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A TECHNICAL ASSESSMENT
OF ELECTROMAGNETIC PROPULSION FOR
SMALL CALIBER WEAPONS APPLICATIONS

KEITH A. JAMISON

NOVEMBER 1990

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1. INTRODUCTION

Concepts for electromagnetic propulsion devices with weapon-like performance have existed for nearly 70 years (Fauchon-Villeplée 1921). Interest in developing an electromagnetic gun has come and gone several times, generally waning due to the lack of a sufficient power source (Hansler 1946; Radnik and Bak 1958) to supply the energy mandated by the gun's performance parameters. The factors which determine the power supply requirements are: the projectile mass, launch velocity, rate of fire, and launcher efficiency. The present wave of interest stems from the success of researchers at the Australian National University in the late 1970s, who accelerated a 3-g mass to 5.9 km/sec (Rashleigh and Marshall 1978). Although the equipment utilized in this experiment was huge and not weaponizable, the conversion of electrical energy to more than 50 kJ of kinetic energy at such high velocity was a very significant achievement. Following this success, a reasonably aggressive program has been established in this country aimed at improving launchers and making power sources portable. Serious consideration was once given to developing a field artillery weapon. Presently, a joint Army, Department of the Army Defense Advanced Research Projects Association (DARPA), and Defense Nuclear Agency (DNA) program is underway to develop an anti-armor gun with an output of 9 MJ of projectile kinetic energy. Space-based applications of electromagnetic launchers (EMLs) are also being researched by the Strategic Defense Initiative Office (SDIO) and Air Force laboratories.

The central premise of any EML research or development program is that a more effective weapons system may be devised when the projectile acceleration is achieved by electromagnetic forces. It is generally thought that fielded, chemical propulsion weapons are not approaching any fundamental limits of performance. However, over the years, the rather slow improvement in projectile velocity and kinetic energy suggests that severe system burdens are associated with increased projectile performance (Bechtol et al. 1983). The accepted problems in improving projectile performance are:

- (1) A need to select a larger bore gun tube and the weight penalties that propagate through the system due to a heavier barrel.
- (2) The tube lifetime is reduced as performance increases.

- (3) Increases in system mass and volume result from the addition of more propellant. This is particularly acute, as attempts are made to increase projectile velocity. Because efficiencies decrease significantly between velocities of 1.0 and 2.5 km/sec, the required propellant mass is more than proportional to the square of the velocity.

The problems with increasing the performance of conventional guns, as listed above, suggest three straightforward goals for the developers of EMLs. First, they need to demonstrate improved projectile performance in a similar sized barrel. Second, they must show that a higher performance barrel can have an equal or greater lifetime than today's gun tubes. Third, and probably the most critical, they must show that the mass and volume penalties associated with the high performance EML system are less than the size and weight additions expected if the performance of a conventional weapon was increased. With minimal inspection, one might assume that the mass and volume of the electrical generation equipment would exclude EMLs from competition as future weapons. One important factor that may change this pedestrian analysis is that common fuels used in engines which drive generators have ten times more energy per unit mass than typical munition propellants. If the chemical gun is inefficient enough, or the stowed load of propellant is large enough, then EMLs mass and volume may not be excessive. There are two strong considerations which must also be applied to the third goal. One consideration is that the increase in performance is worth the extra burden the user must bear, and the other is that the cost of the new system is justified by the increase in the weapon's effectiveness. In the case of an EML-based weapon, the system may be large, placing a weight burden on its platform, while the resupply burden can be quite small. These considerations may be more applicable to development than to research, but long-range planning is usually valuable to the researcher, especially when choosing priorities.

In 1982, the Future Weapons Branch of the Close Combat Armament Center, Dover, NJ, embarked on a feasibility study of the potential of EMLs for small caliber weapons applications. The program today has evolved into an effort to develop effective projectiles which can be launched by a railgun and to demonstrate, in principle, a portable EML capable of salvo fire and delivering far more projectile kinetic energy than an M2HB machine gun. The purpose of this report is to assess the technical merits of the present research program. A direct evaluation would involve the dissection of present program plans versus technical progress over the years since the program was initiated. One is, of course, tempted to take the global view and try to answer the question, "What can this emerging technology offer to the future needs of the small caliber weapons user?" Because the technology is

still immature and so many unknowns exist, this report will attempt to address both areas, but with reservations.

A panel of experts with very different backgrounds in electromagnetic propulsion was convened at the request of the Joint Services Small Arms Office (JSSAP) to assist the author in the technical evaluation. The panel members are listed in Appendix A. Those providing written evaluations are denoted by the symbol "(E)." Each of the evaluators was asked to answer questions in the following areas:

- (1) Selection of future EML weapon systems.
- (2) Assessment of possible benefits from EMLs.
- (3) Ranking of necessary research tasks.
- (4) Essay questions on the value of EML to the JSSAP program, technical barriers for EML, suggested milestones for the program, and a cost estimate for the development processes.

Prior to the written assessment, the panel was given a briefing of the initial reasons for proceeding in EML technology, program accomplishments to date, a review of other EML research, and a brief overview of the weapons systems which fall under JSSAP's charter. Draft questionnaires were then shown to the panel for comments and corrections as a method of explaining the evaluation process. A group discussion was then conducted to obtain a cross-section of viewpoints on possible component specifications. Topics ranged from maximum allowable pressure in a railgun bore to energy and power densities of potential power train components. Several of these parameters are discussed in Section 3.3 and utilized in Appendix C. Following the discussions, the panel members provided written comments on the four-page questionnaire. The average scores and standard deviations are discussed in the body of this report. A copy of the questionnaire is provided in Appendix B.

The report is organized as follows. An explanation of the components necessary for an EML-based weapon system is given, followed by a review of the JSSAP EML program. Next, three sections give the panel's views on mission applications, potential benefits, and R&D requirements needed to mature EML through a pre-prototype stage. A net assessment follows which attempts to compare a future EML weapons system to an advanced, conventional gun system. A concluding

section summarizes the results and gives recommendations for improving the small caliber EML program.

2. COMPONENTS OF AN EML

It must be remembered that when one is attempting to weaponize an electromagnetic launcher, much more than just a barrel and projectile are involved. Figure 1 shows the generic components needed for a field-portable device. Starting from the left, a fuel is needed to provide energy for conversion to projectile kinetic energy. The fuel is consumed in some prime power engine which drives an electrical generation device. The EML requires far too large an electrical input for the needed electrical power to be generated directly, so some form of energy storage is required. Energy storage can take many forms. It could, for example, be placed to the left of the generator in the form of a flywheel, which stores a large amount of rotational kinetic energy. Rotational kinetic energy storage may also be integral with the generator in the form of a massive rotor, which also stores energy via rotational kinetic energy. Batteries can be utilized to store large amounts of energy in an electrochemical fashion. Capacitors, which contain an electrically stressed medium, are another choice of energy storage. For short times, inductors may also serve as energy storage devices, storing energy in a volume filled with magnetic field. Many possibilities exist, including combinations of two or more of the items listed above.

Further to the right in Figure 1 is a power conditioning section, which also may be in several forms. An opening switch for the inductive energy store is one example. A variable inductor coupled to a battery energy store is another. A series inductor with closing and crowbar switches is yet another form of power conditioning. In the case of the pulsed alternator or Compulsator, the power conditioning is built into the device by engineering it to operate in a fast pulse-discharge mode.

With the energy generated, stored, and properly conditioned, it must be transmitted to the EML. In laboratory devices, this is usually done by a set of bus bars. As the path to weaponization is taken, much more flexible power transmission conductors must be found which allow the barrel to be rapidly aimed. The loss mechanisms in this power transmission must be well understood and reduced as much as possible to permit a reasonable sustained rate of fire. The dashed lines in the figure illustrate that coolant may be required in several of the components depending on performance and efficiency.

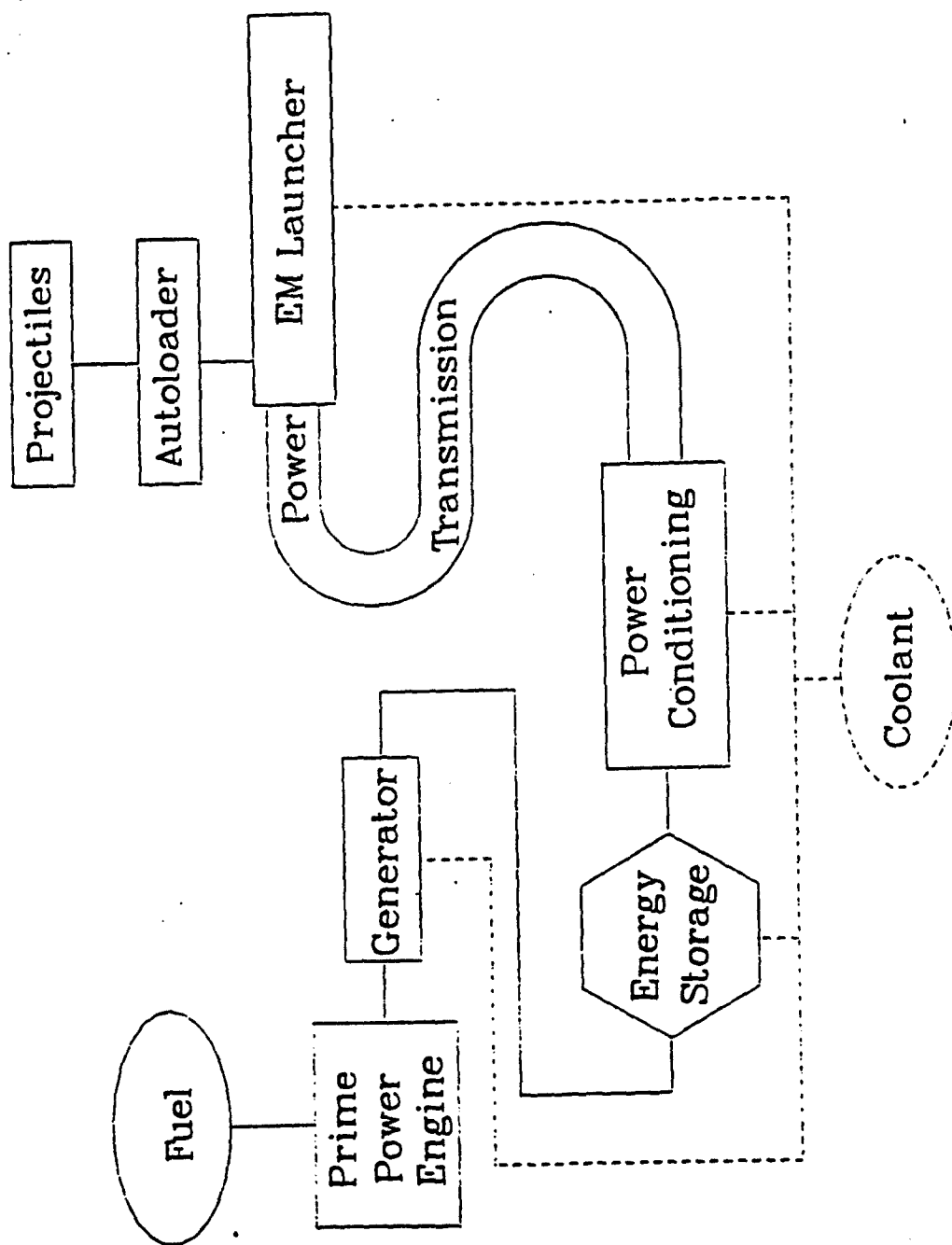


Figure 1. Generic Components of an Electromagnetic Launcher System.

The rightmost portion of Figure 1 is the gun itself, with ammunition stowage in a magazine or autoloader. The barrel, of course, must be aimed and fired, either by the soldier or by remote control, if the weapon is mounted outside an armored, airborne, or sea-going vehicle. Since projectiles for EMLs can be radically different from conventional ammunition, they too are shown in Figure 1 as a reminder that significant development is also needed in this area.

It is, of course, possible to break the system in parts. With a large energy storage capability, one may leave the prime power and electrical generation components in the resupply area. One can easily envision trading depleted battery packs for charged ones when the weapons system is resupplied with projectiles. Possibilities such as this, together with the large number of options listed above, make a general technical assessment of the potential of the technology extremely difficult, if not impossible. At the same time, the multiplicity of solutions to the system configuration may improve the chances for harnessing EML technology for future weapons technology. Also, the range of possibilities places on the developer the burden of maintaining currency in many rapidly advancing areas. Much of what the developer must know is in the form of power and energy densities of the power train components. Properties of the components for a specific configuration of Compulsator-driven railgun are discussed in Appendix C. These specifications are used to project the mass and volumes of future weapons systems. The projected values are estimates based on the FY95 - FY98 time frame when full-scale development might begin.

3. JSSAP PROGRAM

This section offers a brief review of the small caliber EML program and outlines the future plans through the 6.2 portion of the Research and Development (R&D) cycle. The direction of the present program is generally built on the results and progress to date as well as technology developments from other programs.

3.1 Background and Progress. At the request of the JSSAP office, the Future Weapons Branch, Close Combat Armaments Center, Armament Research, Development and Engineering Center (ARDEC) began to consider the possibility of utilizing electromagnetic launcher technology to improve performance of small caliber weapons. A very short proof-of-concept program was undertaken in which a small, one-meter long, 6-mm bore railgun was constructed and fired in a laboratory setting using a capacitor bank. The limited success in this program (owing in part to its

very short schedule) indicated the promise of EML technology for future needs. Throughout the lifetime of this project, the managers have maintained an excellent rapport with other government organizations, national laboratories, universities, and industries. The scope of their affiliations has been a very positive factor in the progression of this effort.

By fiscal year 1985, a more aggressive effort was underway. Four small contracts were placed which would yield the answers directing the future research program. Those four contracts concentrated in two general areas: launchers and power supplies. They identified the following technical barriers to the development of EML-based weapons:

- projectile/armature design
- armature materials
- rail materials
- power transmission from supply to launcher
- portable power generation and conditioning
- minimization of system weight.

The barriers listed above are still a reasonably complete set with the exception of power transmission, which has already been examined and appears to be a difficult engineering task rather than an actual barrier. This relates to the rapid slewing of the launcher simultaneously with feeding a large current to the breech.

The projectile/armature design has been receiving the most attention in the past two years. The BRL has been involved in designing and firing an integrated armature projectile designed to be mass stabilized (Zielinski and Garner 1990). The design has undergone some preliminary testing and is awaiting higher velocity testing. In addition, some aerodynamic flight characterization has been performed on these types of projectiles launched from a high pressure propellant gun (Garner, Zielinski, and Jamison 1989). The decision between flying or discarding the armature is being critically analyzed. Two designs, the present integrated armature and a newly-conceived, armor piercing finned stabilized discarding armature (APFSDA) are undergoing extensive numerical modeling to determine which provides the greatest terminal effectiveness for a given range and launch energy. Initial modeling of the APFSDA has been started (Zielinski 1990).

Materials development for rails and armatures is likely to be far beyond the fiscal scope of the JSSAP program. However, other EML programs with far more demanding materials needs are addressing this issue, and the likelihood of a direct spinoff is high. As an example, the Air Force Armaments Laboratory, which now has two Phase II Small Business Innovative Research (SBIR) contracts for railgun bore materials, will very soon have as many as four armature contracts and a significant effort in thermal management of railgun materials. Since the Air Force EML goals mandate projectile kinetic energies up to three orders of magnitude larger than those in the JSSAP program, even a partial success in the Air Force effort could completely solve the small caliber materials needs.

The issues of portable electrical power and power conditioning were addressed in two of the contracts started in FY85. One study addressed the possibility of a cartridge-based magnetohydrodynamic (MHD) generator supplying power to a railgun (Butz and Levin 1986). This was undertaken because of reports of MHD-railgun systems in the foreign literature, and also due to optimistic claims of those working in the field. The outcome of that study was that an MHD-railgun rifle was not considered to be technically feasible in the near future.

The outcome of the second power supply study (based on 1985 technology) concluded that the only possible mission for small caliber EMLs was in the area of the vehicle-mounted, crew-served launcher. Further, the Compulsator (or pulsed alternator/generator) emerged as the leading candidate to generate and condition the electrical energy. This study assumed that salvo fire (a very rapid burst of a few rounds) was a requirement. Early engineering estimates were that an armament system could be envisioned which weighed approximately one ton (1,000 kg), which could fire 100 rounds per minute, with each projectile having several times the kinetic energy of the present 50-caliber machine gun, and which included a stowed load of more than 1,000 rounds. These estimates were not overly optimistic as to weights of the individual components but did, of course, assume that projectiles and launchers could be built to exploit the power generated by the Compulsator. A key factor also identified in the follow-on power generation study was that the lead time for constructing the Compulsator would be approximately 24 months, with an additional 12 months needed to characterize the machine performance and complete testing with a railgun serving as the electrical load. Because the long lead time in demonstrating the technology for a salvo fire EML was driven by the power supply development, a considerable effort was expended in the latter part of FY86 to define the requirements for a field-portable EML system. The goal of this device was to demonstrate that a

portable EML could launch projectiles with kinetic energies several times those typical of crew-served automatic weapons.

The result of this planning effort, embodied as a statement of work, began the procurement cycle a few weeks before the beginning of FY87. A contract was awarded to the University of Texas' Center for Electromechanics in the last month of FY87. Several factors may have contributed to the length of this cycle and thereby account for the minimal progress in the power supply area during FY87. The delays due to these events, though not definitely quantifiable, must be considered when evaluating the progress of power supply development for the small caliber EML program. These changes, although reducing risk and immediate cost, will likely account for a one-year delay in reaching the prototype stage.

3.2 Program Plans. The present plan calls for a projectile-intensive program and a re-examination of the power supply selection rationale in FY88. Recently, some of the power supply parameters have changed significantly, especially the energy density of capacitors. In 1985, capacitors could store only 350 J/kg. The DNA has an on-going program to reduce the size of capacitors and, at present, has demonstrated an energy density of approximately 2,200 J/kg. Final goals for the DNA program are not known, but another factor of three improvement appears technically feasible. Here we must stress that the figures above for both capacitors and rotating machinery do not represent ruggedized, system-ready capacitors, but rather laboratory devices.

Detailed engineering designs have been completed for a two-pole air-core Compulsator, and details concerning the machine's technical aspects can be found in Fulcher, et al. (1989), although the design considered here is based on the demonstrated iron-core machine. In FY90, the laboratory system is to demonstrate salvo fire of 32-g projectiles at 2 km/sec at 10 Hz in a three-shot burst.

The armature and projectile work in FY88 through FY90 is timed so that when the test bed power and railgun are ready, an effective demonstration may be conducted showing not only that a small caliber EML can produce weapon-like kinetic energy at the muzzle, but also that the output will be salvos of highly lethal projectiles.

3.3 Panel Discussions. The panel's general view was that the research efforts as described were well founded. Technical differences were, however, apparent and discussed in some detail. The first

concerned the selection of bore size barrel length, and projectile kinetic energy. The relation between these parameters is calculable, given the acceleration profile and assuming that frictional forces may be neglected. The panel was polled to obtain a collective opinion of the peak magnetic pressure and the peak-to-average acceleration ratio readily achievable in a small caliber railgun. The dominant answer for peak pressure was 347 to 416 MPa (50 to 60 ksi). Most agreed that the current per-unit rail height was the controlling factor. This will permit higher pressures for augmented railgun designs. A peak-to-average force ratio of 2.0 was taken as representative for the current waveforms of both the simple Compulsator and the L-C resonant circuit. All agreed that envisioning a ratio as low as 1.2 was unrealistic, but that a ratio of 1.8 is an achievable goal.

The parameters supplied by the panel's members were used to construct the data set shown in Table 1. The bore dimensions and barrel lengths in the first and second columns span the range of interest for crew-served weapons. The peak pressures bracket the upper bound considered possible by the panel. Assuming a peak-to-average driving force ratio of 1.8 and neglecting friction, the kinetic energy is readily calculable. Note that a square bore configuration is assumed.

The panel members were also polled concerning the allowable acceleration, and their responses varied dramatically. The values for allowable peak acceleration ranged from 50 kg's to 1 Mg, with the average being about 300 kg's. One would hope that this reflects the panel's concern with large, complex projectiles and lack of familiarity with small caliber rounds which must reach high velocities in short barrels. The maximum acceleration values in column six of Table 1 were arbitrarily selected to provide velocities in the neighborhood of the program goals. The velocity is calculated from the barrel length, peak acceleration, and again assuming a peak-to-average accelerating force ratio of 1.8. Finally, the total launch package mass is computed from the velocity and kinetic energy.

It can be inferred from Table 1 that the pressure required for the performance specified in the present plan is larger by a factor of about three than what the panel views as possible. The first recommendation offered by this report is that the railgun bore dimension be increased to 15 mm and the length to at least 1.5 m.

Although neither the author nor the panel members are projectile designers, a second recommendation of this report is to initiate a small basic research effort into the allowable accelerations of small caliber railgun armatures carrying high-density payloads.

Table 1. Candidate Small Caliber Barrel and Projectile Specifications

Bore (mm)	Barrel (M)	Peak Pressure (ksi)	Peak Pressure (MPa)	Kinetic Energy (kJ)	Max. Accel. (kgee)	Mass (g)	Velocity (m/sec)
7.62	0.60	45.0	310.3	6.04	350	5.3	1,512
7.62	0.80	45.0	310.3	8.06	350	5.3	1,746
7.62	1.00	45.0	310.3	10.07	350	5.3	1,952
7.62	1.20	45.0	310.3	12.09	350	5.3	2,139
7.62	0.60	50.0	344.7	6.72	350	5.9	1,512
7.62	0.80	50.0	344.7	8.95	350	5.9	1,746
7.62	1.00	50.0	344.7	11.19	350	5.9	1,952*
7.62	1.20	50.0	344.7	13.43	350	5.9	2,139
7.62	0.60	55.0	379.2	7.39	350	6.5	1,512
7.62	0.80	55.0	379.2	9.85	350	6.5	1,746
7.62	1.00	55.0	379.2	12.31	350	6.5	1,952
7.62	1.20	55.0	379.2	14.78	350	6.5	2,139
12.70	0.75	50.0	344.7	23.32	300	19.0	1,565
12.70	1.00	50.0	344.7	31.09	300	19.0	1,807
12.70	1.25	50.0	344.7	38.87	300	19.0	2,021
12.70	1.50	50.0	344.7	46.64	300	19.0	2,214
12.70	0.75	55.0	379.2	25.65	300	20.9	1,565
12.70	1.00	55.0	379.2	34.20	300	20.9	1,807
12.70	1.25	55.0	379.2	42.75	300	20.9	2,021*
12.70	1.50	55.0	379.2	51.30	300	20.9	2,214
12.70	0.75	60.0	413.7	27.98	300	22.8	1,565
12.70	1.00	60.0	413.7	37.31	300	22.8	1,807
12.70	1.25	60.0	413.7	46.64	300	22.8	2,021
12.70	1.50	60.0	413.7	55.97	300	22.8	2,214
15.20	1.00	50.0	344.7	44.54	275	29.7	1,730
15.20	1.25	50.0	344.7	55.67	275	29.7	1,935
15.20	1.50	50.0	344.7	66.81	275	29.7	2,119
15.20	1.75	50.0	344.7	77.94	275	29.7	2,289
15.20	1.00	60.0	413.7	53.45	275	35.7	1,730
15.20	1.25	60.0	413.7	66.81	275	35.7	1,935
15.20	1.50	60.0	413.7	80.17	275	35.7	2,119*
15.20	1.75	60.0	413.7	93.53	275	35.7	2,289
15.20	1.00	70.0	482.6	62.36	275	41.6	1,730
15.20	1.25	70.0	482.6	77.94	275	41.6	1,935
15.20	1.50	70.0	482.6	93.53	275	41.6	2,119
15.20	1.75	70.0	482.6	109.12	275	41.6	2,289

* Launcher specifications have been selected for study in Section 7.

A third recommendation was evident in the written evaluation sheets. Several of the evaluators felt very strongly that alternate power supply options should be tested. It is very important not only to study the possible options, but also to perform adequate testing before downselecting. Clearly, multiple programs developing different power supplies would exceed JSSAP's resources. A compromise might be considered in which the scope of projectile work, armature research, and barrel development are somewhat diminished so that each of the several groups could be encouraged to adopt different configurations to power the research railguns. Regardless of the method, a competitive distribution of power supply types among the hardware programs is a recommendation of this report.

4. POSSIBLE MISSION APPLICATIONS

The role of small arms is very significant to all branches of the military. The spectrum of weapons which falls under the JSSAP charter is indeed rich. It ranges among personal-defense handguns, automatic rifles, vehicle-mounted machine guns, and even grenade launchers. The present JSSAP-sponsored program is limited to an R&D effort focused on crew-served, vehicle-mounted automatic weapons which might serve as a future improvement for any vehicle presently incorporating a small caliber machine gun as part of its armament. In past years, the program also examined the feasibility of developing an EML-based sniper rifle, but the conclusion of that study was that success would require breakthrough improvements in batteries and capacitors. Furthermore, research in those areas was projected to be beyond the funding limitations of this program. An application of a capacitor power supply supplying a sinusoidal-type current pulse has been considered for a machine gun-type weapon, but will not be included here (Zielinski and Jamison 1989).

Since the application addressed by the present program has often been misunderstood, it appeared worthwhile to poll the evaluators for their opinions of the segment of the broad spectrum of JSSAP weapons over which EMLs could most significantly improve fire power. A sample of the performance of three small caliber weapons and one cannon caliber weapon are shown in Table 2. The larger gun is included for reference, since it is certainly higher performance.

The first sheet in the questionnaire (see Appendix B) asks the evaluators to rate the value of EML technology to different weapons. Scoring was on a 0-100 scale, with 50 representing the point at which risks and probable burdens equaled the potential benefits from an EML system. The average

Table 2. Conventional Gun System Parameters

Nomenclature	M249	M60	M2	M242
Caliber, mm	5.56	7.62	12.7	25
Barrel length, m	0.46	0.58	1.14	2.03
Rate of fire, rpm	900	550	500	150
Burst size	3	5, 10, 20	5, 10, 20	5
Barrel weight, kg	6.8	10.5	20.5	109
Ammunition	M855 Ball	XM948 SLAP	XM903 SLAP	M791 APDST
Projectile mass, g	4.0	3.4	23.0	105
Muzzle velocity, m/s	911	1218	1213	1343
Projectile kinetic energy, kj	1.7	2.1	16.9	94.1
Cartridge weight, g	12.3	19	102	500

scores from all evaluators rated only the two crew-served weapons as worthy of the risks and burdens. Listed below, in order of rating, are arbitrarily selected applications. The average score for each application is listed with its title and is followed by the standard deviation of the scores.

- Crew-Served, 12—15-mm Machine Gun Rating: 84 ± 17 - This application was not only most highly rated by the panel but also, as shown by the standard deviation, the panel members were in better agreement than on any other system. The advantage of the larger bore system is that, given equal magnetic pressures, the larger gun has twice the kinetic energy. The view is that, as the need for greater projectile energy increases, electromagnetic propulsion becomes more significant. Several of the evaluators cited anti-light-armor and antiaircraft as missions for this system. Also, those who have built differently sized systems know that manufacture of large bore railguns and armatures is somewhat easier.
- Crew-Served, 8—10-mm Machine Gun Rating: 80 ± 19 - This configuration is not significantly different from the one above except that the sizes of the electrical generation and energy storage devices are likely to be half those required for the larger gun. The same prime power could double the rate of fire in this smaller system. In terms of the R&D effort needed to mature this system, several of the evaluators thought that less work would be required. This is an important point to consider. The equipment costs in an R&D program should follow to some degree the kinetic energy of the projectile. The small caliber program might serve as an excellent subscale proving ground for programs with much larger energy requirements.
- Sniper Rifle Rating: 32 ± 34 - A flashless, nearly silent, high velocity rifle powered by a battery pack and capacitor bank is an attractive research goal to fill obvious needs in covert fire. (A Mach 6+ projectile is, of course, not silent.) However, the panel's rating would appear to close the book on this application. Some evaluators did cite that, given a breakthrough in batteries and the projected developments in capacitors, this might logically follow the development of the crew-served weapon. One evaluator who has studied this system in some detail believes the technology is not far away from performing this mission if the rate of fire is slow enough to allow the marksman to re-aim, and the total number of rounds for a single mission is not large. The large standard deviation in the scores indicates that agreement was not universal among the evaluators. Again, this application is not part of the JSSAP program, although it was once considered.

- Automatic Rifle Rating: 25 ± 29 - For the combat rifle, EML power supplies are either very far term or unimaginable. Further, it is difficult to envision the soldier drawing ammunition and swapping large battery packs in a battlefield setting. In addition, large gains in performance may result in an unacceptably large impulse on the soldier. The rating, in the estimation of the author, is too high, possibly because the word "automatic" was inadvertently left off the questionnaire.
- Grenade Launcher Rating: 15 ± 19 - This application has not been examined in detail, but may be more suitable to a coilgun. Certainly, one does not need high velocity, so most of the claimed electrical advantages are negated by the efficiency of chemical propellants.
- Shotgun Rating: 11 ± 26 - The rating is so low for this application, it hardly justifies discussion. It is curious to note that this system showed the largest percentage standard deviation of all applications.
- Hand Gun Rating: 10 ± 17 - As with the previous example, one should not consider EMLs when hoping to improve performance without overburdening the user.

The purpose of the above exercise was to establish, via the opinions of technical experts in the EML field, whether or not the correct weapon system had been chosen from the large number which fall under JSSAP's charter. The universal conclusion is that the correct application is being pursued in the present program.

4.1 Configurations. The platform for the crew-served weapon will undoubtedly impact the full-scale development and the specifics of the final design of the first small caliber EML to be put into service. The possibilities of weapon platforms (vehicles) vary greatly in this joint services program. While even the pre-prototype program is a few years away, it is not too early to speculate on the possible platforms for a crew-served EML. Because of the relatively large system mass and volume, airborne uses may be limited to rotary wing, rear area, or defensive-type craft. Attack helicopters will unquestionably need far more firepower, as will large defensive systems in a naval role. However, the PT boat might be a very appropriate vehicle. Amphibious or simple landing craft could take advantage of EMLs if their missions require a large stowed load of ammunition. Ground forces in

lightly armored vehicles, or even secondary guns on armored personnel carriers (APCs) and missile launchers, could also benefit from the potential advancements of EMLs over today's armament.

Even in the far term view, the EML armament system will be applicable when large stowed loads are required and when the power components can be integrated into the vehicle some distance from the gun. Locating the power far from the gun suggests the need for a higher impedance launcher (such as the augmented or multiturn railgun) to reduce power train losses. Longer sustained firing would be possible before too much heat builds up in the system. The question of coolant for the power plant is difficult to resolve without exact mission scenarios.

The relative ease of remote control of an all-electric system, without the need for breech closure or a cartridge case ejection system, may ultimately become one of the EML's strongest selling points. The need for such remote control, given some estimations of the threat of nuclear, biological, and chemical (NBC) capabilities, is likely to be ever increasing.

4.2 Targets. Two general classes of targets exist for the crew-served weapon. Point targets include personnel, equipment, supplies, and unarmored and lightly armored vehicles. Area targets such as buildings and wooded areas require a high rate of fire and depend on a large number of dispersed rounds to achieve a hit. In later sections, the prime power problems associated with high rate-of-fire systems will be discussed. The gains that EMLs offer are strongly centered on addressing point targets. The JSSTO document (1986) lists a need for a much greater terminal performance. The reason may be obvious. If the armament on an unarmored vehicle can address lightly armored targets outside the range of the threat, a significant battlefield advantage would exist. For the armament system, this translates to effective projectile designs with increased kinetic energy. These are exactly the aims of the JSSAP small caliber EML program. Other advantages possible with EMLs would also be of value on the battlefield. The question of signature from the muzzle blast is very important to an unarmored mount. One cannot expect an unarmored vehicle to announce its presence in close proximity to an armored threat. When either the gun or target is moving, higher projectile velocity will reduce lead angles and should increase hit probability. The ability of electromagnetic (EM) systems to completely remove the driving force before the projectile exits the barrel and the absence of propelling gases should reduce launch dispersion. These problems are far more acute for smaller caliber projectiles than for larger ones.

5. POTENTIAL BENEFITS FROM EML

The author, rather than rely solely on his own opinions, asked a panel of experts to score the potential advantages of EMLs on a 0-10 point scale. Since the risk and R&D effort required to achieve a given advantage varies greatly among all those claimed, the panel was asked to reduce the score of the possible advantage if it would be more difficult to achieve. The second page of Appendix B is the potential improvement portion of the questionnaire. In addition to estimating a combined rating and difficulty, the evaluators were asked to rank the improvements in order of importance to the JSSAP program. The evaluators were also asked to list an alternate technology that would offer an equal potential benefit in the area being considered. The following paragraphs are listed in order of importance as determined by the evaluators. After each title, the average rating and the standard deviation of the ratings are given.

- Improved Lethality 8.1 ± 1.7 - Again, the central premise of EML technology programs is that, ultimately, a more effective weapon will be developed and used. Although this advantage was ranked first by the evaluators, the lower rating score than several other items reflects the difficulty in achieving this potential. Also, any of the factors in this list could contribute to a superior system, but lethality is generally considered to be the primary objective.

Several alternate technologies were listed which offered payoffs in this area. Electrothermal (ET), Combustion Augmented Plasma (CAP), Ram Cannon, and a particle bed gun were all suggested as candidates to be considered for improving lethality.

- Extended Range 9.0 ± 1.1 - Good projectile designs will permit extended range if higher muzzle velocity is achieved. The increased range will not translate into effectiveness unless accuracy and aiming promote increased hit probability. This benefit is therefore dependent on the realization of other goals. Several evaluators listed decreased time of flight as a potential benefit, especially if the weapon must address aerial targets or moving vehicles. Higher velocity does reduce lead angles and, in general, simplifies the fire control solution.

Again, several alternate technologies were listed which offered payoffs in this area. ET, CAP, RAM cannon, and a particle bed gun were all suggested as candidates to be considered for extending

range. All except RAM cannon will suffer launch accuracy problems due to muzzle blast as performance is increased.

- Reduced Ammunition Logistics 8.6 ± 1.6 - This is the most realizable goal, since no propellant, cartridge case, or primer is needed; the resupply logistics is reduced to extra fuel and projectiles. The great reduction in ammunition vulnerability also impacts logistics and cost of the entire chain from manufacture to use.

Liquid propellant is a propulsion technology which also has potential in this area. This is not as significant as the advantage of EML, where a common fuel is proposed for gun and vehicle drive.

- Reduced Ammunition Vulnerability 9.2 ± 1.1 - The trade of chemical propellants for simple fuels should make ammunition vulnerability reductions automatic. The drawback is that the total armament system is large and may present a large target area. A hit in this area could do more than make the gun inoperative. Energized portions of the EML power train will produce some secondary effects if damaged by incoming rounds. These factors are not well known and should be addressed prior to a prototype program.

Liquid propellant and Low Vulnerability Ammunition (LOVA) development efforts also show promise in reducing the ammunition vulnerability.

- Reduced Signature 7.4 ± 3.9 - The elimination of all hot gases driving the projectile should greatly reduce muzzle flash, smoke, and blast. Railgun armatures have not yet demonstrated this at the required energy levels. For systems which are unarmored or lightly armored, this may be a large battlefield advantage. Other signatures may be present, however, particularly electromagnetic signatures from the switchgear.

No other technologies were thought to offer this potential advantage.

- Improved Safety 7.3 ± 2.8 - The relative safety of high power electrical generation equipment and conventional munitions is very difficult to judge. It is evident that the evaluators were comfortable enough with their own work in EMLs to believe that the electric system could

have a better safety rating than conventional systems with large stowed loads of high performance ammunition.

- RAM (Reliability, Availability, and Maintainability) 4.6 ± 2.0 - This rating reflects the multiplicity of difficult engineering tasks to be addressed. This is especially true if EML systems are to fire several stowed loads. The future EML system will be comprised of several complex components; each will have its own probability of failure. To the author's knowledge, no mean-time-between-failure studies have been attempted. Without such studies, even educated guesses of availability are not possible. Clearly, with all the components needed for the EML system, significant maintenance will be required. Reliability and downtimes must be carefully considered before selecting EML as the weapon of the future.

An improved conventional propulsion system was to be selected if RAM was the prime consideration in a future weapon.

- Enhanced Accuracy 5.5 ± 2.0 - The accuracy of an EML is one area which has been almost totally neglected. The evaluators ranked extended range very highly, implying that enhanced accuracy is a firm requirement. The general belief among those in the EML field is that electrical pulses are easier to control and reproduce than propellant burn cycles. Also, the removal of the driving force before the projectile leaves the barrel and the reduced muzzle blast should help improve accuracy.
- Higher Rate of Fire 3.8 ± 2.6 - The evaluators' ratings indicate a potential problem. Chemical energy is input to the breech of the 50-caliber machine at a rate roughly equivalent to 800 hp, when the firing rate is 500 rounds per minute. Even if the generator and launcher in an EML can be made highly efficient, the prime power engine will be of significant size and weight. This will exclude very small vehicles from serving as platforms for the EML, unless the rate of fire is reduced over today's capabilities. As previously stated, the user may wish to accept reduced effectiveness against area targets to gain a large advantage against point targets.
- Reduction in Component Logistics 3.9 ± 1.8 - This is almost a statement of the obvious. The main components in the EML must each be hardened against failure if the logistics of spare parts is to be manageable.

- **Variety/Novelty Projectiles 7.0 ± 2.3** - The possibilities of multiple types of projectiles has not been fully explored, but does seem tractable. The more benign muzzle exit conditions should produce fewer restrictions on the projectile designs.
- **Improvement in Environmental Factors 5.5 ± 3.3** - Engineering the EML to work in all types of battlefield environments is a very difficult task. In the opinion of the author, this score is too high. Laboratory EMLs are subject to failures with even relatively minor problems with the environment. Dirt, mud, rain, salt spray, and snow are just a few of the factors which must be considered in the weaponization of EMLs. A weapon of this type, which is not truly weatherproof, is of little value.
- **Reduction in Recoil 6.8 ± 3.0** - For an automatic weapon, even if fixed to a mount, the recoil is a significant factor in aiming all but the first shot. The EML eliminates the portion of the recoil due to the propellant gases. Also, for equal kinetic energies, a higher velocity, lower mass projectile imparts less recoil to the launcher.
- **Ease of Fire Control Interface 6.3 ± 2.1** - For remotely aimed guns, advanced fire control, or precision aim techniques, the relative ease of interface to an all-electric system will be an advantage. This is a far term advantage, but is an excellent example of the growth potential of EML.
- **Synergism with Electric Vehicle 8.0 ± 2.1** - The probability that electric drive vehicles will appear on the battlefield of the future is unknown. The maneuvering capabilities of an electrically driven vehicle are clearly an advantage since the electric motor develops full torque even at zero rotational speed. Electrically driven turrets are already in use today, so the inclusion of significant electrical power within future vehicles does not appear totally remote. The sharing of components between gun and drive train would certainly reduce the burden of an EM or ET gun. As one evaluator put it, "The question provides the answer."

The above paragraphs reflect the optimism of those working in the EM field. Many of the improvements will be very difficult engineering tasks. The general belief that no breakthroughs are needed (except possibly in system mass and armature contacts) and that many of the basics have already been demonstrated on the small caliber scale is, however, correct.

6. R&D REQUIREMENTS

All of the evaluators have been involved in planning R&D for some aspects of electromagnetic launchers. Their judgement in the importance and sequence of the many tasks needed to mature EMLs must be highly valued. The JSSAP program planners are strongly urged to study the following sections as a guide to efficiently researching small caliber EMLs.

The third page of the questionnaire in Appendix B was discussed and edited by the panel prior to the written evaluation. This worksheet lists 18 research tasks needed to advance the technology so that a development decision can be made. The evaluators were asked to judge the relative importance of each task, again on a 0-10 point scale. Also, panel members were to indicate a time frame in which each task should be performed. The averages of the time frame scores are used to sequence the following paragraphs from tasks which should be done early to tasks which should be done later. The average "importance" score and the standard deviation are given after each task title.

6.1 Research Tasks.

- **Armature Effectiveness 8.7 ± 1.3** - The function of the railgun armature is key to the ultimate success of this program. The armature must maintain two good electrical contacts while sliding at a high velocity, conduct the full railgun current without overheating, incur the magnetic acceleration forces, and transfer these forces to the other parts of the projectile. To date, solid armatures have not performed at the levels needed for the stated goals. Further, many research efforts have revealed a certain randomness to the behavior of solid armature contacts. To be effective, the armature should have low mass, maintain a very low (ten volts or less) potential as it conducts current from one rail to the other, and accelerate a payload larger than itself to a high velocity. This is an area where basic research is needed. As the panel selection indicates, this effort should begin immediately.
- **Armature Efficiency/Payload 8.1 ± 1.9** - There are a number of possible energy-loss mechanisms associated with the armature. As an electrical element, it has both contact and ohmic loss terms affecting the power supply specifications. Friction with the bore surfaces can consume kinetic energy requiring additional power to be input to the railgun. If the aerodynamics of the armature are unsuitable for high velocity atmospheric flight, it must be discarded from the

payload after launch. This represents an additional inefficiency, as all the kinetic energy of the armature would be lost.

- **Projectile Design - Target Effects 7.3 ± 2.5** - This task is key to the central premise of the EML program. If a more lethal projectile cannot be delivered from an EML than from a conventional gun, the program value will be greatly diminished. At this early stage in the R&D cycle, a proof of principle effort is far more appropriate than an attempt to design the ultimate projectile for a full-scale development effort.
- **Projectile Design - Aerodynamics 7.4 ± 2.8** - The loss of projectile velocity and lethality between the launcher and target is particularly acute in the small caliber systems. As with the previous task, the design of a projectile to function well in an EML and still have good aerodynamic characteristics is highly important to a decision to proceed from research to development. In the case of small caliber projectiles, accuracy and range are also extremely sensitive to aerodynamic effects. Both projectile design areas must be initiated early so that a worthwhile package may be launched as launchers and power supplies become available.
- **Barrels - Structural 8.6 ± 1.6** - The rather formidable kinetic energy selected as a goal for this program requires a barrel which can withstand a high magnetic pressure. Further, this barrel must be lightweight and maneuverable so that it may be quickly aimed by the soldier. Since Section 6.2 will list rails as a technical barrier to launcher development, it should be pointed out that the panel views the development of the barrel structure as more important.
- **Power - Electrical Generation 7.6 ± 2.6** - As stated previously, the acquisition of a compact generation device for a specific EML is a long lead time item. Devices which supply several times the energy needed in this program have already been constructed and operated in a laboratory setting. Compact electrical generation is seen more as a development issue than a technical barrier.
- **Barrels - Rail Lifetimes 8.4 ± 1.5** - Historically, gains in performance of conventional guns have been accompanied with reduction in component lifetimes and reductions in reliability. If

higher performance is a genuine need, then the lifetime issue of railgun barrels must be resolved. As previously discussed, advances from other programs are expected in this area. A demonstration of a barrel which can fire more than 100 rounds without serious degradation is a worthwhile milestone.

- **Power - Energy Storage 7.1 ± 2.0** - In laboratory experiments, capacitors and inductors have served quite well as energy storage devices. Work is needed in size and weight reduction before the final selection of energy storage is made. Thermal management has not been adequately addressed for any of the types of energy storage under conditions of sustained rapid fire.
- **Power Transmission 6.3 ± 2.7** - In any practical configuration, the launcher and power supply will be at different locations in the vehicle. This requires efficient transmission of high current power pulses to the gun. While the resolution of this problem will fall largely in the systems integration package, issues such as firing with a moving launcher must be addressed early.
- **Power - Switchgear 5.7 ± 2.7** - The bulk of the EM community is researching systems with far greater power and energy requirements than the small caliber effort. Larger systems must have significantly more robust switchgear. This is an area in which spinoff from other research endeavors will have a very positive effect in small caliber R&D. Solid-state switches are also progressing as a result of influences other than EMLs. Solid-state devices exist today which are nearly compatible with the needs of the JSSAP program.
- **Barrels - Reduction of Losses 7.0 ± 2.5** - For very rapid fire, particularly in sustained missions, ohmic and frictional losses in the barrel must be minimized. Results from other programs suggest that this may not be a difficult technical issue especially if more effective projectiles permit a reduced firing rate.
- **System Engineering - Volume Economy 6.9 ± 1.9** - Limiting the volume of an EML system may prove to be the most challenging task of vehicle integration. The ammunition stowage will require a very small part of the system volume, while the prime power and energy storage will require the largest portion.

- **System Engineering - Weight Economy 6.4 ± 2.1** - All three systems, issues, volume, weight, and RAM, were rated relatively low. This may be an indication that they are development issues rather than research tasks. Research is needed to prove that a realizable connection exists between laboratory devices and a system concept which will be attractive to the user.
- **Utility Analysis 7.8 ± 1.9** - This task was rated as the fifth most important by the panel, even though it does not require an early start. All the component performance parameters depend strongly on the mission. Research in all areas could be simplified if a single set of system specifications were selected by a well-executed utility analysis. The drawback to this approach is that before all the fundamental restrictions are known, an incorrect choice of mission might be made.
- **Thermal Management 5.9 ± 2.1** - Again, in this area, because the power and energy requirements are so much lower than the systems, most of the evaluators are concluding that rejection of heat due to electrical or frictional inefficiencies does not seem to be a pacing issue. Depending on the fire rate and the length of each mission, thermal management may be a very important issue.
- **System Engineering - RAM Issues 5.6 ± 2.6** - Reliability, availability, and maintainability will be among the leading factors should this research lead to a full-scale development program. The power supply portion of the system will be complex. Quality control must be high if one expects EMLs to have a reasonable RAM record. With so many unknowns and technical issues, RAM issues should be held for later efforts.
- **Power - Prime Engine 4.4 ± 2.6** - Engines which can deliver the required power exist today. The only issues which remain are adaptation to the EML power train and vehicle integration. As stated above, system volume and weight can both be significantly reduced by improving the driving engine.
- **Armature Signature Reduction 4.8 ± 2.2** - The conclusion based on the scores given this task appears to be that if the armature functions well both electrically and mechanically, the signature will be extremely small. The goal of eliminating muzzle flash and most of the blast will be achieved by reducing the current to zero before the armature exits the launcher.

One inference which may be drawn from the high scores given many tasks is that the technical risk is compounded by the number and complexity of the components which comprise an EML system. This is the view of the author and many of the panel members. While the risk in rapid development is high, the possible benefits and growth potential are also very high. The risk of this program is greatly reduced by the complementary nature of several other EML programs and by the realistic time lines which have been adopted. These possibilities certainly justify research in this area, though perhaps not with huge expenditures. The situation certainly does not permit the omission of regular critical reviews.

6.2 Technical Barriers. The term "technical barrier" has become popular when relating research efforts to their long-term applications. As is typical for these terms, Webster's Third New International Dictionary (Unabridged) offers seven definitions of the word "barrier." There are two definitions which might be applied for our purposes. One is "an obstruction which prevents progress" and the other is "a hindrance which impedes progress." The latter definition is more appropriate here. There are no obstructions which must be removed, or new pathways found around them; rather, there are areas in which work is needed before the total system will be attractive to the user. This work will take time and resources to complete. If the problems in these areas are not solved, the end item will be degraded in value but not become impossible to build.

The following paragraphs describe the impact on a future EML if the technical barriers cited by the evaluators are not solved. The sequence of the list is determined by the number of times a barrier was cited in the 14 written evaluations. Although the list is extensive, the collective view is that most, if not all, of these issues could be resolved with R&D efforts in a reasonable time.

- **Long Life Rails/Barrel** - Most laboratory railguns suffer erosion and gouging of the bore, so that only a few firings are possible before replacement or refurbishing is necessary. Railguns with injectors have longer life, and sections of the bore where solid armatures have functioned properly show almost no wear. If a long-lived bore cannot be developed, then the user will be burdened with frequent replacement of the barrel and the logistics/battle management problems which result.
- **Compulsator Function** - The program as structured now is based heavily on the use of an air-core Compulsator which is not a proven device. If problems are found in the Compulsator, an

alternate power train must be employed. This will increase both the volume and mass of the system, but the magnitude of the increase is difficult to predict.

- **Effective Armatures with 2 km/sec Sliding Contacts** - To date, the highest repeatable velocity at which an armature has maintained good sliding contact has been 1.1 km/sec. If no improvement can be achieved, this may be the maximum muzzle velocity of the EML, and many of the performance advantages will not be realized. If this is unacceptable, then a transitioning armature may be used, and the user must accept the flash, inefficiency, and bore erosion problems associated with plasma armatures.
- **Projectile Design** - The design compromises between launch environment, aerodynamics, and terminal effects may restrict the lethality of the EML round. If no improvement can be made over today's capabilities, the user must consider secondary factors such as muzzle flash and logistics in assessing the value of EMLs to the battlefield.
- **Efficiency** - Inefficiency in any of the components has two consequences. First, the waste energy must be expelled from the system, and second, all components which supply energy to the inefficient section must be increased in capacity. More robust coolant systems and increased system size are the penalties when high efficiency cannot be achieved. If these cannot be tolerated, fire rate or projectile kinetic energy may be reduced.
- **Barrel Design** - The launch tube is the hardware which must withstand the reaction forces associated with imparting the desired kinetic energy to the projectile. If high pressure railguns cannot be designed, then a larger bore launcher and a discarding sabot and armature will be required. An optimization must then be performed weighing a larger total system mass against reduced kinetic energy arriving at the target.
- **System Mass and Volume** - If the total EML system is too large for a given vehicle, the performance must be scaled down or the vehicle redesigned. Both options are critical to the user.
- **Systems Integration** - Even if the mass and volume of the system are within the platform constraints, the required layout may prevent simple integration of the launcher and vehicle. Again, lack of success in this area leaves the unpleasant choice between vehicle redesign and reduction of fire

power. Since little study has occurred in this area, it is difficult to judge the magnitude of the system integration problem.

- **Thermal Management** - This area assumes importance when one cannot achieve the efficiency needed to operate for a sustained mission without overheating some portion of one or more of the components. As an example, the rail surface may become very hot during a shot and not recover before the next firing. Failure in this area will result in reduction of firing rate or the addition of cooling systems. In an extreme case, a highly complex, perhaps even cryogenic, coolant system might be required.
- **High Current Switches** - In the laboratory, most railguns rely on switches which cannot be weaponized. If solid-state switches do not progress to the level needed for the small EML, an alternate path may be needed. For many power configurations, the projectile can function as one of the switches. This will result in the so-called "hot rail" configuration in which one rail is subject to the full power supply voltage for some length of time before firing. Safety and environmental factors such as keeping the bore dry and clean will be harder to resolve.
- **Prime Power** - Present machine guns and automatic rifles have very high rates of fire. To duplicate, this rate of fire requires a significant power rating for the prime engine. Failure to weaponize a turbine or other lightweight drive engine will result in either a much heavier system or a much reduced rate of fire.
- **Recoil Management** - The extra recoil which accompanies increased projectile kinetic energy must be transmitted to the vehicle via some mounting bracket. This may require a damping mechanism to hold the barrel, a much stronger bracket, or even place limits on the locations on the vehicle where the launcher may be mounted.

The list of work areas above is reasonably complete for both initial research and the early stages of development. Other EML programs are also addressing these same issues so that the removal of these barriers is not the sole responsibility of a single program. For nearly every "barrier," the small caliber requirements are less demanding than the requirements to be met in other EML programs. The technical leverage the JSSAP program receives from other efforts is indeed large. One would expect the JSSAP program managers to be able to quantify the state-of-the-art in each area before the

beginning of a 6.3A effort. Further, they should be able to show either projected improvements or an assessment of the impact of negative results on the desirability of the projected system. This must be done carefully before any large expenditures of development resources.

6.3 Suggested Milestones. The milestones listed by the evaluators were quite varied so that compilation of the input is difficult. Four general areas of milestones were evident: projectiles, power supplies, barrels, and system demonstrations.

6.3.1 Projectile Milestones.

- (1) Define Performance Specifications - At the earliest possible time, and at re-evaluation points, define the goals for the projectile in terms of range to target, kinetic energy on target, and time of flight requirements. This information is essential, as projectile design compromises take place among interior, exterior, and terminal ballistic performance.
- (2) Prove Sliding Armature Contacts at 2 km/sec - A key advance in high-speed nonarcing armature contacts is needed if the projectile velocity is to exceed today's capabilities.
- (3) Design a Functional Armature at 2 km/sec - Once armatures have been made to function, they must also be able to accelerate payloads. For terminal effects, a high density, high aspect ratio component is likely to be the payload of choice.
- (4) Demonstrate a Flyable, Effective Projectile - This demonstration is the goal of the projectile program. Optimization where possible is, of course, beneficial.

6.3.2 Power Source Milestones.

- (1) Perform Comparison of Power Train Options - The application of any of the potential power trains to this program has a moderate risk. Comparison studies not only assure that the best option has been chosen but also help define the back-up candidate power sources.

- (2) Complete Power Source Design - A design for any of the demonstrations listed below should include the launcher performance as a result of the power pulse delivered. If this is done early, it will benefit both the launcher and projectile designers.
- (3) Demonstrate Power Supply on a Single-Shot Launcher - The first tests of a power train should use heavily diagnosed, single-pulse discharges into dummy loads and then into a launcher.
- (4) Demonstrate Power Supply with Multi-Shot Firings - Since salvo fire is important to this mission, the power supply should demonstrate single-salvo and then multiple-salvo firings.

6.3.3 Launcher Milestones.

- (1) Evaluate Railgun Concepts - There are several different configurations for railgun launchers. Among these designs are augmented, multiturn and multirail type configurations. Each has its own internal pros and cons as well as an impact on the other system components. Ranking of candidate configurations should be completed early as input to the projectile and power supply designers.
- (2) Launcher Design - A design for the demonstrations below is necessary for review by researchers in all other areas, especially the armature program.
- (3) Multi-Shot Barrel- A reasonable milestone is to complete, without launcher refurbishment, a ten-shot sequence which shows no degradation of performance. Also, a second milestone, a 100-shot test, is highly recommended.
- (4) Conduct Simplified Dispersion Tests - Since no information exists on the accuracy or dispersion of EMLs, a simple experiment in this area is required as soon as a launcher capable of many rounds is available.

6.3.4 Demonstrations of EML Systems.

- (1) Rapid Fire, Laboratory EML - This is essentially the demonstration that the present University of Texas, Center of Electromechanics (UT-CEM) contract (DAAA21-87-C-0206) requires. It should encompass many, if not all, of the milestones above.

- (2) System Definition - As performance limits and component specifications become known, an effort should be made to describe a "best guess" future armament system.
- (3) System Integration Study - The lore in this area suggests that the integration task can never begin too early. Candidate platforms should be surveyed for weight and volume availability. Estimated layouts of all system components should be performed on a simplified basis, checking for special restrictions on the power train and launcher.
- (4) Pre-Prototype - Assuming moderate success in all of the above, the transition to 6.3A development should begin with a review and assessment of the potential benefits and burdens which must be accepted by the user.

6.4 Cost Estimates. Each of the evaluators was asked to estimate the cost of maturing EML technology through the prototype stage. It was evident that many of the evaluators chose different definitions of the word "prototype." Most considered only the research lab demonstration and early projectile work. These estimates were in the \$3-5 million range. An average for those who totaled the cost of a lab demo, a pre-prototype, and a prototype program is around \$60 million. The costs are driven by the success or failure in each task and are also strongly dependent on the fire power which is chosen for each of the demonstrations.

The ultimate cost of an EML armament system is very difficult to predict. It is safe to assume that the capital investment for an EML armament system will be far greater than today's costs. This cost will be offset by the elimination of propellant and cartridge cases only if the system can be made reliable enough that very large numbers of rounds can be fired without significant repair and replacement costs.

7. NET ASSESSMENT

The most difficult task in this evaluation is to determine if there are clear technical reasons for believing that EMLs can mature into weapons systems with definitive advantages over other systems that might be available in the same time frame. Although there are many approaches to answering this unanswerable question, the comparison of envisioned equal risk, equal burden, and point designs is as attractive as any. As desirable as the net assessment may be to the research planner, it is full of

conjectures and assumptions. Further, if the assessment is done by a technologist working in a particular area, a bias is almost certain to be included. Considering the difficulties listed above, the reader is cautioned to keep this assessment in perspective. Like the author (who has been engaged in EML research for the last ten years), all of the evaluators have backgrounds in the EML field.

The comparison process is illustrated in Figure 2. Central to the assessment is the point design of an envisioned future weapons system. It has a projected utility determined by its platform and the targets it will address. The targets and the specifications of the system components will set limits on the gun performance. One must be assured that the platform vehicle is not overburdened. Since this new weapon concept is proposed for the future, one must not make comparisons to today's capabilities, but rather to systems with projected improvements. Ideally, one would select developments in both systems posing equal risk, but this is nearly impossible. For the purpose of this assessment, we will project eight to ten years into the future, which is the earliest point at which full-scale development (FSD) could begin on small caliber EMLs. To achieve a baseline of comparison, at least three of the six items of the triangle in Figure 2 should be similar for both the EML and advanced conventional technology. Certainly, the component specifications cannot be matched. If the gun performances are the same, equal target effectiveness may be assumed. The projected point designs will be adjusted so that equal performance and system burdens will be compared. Burden is defined here as the total weight of the armament which the platform must carry. In designing the EML system, there are two relatively easy methods of changing the system weight. First, the rate of fire may be adjusted to change the prime power; and second, the stowed load may be adjusted to change the total armament weight.

The methodologies for estimating the mass of future EML or improved conventional weapons systems are briefly described in Appendices C and D, respectively. Details of the specific equations used to estimate various weights and volumes are available in the computer codes at the end of each appendix. Both the electromagnetic and the conventional estimations use energy- and efficiency-oriented methods with scaling relations liberally applied to obtain representative values of component mass and volume. Perhaps the most critical estimate for the EML system is the mass of the Compulsator. Figure 3 reflects the uncertainty of estimating the Compulsator mass. The region between the upper and lower curves brackets the conceptual design points from uncooled iron-core Compulsators to cryogenically-cooled air-core Compulsators. In both conceptual designs, the

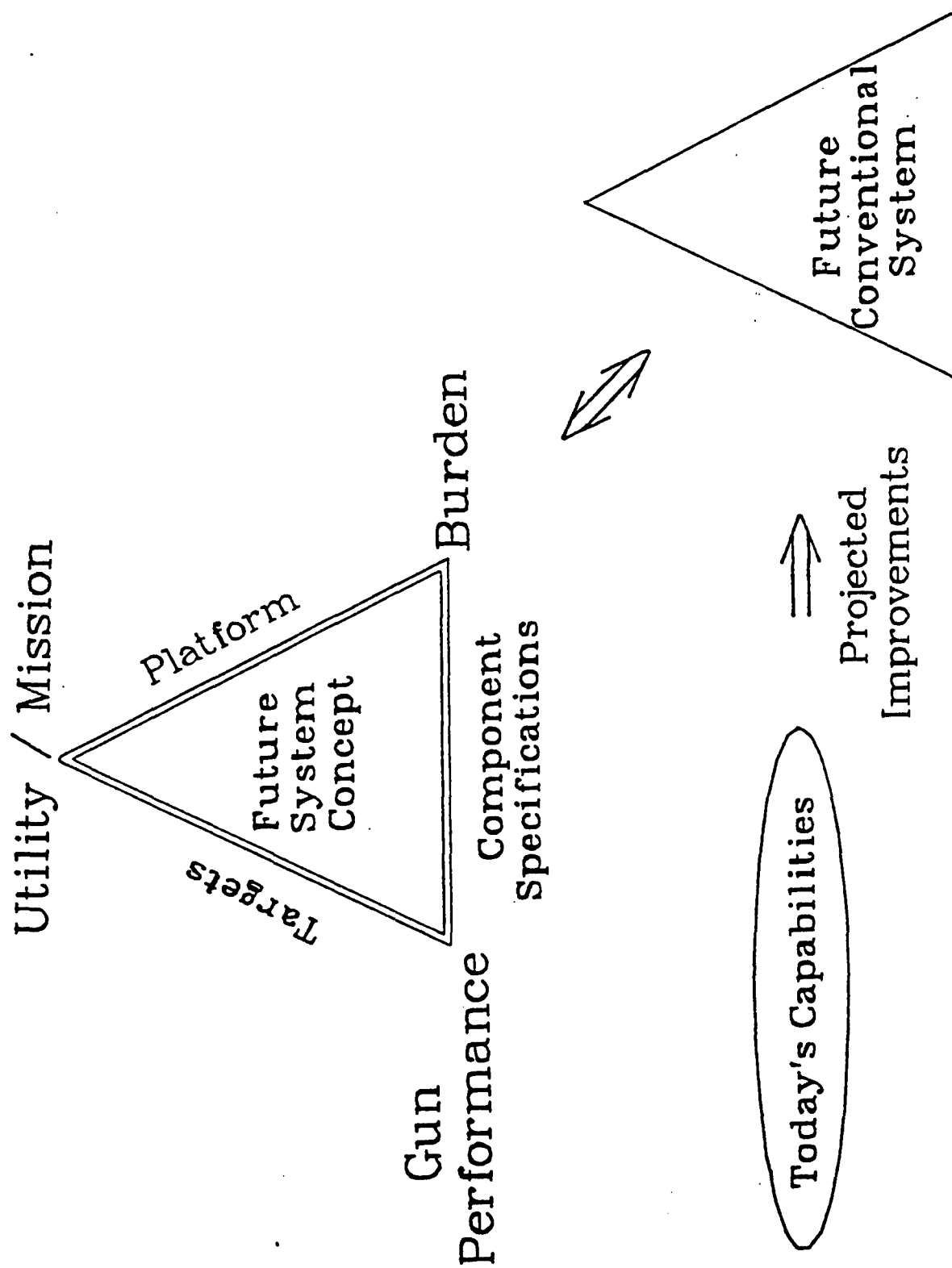


Figure 2. Illustration of Factors Used for Comparison of EML and Improved Conventional Systems.

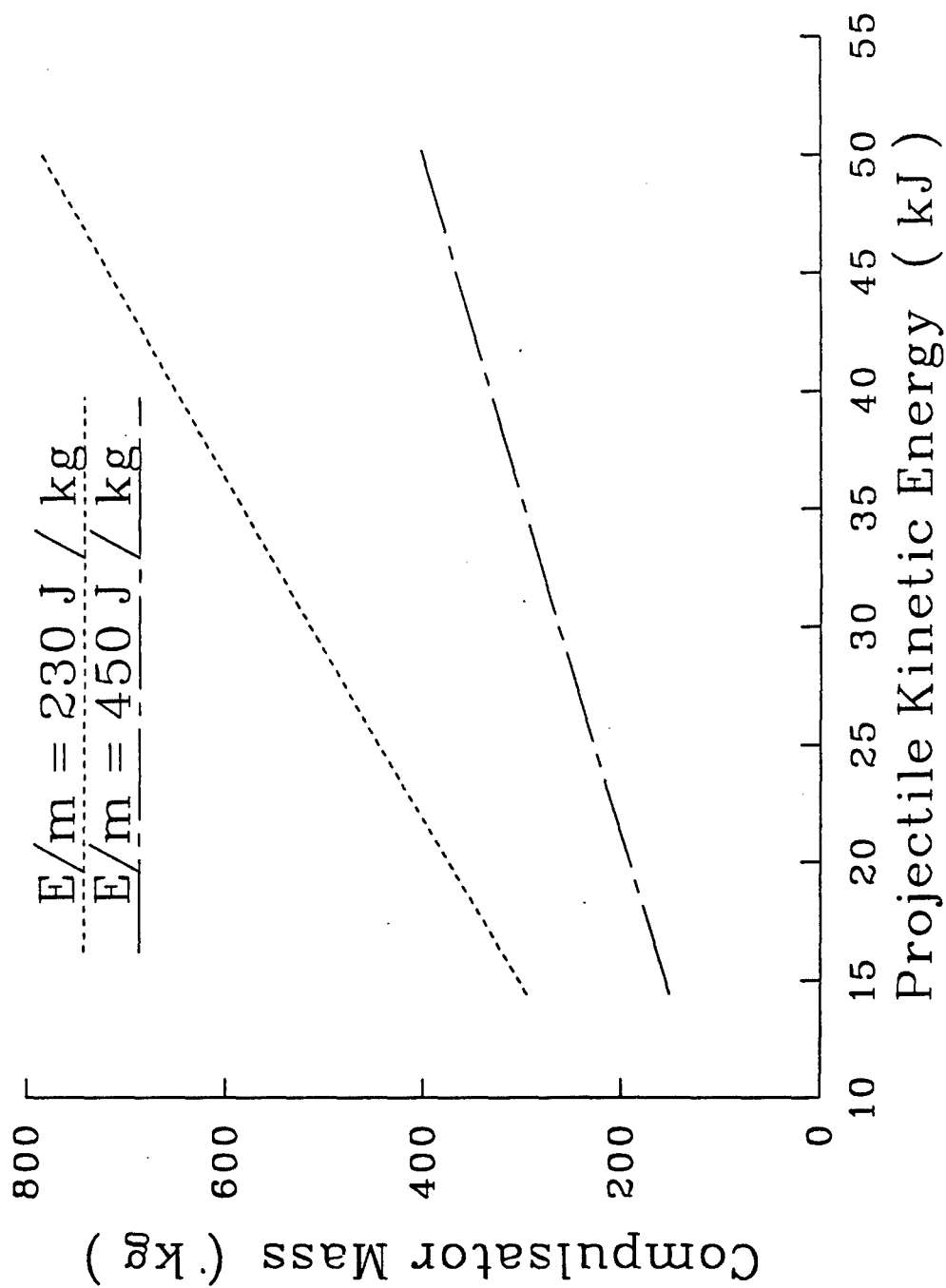


Figure 3. Relation Between Estimated Compulsator Mass and Projectile Kinetic Energy.

Compulsator was sized to fire three-shot salvos from its own rotational kinetic energy. The Compulsator mass is plotted as a function of kinetic energy of a single projectile, given the inefficiencies as described in Appendix C. In reality, these machines must store many times the energy needed to fire a single round. This makes the Compulsator a fairly natural choice for burst firing if the burst does not consist of many (more than 10) rounds. The energy density rating is based on the energy which appears on the output of the Compulsator in each of the three pulses. The computer code in Appendix C reduced this single pulse energy by the railgun, armature, and power transmission inefficiencies to obtain the projectile kinetic energy. The railgun and transmission inefficiencies are treated as electrical loss terms, while the armature inefficiency is treated as a mass which must be discarded from the launch package. The term "projectile" is reserved for the body which flies to the target. While one may feel justified in assuming the higher Compulsator energy density curve, the inclusion of a cryogenic cooling system appears unlikely for a fielded small weapon. A conservative estimation of the pulse energy density of 270 kJ/kg seems reasonable for the near term and is selected for the computer code. Wehrlein and Gully (1986) did point out that better ferromagnetic materials were available and would reduce the mass of an iron-core machine. The selection of this energy density is arbitrary, but is considered to lead to a realistic projection.

In all, masses of ten items are included in the sum of the system mass. These items comprise the lower block in Table 3, which is a printout summary sheet from the EML estimation code. The launcher parameters used as input in the calculations are selected from the candidate options given in Table 1 of Section 3.3. These parameters were calculated from more fundamental properties suggested by the panel as appropriate for small railguns. The rate of fire and number of rounds stored in the high speed autoloader are arbitrary inputs at this point, but have been selected to match a chemical gun system with identical projectile performance parameters.

The mass estimation technique for the future conventional system is outlined in Appendix D. The output of this technique is highly sensitive to two assumptions. The first is the efficiency of the chemical gun which decreases as velocity is increased. A simple relation between efficiency and the inverse of the muzzle velocity has been selected. A more rigorous interior ballistic calculation should be implemented if system parameters become more clearly defined, or if more accuracy is deemed appropriate. The second assumption, which is a critical factor in the system mass estimation, is the autoloader scaling relation. Again, if mission requirements become more exact, this scaling relation should be replaced by an engineering estimate of the mass of an actual conceptual design. Table 4 is

Table 3. Point Design Estimates for Crew-Served, Small Caliber EML

INPUT PARAMETERS

Launch Package Mass 20.9 g
 Barrel Length 1.25 m
 Stowed Load 2575 rounds
 Muzzle Velocity 2021. m/sec
 Bore Diameter 12.7 mm
 Fire Rate 240.00 rounds per minute
 (Three round salvo, 0.75-second pause)

COMPONENT VOLUME (full stowed load)

Fuel 0.111 m³
 Rail Coolant 0.123 m³
 Compulsator 0.08 m³
 Turbine 0.238 m³
 Recoil Mechanism 0.004 m³
 Compulsator Coolant 0.035 m³
 Autoloader 0.018 m³
 Power Trans. 0.010 m³
 Barrel 0.011 m³

CALCULATED PARAMETERS

Projectile Mass 17.46 g
 Useful KE 35.69 kJ
 Acceleration Time 1.30 ms
 Peak Current 554 kA
 Rail Thickness 1.28 cm
 Mass of both rails 4.80 kg
 Peak Acceleration 300.1 kg
 Launch KE 42.7 kJ
 Peak Bore Field 17.5 Tesla
 Current Density 437 kA/cm
 Peak Pressure 55.3 ksi
 Drag Losses 3.0%
 Bulk Rail Temperature Rise Per Shot 39.0° C
 Breech Rail Surface Temperature Rise 91° C
 Railgun & Armature Efficiency 30.4%

TOTAL SYSTEM VOLUME (excluding barrel)

0.60 m³
 (21.1 ft³)

COMPONENT RATINGS

Compulsator Energy 2613 kJ
 Turbine Power 951 Hp

COMPONENT MASS (full stowed load)

Fuel 66.9 kg
 Rail Coolant 73.7 kg
 Compulsator 484. kg
 Turbine 219. kg
 Recoil Mechanism 6.9 kg
 Compulsator Coolant 35.3 kg
 Autoloader 44.8 kg
 Power Transmission 50.4 kg
 Barrel 20.7 kg
 Projectiles 53.8 kg

EXPENDABLES PER SALVO (three shots)

Fuel 0.067 kg
 Rail Coolant 0.086 kg
 Compulsator Coolant 0.041 kg
 Projectiles 0.063 kg

TOTAL SYSTEM MASS 1055 kg

TOTAL RESUPPLY MASS 229.8 kg

Table 4. Point Design Estimates for Future Conventional Systems

INPUT PARAMETERS	ESTIMATED COMPONENTS
Kinetic Energy 35.69 kJ	Barrel 59.6 kg
Stowed Load 2575 rounds	Cartridge Mass 206 g
Muzzle Velocity 2021 m/sec	Autoloader Volume .34 m ³
Fire Rate 240.00 rounds per minute (Three round salvo, 0.75-second pause)	TOTAL RESUPPLY MASS 532 kg
TOTAL SYSTEM MASS 1055 kg	

a sample estimate of the future conventional system which has been done for comparison to the EML system as listed in Table 3.

The point design selection above is, of course, arbitrary. The technique for matching the system masses is worthy of some discussion. For the estimation technique presented here, the four factors which contribute most strongly to the system mass approximation are:

- rate of fire
- number of stowed rounds
- muzzle velocity
- projectile mass.

The selection of the last two parameters reflects the viewpoints of the panel. The first two parameters are used to match the EML and future conventional system masses. In principle, a rate of fire could be selected and a stowed load computed which will give both systems equal mass. The inverse is true only if the arbitrary stowed load is large enough to offset the EML generation equipment. Figure 4 shows the relation between firing rate and number of rounds stored if both the EML and future conventional system masses are constrained to be equal. The minimum stowed load under these assumptions is slightly less than 2,000 rounds. The actual number of rounds stored to achieve this matching of conventional and EML system masses is dependent on the technique, launcher parameters, and assumptions. It may be generally true that the stowed load must be significant if an EML system is to be weight-competitive with a chemical gun system. Without much

Velocity = 2021 m/s, Projectile Mass = 17.5 grams

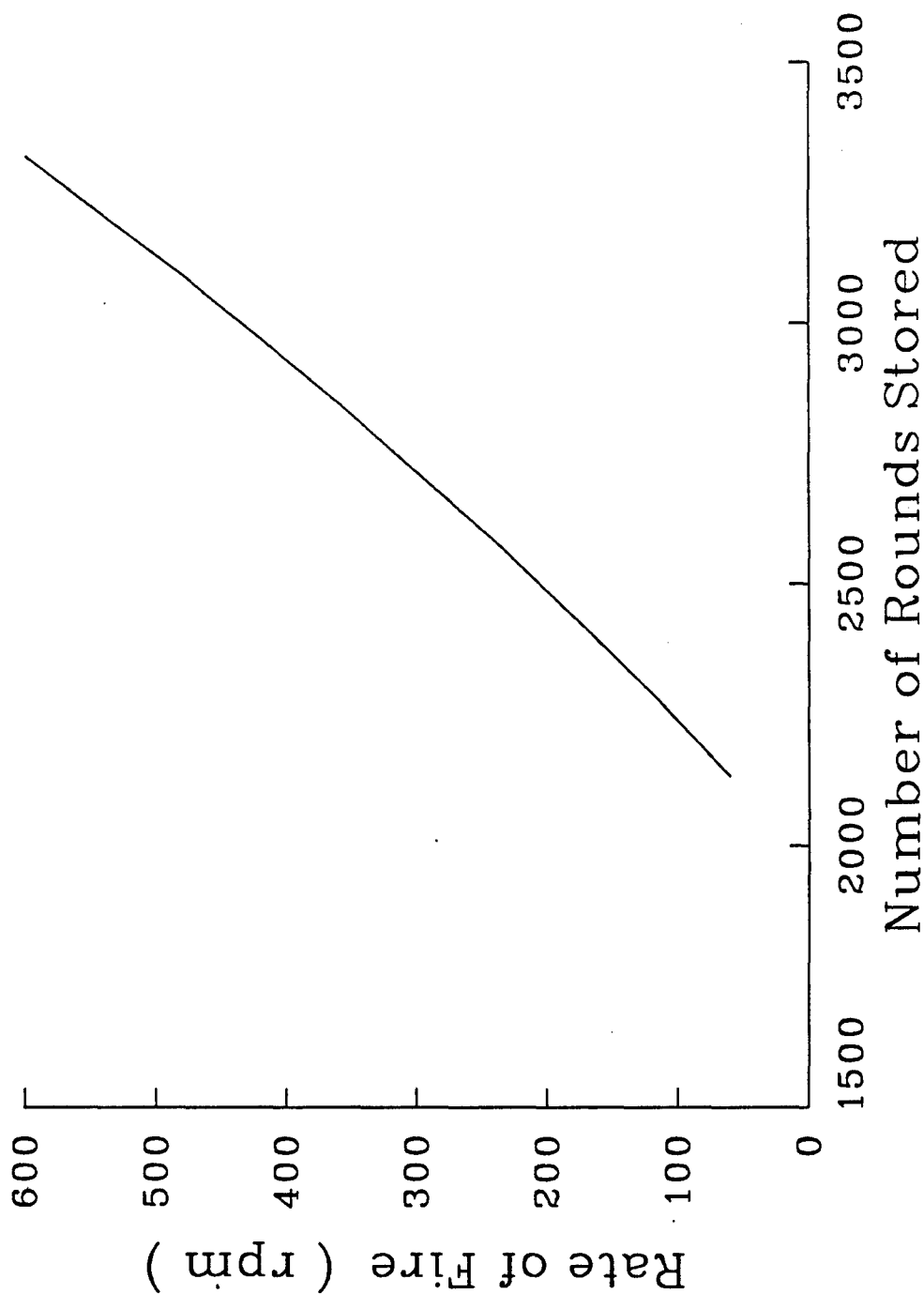


Figure 4. Average Firing Rate and Stowed Load Which Permit Equal Mass EML and Future Conventional Systems.

justification, an average rate of fire of 240 rounds per minute and a stowed load of 2,575 rounds is selected as the matching point for the assessment process. Both system masses are estimated at 1055 kg. This mass estimation is in reasonable agreement with the estimation of a different type of EML system with similar performance parameters (Barber, McCormick, and Bauer 1981). A critical point in the assessment process is now apparent. The platforms which will be equipped with this system must be capable of carrying a load of more than one ton. Further, some indication should be obtained that the user is interested in a system with this performance and magnitude of weight.

The first portion of the comparison of these equal mass, equal performance systems is to examine the divergence of the mass estimations with variance of each of the four critical factors. Figure 5 shows the effect on system mass if the firing rate is varied. The insensitivity of the chemical gun system to firing rate is expected, because only the autoloader must be changed. Since the autoloader is envisioned as one capable of salvo fire, decreasing the time between salvos should be a minimal effect. The EML system requires an ever-increasing power rating on its drive engine as the rate of fire increases. The inference which may be drawn here is that if one wants improvement in firing rate over the baseline system, conventional propulsion is the technology of choice. This comparison does not address the sustained fire question. The EML system is estimated with both power and barrel coolant, so as the length of the mission is increased, the EML would show an advantage.

Figure 6 shows the effect on the system mass of a change in the stowed load. Since the launch package for the EML is much smaller than the chemical gun round, the stowed load has a far greater impact on the chemical system mass. Likewise, the resupply mass for the EML system is more than a factor of two smaller for the EML than that for the conventional system. This resupply advantage may be very attractive from a logistics point of view. As stated in the review of the panel discussions, this advantage will not be useful unless the components require very few replacement parts.

Perhaps the advantage claimed most often for electromagnetic guns is the high velocity performance. Since we are not considering velocities which cannot be achieved by conventional techniques, the divergence of system masses with variance of muzzle velocity is not as great as one might anticipate. Figure 7 illustrates the effect on system mass of changing the projectile velocity. The EML barrel length was varied directly with the velocity to constrain the acceleration to the value recommended by the panel. Both the conventional and EML systems exhibit somewhat parabolic

Velocity = 2021 m/s, Projectile = 17.5 grams SL = 2575 rds

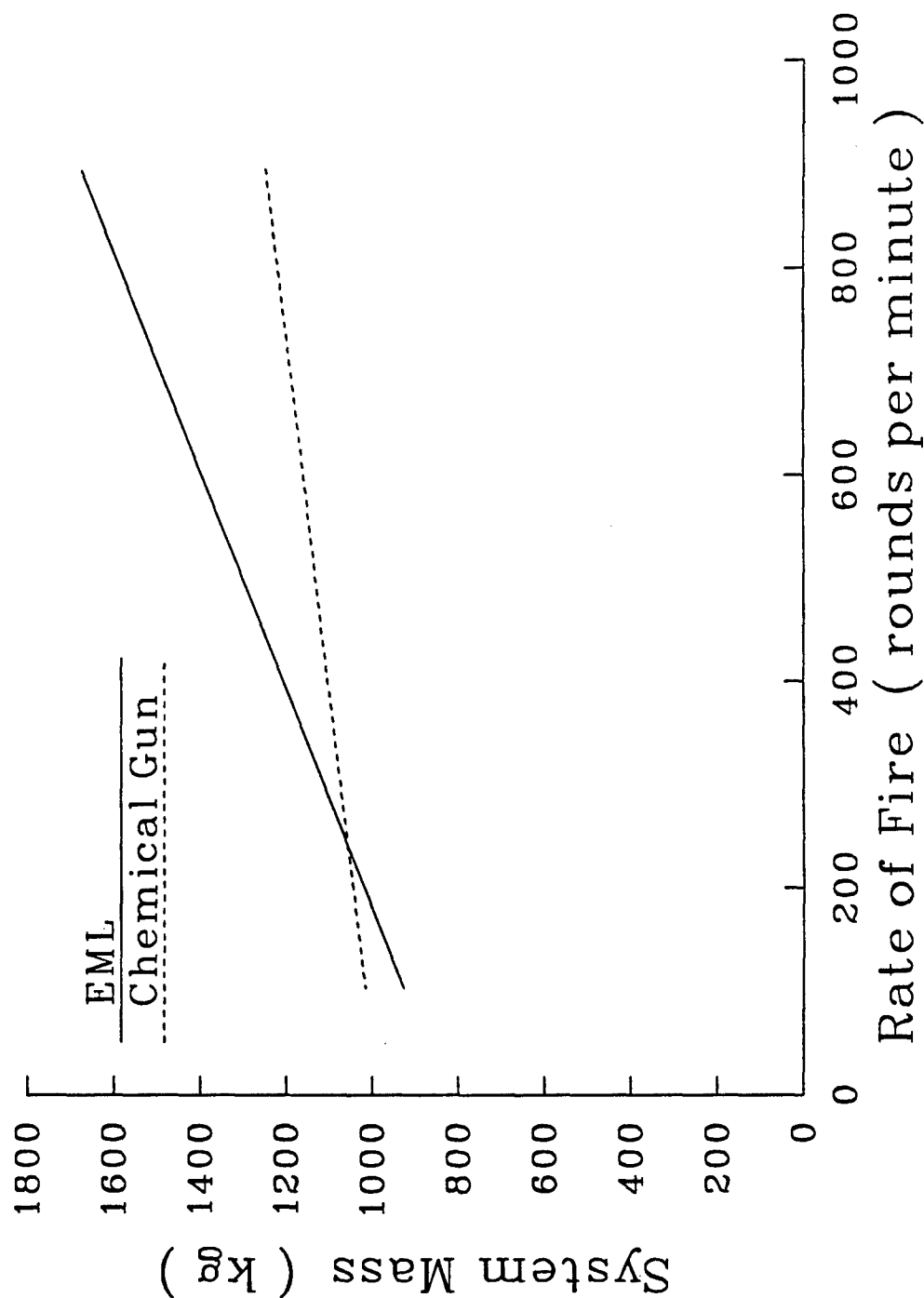


Figure 5. Variation of Point Design System Masses With Firing Rate.

Velocity = 2021 m/s, Projectile = 17.5 grams RoF = 240 rpm

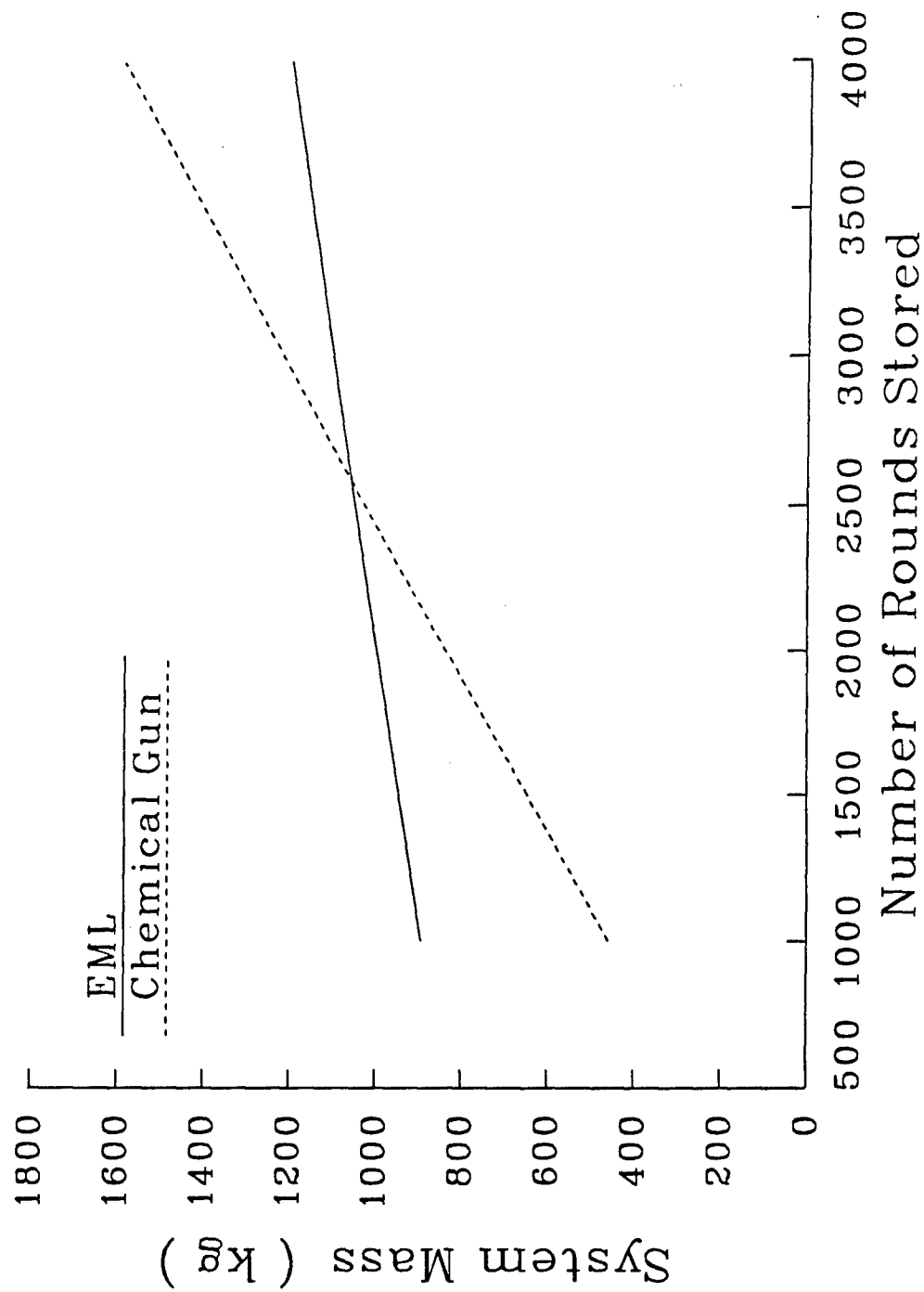


Figure 6. Variation of Point Design System Masses With Stowed Load.

Projectile = 17.5 grams, RoF = 240 rpm, SL = 2575

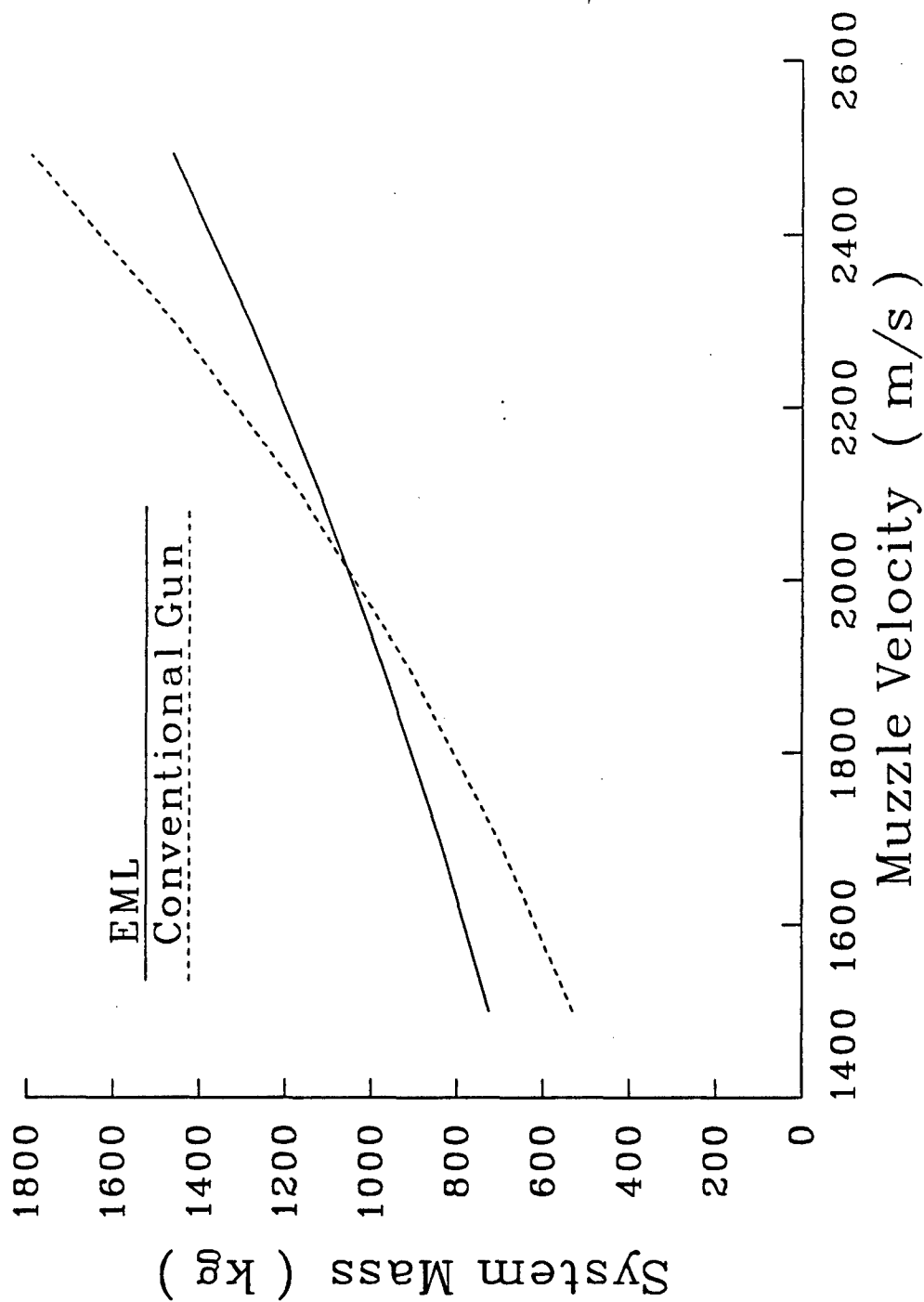


Figure 7. Variation of Point Design System Masses With Muzzle Velocity.

behavior. This is a result of the direct relation between the square of the velocity and the kinetic energy. The manifestation of the decreasing chemical gun efficiency with increasing velocity results in very massive systems as the velocity approaches and exceeds 2.5 km/sec. Clearly, if the need exists to increase velocity of these point designs, EML is the technology of choice.

Figure 8 depicts the rather small difference in the EML and chemical systems as the projectile mass is varied. The EML bore dimension was varied as the square root of the mass to maintain the pressure at that recommended by the panel. Increasing the projectile mass gives a slight advantage to the EML system. EML technologists often state this dependence inversely: smaller systems are not as efficient as large ones. This trend is weak and may be an artifact of the assumptions in the estimation codes. The reader is reminded that, for acceleration of very large masses such as railroad trains, electrical power is often utilized. The abscissas of Figures 5, 6, 7, and 8 have been made identical so that the reader may directly compare the relative effects of each variation.

The remainder of the net assessment is more conjecture than fact. Because of the large quantities of high velocity gases which flow down the bore, factors such as barrel life for the conventional system are likely to be a problem. The peak bore pressures in the chemical guns may make safety an issue. The large difference in autoloader volumes would make an EML far easier to locate outside a vehicle for remote operation. The components of the EML system may be far easier to distribute throughout the vehicle than the single massive autoloader in the conventional system.

Although the mass and velocity of the projectile flight body are identical, the launch conditions should favor the EML system. The conventional system at this projectile energy level will produce a large blast and muzzle flash. Both signature and launch dispersion problems are expected to be smaller for the EML.

Because the energetic propellant has been replaced by common fuel, safety aspects all through the logistic and manufacturing chain will be enhanced for the EML system. The logistics load and time to resupply the vehicle's stowed load will be eased significantly.

Generally, comparing these two point designs, the EML system shows many advantages. The growth potential in all areas, except rate of fire, indicate that an EML weapon is a good choice for

Velocity = 2021 m/s, RoF = 240 rpm, SL = 2575

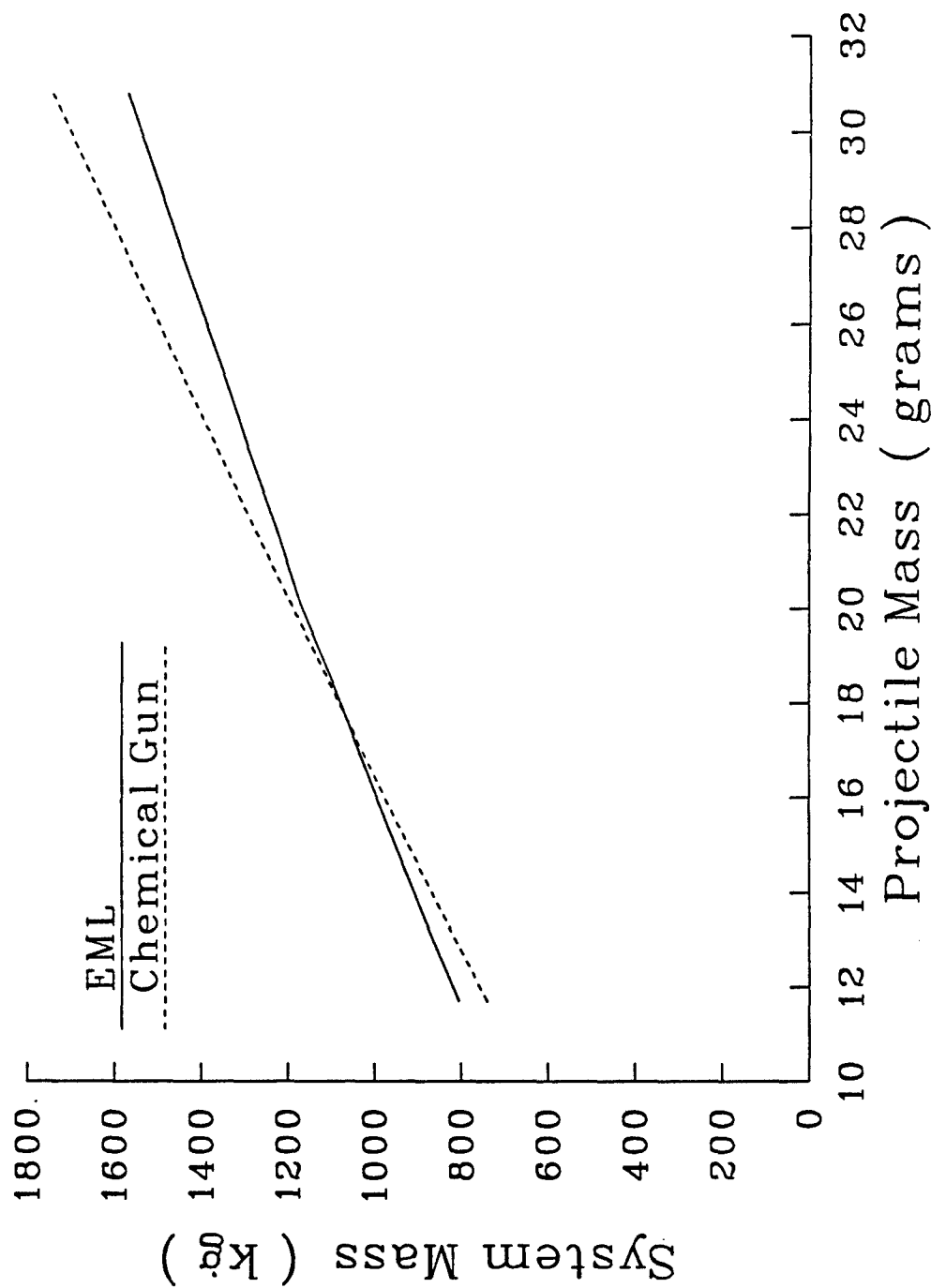


Figure 8. Variation of Point Design System Masses With Projectile Mass.

point targets. If area targets, which require many rounds to be fired in a very short time, are deemed to be more important than point targets then the conventional system is recommended.

8. CONCLUSION

The general conclusion of this study is that the potential for electromagnetic launchers for vehicle mounted, small caliber weapons is significant. This potential and the laboratory accomplishments to-date certainly justify a research effort in the applications of small EMLs. If reasonable success is achieved in the research program, a development effort would also appear well-founded, given user interest in the potential payoffs which may be attainable. The present JSSAP sponsored program is solidly based; however, the following recommendations are made for improving the probability of success.

- (1) Change the bore dimensions for the laboratory demonstration railgun from 1-m length, 10-mm bore to 1.5-m length, 15-mm bore.
- (2) Initiate a research effort on the maximum allowable acceleration for the armature/projectile package.
- (3) Maintain alternate power supply programs with hardware, if possible.
- (4) Place more emphasis on barrel structures, and establish a barrel lifetime milestone.
- (5) Survey candidate platform vehicles and inventory-carrying capabilities.
- (6) Continue a periodic review and assessment process.

The panel assembled to help in this assessment was overwhelmingly in favor of the selected mission and generally in agreement in the areas that EMLs could provide significant improvement over today's weapons. The nearness of term is more difficult to assess, but the growth potential for electromagnetic guns is one of its strongest selling points.

Several technical barriers are listed; however, few are viewed as rigid obstructions to the program. The consensus view was that very few basic physics issues remain unsolved. Long-lived rails and armature function were of greatest concern to the panel. Projectile and barrel design as well as a general need to reduce power supply size and weight were also cited as required research areas. RAM and associated issues like the logistics of components are viewed as very difficult areas to assess. Significant RAM problems may not prevent the construction of an EML weapon, but may prevent it from being selected by a user. One panel member put this in perspective by stating his interest in new technology, but asked for the time honored M60 if he were called to combat in the near future.

Suggested milestones separated into four areas: projectiles, power, launchers, and system demonstrations. Developing a "flashless," non-arcing armature capable of accelerating a payload to 2 km/sec or higher was frequently recommended. Demonstrating a field-portable power supply and constructing a high-pressure, long-life barrel were also cited. Most of the evaluators agreed with the present plan, which combines many of these milestones in a laboratory demonstration of a salvo-fire EML. Assuming success and user interest, this research should be followed by a pre-prototype demonstration. If clearly defined armament needs are met by EML capabilities, an actual prototype weapon program could follow. Cost estimates by the evaluators for maturing EML technology through the pre-prototype stage ranged from \$3-200 million.

The comparison of envisioned point designs for EML and improved conventional armament systems echoed the mission discussions. For area targets where high rate of fire is important, the conventional system is potentially better. For point targets where increases in projectile mass and velocity will improve weapon effectiveness, the EML system is preferred. For systems and missions which require a very large stowed load, again, the EML showed more potential for improvement. The resupply weight was far smaller for the EML system, suggesting improvements in logistics in addition to the elimination of energetic chemical propellants. Several other factors such as muzzle blast, launch accuracy, and weight distribution of the system in the platform, would also be more favorable to the EML system. The comparison of these factors is more subjective, but serves as a reminder that many benefits may be possible with electromagnetic propulsion which are not possible with conventional chemical propulsion.

The growth potential of EML technology is the strongest reason for actively researching this area. It is too early to project actual weapons systems, but clearly the possibility for such systems exists

without the need for breakthroughs in technical areas. The effort required to mature each of the components of an EML system varies widely, but armatures, barrels, and power supplies require the most work. Periodic review and assessment as technology advances will insure that the present effort remains well-founded.

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**APPENDIX A:
LIST OF PARTICIPANTS**

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The following list of personnel are those who participated in the panel discussions of the technical assessment of the small caliber electromagnetic launcher program. Those providing written evaluations are denoted with the symbol "(E)."

Ted Gora	ARDEC
John Pappas (E)	ARDEC c/o Univ. of Texas
LT Jeff Martin (E)	AFATL
Dave Bauer (E)	IAP Research, Inc.
Anas Abo-Zena	ARDEC
Jack Bernardes (E)	Naval Surface Weapons Lab.
Charles E. Christianson (E)	ARDEC
Keith A. Jamison	BRL
CPT Robert Otlowski (E)	ARDEC
Patrick Vottis (E)	Benet Laboratories
Bill Condit (E)	LANL
Clarke Homan (E)	Benet Laboratories
Lucian Sadowski	ARDEC
LT Rich Byers (E)	AFATL
J. Wade Hill	ARDEC
Harry Moore (E)	ARDEC
John Bennet (E)	ARDEC
Joel Goldman	ARDEC
Bob Schlenner	ARDEC
Angelo Mancini	ARDEC
Joe Brady	ARDEC
Rolf Dethlefsen (E)	Maxwell Laboratories, Inc.
Lou Jasper (E)	ETDL
Henry Kahn	ARDEC

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APPENDIX B:
SAMPLE SURVEY QUESTIONNAIRE

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Application of Electromagnetic Launcher Technology

to

Future Small Caliber Weapons

VALUE TO MISSION:

Please score the following applications as per the value of EML R&D towards future weapons systems. (100 for extremely high value, 50 when risks and projected burdens equal potential benefits, 0 for no gain, high risk, and large potential burden).

For any non-zero score, please indicate the relative work required to obtain a prototype weapon system (use 10 point maximum).

Value Score		Basic Research	Applied Research	Development	Systems Engineering
_____	Combat Hand Gun Personal Defense	_____	_____	_____	_____
_____	Rifle Anti-Personnel Long-Range	_____	_____	_____	_____
_____	Sniper Rifle Covert Operations	_____	_____	_____	_____
_____	Crew-Served MG 8—10-mm Area Target Anti-Personnel Anti-Material	_____	_____	_____	_____
_____	Crew-Served MG Area Target Anti-Armor Anti-Personnel	_____	_____	_____	_____
_____	Shotgun Area Target Short Range	_____	_____	_____	_____
_____	Grenade Launcher Area Target	_____	_____	_____	_____

COMMENTS:

Application of Electromagnetic Launcher Technology

to

Future Small Caliber Weapons

POTENTIAL IMPROVEMENTS:

Please rate the following areas where EM technology could improve small caliber weapons. Fold the difficulty in achieving the goal together with an amount of improvement to be gained. Score 10 for an easily attainable, very significant improvement, 4 for no improvement with moderate effort, and zero for less than today's capability with difficult development. On the right hand side of the page, list other technologies which have nearly equal potential benefits. Feel free to make comments as often as you like. Evaluators are asked to focus on a baseline crew-served weapon firing a 32-g projectile at 2 km/sec.

Ranking	Rating	Alternative Technology
_____	_____	Extended Range
_____	_____	Improved Lethality
_____	_____	Higher Rate of Fire
_____	_____	Reduced Signature
_____	_____	Better Environmental Factors
_____	_____	Improved Safety
_____	_____	Reduced Logistics - Gun System Components
_____	_____	Reduced Logistics - Ammunition
_____	_____	Fire Control Interface
_____	_____	Recoil
_____	_____	RAM
_____	_____	Synergism with All-Electric Vehicles
_____	_____	Novel Projectiles (Variety)
_____	_____	Accuracy
_____	_____	Ammunition Vulnerability
_____	_____	Other

COMMENTS:

Application of Electromagnetic Launcher Technology

to

Future Small Caliber Weapons

COMPONENTS OF AN EML R&D PROGRAM:

Please rate the following components of a small caliber EML program given the national effort which is on-going. (10 for the most important, 1 for the least important) Again, comments are appreciated! Please limit time frame score to early, mid, or late.

Time Frame	Rating	
_____	_____	Projectile Design - Aerodynamics
_____	_____	Projectile Design - Target Effects
_____	_____	Armature Effectiveness
_____	_____	Armature Efficiency/Payload
_____	_____	Armature Signature Reduction
_____	_____	Barrels - Rail Lifetimes
_____	_____	Barrels - Structural
_____	_____	Barrels - Reduction of Losses
_____	_____	Power - Prime Engine
_____	_____	Power - Electrical Generation
_____	_____	Power - Energy Storage
_____	_____	Power - Switch Gear
_____	_____	Power - Transmission from Source to Breech
_____	_____	System Engineering - Weight Economy
_____	_____	System Engineering - Volume Economy
_____	_____	System Engineering - RAM Issues

_____	_____	Thermal Management
_____	_____	Utility Analysis
_____	_____	Other (Specify)

COMMENTS:

Application of Electromagnetic Launcher Technology

to

Future Small Caliber Weapons

DO YOU SEE EML TECHNOLOGY AS WORTHWHILE FOR THE PRESENT JSSAP PROGRAM?

PLEASE LIST THE TECHNICAL BARRIERS AND THE LEVEL OF EFFORT YOU BELIEVE IS REQUIRED FOR EACH.

PLEASE LIST AN APPROPRIATE SET OF MILESTONES FOR A SMALL CALIBER EML PROGRAM.

ESTIMATE THE COST OF MATURING EML TECHNOLOGY TO A WEAPONS SYSTEM PROTOTYPE.

PLEASE GIVE YOUR HONEST OPINION OF THIS ASSESSMENT PROCESS. (BETTER IDEA?)

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**APPENDIX C:
ESTIMATION OF EML SYSTEM MASS**

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There are a great many assumptions and scaling relations which must be used to estimate the size and weight of any EML weapon system which might be a candidate for the armament of some future system. A list of scaling relations is given in Table C-1. The most straightforward method of describing the estimation procedure is to outline the program flow of the computer code which follows in this appendix. The first section establishes the constants relating to operation of a railgun and makes an assumption about the efficiency of a turbine engine. It is assumed that the turbine can convert 20% of the fuel's chemical energy to rotational energy. This is consistent with fuel consumption rates typical of aircraft turbines.

The next section obtains the input parameters necessary for the calculations. The launch package mass and velocity, barrel dimensions, firing rate, and stowed load of ammunition are all used to compute values descriptive of different parts of the system. Given the input, several parameters relating to the railgun performance may be directly calculated. These include the kinetic energy, the average rate of fire assuming a three-round burst, and the peak current needed by the railgun to accelerate the launch package. The dwell time of the launch package in the barrel is estimated from the velocity and barrel length. The "skin-depth" or useful thickness of conductor is calculated from this dwell time. The thickness of the rails is chosen to be one and a half times the "skin-depth," and the rails are assumed to be 4 mm wider than the bore. These dimensions allow the mass of the rails to be estimated. The peak magnetic field and current per unit rail height are also computed and used to estimate the ohmic heating of the rail surface due to the rapid application of current.

A simplified railgun simulation section is contained in the program to estimate the losses and input power requirements for the gun. The rail resistance is calculated with a constant current approximation, but does not assume constant acceleration. This underestimates resistance in the first half of the shot when the current is rising, but overestimates the resistance in the latter portion of the shot. This is a conservative estimate, since the resistive losses are far larger when the projectile nears the muzzle, and velocity is high. A simply approximated armature drag and a 10-V armature drop are counted as loss terms. This is consistent with experimental results when good contact is made by both armature surfaces.

As the simulated shot proceeds, the losses are integrated as is the square of the current. The integral of the current squared is directly related through an action constant to the heating of armature material. Again opting for the conservative estimate, the code calculates the mass of aluminum which

Table C-1. Constants and Approximations for Estimation of EML System Mass

Railgun Inductance Gradient	0.4 $\mu\text{H/m}$
Conductivity of Warm Copper	$4.45 \times 10^7 \text{ } \Omega/\text{m}$
Copper Density	8968 kg/m^3
Specific Heat of Copper	382 $\text{J/kg}^\circ\text{C}$
Efficiency of Drive Engine	20%
Peak-to-Average Acceleration Ratio	1.8
Rail Surface Temperature Rise	0.3 Multiplied by the Induction Field Squared
Rail Thickness	1.5 Multiplied by the Skin Depth for the Acceleration Time
Rail Resistance	Constant Current, Non-Constant Acceleration Approximation
Armature Voltage Drop	10 V
Action Constant to Raise A1 300° C	$2.1 \times 10^{16} \text{ A}^2 \cdot \text{sec/m}^4$
Distance From Compulsator to Railgun	2.0 m
Compulsator Pulse Energy per Unit Mass (Assume three-shot salvo)	270 J/kg
Drive Engine Weight	0.5 lb/Hp 0.3 kg/per kW
Fuel Energy Density	40 MJ/kg

would be heated to 300° C and assumes that it must be separated from the launch package and not considered as part of the projectile which flies to the target. The program rather arbitrarily budgets the discarded mass as an armature inefficiency and the armature voltage drop as a gun inefficiency.

The program bases the launch package kinetic energy calculation on the simulation results and adjusts the current amplitude if the required energy and the simulated energies do not match within 2%. If the energy output of the railgun has been properly simulated, the program bases the computation of the temperature rise of the rails on the resistive loss, and half the drag and armature voltage loss.

At this point, the launcher performance and input requirements are completed leaving the power transmission losses to be assessed to specify the Compulsator output. The gun is assumed to be located two meters from the launcher. The sizing of the electrical conductors is chosen to allow a 0.7° temperature rise per shot. The conductor resistance is always assumed to be that of 100° C copper. The losses will be overestimated for at least the first 100 rounds of a mission. For much longer missions, this approximation may be optimistic.

The mass of the Compulsator is estimated according to the preliminary designs of Wehrle and Gulley (1986). They have studied both iron-core and air-core machines and offer two concepts in their paper. The estimation of the Compulsator assumes a 15% improvement in energy density over the heavier, iron-core machine. The air-core machine, which requires cryogenic cooling, was not selected for this calculation. A Compulsator efficiency is estimated by scaling the internal resistance linearly with the mass of the conceptual iron-core machine.

The prime drive engine needed to power the Compulsator is sized to be consistent with the average rate of fire, launcher output, and all power train efficiencies. The mass and volume of the engine are estimated from aircraft-type turbines. The mass of the turbine itself is doubled to account for auxiliary systems.

The autoloader mass and volume are difficult to accurately estimate. High-speed designs are typically as massive or more massive than the stowed load they contain. For estimation purposes, a very weak dependence on the average firing rate has been assumed. As is seen in the output tables, the autoloader for the EML, which carries only launch packages, is a small part of the total system.

The barrel mass is calculated in a subroutine, starting with the mass of the rails and assuming that the insulator's density is one third that of copper. A very conservative estimation of the Kevlar required to contain the magnetic repulsion of the rails is made to estimate the barrel mass. This is not likely to be the actual construction technique, but is used to base the mass estimate on physical properties of the launcher.

Fuel and coolant requirements are calculated from the component efficiencies. Energy density of the fuel is taken as 40 MJ/kg, which is appropriate for most hydrocarbon fuels. The coolant is assumed to be an open-loop conversion of water to steam with a cooling capacity of 2.5 MJ/kg. All totals computed are based on firing the entire stowed load with the exception of the fuel; added fuel, allowing for an additional 30 "spin-ups" of the Compulsator, is provided to account for multiple missions from a single stowed load.

The last portion of the program is an output section coded to print out the results in tabular format. The FORTRAN code and sample outputs follow.

```

C
C      THIS PROGRAM ESTIMATES THE MASS AND VOLUME OF SMALL CAL EML SYSTEM
C
      IMPLICIT REAL*4(L,I,M)
      DIMENSION XR(401)
C
C      CONSTANTS AND ASSUMPTIONS
C
      LPRIME = 4.0E-07          ! Henries per Meter
      PI = 3.41593
      MU = 4*PI*1.0E-07
      SIGMA = 4.45E+07          ! Mhos per Meter
      RHOCU = 8.968E+03         ! Kilograms per Cubic Meter
      CPCU = 382.8              ! Joules per Kilogram per Degree Centigrade
      EFTURB = .2               ! Assume turbine efficiency of 20%
      OPEN(UNIT=2,FILE='RESULT.DAT',STATUS='NEW')
      WRITE(6,*)' TYPE ONE IF DATA FROM FILE'
      READ(5,*)NFILE
      IF(NFILE.NE.1)GOTO1
      OPEN(UNIT=5,FILE='INPUT.DAT',STATUS='OLD')
C
C      GET INPUTS
C
1      WRITE(6,*)' LAUNCH PACKAGE MASS (grams)?'
      READ(5,*)M
      M=M/1000.
      IF(M .LE. 0.0) GO TO 99
      WRITE(6,101)
101     FORMAT(' BORE SIZE IN MILLIMETERS?')
      READ(5,*)W
      W=W/1000.0
      WRITE(6,102)
102     FORMAT(' FINAL VELOCITY IN METERS PER SECOND?')
      READ(5,*)VEL
      VMUZ = VEL
      WRITE(6,103)
103     FORMAT(' BARREL LENGTH IN METERS?')
      READ(5,*)XF
      WRITE(6,*)'WHAT IS THE TIME BETWEEN SALVOS (seconds)?'
      READ(5,*)TBS
      AROF=3.0/TBS
      WRITE(6,*)'HOW MANY ROUNDS STOWED?'
      READ(5,*)STWLD
C
C      DO CALCULATED SYSTEM PARAMETERS
C
      FENRG = 0.5*M*VMUZ*VMUZ
C
      PEAK ACCELERATION ASSUMING PEAK TO AVERAGE PRESSURE OF 1.8
      AAVG = FENRG/XF/M
      APEAK = AAVG*1.8
      TF=VMUZ/AAVG*1.05          ! ADJUSTED FOR INTEGRAL OF FORCE
      IMAX = SQRT(2.0*M*APEAK/LPRIME)
10     PEAKPRES = 0.5*LPRIME*IMAX*IMAX/W/W/6894700.    ! In ksi

```

```

JMAX = IMAX/W
BMAX = LPRIME * JMAX
RTHICK = 1.5 * SQRT(PI*TF/MU/SIGMA)
RAILMASS = XF*(W + 0.004)*RTHICK*RHOCU
C
C   CALCULATE BARBER'S RAIL SURFACE TEMPRATURE RISE
STRISE = 0.3*BMAX*BMAX
C
C   DO SIMPLE SIMULATION BASED ASSUMING CURRENT VARIES AS SINE**0.68
C
  DT = TF/400.0
  OMEGA = PI/TF                                ! Frequency of Driving Current
  XD = 0.0                                       ! Initial velocity
  XPOS = 0.0                                    ! Initial position
  ERAIL = 0.0                                  ! Rail Losses
  EDRAI = 0.0                                  ! Drag Losses
  EARM = 0.0                                   ! Armature Losses
  DRAG = 0.0
  ERAIL2 = 0.0
  AIN = 0.0                                     ! Integral of current squared
  DO 2, K = 1, 400
    TIME = FLOAT(K)*DT
    F = SIN(OMEGA*TIME)
    IF (F .LE. 0.0) GO TO 2
    CUR = IMAX * F**0.68
    AIN = AIN + CUR*CUR*DT
    DRAG = 2.5 * W * W * XD * XD                ! ESTIMATE ONLY.....
    XDD = 0.5*LPRIME*CUR*CUR / M - DRAG
    XD = XD + XDD*DT
    XPOS = XPOS + XD*DT
    XR(K) = XPOS
    RESRAIL = 2.0 * XPOS / SIGMA / W / SQRT(PI*TIME/MU/SIGMA)
    IF (K.GE.2) THEN
      RSUM = 0.0
      DO 3 NR = 1, K-1
        DELTAW = SQRT(PI*DT*FLOAT(K-NR)/MU/SIGMA)
        RSUM = RSUM + (XR(NR) - XR(NR-1))/SIGMA/(W+.004)/DELTAW
        RESRAIL = 2.0*RSUM
      END IF
    ERAIL = ERAIL + RESRAIL*CUR*CUR*DT
    EARM = EARM + 10.0 * CUR * DT                ! Ten Volt Armature Voltage Drop
    EDRAI = EDRAI + DRAG * XD * DT              ! F*dx LOSSES
  2 CONTINUE
  ARMALOSS = W*2700.0*SQRT(AIN/2.1E+16)
  ARMKELOSS = 0.5*ARMALOSS*XD*XD
  EFARM = (FENRG-ARMKELOSS)/FENRG
  USEPROM = M*EFARM                             ! DROP PART OF ARMATURE
  CALCKE = 0.5*M*XD*XD                          ! Calculate KE in case of error in approx.
  USEFULKE = 0.5*USEPROM*XD*XD                  ! USABLE KE AFTER ARMATURE DROP
  IF (CALCKE.GT.1.02*FENRG .OR. CALCKE.LT.0.98*FENRG) THEN
    INEW = IMAX*SQRT(FENRG/CALCKE)
    IMAX = (IMAX+INEW)/2.0
    GO TO 10
  END IF

```

```

EFGUN = CALCKE / (CALCKE + EARM + ERAIL + EDRAE)
C
C   ASSUME HALF ARMATURE AND DRAG LOSSES GO INTO RAILS
RAILTEMP = (ERAIL + 0.5*(EARM+EDRAE))/(2.0*RAILMASS*CPCU)
C
C   POWER TRANSMISSION SECTION: SIZE FOR 0.7 DEGREE TEMPERATURE RISE, eg.
C   NO COOLANT FOR 100 ROUND MISSION
C
DELTPT = 0.7
LENPT = 2.0           !   Locate gun six feet from power
AREAPT = SQRT(AIN/(SIGMA*RHOCU*CPCU*DELTPT))
MASSPT = RHOCU*2.0*LENPT*AREAPT
PTLOSS = AIN*2.0*LENPT/SIGMA/AREAPT
EFPT = CALCKE/EFGUN / (PTLOSS + CALCKE/EFGUN)
C
C   CALCULATE COMPULSATOR MASS BASED ON IRON CORE ENERGY DENSITY
COMPDEN = 270.           ! .27 kilojoule of pulse per kg
COMPMASS = FENRG/EFGUN/EFPT/COMPDEN
COMRATE = 20.0*FENRG/EFGUN/EFPT           ! Rating approx 20 times pulse
C
C   SCALE COMPULSATOR RESISTANCE LIKE INVERSE OF MASS,
C   USE 500 MICRO OHMS AT 213 KILOGRAM MASS FROM WEHRLIN AND GULLEY STUDY
COMPLLOSS = AIN*5.0E-04*213.0/COMPMASS
EFCOMP = CALCKE/EFGUN/EFPT / (COMPLLOSS + CALCKE/EFGUN/EFPT)
C
C   SIZE TURBINE WITH FIRE RATE, KE AND EFFICIENCIES
C
TP = AROF*CALCKE/EFGUN/EFPT/EFCOMP/746.0! Convert watts to horsepower
TMASS=TP*.23           ! Assume aircraft type mass
TURBV=TP/4000.         !   and volumes for turbine
C
C   ASSUME AUTOLOADER AND MAGAZINE MASS EQUAL MASS OF STOWED LOAD AT
C   TEN HERTZ
C   AUTOLOADER VOLUME EQUALS 1/4 OF FULLY DENSE IRON
PROM=M*STWLD
C
C   Weak dependence of autoloader mass on fire rate
AUTLOD=PROM*(0.7 + AROF/30.0)
ATLODV=4.0*AUTLOD/7.9E+03
C
C   CALCULATE BARREL MASS AND ASSUME RECOIL MECHANISM EQUAL
C   1/3 BARREL MASS AS FROM GAY TABLES
C
CALL BMAS(W,RTHICK,PEAKPRES,BARMASS,BVOL,XF,RAILMASS)
RCLMS = BARMASS / 3.
222  FORMAT(' ')
C
C   CALCULATE FUEL, COOLANT AND TOTALS
LOSSES = EDRAE+ERAILE+EARM+PTLOSS+COMPLLOSS
FUEL = CALCKE/EFGUN/EFPT/EFCOMP/EFTURB/4.0E+07           ! Fuel at 40 MJ/kg
TFUEL = FUEL*STWLD+30.0*COMRATE/EFTURB/4.0E+07           ! Add * spin-ups
COOLCOMP = (1.0-EFCOMP)*CALCKE/EFGUN/EFPT/2.5E+06
COOLRAILE = (ERAILE + 0.5*(EARM+EDRAE))/2.5E+06
TUTCOOL = (COOLRAILE + COOLCOMP)*STWLD

```

```

RESUPPLY = TOTCOOL + PROM + TFUEL
SYSMASS=BARMASS+RCLMS+COMPMASS+AUTLOD+PROM+TFUEL
* +TOTCOOL+TMASS+MASSPT
C
C ESTIMATE VOLUMES
C
TFUELV = TFUEL/600.0
TCCV = COOLCOMP*STWLD/1000.0
TRCV = COOLRAIL*STWLD/600.0
RCLVOL = BVOL/3.0
ALOADV = AUTLOD/6000.0 + M*STWLD*1.5/8000.0 ! PROJ. PACKING F OF 1.5
PTVOL = MASSPT/5000.
COMPVOL = COMPMASS/6000.
TSV=TFUELV+TCCV+TRCV+TURBV+PTVOL+COMPVOL
C
C OUTPUT SECTION
WRITE(2,91)
91 FORMAT(8X,'Point Design Estimate for Crew-Served, Small Caliber EML')
WRITE(2,301)
301 FORMAT(//' INPUT PARAMETERS')
WRITE(2,302)M*1000,VMUZ
302 FORMAT('/' Launch Package Mass ',F4.1,' grams',5x,
*'Muzzle Velocity ',F7.0,' m/s')
WRITE(2,303)XF,W*1000.
303 FORMAT('/' Barrel Length ',F5.2,' meters',9x,'Bore Diameter ',
*'F5.1,' mm')
WRITE(2,304)STWLD,AROF*60.
304 FORMAT('/' Stowed Load ',F6.0,' rounds'10x,'Fire Rate ',F6.2,
*' rounds per minute')
WRITE(2,305) TBS
305 FORMAT(38x,'(Three round salvo',F5.2,' second pause)')
WRITE(2,307)
307 FORMAT(//' CALCULATED PARAMETERS')
WRITE(2,308)USEPROM*1000.0,USEFULKE/1000.0
308 FORMAT('/' Projectile Mass 'F6.2,' grams',7x,'Useful KE ',
*'F6.2,' kilojoules')
WRITE(2,408)TF*1000.0,IMAX/1.0E+03
408 FORMAT('/' Acceleration Time 'F6.2,' msec',6x,'Peak Current ',
*'F5.0,' kA')
WRITE(2,309)RTHICK*100.0,RAILMASS*2.0
309 FORMAT('/' Rail Thickness ',F6.2,' cm',11x,'Mass of both rails',
*'F5.2' kilograms')
WRITE(2,409)APEAK/9800.,FENRG/1.0E+03
409 FORMAT('/' Peak Acceleration ',F6.1,' kgee',6X,'Launch KE',
*'F5.1,' kilojoules')
WRITE(2,509)BMAX,JMAX/1.0E+05
509 FORMAT('/' Peak Bore Field ',F6.1,' Tesla ',6X,'Current Density',
*'F6.0,' kA/centimeter')
WRITE(2,609)PEAKPRES,100.0*EDRAG/FENRG
609 FORMAT('/' Peak Pressure ',F5.1,' ksi ',11X,'Drag Losses',
*'F5.1,' Percent')
WRITE(2,310)RAILTEMP
310 FORMAT('/' Bulk Rail Temperature Rise Per Shot',F5.1,
*' degrees Centigrade')

```

```

WRITE(2,311)STRISE
311  FORMAT('  Breech Rail Surface Temperature Rise',F6.0,
*' degrees Centigrade')
WRITE(2,411)EFGUN*EFARM*100.0
411  FORMAT('  Railgun & Armature Efficiency ',F5.1,
*' percent')
WRITE(2,312)
312  FORMAT(//' COMPONENT RATINGS')
WRITE(2,313)COMRATE/1.0E+03,TP
313  FORMAT('/'  Compulsator Energy ',F6.0,' kJ',8x,'Turbine Power',
*F7.0,' horsepower')
WRITE(2,314)
314  FORMAT(//' EXPENDABLES PER SALVO (THREE SHOTS)')
WRITE(2,315)FUEL*3.0,COOLCOMP*3.0
315  FORMAT('/'  Fuel ',F6.3,' kg',20x,'Compulsator Coolant ',F6.3,
*' kg')
WRITE(2,316)COOLRAIL*3.0,M*3.0
316  FORMAT('  Rail Coolant ',F6.3,' kg',12X,'Projectiles ',F5.3,
*' kg')
WRITE(2,317)
317  FORMAT(//' COMPONENT VOLUME (full stowed load)')
WRITE(2,318)TFUELV,TCCV
318  FORMAT('/'  Fuel ',F6.3,' cubic meters',11x,'Compulsator Coolant '
*,F6.3,' cubic meters')
WRITE(2,319)TRCV,ALOADV
319  FORMAT('  Rail Coolant ',F6.3,' cubic meters ',
*'Autoloader ',F5.3,' cubic meters')
WRITE(2,320)COMPVOL,PTVOL
320  FORMAT('  Compulsator ',F5.2,' cubic meters',5x,
*'Power Trans.',F5.3,' cubic meters')
WRITE(2,321)TURBV,BVOL
321  FORMAT('  Turbine ',F5.3,' cubic meters',9x,'Barrel ',F5.3,
*' cubic meters')
WRITE(2,322)RCLVOL
322  FORMAT('  Recoil Mechanism ',F5.3,' cubic meters')
WRITE(2,323)TSV,TSV*35.3
323  FORMAT('/'  TOTAL SYSTEM VOLUME (excluding barrel) ',F5.2,
*' cubic meters'/42x,(' ',F5.1,' cubic feet'))
WRITE(2,324)
324  FORMAT('/'  COMPONENT MASS (full stowed load)')
WRITE(2,325)TFUEL,COOLCOMP*STWLD
325  FORMAT('/'  Fuel ',F5.1,' kg',22x,'Compulsator Coolant '
*,F5.1,' kg')
WRITE(2,326)COOLRAIL*STWLD,AUTLOD
326  FORMAT('  Rail Coolant ',F5.1,' kg',14x,
*'Autoloader ',F6.1,' kg')
WRITE(2,327)COMPMASS,MASSPT
327  FORMAT('  Compulsator',F6.0,' kg',15x,'Power Transmission'
*,F6.1,' kg')
WRITE(2,328)TMASS,BARMASS
328  FORMAT('  Turbine ',F6.0,' kg',18x,'Barrel ',F6.1,
*' kg')
WRITE(2,329)RCLMS,M*STWLD
329  FORMAT('  Recoil Mechanism ',F5.1,' kg',10X,'Projectiles '

```

```

*,F6.1,' kg')
WRITE(2,330)SYSMAS,RESUPPLY
330  FORMAT(/' TOTAL SYSTEM MASS',F8.1,' kg',10X,
*'RESUPPLY MASS',F7.1,' kg',///)
GO TO 1
99  IF (NFILE.EQ.1) CLOSE(5)
CLOSE(2)
STOP
END

C
C  BARREL MASS CALCULATION
C
SUBROUTINE BMAS(W,CUT,PEAKPRES,BM,BVOL,XF,RAILMASS)
IMPLICIT REAL*4(L,I,M)
ID=(W+2*CUT)*39.4
XFI = XF*39.4          ! CONVERT TO INCHES
YS=4E+05

C
C  REDUCE KEVLAR YIELD STRENGTH BY .6 FOR SPIRAL WRAP
C  REDUCE BY .5 FOR BONDING MATRIX
C  REDUCE BY .4 FOR FACTOR OF SAFETY
C
THCK=ID*3.14/4*PEAKPRES*1000/(YS*.6*.5*.4)
BVOL = XF*3.14*(W/2+CUT+THCK/39.4)**2
A = (((ID+THCK*2)**2)-ID*ID)*3.14/4
V = XFI*A
MKEV =.052*V
BM = MKEV/2.2 + 2.0*RAILMASS + .66*RAILMASS ! Add rails and insulators
RETURN
END

```

SAMPLE OUTPUT

Point Design Estimate for Crew-Served, Small Caliber EML

INPUT PARAMETERS

Launch Package Mass	5.9 grams	Muzzle Velocity	1952. m/s
Barrel Length	1.00 meters	Bore Diameter	7.6 mm
Stowed Load	3000. rounds	Fire Rate	300.00 rounds per minute
			(Three round salvo, 0.60 second pause)

CALCULATED PARAMETERS

Projectile Mass	4.82 grams	Useful KE	9.20 kilojoules
Acceleration Time	1.08 msec	Peak Current	318. kA
Rail Thickness	1.17 cm	Mass of both rails	2.43 kilograms
Peak Acceleration	349.9 kgee	Launch KE	11.2 kilojoules
Peak Bore Field	16.7 Tesla	Current Density	417. kA/centimeter
Peak Pressure	50.5 ksi	Drag Losses	3.1 Percent
Bulk Rail Temperature Rise Per Shot	26.8 degrees Centigrade		
Breech Rail Surface Temperature Rise	84. degrees Centigrade		
Railgun & Armature Efficiency	24.6 percent		

COMPONENT RATINGS

Compulsator Energy	889. kJ	Turbine Power	548. horsepower
--------------------	---------	---------------	-----------------

EXPENDABLES PER SALVO (THREE SHOTS)

Fuel	0.031 kg	Compulsator Coolant	0.024 kg
Rail Coolant	0.030 kg	Projectiles	0.018kg

COMPONENT VOLUME (full stowed load)

Fuel	0.057 cubic meters	Compulsator Coolant	0.024 cubic meters
Rail Coolant	0.050 cubic meters	Autoloader	0.006 cubic meters
Compulsator	0.03 cubic meters	Power Trans.	0.005 cubic meters
Turbine	0.137 cubic meters	Barrel	0.005 cubic meters
Recoil Mechanism	0.002 cubic meters		

TOTAL SYSTEM VOLUME (excluding barrel) 0.30 cubic meters
(10.6 cubic feet)

COMPONENT MASS (full stowed load)

Fuel	34.0 kg	Compulsator Coolant	24.4 kg
Rail Coolant	29.9 kg	Autoloader	15.3 kg
Compulsator	165. kg	Power Transmission	26.3 kg
Turbine	126. kg	Barrel	9.8 kg
Recoil Mechanism	3.3 kg	Projectiles	17.7 kg
TOTAL SYSTEM MASS	451.4 kg	RESUPPLY MASS	106.0 kg

SAMPLE OUTPUT

Point Design Estimate for Crew-Served, Small Caliber EML

INPUT PARAMETERS

Launch Package Mass 20.9 grams	Muzzle Velocity 2021. m/s
Barrel Length 1.25 meters	Bore Diameter 12.7 mm
Stowed Load 2000. rounds	Fire Rate 200.00 rounds per minute
	(Three round salvo, 0.90 second pause)

CALCULATED PARAMETERS

Projectile Mass 17.46 grams	Useful KE 35.69 kilojoules
Acceleration Time 1.30 msec	Peak Current 554. kA
Rail Thickness 1.28 cm	Mass of both rails 4.80 kilograms
Peak Acceleration 300.1 kgee	Launch KE 42.7 kilojoules
Peak Bore Field 17.5 Tesla	Current Density 437. kA/centimeter
Peak Pressure 55.3 ksi	Drag Losses 3.0 Percent
Bulk Rail Temperature Rise Per Shot 39.0 degrees Centigrade	
Breech Rail Surface Temperature Rise 91. degrees Centigrade	
Railgun & Armature Efficiency 30.4 percent	

COMPONENT RATINGS

Compulsator Energy 2613. kJ	Turbine Power 792. horsepower
-----------------------------	-------------------------------

EXPENDABLES PER SALVO (THREE SHOTS)

Fuel 0.067 kg	Compulsator Coolant 0.041 kg
Rail Coolant 0.086 kg	Projectiles 0.063kg

COMPONENT VOLUME (full stowed load)

Fuel 0.090 cubic meters	Compulsator Coolant 0.027 cubic meters
Rail Coolant 0.095 cubic meters	Autoloader 0.013 cubic meters
Compulsator 0.08 cubic meters	Power Trans.0.010 cubic meters
Turbine 0.198 cubic meters	Barrel 0.011 cubic meters
Recoil Mechanism 0.004 cubic meters	

TOTAL SYSTEM VOLUME (excluding barrel) 0.50 cubic meters
(17.7 cubic feet)

COMPONENT MASS (full stowed load)

Fuel 54.1 kg	Compulsator Coolant 27.5 kg
Rail Coolant 57.3 kg	Autoloader 33.9 kg
Compulsator 484. kg	Power Transmission 50.4 kg
Turbine 182. kg	Barrel 20.7 kg
Recoil Mechanism 6.9 kg	Projectiles 41.8 kg

TOTAL SYSTEM MASS 958.9 kg	RESUPPLY MASS 180.7 kg
----------------------------	------------------------

SAMPLE OUTPUT

Point Design Estimate for Crew-Served, Small Caliber EML

INPUT PARAMETERS

Launch Package Mass 35.7 grams	Muzzle Velocity 2119. m/s
Barrel Length 1.50 meters	Bore Diameter 15.2 mm
Stowed Load 1000. rounds	Fire Rate 150.00 rounds per minute
	(Three round salvo, 1.20 second pause)

CALCULATED PARAMETERS

Projectile Mass 30.19 grams	Useful KE 67.81 kilojoules
Acceleration Time 1.49 msec	Peak Current 693. kA
Rail Thickness 1.37 cm	Mass of both rails 7.08 kilograms
Peak Acceleration 274.9 kgee	Launch KE 80.1 kilojoules
Peak Bore Field 18.2 Tesla	Current Density 456. kA/centimeter
Peak Pressure 60.4 ksi	Drag Losses 3.1 Percent
Bulk Rail Temperature Rise Per Shot 45.9 degrees Centigrade	
Breech Rail Surface Temperature Rise 100. degrees Centigrade	
Railgun & Armature Efficiency 32.4 percent	

COMPONENT RATINGS

Compulsator Energy 4543. kJ	Turbine Power 922. horsepower
-----------------------------	-------------------------------

EXPENDABLES PER SALVO (THREE SHOTS)

Fuel 0.103 kg	Compulsator Coolant 0.047 kg
Rail Coolant 0.149 kg	Projectiles 0.107kg

COMPONENT VOLUME (full stowed load)

Fuel 0.086 cubic meters	Compulsator Coolant 0.016 cubic meters
Rail Coolant 0.083 cubic meters	Autoloader 0.011 cubic meters
Compulsator 0.14 cubic meters	Power Trans.0.013 cubic meters
Turbine 0.231 cubic meters	Barrel 0.019 cubic meters
Recoil Mechanism 0.006 cubic meters	

TOTAL SYSTEM VOLUME (excluding barrel) 0.57 cubic meters
(20.1 cubic feet)

COMPONENT MASS (full stowed load)

Fuel 51.4 kg	Compulsator Coolant 15.8 kg
Rail Coolant 49.8 kg	Autoloader 28.0 kg
Compulsator 841. kg	Power Transmission 67.5 kg
Turbine 212. kg	Barrel 33.7 kg
Recoil Mechanism 11.2 kg	Projectiles 35.7 kg

TOTAL SYSTEM MASS 1346.5 kg	RESUPPLY MASS 152.7 kg
-----------------------------	------------------------

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APPENDIX D:
ESTIMATION OF IMPROVED CONVENTIONAL SYSTEM MASS

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Fortunately, many chemical guns exist today which span the range of projectile kinetic energies to be considered here. With simple approximations, scaling relations may be developed for interpolation of system parameters. A caution is issued here to avoid projecting these estimation techniques outside the range over which they were generated. The range of energies extends from 2 kJ to 94 kJ; the range of projectile masses, from 3 to 100 g.

Four scaling relations have a critical impact on the estimation of the system. They provide the methodology for determining barrel mass, propellant mass, casing mass, and autoloader mass. The barrel may be thought of as a pressure vessel which must contain the energy liberated by the burning of the propellant. Accordingly, one might expect the barrel mass to be proportional to the two-thirds power of the propellant mass. The efficiency of the chemical gun falls as the velocity increases, so the assumption is made that the efficiency scales in inverse proportion to the velocity. After determination of the scale factors, the propellant mass is calculated from the chemical energy density and the efficiency. The cartridge case mass was found to scale reasonably well with the propellant mass raised to the 0.85 power. The autoloader, which must be capable of salvo fire and handle relatively high aspect ratio cartridges, is assumed to equal the weight of the projectiles it contains if the average rate of fire is 600 rounds per minute. A very weak scaling of the autoloader mass with firing rate is also assumed.

The scaling factors and relations are employed in the short computer code which follows this appendix. The test of the scaling relations is shown in Table D-1 for three different weapons which are in use today. Since the comparisons are to be made to an EML system which cannot exist for several years, the following improvements are included in the scaling relations to project future systems:

- Ten percent greater chemical energy density propellants
- Five percent greater efficiency
- Ten percent lighter cartridge cases
- Twenty percent lighter barrels

The effect of these improvements is also shown in the rows labeled "Future" in Table D-1. The net reduction in total mass of a round is approximately 17% compared to the actual rounds of today.

Table D-1. Comparison of Actual and Scaled Barrel and Ammunition Masses.

Nomenclature	M60	M2	M242
Barrel Mass (kg)			
Actual	10.5	36.8	109.1
Scaled	10.4	36.6	108.9
Future	7.9	27.9	83.3
Total Cartridge			
Mass (g)			
Actual	19	102	500
Scaled	15	98	483
Future	12	84	416

The program which follows requires input values for projectile kinetic energy, muzzle velocity, rate of fire, and stowed load. System mass and volume are estimated for the input specifications. A resupply mass is also calculated, which is simply the mass of one round multiplied by the stowed load.

```

C
C PROGRAM TO ESTIMATE THE SIZE AND MASS OF A CONVENTIONAL GUN
C

```

```

      IFUT = 1                                ! Future improvements flag
      CERHO = 4.0E+06
      IF (IFUT .EQ. 1) CERHO = CERHO *1.1
1     WRITE(6,*) ' KE IN KILOJOULES?'
      READ(5,*)EPROJ
      IF (EPROJ .LE. 0.0) GO TO 999
      EPROJ = EPROJ*1000.0
      WRITE(6,*) ' VELOCITY IN METERS PER SECOND'
      READ(5,*)VEL
      WRITE(6,*) ' RATE OF FIRE (ROUNDS PER MINUTE)'
      READ(5,*)ROF
      AROF = ROF/60.0
      WRITE(6,*) ' STOWED LOAD?'
      READ(5,*)STWLD

```

```

C
C BASE ALL ESTIMATIONS ON AMOUNT OF PROPELLANT REQUIRED
C

```

```

      EFF = 0.217*1255.0/VEL
      IF (IFUT .EQ. 1) EFF = EFF*1.05
      PMASS = EPROJ/EFF/CERHO
      BARMASS = 6.3*(PMASS*1000.0)**0.6
      IF (IFUT .EQ. 1) BARMASS = BARMASS/1.2
      RCLMASS = BARMASS/3.0
      CARTMASS = .00464*(PMASS*1000.0)**0.85
      IF (IFUT .EQ. 1) CARTMASS = CARTMASS/1.1
      PROJMASS = 2.0*EPROJ/VEL/VEL
      ROUDMASS = PROJMASS + PMASS + CARTMASS
      RESUPPLY = ROUDMASS*STWLD
      AUTOLD = RESUPPLY * (.7+AROF/30.0)
      AUTOVOL = 3.0*STWLD*PMASS/1300.0

```

```

C
C DO TOTALS
C

```

```

      SYMASS = BARMASS+AUTOLD+RESUPPLY+RCLMASS
      WRITE(6,*) ' MASS OF ROUND',ROUDMASS
      WRITE(6,*) ' BARREL MASS',BARMASS
      WRITE(6,*) ' AUTOLOADER VOLUME',AUTOVOL
      WRITE(6,*) ' TOTAL SYSTEM MASS',SYMASS,' RESUPPLY MASS',RESUPPLY
      GO TO 1
999 STOP
      END

```

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**APPENDIX E:
FACTORS NOT CONSIDERED**

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As one panel member so succinctly stated, "Don't evaluate the world." The scope of an emerging technology such as electromagnetic propulsion is clearly beyond the the scope of this report. It does, however, appear worthwhile to list some of the factors not considered and the reasons for their omission. It should be noted that with future developments or breakthroughs, these reasons may become invalid.

PLASMA ARMATURES

This study is primarily concerned with railguns whose armatures may be either solid, plasma, transitioning, or combination of solid and plasma. Since plasmas tend to show constant voltage drops independent of current at lower power levels, the resistance is high. This makes the losses significant in small caliber railguns. Other problems with plasmas include the material damage to the bore surface, which is of major concern when one is developing systems which must have barrel lifetimes of many thousands of rounds. The dominant plasma loss term is by radiation through its surface area. Since conduction is done through the volume of the plasma and the loss is a surface area phenomenon, scaling to smaller size is not favorable. Finally, the problems of muzzle blast tipping projectiles on launch and creating an easily recognizable signature defeat two of the prime benefits possible for solid armature EM launchers.

HOMOPOLAR GENERATORS

The scaling studies, done by Gully (1986) as an earlier portion of the JSSAP program, identified a barrier with small HPGs. When one attempts a design for the energy levels needed for the 50-caliber, crew-served weapon application, the voltage generated is less than five volts. With such a low driving voltage, it is doubtful that an efficient energy compression circuit could be constructed. The study did not address the DC homopolar generator driving an inductor throughout the entire firing burst as proposed by Barber and Bauer (1981). This concept may warrant further investigation.

COILGUNS

The general consensus in the EML community appears to be that coilguns are far more effective as the bore size increases. This is in part because the coupling efficiency is limited by the ratio of the projectile cross-sectional area to the difference between the projectile and driver (barrel) coil areas.

Coilgun barrels also tend to be more complex, making their manufacture difficult in small sizes. Coilgun concepts, which require switching in the barrel, may also be far more difficult to weaponize both in terms of technical difficulty and in ultimately achieving a barrel which can be rapidly slewed by a gunner or lightweight, remote control system. This is an area, although excluded from this evaluation, that should be critically reviewed in light of future breakthroughs which may occur.

ET/CAP TECHNOLOGY

Several of the panel members pointed out that many of the potential benefits of EM launchers were also available from ET or CAP technology. They also suggest that for velocities below 2 km/sec, the launcher efficiency is likely to be better requiring a less massive power plant. Gains are not likely in muzzle blast, signature reduction, or accuracy, although the barrel development would be substantially easier with the thermal technologies. The single reason it is not included in this evaluation is simply that it is not a part of the JSSAP EML program. As a side note, a proposal is expected by the JSSAP office for a feasibility study of ET/CAP technology for small caliber applications.

HYBRID SYSTEMS USING CHEMICAL PROPELLANTS

The need for an injection velocity of a solid armature in a railgun is not well resolved at this time. Whatever the outcome, one can show a benefit from an initial velocity before the railgun current is applied. The action integral of the current relates directly to the heating of the armature and to the difference in initial and final velocity of the projectile. Since the kinetic energy is proportional to the square of the final velocity, the energy per unit armature mass ratio is clearly improved with injection velocity. There are other phenomena concerning static versus sliding friction and design considerations as to how one maintains the armature contact pressure, which also appear to be improved upon by an injection velocity. In principle, it is possible to obtain an injection velocity without the use of chemical propellants. Since the need for injection velocity is not clear, and chemical propellant may not be necessary, hybrid systems are not considered in this study. Also, the benefits of low ammunition vulnerability, muzzle blast, and signature reduction would be more difficult to achieve with the inclusion of burning propellants.

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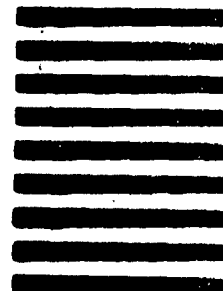
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