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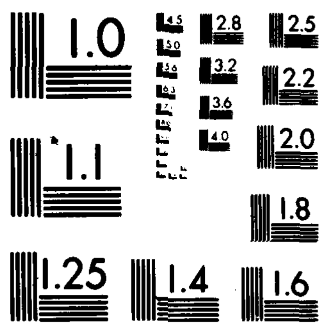

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ELECTROMAGNETIC LAUNCHERS: BACKGROUND AND THE MRL PROGRAM

Yong-Chia Thio

Approved for Public Release

MARCH, 1982

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ABSTRACT*

An active R. & D. program is being undertaken into the technology of electromagnetic launchers. These have potential applications in weaponry, controlled thermonuclear fusion, space launch, advanced industrial processes, equation-of-state research, generation of intense magnetic fields and as facilities for a wide range of studies in penetration mechanics, detonation, and warheads. This paper draws attention to these matters and gives a description of the current Australian DSTO program in the development of this technology.

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ABSTRACT

An active R. & D. program is being undertaken into the technology of electromagnetic launchers. These have potential applications in weaponry, controlled thermonuc[illegible] fusion, space launch, advanced industrial processes, equation-of-state [illegible]h, generation of intense magnetic fields and as facilities for a wide r[illegible] studies in penetration mechanics, detonation, and warheads. This [illegible] draws attention to these matters and gives a description of the current Australian DSTO program in the development of this technology.

CONTENTS

ELECTROMAGNETIC LAUNCHERS : BACKGROUND AND THE MRL PROGRAM

1. INTRODUCTION

Two basic modes have been considered for launching projectiles to very high velocity (up to several hundreds of km/s) by the use of electrical and magnetic forces. One consists of using the interaction of a travelling magnetic wave with a permanent or an induced magnetic dipole. The other makes use of the interaction of a magnetic field with a current in a rail-type system. A substantial program to investigate the scientific and technological feasibility of electromagnetic launchers and to develop such a technology is being sponsored and monitored by the U.S. Defense Advanced Research Projects Agency (DARPA) and the U.S. Army Armament Research and Development Command (ARRADCOM). Current interest in the technology was aroused by (a) a recent assessment by DARPA and ARRADCOM of the state of the supporting electrical and material technologies [1], (b) a highly successful experiment conducted at the Australian National University (ANU) during the early 1970's, and (c) the high rewards which may eventuate from a successful development of an electromagnetic propulsion technology.

In this report the background to the subject of electromagnetic launchers is discussed in terms of their potential applications, both military and non-military, their potential advantages and the history of the subject. This is followed by a description of the Australian Defence Science and Technology Organisation (DSTO) program in electromagnetic launcher technology which is being pursued at the Materials Research Laboratories (MRL). The Australian DSTO program is devoted to investigating the problems of developing rail-type electromagnetic launchers using a plasma as the driving armature. The critical problems associated with the development of this type of launcher are identified. The theory developed at MRL for these launchers is outlined and results obtained from the theory for a typical case are presented. An outline of the experimental program being pursued at MRL is then given. The report deals principally with rail-type accelerators; extensive discussions of travelling magnetic wave accelerators can be found in Kolm et al [2], O'Neil and Kolm [3], Chilton [4], Wipf [5], Chen [6] and Burgess [7].

2. POTENTIAL APPLICATIONS

1. Military. Electromagnetic launchers have been examined for application as tactical weapons in surface, anti-aircraft and anti-missile defence [1,8] and as means of speedy transportation of military supplies [1]. The thorough evaluation of their military potential remains a subject of active current investigation. Much shorter time of flight between launcher and target can be achieved with projectiles or warheads launched by electromagnetic launchers. This should prove to be a great advantage in anti-missile applications (e.g. in defence against sea-skimmers), and in surface-to-air and air-to-air combat. Further discussion of potential advantages of these weapons is given in Section 3. Strategic applications of electromagnetic launchers could be very attractive including the launching of inter-continental ballistic missiles.

   For military R. & D., they can be used as hypervelocity facilities for: (a) penetration mechanics studies, (b) detonation studies, and (c) simulation of attack of explosives by projectiles and warheads of different type and geometry.

2. Space applications. Theoretically, electromagnetic propulsion could provide an economical method for launching huge payloads into space [11-14] and for the disposal of nuclear waste into the sun. It has also been considered for reaction engines for propelling space-craft [15,16]. The launchers could also be used as experimental facilities for simulating atmospheric re-entry of space-craft and the impact of meteorites with space-craft and planetary bodies.

3. Industrial applications. Electromagnetic launchers have the potential capability of producing economically, reliably and in a controllable manner, rapid pulses of concentrated kinetic energy. They could make possible a wide range of new and advanced industrial processes such as high-pressure fabrication of industrial diamonds, isentropic powder compaction, high-speed cutting, drilling and tunnelling. The power sources developed in the program may be applied to welding and metal forming.

4. Equation-of-state research. The equation of state of certain materials has been studied experimentally and theoretically for pressures up to 0.5 TPa. For extremely high pressures, above 10 TPa for most materials, one may apply the Thomas-Fermi-Dirac equation of state, which is obtained from quantum mechanical calculations assuming all the atoms of the materials to be completely stripped of their electrons under the extreme pressure and densities. In between 0.5 TPa and 10 TPa is a range of pressures for which there are very few theoretical models which have the same degree of rigour, nor are there direct experimental data on the equation of state. Pressures in this range may be achieved by shock impact at velocities up to 50 km/s with materials such as tantalum or copper. By measuring the velocity of the shock front and of the particles in the material during the impact and using the

Hugoniot-Rankine relationships, the equation of state of the shocked material can be determined [18]. The problems of carrying out such experiments using railguns were examined recently by Hawke et al [17].

5. Generation of very intense magnetic fields. Very intense magnetic fields can be generated by the method of magnetic flux compression [19,20]. This involves the use of conductors moving at extremely high velocity. To attain fields above 10 kilotesla, which would represent a significant advance in the state of the art, conductors such as copper moving at velocities in excess of 50 km/s are required. Intense magnetic fields play a significant role in high-energy particle physics, in solid-state physics, in plasma physics and in materials science [19-21].

6. Refuelling of a Tokamak fusion reactor. If such a reactor should be developed, frozen deuterium-tritium pellets will have to be launched into it at sufficiently high velocity (approximately 10 km/s) so that they will not evaporate before they reach the centre of the reactor.

7. Impact fusion - Thermonuclear fusion temperature may be reached by hypervelocity impact between macro-objects due to heating by shock and adiabatic compression. Though detailed theoretical analysis remains to be done, global estimates suggest that about 1 GJ of fusion energy may be produced when a projectile with a layer coating of a heavy element such as tantalum, possessing approximately 10 MJ of kinetic energy and travelling at about 200 km/s, strikes a frozen deuterium-tritium pellet 1 cm^3 in volume [9,10].

3. ENVISAGED ADVANTAGES

Electromagnetic launchers may have significant advantages over their chemical counterparts in some or all of the applications mentioned above. The following are some of the considerations:

1. So far no fundamental problems have been perceived for such accelerators to launch projectiles with velocities up to several hundreds of km/s, and cheaply [22,23].

2. It is not necessary for the primary energy of EM systems to be in chemical form. If chemical propellants or explosives are not used to power them, electromagnetic launchers could be made to be much less vulnerable than their chemical counterparts.

3. Being electrical, they are intrinsically more controllable than chemical ones. Muzzle velocity would be more controllable. Targeting would be more accurate.

4. Electromagnetic systems have an intrinsic capability for high repetition rate of firing because the breech can be open. Also a second projectile can be fired before the first leaves the barrel.

5. In electromagnetic systems, projectile acceleration can be made more uniform than in chemical systems. Injection of energy can be spread over the whole length of the barrel, thus reducing the peak pressure in the barrel for a given muzzle velocity.

4. A BRIEF HISTORY

Documented history of the concept of employing electromagnetic forces for propulsion dates at least as far back as 1916 [24,25]. Experimental research on railguns began during World War II when Hansler of Germany launched a 10-g projectile to a velocity of 1 km/s in 1944 [26]. The concept was investigated in the UK after the war. General Electric of USA launched a mass of 0.1 lb to a velocity of 1800 ft/s in 1957 [27]. Brast and Sawle accelerated 30 mg to 6 km/s in 1964 [28]. Chapman, Harm and Sorenson achieved 9.5 km/s with 210 mg in 1963 [29]. Adams accelerated a 300 mg cube to 3 km/s in 1970 [30]. All of the last four used a railgun system.

Though some of these experiments were only partially successful, many of the results were indicative of the soundness of the broad principles involved. A highly successful experiment followed at the Australian National University [31,32] where a 3-g projectile was accelerated to 6 km/s with a railgun system. The experiment used, for the first time in railgun experimentation, a homopolar generator as the source of primary energy and a large storage inductor for pulse conditioning. The promising features and success of this experiment, together with active programs at MIT and Princeton on travelling magnetic wave launchers induced DARPA and ARRADCOM to access the timeliness of the supporting electrical and materials technology for, and the potential benefits of, a substantial R. & D. program in electromagnetic propulsion. This took place in the latter half of the 1970's. Major programs are now under way in several institutions including Westinghouse Research Center, Los Alamos National Scientific Laboratory, Lawrence Livermore National Laboratory, University of Texas, ARRADCOM, Ballistics Research Laboratory, Massachusetts Institute of Technology, Princeton University and Materials Research Laboratories [3, 33-44]. In this period, the group at Lawrence Livermore and Los Alamos has jointly launched a projectile of 3.1 g to 5.5 km/s and 165 g to 0.35 km/s [33]. That group also believes that velocity up to 10 km/s was achieved in one of their launchings with a 3.1-g projectile though the integrity of the projectile could not be established. A major program is in progress at Westinghouse to launch a projectile of 300 g to 3 km/s [34].

5. THE AUSTRALIAN DSTO PROGRAM

The Australian DSTO program on electromagnetic propulsion is devoted to investigating the problems of developing rail-type accelerators using a plasma as the driving armature. The simplest version of such an accelerator consists of a pair of conducting rails connected to a power source; an arc (the plasma armature) provides an electrical short between the rails. The current in the rails produces a strong magnetic field which acts on the plasma producing a force which is used to accelerate a projectile (Figure 1). Presently, the critical areas requiring investigation are as follows.

1. Dynamics of the plasma armature, an understanding of which is the key to many of the engineering and materials problems of the railgun.

2. Problems of segmentation -- for very high velocity and high efficiency, the accelerator needs to be segmented so that energy can be injected at more than one point along the length of the accelerator. This reduces resistive losses and the amount of energy trapped in the inductance of the circuit.

3. Problems of materials -- the metallic rails tend to be damaged by the arc. The plasma can induce chemical processes such as ion implantation of the dielectric separating the rails leading to degradation of electrical insulation between the rails. The high temperature of the plasma itself is a cause of many materials problems. Refractory materials such as ceramics may have to be considered for the barrel as well as the projectile.

4. Power source -- advanced pulse-power energy storage and conversion systems are being investigated by various institutions for application to railguns. These include homopolar generators [34,36,37], magnetic flux compression generators [38], magnetoplasmadynamic generators [39,40], and pulse-power nuclear generators [41]. At MRL, in conjunction with Monash University, the use of a pulse transformer is being investigated; the primary of the transformer is connected to high-performance batteries and the secondary is used to power the gun. The idea is to interrupt abruptly a steady current in the primary and allow the magnetic energy stored in the primary windings to collapse into the secondary inducing a current in the secondary. Chemical batteries have very high energy density, but the energy can be drawn only at a very slow rate. The pulse transformer converts this chemical energy into a concentrated intense pulse of current.

5. Tribophysics at hypervelocity.

6. Exterior ballistics at hypervelocity.

7. Terminal effects of hypervelocity projectiles.

Our program at present involves studies in the first five areas listed above.

6. THEORETICAL INVESTIGATIONS : PLASMA DYNAMICS AND RAILGUN SIMULATION

Analysis of the behaviour of the plasma armature in rail-type electromagnetic launchers was first given by McNab [42]. This was extended to the next order of approximation by Powell and Batteh [43]. These studies were primarily steady-state analyses and did not embed the plasma model in a railgun simulation code. Independently and almost concurrently, work began at MRL towards the formulation of a comprehensive dynamic theory for modelling the performance of plasma-armature rail launchers [44]. In the formulation developed at MRL, the state of the plasma is allowed to vary with time in a quasi-stationary manner, and the model developed for the plasma armature is incorporated as a component of a larger theoretical framework for simulating the operation of rail-type electromagnetic launchers. A descriptive outline of the theory follows; the mathematical details will be presented elsewhere.

6.1 Outline of the Theory

We begin with Maxwell's equations of electrodynamics. Using a lump-element approximation to the equations, the system is divided into 4 elements: the power source, the bus-bars, the rails and the plasma. For each element, a model is developed from which the electrical impedance of the element is calculated. The impedances are combined in the equation governing the electrical circuit. Combined with the equation of motion for the projectile, the system of equations is now complete and may be integrated numerically. The outcome is a computer simulation code for the operation of plasma armature rail accelerators (PARA).

Approximate models for power source, bus-bars and rails exist and are adequate for the present purpose. The element which required substantial modelling development was the plasma.

Figure 2 shows the overall structure of the plasma model used. Starting with the equation of magnetohydrodynamics and the equation of state, the pressure distribution within the plasma can be calculated if the temperature is known. The temperature is calculated from the equation of radiative heat transfer. Knowing the temperature, the degree of ionization can be determined. The three aspects, pressure within the plasma, its temperature and degree of ionization then completely specify the dynamical state of the plasma.

From this, the volume of the plasma can be determined. Combined with the degree of ionization, the average electron density can be found. From the temperature and the electron density, the conductivity of the plasma can be determined. Knowing the conductivity and the volume allows the electrical impedance of the plasma to be specified.

A second line of calculation which makes use of a knowledge of the gas pressure leads to the determination of the force on the projectile. Two cases need to be considered. The first is the case in which the plasma is completely confined by magnetic pressure and stands clear of the breech. In this case the forces acting on the plasma are purely electromagnetic. The second is the case in which the plasma is in contact with the breech. The breech adds a secondary pressure to the plasma as the plasma expands thermally; very much like the explosive effect of a conventional gun. Both the electromagnetic and explosive effects are incorporated in our theory.

Actually, the system of equations formulated from the framework are implicit and are combined with the equations from the other parts of the system before integrations of the equations are made.

The following assumptions are made:

(1) Electrons, ions and neutral particles are assumed to share the same temperature at a given instant of time.

(2) The degree of ionization in the plasma at any time may be calculated from Saha's equation.

(3) A magneto-fluid-dynamical approach is used to determine the interaction of the electromagnetic field with the plasma.

(4) The electrical conductivity of the plasma is calculated using the expressions of Spitzer and of Schmidt. Both these expressions assume strong ionization and ignore the presence of a magnetic field.

(5) All field quantities are assumed to vary only in the direction parallel to the rails, i.e. a 1-D model is adopted.

(6) The current density and the temperature are assumed uniform throughout the plasma.

(7) Effects due to viscosity are neglected.

(8) The force required to accelerate the plasma is vanishingly smaller than the force accelerating the projectile.

(9) The mass of the plasma is assumed constant.

Assumptions (1) and (2) are valid if the time-scale for the thermalisation of the plasma (i.e. the time required for the Maxwellisation of the velocity distribution of all the particles) is very much smaller than the time-scale of the effects to be investigated. Assumption (3) is appropriate if the Debye length for collective behaviour is very much smaller than the system dimensions. As for assumption (4), since electrical resistivity is a manifestation of the collisional processes among the particles, the presence of a magnetic field can be ignored only if the cyclotron frequency of the charged particles induced by the magnetic field is very much smaller than the collision frequency of the particles.

Since the thermalisation time, the Debye length, the cyclotron frequency and the collision frequency can be readily calculated, the validity of assumptions (1)-(4) can be checked a posteriori.

Assumptions (5), (6), (7) and (9) are made for reasons of mathematical simplicity. The consequences of assumption (5), i.e. a 1-D model, are far reaching: many plasma dynamical effects can be overlooked as a result of this assumption. The absence of boundary layers between the moving plasma and the rails is a particularly obvious one. As for assumption (9), the mass of the plasma may increase due to vaporisation of the metallic rails, the dielectric between the rails, and the projectile. It may decrease due to recombination at the plasma tail or through escape around the projectile. It is thought, however, that further refinement of these assumptions can be most effectively made only after some experimentation has been conducted to check the results of the present simple model.

Assumption (8) is valid so long as the mass of the plasma is much smaller than that of the projectile.

6.2 Results

Results of the computations from PARA can broadly be divided into 3 classes. The first pertains to overall system performance and includes in-bore dynamics of projectile, overall performance of the electrical circuit, partition of energy, and gas pressure at projectile, rails and breech. The second class of results give macroscopic properties of the plasma such as plasma temperature, length, volume, resistivity, resistance, voltage, radiation intensity, radiation pressure, specific heats, coefficient of compressibility and acoustic wave speed. The third class provides microscopic properties of the plasma such as degree of ionization, electron density, cyclotron frequency, collision frequency, Debye length, plasma frequency and thermalisation time.

A description is given below for some of the results obtained in the case of a railgun powered by a capacitor bank of 10 000 μF charged to a voltage of 14 kV (Figure 6). At this voltage, the bank contains nearly 1 MJ of energy. It is connected in series with an inductor of 6 μH. The projectile is a 1-cm cube of polycarbonate (Lexan) with a mass of 1.2 g. To its back is attached an aluminium foil which is 25 μm thick. The gun has a closed breech and the projectile is placed 5 cm from the breech. The current is turned on with a triggered spark gap. It explodes the aluminium foil creating a plasma behind the projectile. The capacitor bank is equipped with a crow-bar switch which shunts the capacitor when the voltage across it falls below zero. After the crow-bar switch is closed, the circuit behaves like an inductively driven LR circuit. A drop of 10 V is allowed for each plasma-solid interface in the circuit. A fixed resistance of 5 mΩ is allowed for the resistance of the spark gaps and joints in the circuit.

The velocity of the projectile reaches a value of 10 km/s in 560 μs. This can be achieved with a barrel 2.4 m in length. The current reaches a peak of 435 kA in 330 μs and falls off gradually to 300 kA after 560 μs. In a similar manner the magnetic flux density in the region between the rails just behind the plasma increases to a value of 26 tesla and falls off to 18 tesla in the same period. The barrel and the projectile experience a maximum pressure of 290 MPa (Figure 3) when acceleration of the projectile reaches a peak of 2.8×10^7 $m.s^{-2}$.

Across the plasma, a resistive voltage drop of 390 V is reached at about the same instant as the current peak (Figure 4). This is calculated using Spitzer's expression [45] for the plasma resistivity. If Schmidt's expression [46] is used, the value is much higher (640 V). The temperature of the plasma rises to 43 000 K but drops to 32 000 K as the current decreases. The plasma is strongly ionised for most of the time. The length of the plasma varies between 1.8 cm and 5.2 cm (Figure 5). Despite the variation in temperature and the consequent variation in the resistivity, the total resistance of the plasma varies only very slightly with an average value of 1 mΩ. This is so partly because the resistivity of the plasma is low when the temperature is high; this occurs when the current is high, at which time the confining magnetic pressure is also high and so the plasma section is short, with the result that the reduction in resistivity is compensated by a smaller cross-section of the plasma through which the current passes.

For most of the time, the thermalization time for all the particles is less than 1 ns, very much smaller than the time-scale of events we are interested in. This validates our earlier assumptions of equal temperature for the various particles in the plasma and the use of Saha's equation for calculating the degree of ionization. Similarly, the Debye length which is less than 1 μm throughout the period of interest is much less than the system dimensions, thus an MHD approach is appropriate. The cyclotron frequency which is a measure of the influence of the magnetic field on the motion of the electrons has a maximum of 5×10^{12} Hz whereas the maximum collision frequency is slightly beyond 9×10^{13} Hz. These values make the present case just at the limit of applicability of Spitzer's or Schmidt's expression for the resistivity of the plasma.

Overall, these results show that the model is theoretically self consistent. A principal use of the theoretical results has been in the planning and design of our experimental program and apparatus. Results from the experiments should lead to validation of the theory and further development where necessary.

7. EXPERIMENTAL INVESTIGATIONS

Experiments are being carried out in 3 energy ranges: (1) up to 50 kJ, (2) between 50 kJ and 500 kJ, and (3) above 500 kJ. We hope to study and characterise some of the practical problems in developing rail-type accelerators using plasma armatures for launching projectiles at velocities up to 10 km/s.

7.1 *Energy up to 50 kJ : RAPID*

Our first step is to conduct a series of small-scale experiments on the plasma in a railgun-like device which we call RAPID, meaning Railgun Armature Plasma Investigation Device. The electrical circuit is schematically shown in Figure 6.

A bank of capacitors is connected via a set of bus-bars and a triggered spark-gap switch to an inductor and a pair of copper rails which are enclosed in two slabs of polycarbonate bolted together. The length of the barrel varies between 10 cm and 50 cm. The capacitor bank varies between using two 60-μF capacitors and eight 200-μF capacitors and may be charged between 3 kV and 10 kV. At its maximum capacitance of 1600 μF and charged to 8 kV the bank provides 51.2 kJ of energy. The bank is equipped with a crow-bar switch (see Section 7.2). The inductance of the inductor can be varied between 3 μH and 12 μH. The current is controlled not to exceed 100 kA by more than 10%.

The bore is a rectangle of 6 mm x 8 mm with 8 mm being the separation between the two rails. Projectiles are cuboids 6 mm x 8 mm x 8 mm or 6 mm x 8 mm x 6 mm and are made of polycarbonate (Lexan) or vulcanized cellulose fibre.

A Rogowski belt is used to measure the current. Voltage probes are placed at the capacitor terminals, at the breech, at the muzzle and, in future, at one station along the rails between the breech and the muzzle. Out-of-bore velocity is measured with break-wire screens. A fibre optics system is being developed for in-bore diagnostics.

High-speed optical photography is used to capture events throughout the barrel. A transparent barrel was selected with this in mind. The device enabled us to produce the first pictures of the plasma armature in railgun operations.

7.2 *Between 50 kJ and 500 kJ : ERGS-1*

This uses the same electrical circuit, same bore size and same projectiles as RAPID, but a larger energy supply in the form of a capacitor bank of 10000 μF chargeable to 10 kV with a maximum energy storage of 500 kJ. Distributed energy injection is envisaged and a current up to 300 kA is expected. For the initial segment, the capacitor bank is connected in series with an inductor of 6.5 μH and a triggered spark gap which serves as the main switch. The crow-bar switch consists of a fuze wire sitting in a gap between two copper-tungsten electrodes each of which is connected to a terminal of the capacitor bank. Between each end of the fuze wire and a terminal of the capacitor bank is connected a low-current rating, hence cheap, diode (e.g. LA80) which conducts just as the capacitor voltage reverses to produce a small current which is nevertheless large enough to explode a fuze wire. The plasma created by the fuzing of the wire causes the gap between the two copper-tungsten electrodes to break down thus providing the required path for the current to by-pass the capacitor bank. The exploding of the fuze wire breaks the diode circuit and thus protects the diodes from being damaged during the operation.

A cylindrical geometry was adopted for ERGS-1, since it makes more effective use of the materials in containing the very large bursting stresses involved than, say, rectangular ones. A disadvantage of this geometry lies in the difficulty of extracting the rails after firing. A pair of copper-cadmium rails are backed by 2 pieces of alumina ceramic and two more pieces set them apart (Figure 7). The assembly is then potted in epoxy reinforced by silica. Finally the barrel is wound with Kevlar fibre in epoxy. The design is in fact very similar to the one used by the LANSL-LLNL group [33].

Structural design was aided by finite-element analyses. In the course of these analyses, it was found that the nature of the bond between horizontal surfaces of ceramic pieces backing the rails and the silica-epoxy mixture has a significant effect. The stronger the bond, the greater is the stress concentration in this region and the more likely is failure of material. Ideally, the interfaces here should be sliding surfaces. But the method of fabrication makes the introduction of some bonds here inevitable. A compromise is chosen and the design specification is for a bond strength in these regions not exceeding 5 MPa, so that under the operating conditions, these bonds will break and the surfaces will behave as sliding surfaces.

Experimentation with a prototype of ERGS-1 has begun and results will be reported shortly.

7.3 Above 500 kJ : ERGS-2

Besides being an experimental setup for investigational purposes, ERGS-2 has been conceived as a modest demonstration railgun, and as a laboratory launcher with sufficiently high performance to make it an interesting ballistic facility for penetration-mechanics studies. It provides the first opportunity in our program to explore and test fairly advanced design concepts. It uses a bore of 1 square centimetre. A barrel 5 m long which may be segmented and an input energy of 500 kJ is planned at this stage, but total energy up to 1 or 2 MJ may be used at a later date.

The circuit and the mode of operation are similar to those for RAPID and ERGS-1. Like ERGS-1, it is envisaged that the detailed design and implementation of ERGS-2 will be an evolutionary process using results from the total experimental program.

The design concept for the barrel of ERGS-2 (Figure 8) seeks to exploit the potential of modern materials such as ceramics and fibre composites, and in such a way that the production processes are not too formidable.

Alumina ceramic is used around the rails and the bore to provide good electrical insulation and to resist the high temperature of the plasma. The ceramic is split at a suitable angle to release the tension which otherwise would be transmitted to the ceramic sections in between the rails. Tensile stresses within the ceramic pieces are thus minimised. Tensile stresses are absorbed by filament-wound Kevlar fibre epoxy composite which has high tensile strength. The compressive and tensile properties of the two materials, ceramic and fibre composite, are thus exploited in a complementary manner. Again, the design was accomplished with the aid of finite-element analysis.

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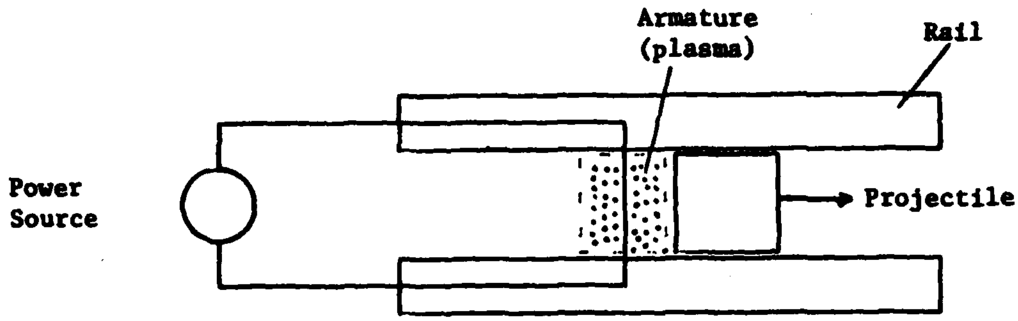

FIGURE 1. Basic configuration of a plasma-armature rail-launcher

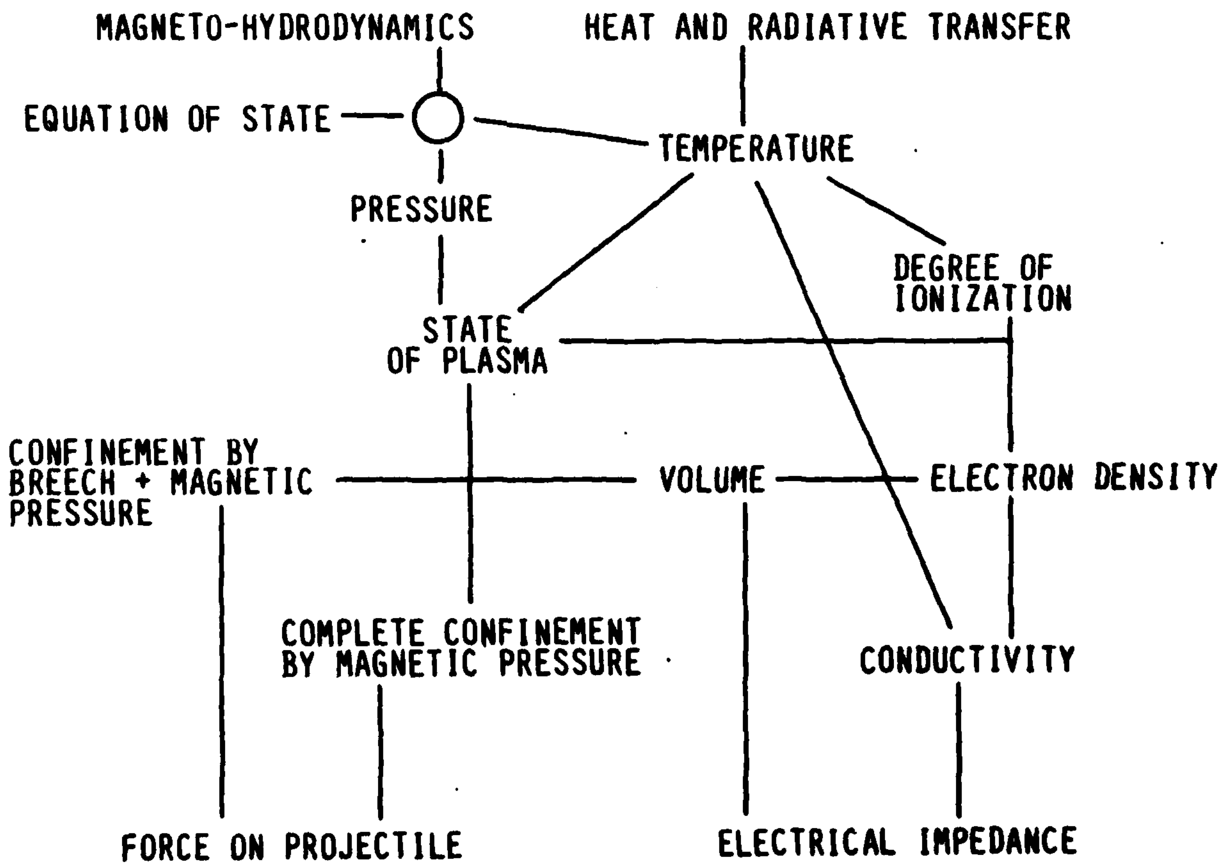

FIGURE 2. Structure of the Theoretical Model of the Plasma

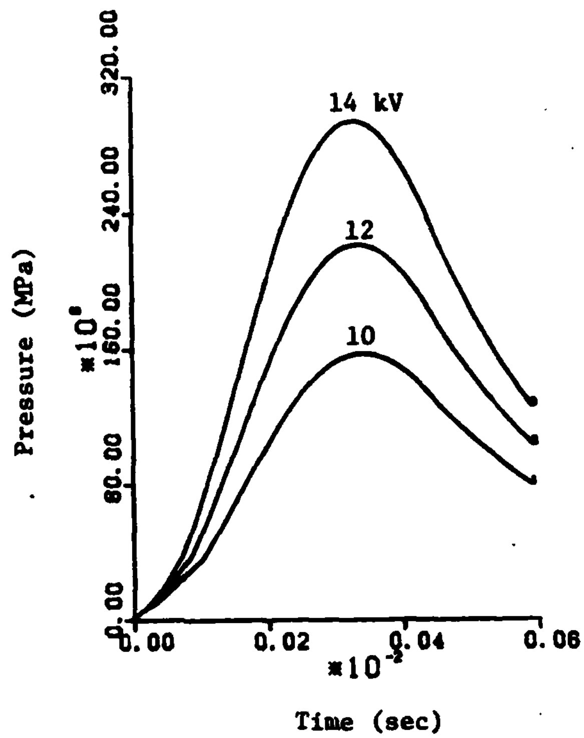

FIGURE 3. Plasma pressure at the projectile

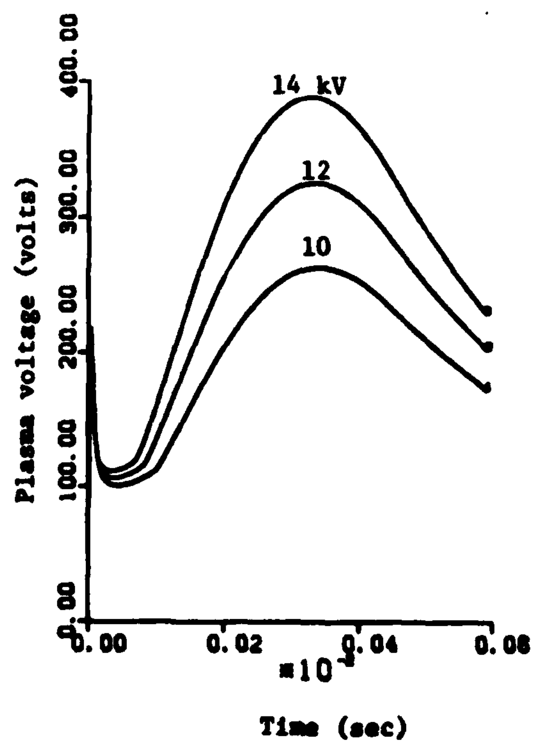

FIGURE 4. Resistive drop across the plasma

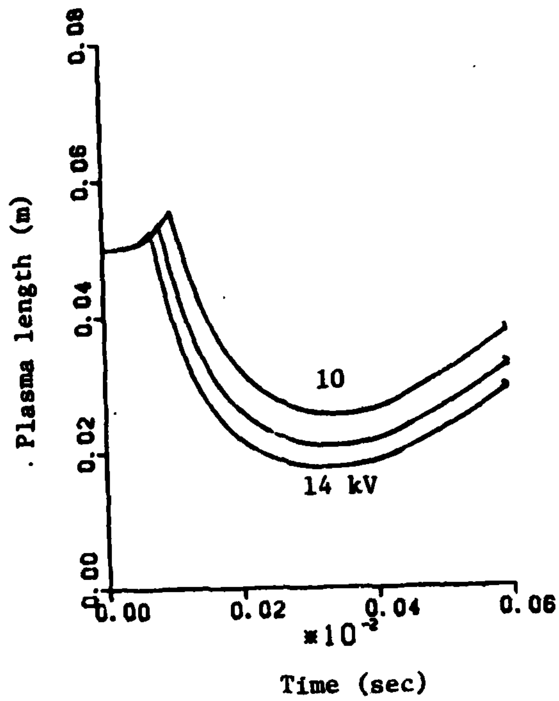

FIGURE 5. Length of the plasma

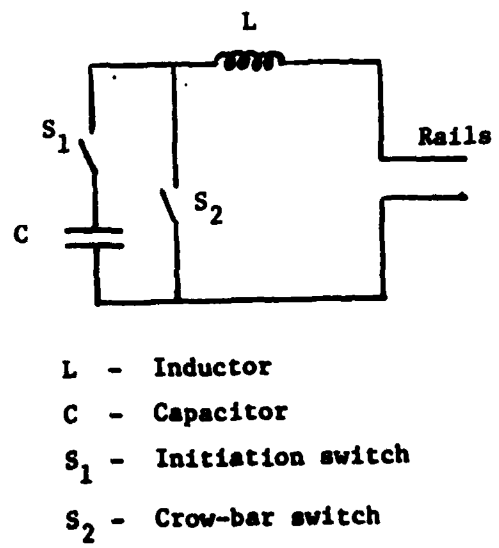

FIGURE 6. Schematic of RAPID and ERGS

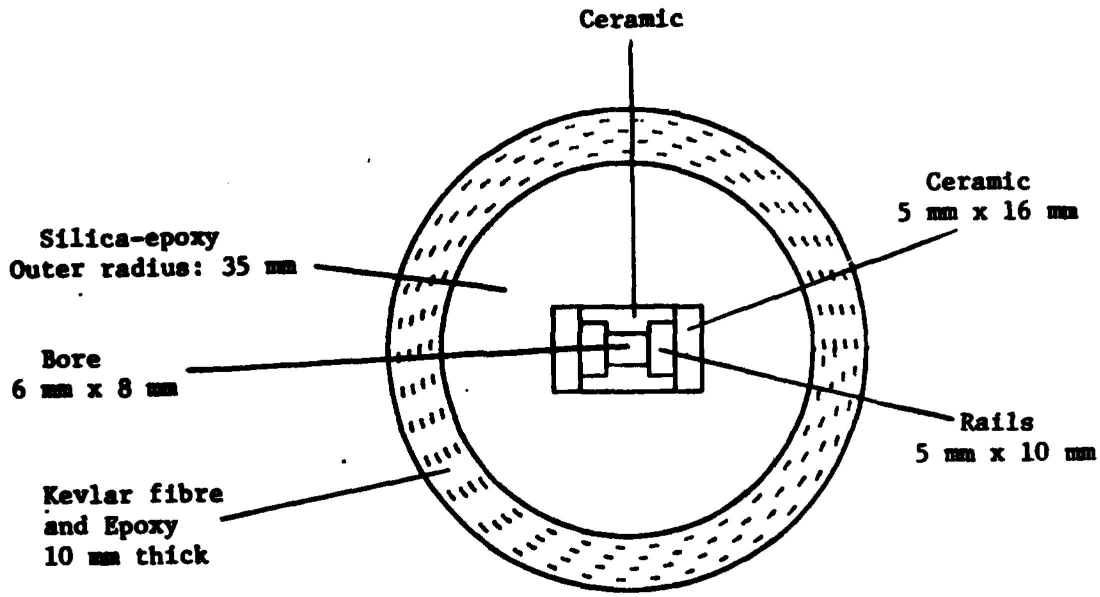

FIGURE 7. Cross-section of barrel: ERGS-1

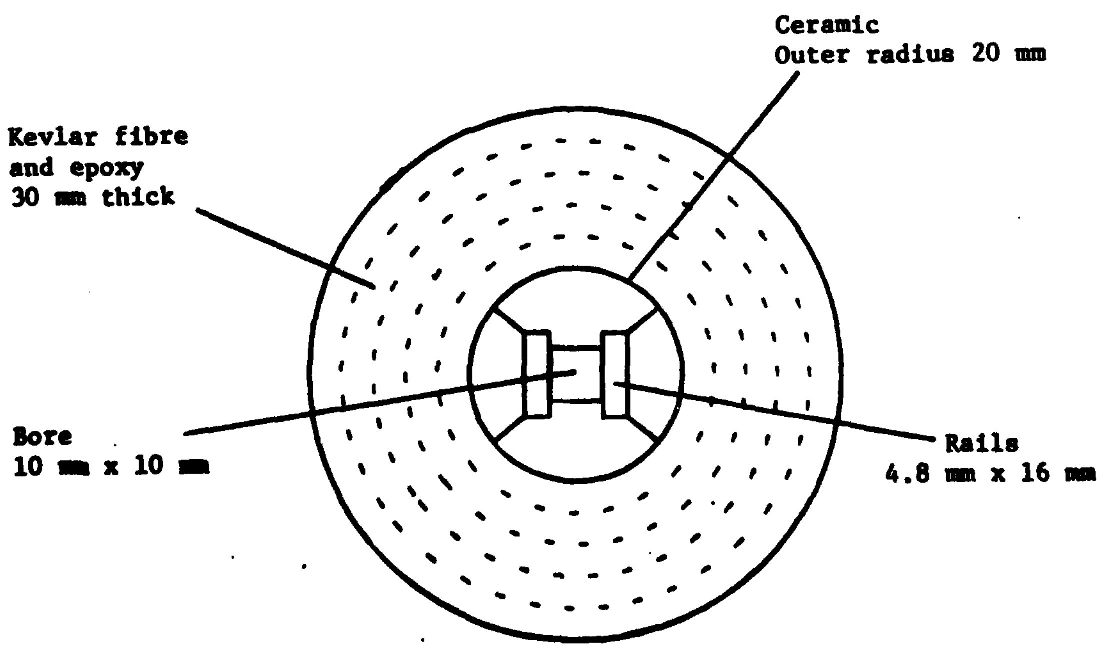

FIGURE 8. Cross-section of barrel: ERGS-2

(MRL-R-828)

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