risetime of 190 nS.

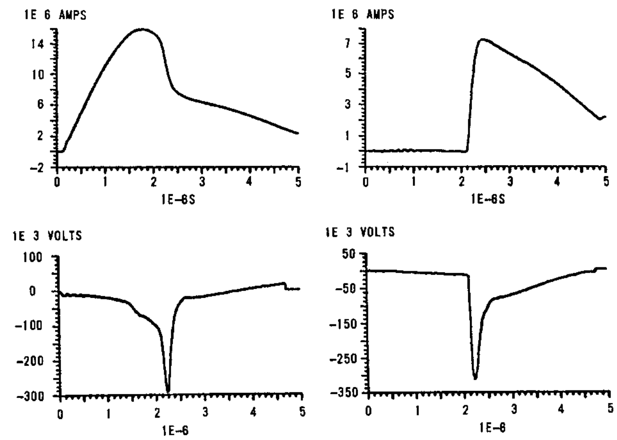

FIGURE 9. Voltage and current delivery to 5.8 nH, .012 OHM load.

In Figure 10, the power delivered to the dummy load is calculated from the voltage and current delivered to the load as shown in Figure 9, and shows a peak power in excess of 1.8 TW. The power delivered to the load by the inductive store/opening switch system can be compared with the power that could be delivered to the same load directly from the capacitor bank which has a capacitance of 266 μF and an internal inductance of 3.5 nH. The lower curve in Figure 10 is the calculated power that the bank would deliver directly to the same dummy load and shows a peak power of .70 TW. Coincidently, the series RLC circuit that results from the direct connection of the

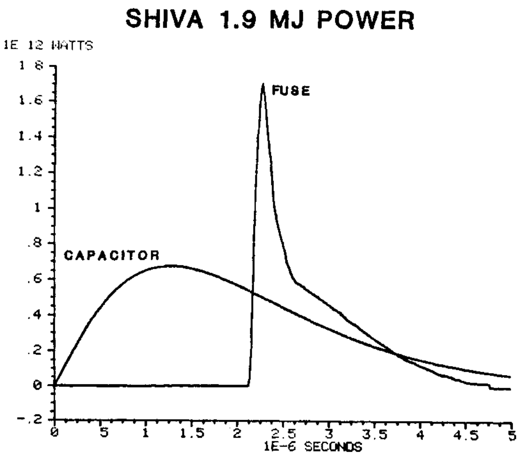

FIGURE 10. Power Delivery to a Resistive Load

load and the bank is very nearly a critically damped circuit and thus represents the case in which maximum power can be delivered to the resistive part of the load impedence. Figure 10 graphically demonstrates the increased performance achieved by an inductive store/opening switch. Not only is the delivery power a factor of 2.5 larger than that obtained directly from the capacitor bank but the risetime of the power peak is more than a factor of 10 less.

Figure 11 shows the current delivered to the dummy load by the inductive store/opening switch system as compared to the current delivered to a matched resistive load by the 1/2 ohm BLACKJACK V water insulated pulse line machine. The pulse line machine delivers a somewhat higher peak dI/dt but the current waveform also contains a significant prepulse which complicates a variety of plasma physics experiments. Prepulses are absent from the inductive store/opening switch current waveform.

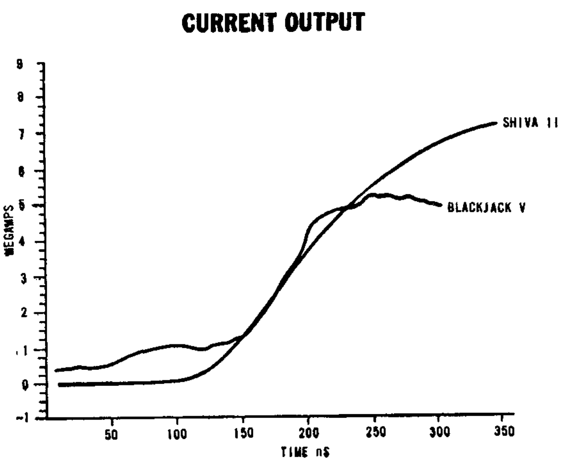

FIGURE 11. Output Current from Water Line and Inductive Pulse Power Systems

The parallel operation of a number of opening switches and closing switches raises the issue of the simultaneity of switch operation and the uniformity with which current can be delivered to the central plasma load. Figure 12 shows the result of a measurement in which current was delivered to a purely inductive cylindrical (but not imploding) load. The

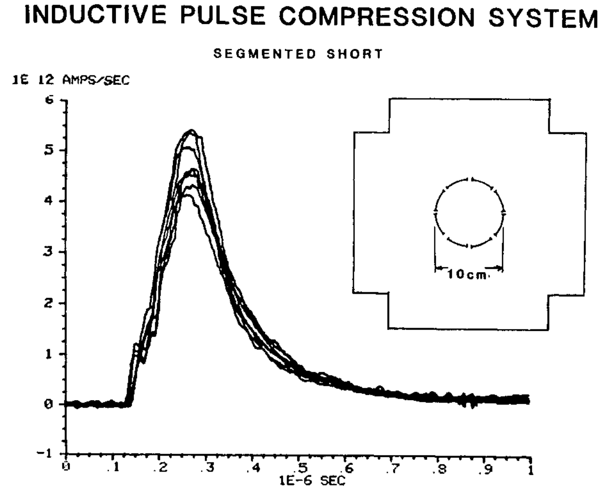

FIGURE 12. dI/dt delivered to eight section segmented short.

load was segmented into eight sections and current was measured using an independent Rogowski coil around each section. The figure shows an overlay of the eight raw dI/dt traces which measure the current in each of the eight sections. Time correlation is obtained by comparing fiducial marks on the traces and the figure shows a 20 nS scatter among the leading edges of the eight traces. This scatter (which represents about 5% of the full sweep) is comparable with the uncertainty of the digitizing process and suggests that the non-simultaneity of current delivery is less than 10% of the 200 nS current risetime. Detailed sensor and recorder calibration is expected to bring the amplitudes into closer agreement.

The inductive pulse compression system has been successfully employed to drive SHIVA imploding plasma loads. The plasma, initially 5 cm in radius and 2 cm tall, is produced by vaporizing a thin metal/plastic foil cylinder which is imploded in about 500 nS resulting in the voltage and current profile shown in Figure 13. Power delivered to the load exceeds 1.8 TW in a 500 nS FWHM pulse and energy of almost 800 KJ is delivered past the vacuum interface during the time of the implosion.

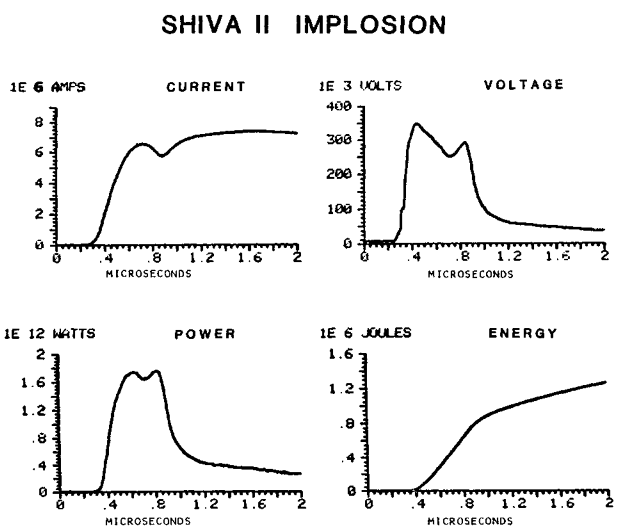

FIGURE 13. Power Delivery to a Plasma Implosion Load.

IV. SCALING

Significant advances in the energy density and performance of both capacitive and rotating primary energy storage systems have recently been reported (5), (6). The availability of very energetic, economical prime sources, coupled with the fundamental scalability of inductive pulse compression systems as described by Equations 2 and 3 make such systems even more attractive as drivers for next generation plasma experiments. Fuse opening switches have been shown to scale over several orders of magnitude of current and energy; and, in Section III, the use of parallel combinations of such switches in tight syncronization was demonstrated. Nevertheless, continued successful scaling to very high power systems hinges on the ability of such switches to deliver large values of R and dR/dt. System concepts in which such switches are paralleled to handle higher currents suffer from the obvious difficulty that parallel arrays result in lower effective switch resistance, and ways must be sought to improve swithc resistance if larger systems are to be contemplated.

The application of parallel staged switch systems in which the store current transfers from one switch to another on successively shorter time scales has been suggested as a possible approach to increasing R and dR/dt (7). By requiring each successive switch (fuse) to carry the store current for a shorter period of time, its cross section can be reduced (and its length increased), and thus its total resistance increased for a given material resistivity. However, the preceeding (low R) switch stages remain in the circuit shunting the later (high R) stages and no net advantage is gained unless the resistivity of the earlier stages can be improved. A possible mechanism for such improvement is the fact that when the current is transferred out of the earlier stages, the power dissipation in those stages drops dramatically, and, hopefully, without additional energy input, hydrodynamic and heat transfer processes may be able to decrease the conductivity of the medium.

To test this possibility, experiments were performed at the 300 KJ level using a circuit similar to that in Figure 6 in which the load inductance was replaced by another fuse opening switch. Parameters for the second fuse were chosen to divert current from the first fuse for 500 nS to 1 μS after the closure of S_1. The second fuse then bursts, reapplying voltage to the first fuse and enabeling a realistic measurement of the late time resistance of the first fuse.

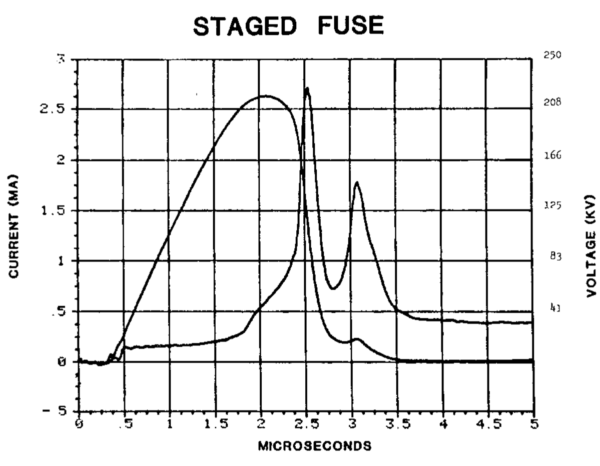

FIGURE 14. Voltage and Current through First of a 2 Stage Fuse System.

Figure 14 shows the voltage measured across the first fuse and the current through the first fuse during the charging of the store, during the first fuse operation, and through the time of second fuse operation. The figure shows that when voltage is reapplied to the first fuse, some current conduction is observed, but the ratio of current to voltage (R) is significantly higher during the second voltage peak than during the initial fuse operation.

Figure 15 compares the resistance of the first of the pair of fuses with the resistivity of a geometrically identical single fuse as a function of energy dissipated in the fuse resistance. The single fuse resistance is taken from the voltage and current data of Figure 4. Figure 14 shows identical early time (low specific energy) behavior of both fuses (as expected). But when the current is transferred away from the first fuse, its resistance continues to rise as compared with the resistance of the single fuse despite the dramatically reduced power input. While such resistance measurements can be suspect when relatively small currents are measured, the fact that very significant voltages are reapplied by the second fuse, without significant current conduction lend added credence to the resistance data.

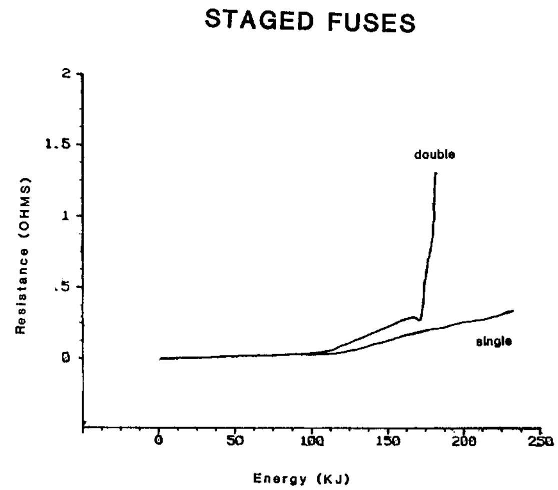

FIGURE 15. Resistance for Geometrically Identical Single and 2 Stage Fuses.

Based on the data of Figure 15, staged fuse techniques appear to be very promising candidates for providing the needed values of resistance to make more energetic inductive store systems possible.

V. CONCLUSIONS

Several major steps toward the development of very high power inductive energy storage and transfer systems have been made. Fuse opening switches have been demonstrated at energy levels up to 0.5 MJ and parallel fuse arrays have been operated with good simultaenity to the 2 MJ level. Energy transfer to both passive and plasma loads has been achieved. Measurement have been made on staged fuse systems which strongly suggest that the needed improvement in fuse resistance can be achieved using the staging technique.

VI. REFERENCES

1. R.P. Henderson, D.L. Smith, and R.E. Reinovsky, "Preliminary Inductive Energy Transfer Experiments", Digest of Technical Papers, 2nd IEEE International Pulsed Power Conference, Lubbock, Tx (1979).

2. Ch. Maisonnier, J.G. Linhart, and C. Gourlan, "Rapid Transfer of Magnetic energy by Means of Exploding Foils", Rev. Sci. Instrum., 37, (1966) p 1380.

3. W.L. Baker, et al, "Electromagnetic Implosion Generation of Pulsed High Energy Density Plasma", J. Appl. Phys., 49, (1978) p 4694.

4. D.L. Smith, R.P. Henderson, and R.E. Reinovsky, "Considerations For Inductively Driven Plasma Implosions", Digest of Technical Papers, 2nd IEEE International Pulsed Power Conference, Lubbock, Tx (1979).

5. D.L. Smith and R.E. Reinovsky, "High Energy Density Capacitor Evaluation", Proceedings, 3rd IEEE International Pulsed Power Conference, Albuquerque, NM (1980).

6. R.D. Ford, D. Jenkins, W.H. Lupton, I.M. Vitkovitsky, "Pulsed High Voltage and High Current Outputs from Homopolar Energy Storage System", NRL Memorandum Report 4433, (1981).

7. D. Conte, R.D. Ford, W.H. Lupton, and I.M. Vitkovitsky, "TRIDENT - A Megavolt Pulse Generator Using Inductive Energy Storage", Digest of Technical Papers, 2nd IEEE International Pulsed Power Conference, Lubbock, Tx (1970).