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ELECTRIC CARTRIDGE GUNS USING FLUIDS HEATED BY A CAPILLARY PLASMA JET - AN EXTENSION OF CLASSICAL GUN TECHNOLOGY TO HIGH VELOCITIES

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CONTENTS

1. INTRODUCTION

GT-Devices is developing a gun technology in which electrically driven cartridges are used to fire projectiles at hypervelocities using conventional design reusable gun barrels (Figure 1). The technology is essentially an extension of classical gun technology. Its features are summarized below and discussed in more detail in the sections that follow.

The cartridge device makes use of a high impedance capillary plasma jet situated inside the cartridge or breech block. This enables electrical energy to be efficiently injected into a relatively cool low atomic weight propelling fluid. The cartridge can be driven by various power supplies such as a capacitive pulse forming network, homopolar-inductor system, or compulsator. Pulse shaping of the delivered power can be designed to maintain a nearly constant pressure projectile acceleration compatible with the barrel strength. Further, since the propelling fluid can start out in the projectile acceleration cycle at liquid densities, kilobar pressures can be achieved with low fluid temperatures at early times when the projectile dwells near the barrel entrance. The fluid temperature is then increased with time as higher sound speed is needed to maintain pressure on the projectile base during its acceleration along the barrel, thereby minimizing barrel ablation as required for rapid fire guns. Finally we note that since the cartridge has a high impedance of typically $\sim 0.1\Omega$, relatively low currents (only a few 10^5 amps) suffice to couple the required power levels into the gun. Thus, low mass transmission lines can be used to convey this power to the gun from power supplies located at a convenient distance.

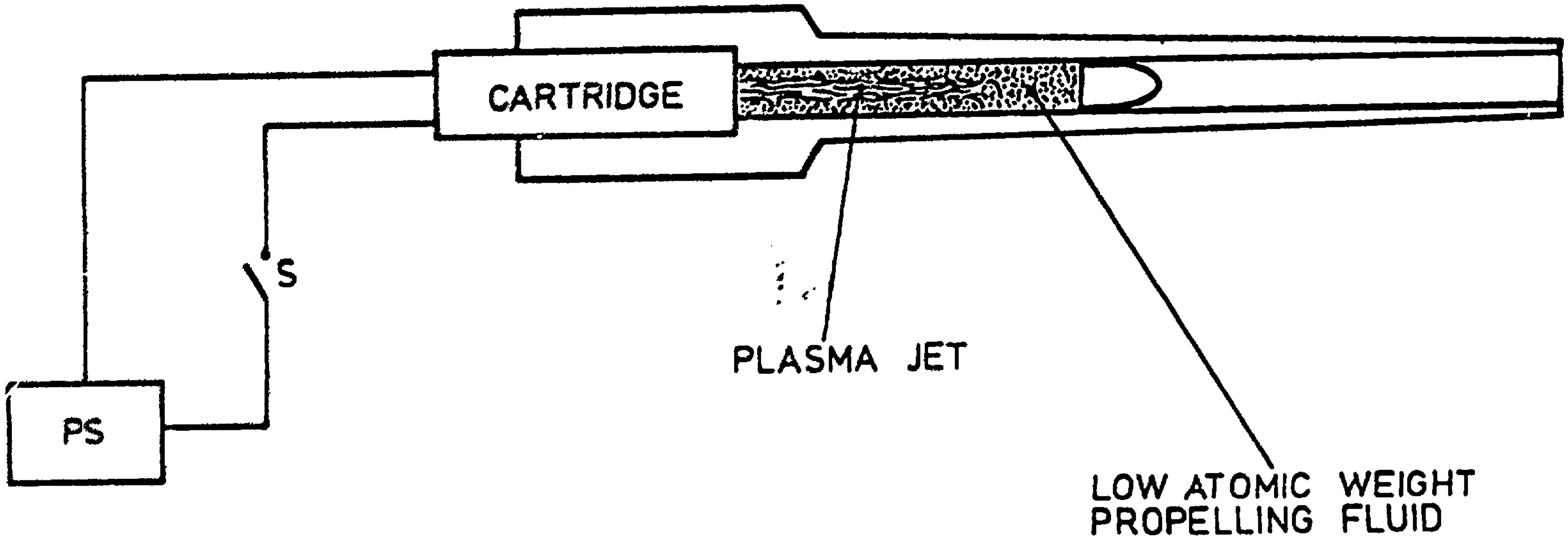


Figure 1

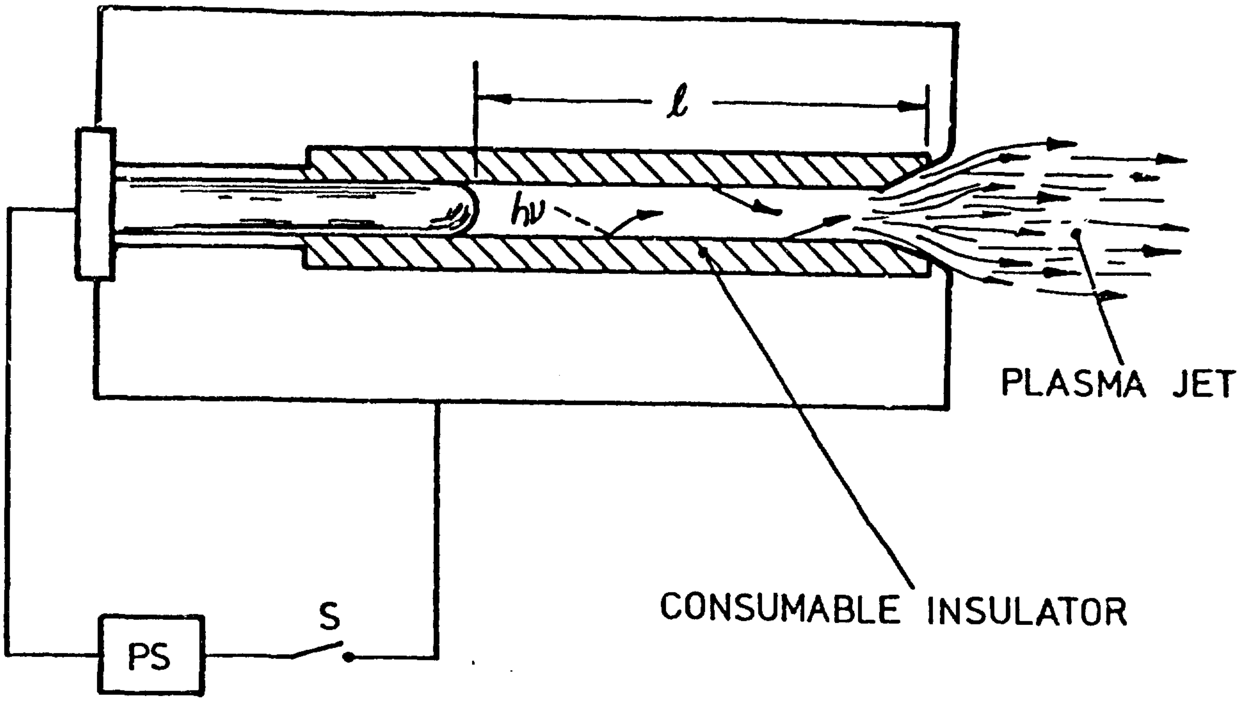
An electrically driven cartridge inserted into a gun breech

The plasma cartridge gun is a close relative of classical guns because it uses existing gun technology and solves the problem of introducing electrical energy into the propelling fluid. Presently fielded guns depend on high energy density exothermic propellants to provide high pressure gases in the chamber and barrel during projectile acceleration. An extensive literature(1) exists on the interior ballistics of these guns, which are efficient reliable devices for projectile velocities below about 2 km/sec. However, sound speed limitations of the 2-phase mixture of burning propellant grains and gaseous combustion products result in a rapid decline in gun efficiency for higher velocities. In this hypervelocity range it thus becomes attractive to use electrical energy generated outside the gun to heat conveniently packaged low atomic weight propellants inside the gun.

2. THE CAPILLARY PLASMA JET AS A HIGH IMPEDANCE ENERGY COUPLER BETWEEN ELECTRICAL POWER SUPPLIES AND PROPELLING FLUIDS

2.1 Capillary Plasma Jet

The device works by establishing a confined discharge channel along the elongated path between a nozzle anode and cathode as shown in Figure 2. The capillary geometry is chosen to give a high resistance ($\sim 0.1\Omega$). Ohmic dissipation, therefore, efficiently transfers energy from the power supply into the plasma which in turn streams out of the nozzle with high velocity directed flow. Simultaneously, plasma is replenished by radiative ablation of the dielectric wall confining the discharge, thereby maintaining the jet. Since the plasma typically consists of dissociated ionized polyethylene with a temperature of



CONSUMABLE WALL CAPILLARY PLASMA JET

Figure 2

Ohmic dissipation in the capillary discharge transfers energy from the electrical store into the plasma with an efficiency approaching 100% since the discharge functions as a simple resistor in the circuit. This energy is then partitioned between plasma pressure, dissociation, ionization energy, and streaming kinetic energy as plasma is ejected through the nozzle. Energy transport to the wall, principally by radiation, simultaneously abaltes polyethylene, thereby providing additional plasma to maintain the discharge. Ablatable fillers are sometimes placed inside the discharge channel to increase the plasma mass production and channel resistance. A large fraction of the plasma internal energy is available for fluid heating if the plasma jet is cooled by mixing with a dense fluid outside the capillary.

several* eV, it has a sound speed > 10 km/sec and thus flows rapidly out of the capillary.

The electrical resistance of a capillary discharge of length ℓ(cm) and radius a(cm) is

$$R = \frac{1.7\ 10^{-3} \ell\ Z\ \ell n\Lambda}{a^2 T_{eV}^{3/2}} \left(1 + \frac{\nu_{eo}}{\nu_{ei}}\right) \text{ ohms,} \tag{1}$$

where T_{eV} is the plasma temperature in eV inside the capillary, n_e(cm^{-3}) the electron density, Z the mean ion charge state, and $\ell n\Lambda$ is typically ~2 for our parameters of interest.(2) The electron-neutral scattering frequency ν_{eo} is comparable with the electron-ion scattering frequency ν_{ei} for temperatures near 1.5 eV. Consumable wall capillary discharges can be operated over a wide parameter range of length scales, radii, temperatures, and power levels. From the above formula it is clear that a resistance of ~0.1Ω is easily attainable.

For the particular case of a capillary operated in a steady state, or for cases in which the current varies slowly on the time scale 2ℓ/(plasma sound speed), a simple model can be used for the device. Ohmically heated plasma flows out of the capillary and also radiates black body radiation to the dielectric channel wall causing evaporation of material that sustains the discharge plasma. (Note, for kilobar pressures at a few eV, these plasmas are optically thick.) The analysis relates the plasma temperature to the current I(amps):

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*1 eV ≡ 11,600 °K

$$T_{eV} = 1.8 \left(\frac{I}{10^5}\right)^{4/11} \frac{1}{a^{6/11}} \left\{\frac{Z \ \ell n\Lambda}{S} \left(1 + \frac{\nu_{eo}}{\nu_{ei}}\right)\right\}^{2/11} \qquad (2)$$

Filler structures can be placed inside the discharge channel to increase the ablating surface area, and the factor S in Eq. (2) is the resulting area enhancement factor [total ablating area $/2\pi a\ell$]. This factor can for example be made $\sim 10^2$ by using a fill of small polyethylene spheres.

Initiation of the capillary discharge at atmospheric (or higher) pressure can be readily performed with a high voltage trigger pulse which sends an ionizing breakdown wave from the cathode to the anode with avalanching sustained by the strong tip electric field extending between the wavefront and the outer cylindrical return electrode.

2.2 Injection of Hot Plasma into Propelling Fluid and Pulse Shaping of Delivered Power

Figure 3 shows an arrangement in which a high pressure jet of hot plasma is fired down the axis into a low atomic weight fluid initially situated at the base of the projectile. Rapid turbulent mixing results in cooling of the plasma and heating of the fluid to temperatures of a few 1000 degrees (between a chemical hot shot, 3000°K, and light gas guns, 6000°K). Further protection of the gun barrel can be provided by silicone oil extruded from a capsule in the projectile,(3) as has been used in 20 mm guns, reducing the temperature of the gun barrel by 60%.

The capillary essentially plays the role of a high impedance coupling device that efficiently transfers energy from the electrical supply into the fluid which initially can start at liquid densities.

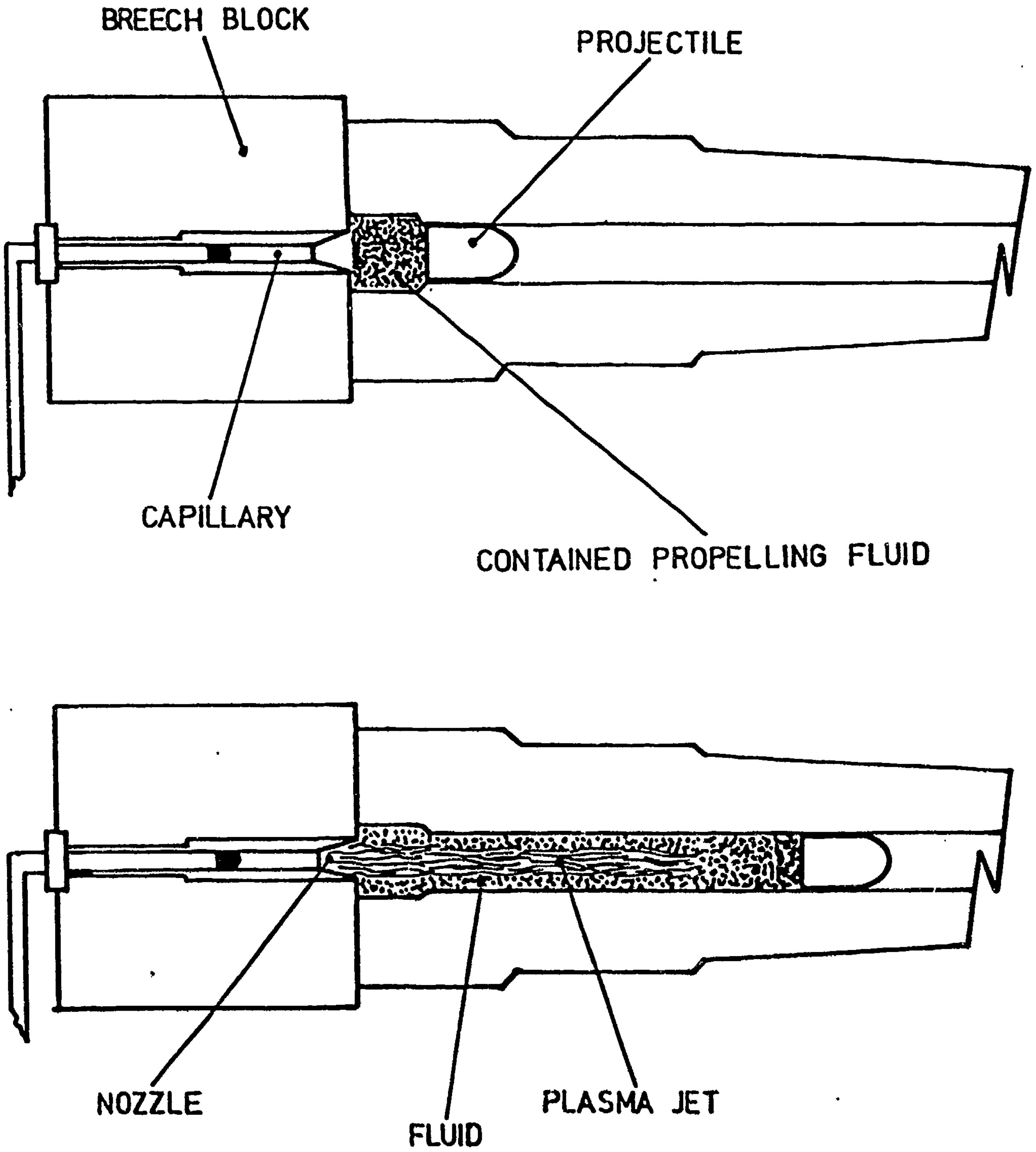


Figure 3

Schematic of a high temperature capillary plasma jet fired axially into cool propelling fluid. The high pressure jet is able to propagate a long axial distance with its average transverse pressure equal to the barrel propellant pressure. Turbulent mixing occurs along thejet propagation path which heats the propelling fluid to a few 1000°K, simultaneously cooling the plasma.

By configuring the power supply as a pulse forming network (PFN), power can be delivered to the propelling fluid with a controlled time dependence so that a constant pressure condition is maintained during the power pulse time. To illustrate the sort of requirements involved, consider an ideal gas propellant. As the projectile of mass M and area A accelerates along the barrel a distance $x = (AP/2M)t^2$ in time t, an energy $Ax\, P\gamma/(\gamma-1)$ must be supplied to maintain the constant pressure P. Thus power must be increased with $I^2R \sim t$. The dependence of I^2R, P, T, and projectile velocity V, are shown schematically in Figure 4 as functions of t for an ideal gas.

It should be emphasized of course that propelling fluids are not ideal gases. Also, pressure drops occur in barrels between chamber and projectile, and molecular co-volume effects influence the equation of state since we typically start at liquid densities. GT-Devices has developed computer codes that model the general interior ballistics including detailed equation of state data as well as codes for the PFNs required to power these guns. Using iterative methods the design parameters of the PFN and capillary can be self-consistently obtained.

At present, various choices for the propelling fluid are being studied using the above codes. These include (but are not limited to) H_2O, $CH_2(CH_3)_2$ (propane), CH_4, H_2, LiH, and typical efficiencies fall in the range of 20 to 40%. Partial dissociation of these materials into their low atomic weight constituents increases the sound speed of the propelling gas during projectile acceleration. Water in some semi-solid form will be experimentally investigated first in forthcoming experiments on the 0.5 Megajoule system. The choice of initial water

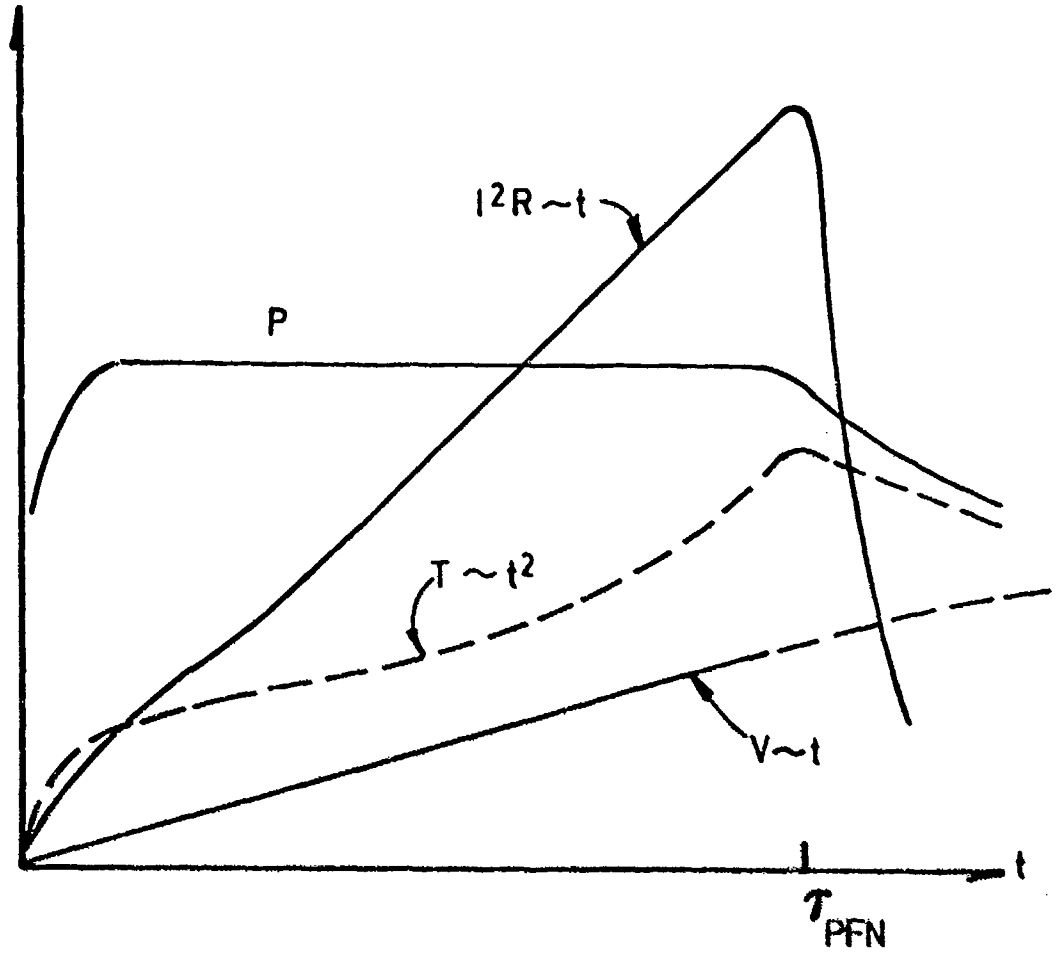


Figure 4

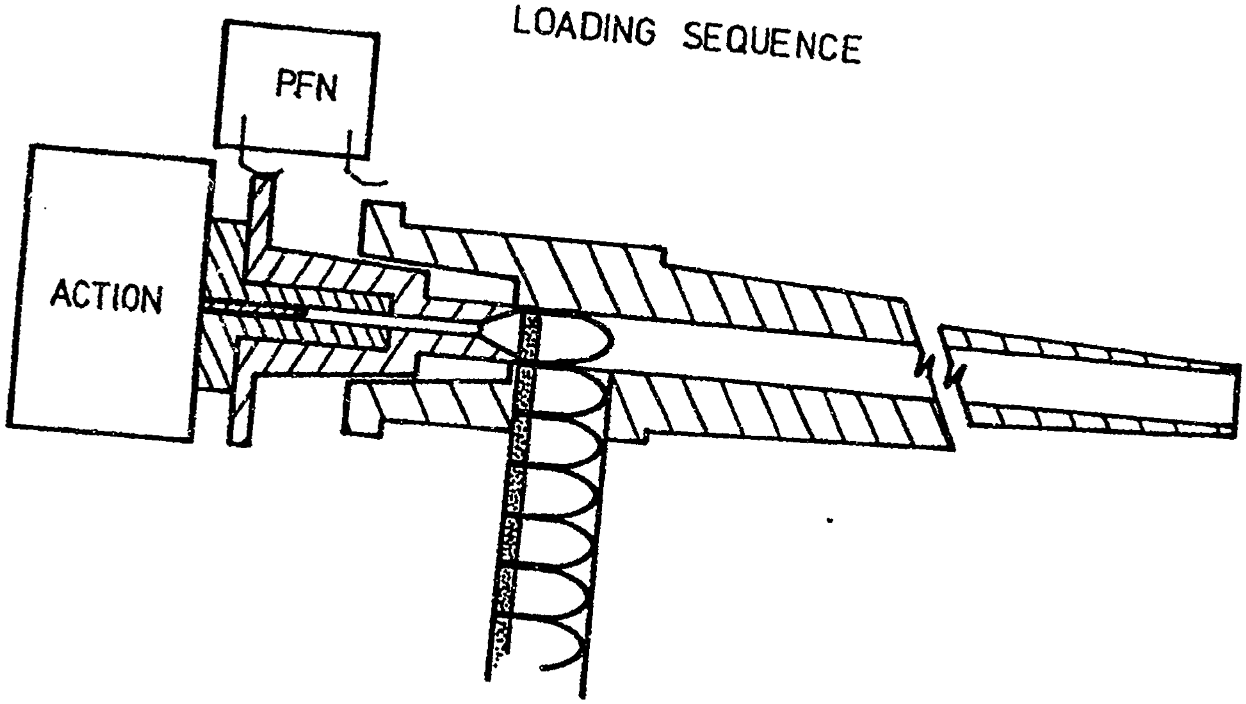
Time dependence of power I^2R, temperature T, velocity V, and pressure P. The dependencies are for the special case of ideal gas behavior (adiabatic constant γ), and more generally will deviate from those shown. Also note that the propelling fluid is a single phase fluid with initially liquid densities and thus achieves kilobar pressure at low temperatures during the early phase of the acceleration process.

mass affects the peak temperature which in turn allows control of barrel ablation and temperature rise. This information base is critical for the design of rapid fire guns.

2.3 A Rapid Fire Gun Concept

A conceptual view of a rapid fire gun is shown in Figure 5. The propelling fluid is inserted as an attachment to the projectile base. When the cartridge is pushed into its firing position by the recoil mechanism, it pushes the projectile into the gun barrel in a similar manner to existing rapid fire guns. The Pulse Forming Network (PFN) then starts to drive current through the cartridge, causing the plasma jet to be injected into the propelling fluid. The current increases as a function of time until it peaks and then is reduced to zero rapidly. The entire pulse may last about 1 ms. By the end of the pulse the cartridge obtains enough recoil momentum to move backwards into the recoil mechanism and a new projectile is loaded. During this interval, energy could be supplied to the PFN at a relatively low power level of only 10's of Megawatts, recharging it for the next shot.

The PFN could be chosen as any one of the following systems: (i) a Capacitor bank, (ii) a Compulsator or Rotating Flux Compressor (RFC), or (iii) an MHD power pulse driven by explosives. Present experiments at GT-Devices makes use of a capacitor bank which is very flexible in its design parameters. Its major drawback is that it is bulky and heavy. Recently available high energy density capacitors capable of storing about 1 MJ/ton could be considered for a rapid fire system, although these are new devices and would have to be checked under field conditions.



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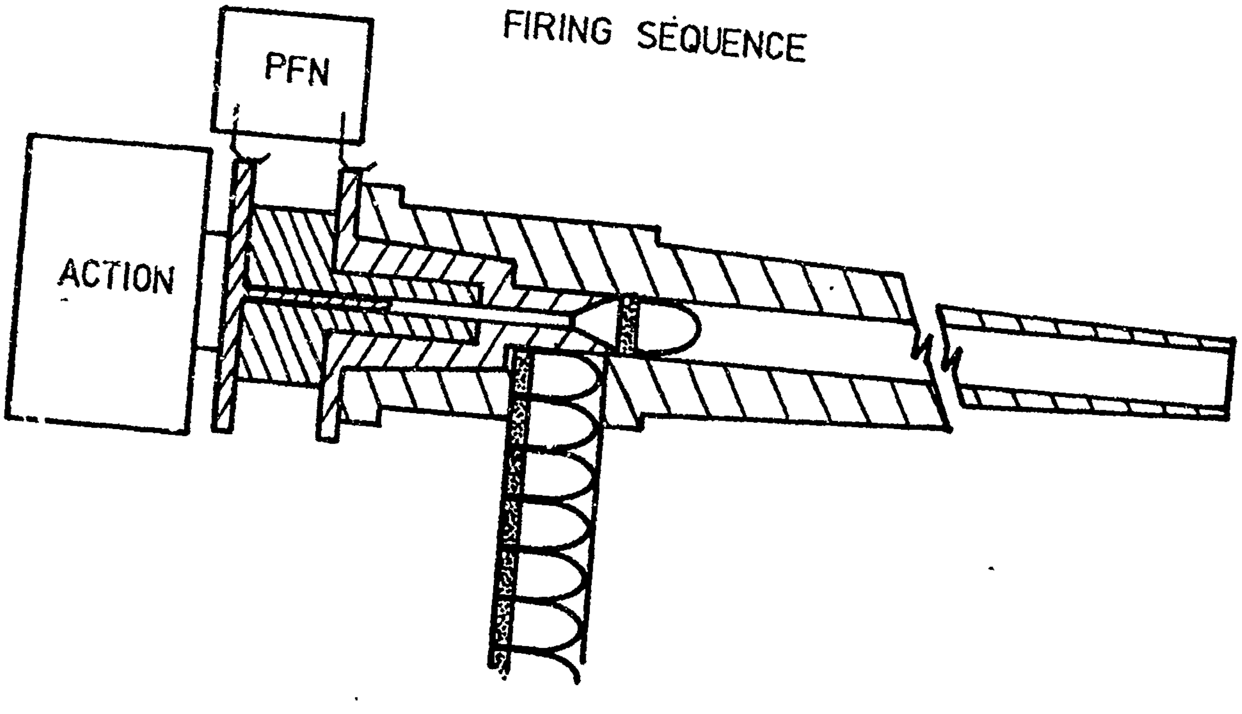

FIRING SEQUENCE

Figure 5

A rapid fire gun concept showing the loading and firing sequence. The projectiles fed into the gun have materials on their base for generation of the low atomic weight propelling fluid for coupling to the plasma jet.

The Compulsator or RFC uses the change of inductance during rotation in order to increase the current output. They usually generate 10-20 kV and are ideally suited for coupling to the high impedance GT-Devices plasma cartridge. The initiation of current through the cartridge could be accomplished by a fast high voltage trigger pulse in order to allow current flow through the compulsator so that it can compress its magnetic flux, transferring mechanical rotational energy to electrical energy. The structure of the compulsator coils could be designed to provide the necessary current shape for constant pressure drive. A major step in the research program will therefore be the coupling of these technologies to generate a useful rapid fire system.

3. COMMENTS ON POTENTIAL APPLICATIONS

A wide range of plasma jet powers and propelling fluid choices are available for accelerating projectiles to various velocities. Some selected parameter ranges are given below.

For example, if the mission parameters require projectiles of mass 50-100 grams accelerated to relatively low velocity ($\sim$2 km/sec), H_2O could be used for the working fluid. In this case the current would be about 150 kA and can be delivered via transmission lines from the power supply located at a convenient distance from the gun. Such guns may be used in closed loop operation for air-air, ground-air, and ship-air missions.

Staying with H_2O for the fluid, but going up in energy, long rod penetrators may be accelerated to velocities of 2-3 km/sec.

For higher velocities, lighter propelling fluid materials like CH_4 or LiH can be used. For example, a point defense system may shoot 1 kg projectiles at 4 km/sec.

Going to missions which require hypervelocities ($\sim$8 km/s) as well as very slow acceleration (for smart projectiles), the working fluid may be limited to hydrogen. In this case, low temperature refrigerators will be an integral part of the system providing the liquid hydrogen in the back of the projectile. Such technology may be useful for space guns (which carry large amounts of liquid hydrogen for the power supply) and for Intercontinental Ballistic Launchers.

In all of the above examples, notice that the power supply dissipates a small fraction of its energy in the transmission lines due to the relatively small driving currents, and hence thermal management problems are greatly alleviated.

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