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TECHNICAL ASSESSMENT REPORT

NON-US
ELECTRODYNAMIC LAUNCHERS RESEARCH AND DEVELOPMENT

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November 1994

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FOREIGN APPLIED SCIENCES ASSESSMENT CENTER

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ABSTRACT

Electrodynamic launcher research and development work of scientists outside the United States is analyzed and assessed by six internationally recognized US experts in the field of electromagnetic and electrothermal launchers. The assessment covers five broad technology areas:

- Experimental railguns
- Railgun theory and design
- Induction launchers
- Electrothermal guns
- Energy storage and power supplies.

The overall conclusion is that non-US work on electrodynamic launchers is maturing rapidly after a relatively late start in many countries. No foreign program challenges the US efforts in scope, but it is evident that the United States may be surpassed in some technologies within the next few years.

Until recently, published Russian work focused on hypervelocity for research purposes. Within the last two years, large facilities have been described where military-oriented development has been underway since the mid-1980s. Financial support for these large facilities appears to have collapsed, leaving no effective effort to develop practical launchers for military or civilian applications.

Electrodynamic launcher research in Europe is making rapid progress by focusing on a single application, tactical launchers for the military. Four major laboratories, in Britain, France, Germany, and the Netherlands, are working on this problem. Though narrower in scope than the US effort, the European work enjoys a continuity of support that has accelerated its progress.

Portable power is still a critical weakness in the international effort to develop practical electrodynamic launch systems. Russia and the European nations are advancing the state of the art in component technologies like solid-state switches and high-energy-density capacitors. The European programs have only recently begun to address mobile power system issues that have been a major US concern.

In some areas, European researchers have a clear superiority—for example, in numerical design codes for electromagnetic launchers in Britain and in laboratory diagnostics in several of the major European laboratories.

The panel was unable to determine the scope of Chinese activity. One Chinese laboratory has reported a substantial effort, the stated purpose of which is the development of electromagnetic guns to accelerate long-rod penetrators.

The next decade will see the deployment of electrodynamic launcher technology, probably in the form of an electrothermal-chemical upgrade for an existing gun system. The time scale for deployment of electromagnetic launchers is entirely dependent on the level of research-and-development effort. If resources remain limited, the advantage will lie with cooperative efforts that have reasonably stable funding such as the present French-German program.

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NON-US ELECTRODYNAMIC LAUNCHERS RESEARCH AND DEVELOPMENT

TABLE OF CONTENTS

Section **Page**

TABLE OF CONTENTS

Section **Page**

Chapter IV **RAILGUN THEORY AND DESIGN**

Chapter V **INDUCTION LAUNCHERS**

Chapter VI **ELECTROTHERMAL GUNS**

TABLE OF CONTENTS

(blank)

LIST OF FIGURES AND TABLES

LIST OF FIGURES AND TABLES

Tables **Page**

FOREWORD

This report, *Non-US Electrodynamic Launchers Research and Development*, is one in a series of technical assessment reports produced by the Foreign Applied Sciences Assessment Center (FASAC), operated for the Federal government by Science Applications International Corporation (SAIC). These reports assess selected fields of foreign basic and applied research, evaluate and compare the state of the art in the country or area of interest with US and world standards, and identify important trends that could lead to future applications of military, economic, or political importance. This report, like others produced by the Center, is intended to enhance US knowledge of foreign applied science activities and trends, to help reduce the risk of technology transfer, and to provide a background for US research and development decisions. Appendix D lists the FASAC reports completed and in production.

This report was prepared by a panel of internationally recognized scientists and engineers who are active in electrodynamic launchers research and development:

• Dr. Jerald V. Parker (Panel Chairman)	Technical Director for Electromagnetic Launchers Institute for Advanced Technology University of Texas at Austin
• Dr. Jad H. Batteh	Manager, Advanced Concepts Division Science Applications International Corporation; Adjunct Associate Professor, Department of Mechanical Engineering, Georgia Institute of Technology
• Dr. J. Robert Greig	Senior Research Scientist GT Devices, Inc.
• Dr. Dennis Keefer	B. H. Goethert Professor of Engineering Sciences and Mechanics The University of Tennessee Space Institute
• Dr. Ian R. McNab	Vice President, Major Systems Sector Maxwell Laboratories
• Dr. Zivan Zabar	Professor of Electrical Engineering Polytechnic University (Brooklyn)

On a part-time basis over the period from May 1993 to March 1994, each panel member devoted a substantial amount of time assessing published foreign literature on electrodynamic launchers research and development.

EXECUTIVE SUMMARY

World-wide interest in electrodynamic launchers has rapidly expanded in the past five years. This assessment examines research performed outside the United States in the past decade, emphasizing the past five years. In the course of preparing this report, a panel of internationally recognized US experts on electrodynamic launch technology reviewed and assessed hundreds of unclassified documents in five broad areas:

- Experimental railguns
- Railgun theory and design
- Induction launchers
- Electrothermal guns
- Energy storage and power supplies.

Each of these topics has its own set of critical technology issues. The assessment examines how these issues are being addressed by non-US research communities.

Because there was accelerated public communication of results by research groups in the former Soviet Union during the early 1990s, few new technical accomplishments were found in the panel's assessment of electrodynamic launchers for research there. However, during the period of the assessment, new information was made public that revealed several major electrodynamic launcher facilities oriented toward military applications.

- Several respected Russian research groups have built and operated plasma armature railguns beginning in the early 1980s. This work was carried out to provide hypervelocity acceleration for impact physics studies. Detailed models of the high-current plasma armature were developed and impressive experimental velocities of 7 to 8 km/s were achieved with small masses (about 1 gram). Little or no attention has been paid to the more difficult problem of accelerating large masses (greater than 100 grams) to hypervelocity.

- Russian researchers have performed important experimental and theoretical research on low-velocity induction launchers for over 20 years. Their ability to analyze coupled electromagnetic circuits has exceeded US capability for many years. A 1994 publication describes an 80-stage induction launcher that achieved a velocity of 1.5 km/s, nearly twice the velocity achieved by any US experiments.

- A major railgun experimental program at the "Soyuz" facility near Moscow was described in an early 1994 conference paper. Funded primarily by the military, this program has utilized both MHD generators and large capacitor banks to investigate railguns in the tactical velocity regime of 2 to 4 km/s.

Although forecasting is extremely difficult in the current international political and economic climate, it now appears that Russia will not play a significant role in electrodynamic launcher research in the 1990s. It is unlikely that the resources will be available to use Russia's outstanding expertise and facilities effectively.

A greater threat to US interests may arise from the ongoing work of our allies in Europe and the Pacific Rim. Since major armament manufacturers play a leadership role in the research in these countries, this research and development will be directed toward near-term, exploitable technologies. Inevitably, this technology will become available to nations that threaten US interests.

- Both railgun and electrothermal gun research in Europe lagged behind US work until 1992. New facilities in Britain, France, Germany, and the Netherlands are now beginning to challenge US preeminence. By focusing on specific tactical missions and building research teams with a long-range perspective, these efforts could equal or exceed US achievements in solid armature physics and engineering and in some areas of electrothermal gun technology within the next three to five years.

- Activity in Pacific Rim countries is also increasing. Japanese researchers have been working in the field of electrodynamic launchers for over a decade. Their research typically is small in scale and explores innovative new concepts. They have plans for expanded work on electrodynamic launchers in the future.

- Mainland China has a well funded, focused project directed at launching long-rod penetrators to 3 km/s. While this experiment is small by US standards, the stated Chinese intention to develop electrodynamic technology for tactical applications is noteworthy.

It is too early to assess whether China will become an important developer and supplier of electrodynamic launchers in the next decade. The potential exists and deserves continued US attention.

A portable, high-energy density pulsed power system is needed for any tactical application of electrodynamic launcher technology. Although non-US research has made significant contributions to pulsed power components, in general, the United States is still the leader in developing portable pulsed power systems.

- Only one portable, high-energy pulsed power system has been reported in the non-US literature. A 60-MJ, trailer-mounted system using four gas-turbine-driven homopolar generators was developed in Ukraine according to a 1993 report.

- The French-German program includes plans to develop a mobile pulsed power system for an all-electric gun by 2002. However, given the technical difficulties encountered by the US program during the past decade, the first fieldable electric gun system may employ electrothermal-chemical technology.

- The Israeli government, in joint work with the United States, has demonstrated a modest increase in the muzzle velocity of a 105-mm electrothermal-chemical gun using less than 10 percent of the electrical energy needed for an all-electric gun.

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CHAPTER I
ASSESSMENTS

A. INTRODUCTION

The term *electrodynamic launchers* is of relatively recent origin, having been coined to refer collectively to both electromagnetic and electrothermal launchers. Though the physics of these two launcher types is quite different, they are both considered in this assessment because they have the same principal application at this time: the acceleration of tactical projectiles to velocities greater than can be achieved with conventional propellants.

Both technologies also need very compact portable sources of large amounts of electrical energy, exceeding the current state of the art. The last chapter of this report is devoted entirely to Energy Storage and Power Supplies, based on the importance of this subject to the entire field of electrodynamic launchers.

Reflecting substantial differences in the physical processes involved, electrothermal launchers are treated in their own chapter. A reader primarily interested in electrothermal launchers should read both the Electrothermal Gun chapter (VI) and the Energy Storage and Power Supplies chapter (VII).

Electromagnetic launchers have been studied intensively since publication of the seminal work of Marshall and Rashleigh on the plasma armature railgun. Reflecting the relatively large amount of work going on in the field, electromagnetic launch research is assessed in three chapters: Experimental Railguns (III), Railgun Theory and Design (IV), and Induction Launchers (V). The Energy Storage and Power Supplies chapter should also interest readers interested in electromagnetic launchers.

To prepare this assessment, a panel of US experts in electrodynamic launchers examined the published literature and many reports and preprints drawn from personal files. Because none of this information was drawn from classified sources and much of the research in electrodynamic launchers is ultimately motivated by military applications, there may be gaps and omissions in this assessment. Recent opening of laboratories in the former Soviet Union to Western visitors, and increased openness in publications from the former Soviet laboratories, has greatly increased our understanding of the Russian work on electrodynamic launchers. Technical details and estimates of the programmatic scope of electrodynamic launcher research in China are probably the most uncertain elements in this report.

B. EXPERIMENTAL RAILGUNS

Railguns use the magnetic force on a moving current element, called the armature, to accelerate a projectile to high velocity. The armature can be one of three types, leading to three categories of railguns.

In the solid armature railgun, the armature is a piece of metal that carries current by maintaining sliding contact with the rails. This type of railgun is characterized by higher efficiency, lower rail wear, and a maximum velocity limited by friction and dynamic forces on the sliding surfaces. If the technology can be refined, this seems to be the electromagnetic launcher of choice for tactical warfare application.

The plasma armature railgun, at another end of the spectrum, uses a gaseous plasma of ions and electrons to carry the current. Gas pressure exerted by this plasma accelerates the payload. The plasma maintains good electrical contact with the rails at very high velocity. However, plasma armature railguns have relatively poor efficiency at low velocity and suffer significant resistive energy losses in the plasma. Interactions between the plasma and materials burned off the bore of the railgun by thermal radiation from the plasma can be quite complex. The performance of plasma armature railguns remains limited to 6 to 7 km/s by the plasma/bore material interaction (not much higher than the approximately 6 km/s of Marshall's seminal experiments), despite almost 15 years of development activity.

The hybrid armature railgun, an intermediate form of railgun, has a solid metal main armature body, with a thin layer of plasma serving as the interface with the rail. Intended to overcome the sliding contact limitations of solid armature railguns, hybrid armature railguns have their own problems of rail surface damage due to the power dissipated in the plasma contact. Too little research has been performed on hybrid armatures to make definitive judgments of their value.

Until 1992 the former Soviet Union had the largest experimental railgun program outside the United States based on both active facilities and level of funding for research. While Russia still has a greater breadth of facilities than any other non-US country, funding for research has virtually disappeared in the last two years. Experimental activities apparently began in the early 1980s at two institutes of the USSR Academy of Sciences: the M. D. Lavrent'yev Hydrodynamics Institute in Novosibirsk and the High Temperatures Institute in Moscow. Both of these institutes have a long-standing interest in high-pressure shock physics, and the stated principal motivation for their work has been attaining high velocity (greater than 8 km/s) for impact physics experiments. Because these velocities are only achievable with plasma armatures, these laboratories have reported no experimental work on solid armatures.

Reported Russian plasma armature research has been carried out in small-bore railguns. Various power sources have been used, including explosive flux compressors, single-stage capacitor banks, and multi-stage capacitor banks. In general, the energy has been modest (100 kJ to 1 MJ). The largest installation used for hypervelocity railguns is a 5-MJ capacitor bank at the High Temperatures Institute.

By 1986, exhaustive experiments had convinced the Russian research groups that the only way to increase velocities was to apply higher and higher pressures to accelerate the projectile. Recently, a group at the A. F. Ioffe Physical Technical Institute in St. Petersburg has reported achieving repeatable velocities of 7.1 km/s in a very short (60 cm) high-acceleration (10 mega-g) plasma armature railgun.

Similarity of experimental approach and intergroup cooperation have led Russian railgun research groups to a consistent physical picture of the plasma armature. Efficient, compact plasmas are unstable, and easily evolve into a plasmadynamic discharge where most of the force is exerted on the plasma (and eroded bore material), and almost none accelerates the projectile. Operating at high current density/high acceleration helps to stabilize the compact form of the plasma armature, and shortens the time available for development of instabilities. The group at the High Temperatures Institute has concluded that the region above 10 km/s is unreachable. Similar conclusions were presented by G. A. Shvetsov of the Lavrent'yev Hydrodynamics Institute in 1988.

Details of a large railgun/electrothermal gun installation at the Electrophysics Problems Institute in St. Petersburg began to circulate in 1992. This installation has now been described in some detail by S. V. Zakharenkov and coworkers and, in US briefings, by the Institute Director, F. G. Rutberg. The installation includes four capacitor banks, ranging from 500 kJ to 5.7 MJ, two firing pads, a 70-m evacuable range tank and several different electrothermal and railgun launchers. The work at the Electrophysics Problems Institute appears to be oriented more toward practical applications than at other Russian laboratories. The capital investment in plant and facility suggests this was intended to be a national facility for electrodynamic launcher research.

Another railgun laboratory revealed only in early 1994 is located at the Lyubertsy Scientific-Production Association "Soyuz" near Moscow. This laboratory has been investigating the application of a solid propellant MHD power source to railguns. Researchers at this facility also report experiments on solid armatures using a 6-MJ modular capacitor bank. The funding of the Soyuz association is primarily from the military. Railgun research is only a small part of the work at the Soyuz operation, and there are indications that funding for this work has been sharply curtailed.

Electrodynamic launcher research was a well-supported activity in the Soviet Union during the 1980s. This situation is changing rapidly. Publications by some of the research groups have virtually disappeared in the last two years. Other groups are writing theory and analysis papers using experimental data obtained three to five years ago. At last report, the large facility at the Electrophysics Problems Institute was virtually abandoned, with scientists trying to guard materials against pilferage. It is unclear how soon, or if, this downward spiral will be reversed.

At the present rate of deterioration, it is likely that the premier Russian electrodynamic launch institutes will cease to function, with effective loss of their accumulated capability and data, within the next year or two.

West European experiments with railguns are carried out primarily in the United Kingdom, France, Germany, and the Netherlands. A variety of experimental work is being done, from small university lab activities to large government-sponsored programs. The larger programs tend to follow a common pattern. They were begun five to eight years after US work began, there was never much interest in the hypervelocity regime (greater than 8 km/s), and the principal focus is on tactical applications.

By delaying their commitment to major facilities, the Europeans have been able to use US experience as a guide in designing and building several large facilities. At present, three facilities are world-class in power supplies, diagnostic capability, and professional staff: the 32-MJ facility at Kirkcudbright, Scotland, with a 2-km flight range; the 10-MJ Pegasus facility at the joint French-German Research Institute Saint-Louis (ISL), France; and the 6.7-MJ homopolar generator facility at the TNO[1] Prins Maurits (PML) Pulse Physics Laboratory in the Netherlands.

Since its commissioning in mid-1993, the Kirkcudbright facility has been brought into full operation quickly. In December 1993, a 4-kg projectile was successfully launched at 3.25-MA current and achieved a muzzle kinetic energy of over 5 MJ. This rapid achievement of operational capability was possible because the first experiments were a joint UK-US effort using mainly US-supplied hardware. Nonetheless, it is a UK facility, and an active program in solid armature development funded by the UK Defence Research Agency (DRA)[2] is ready to exploit its capabilities. Little has been published on the DRA solid armature program. The DRA has supported building and operating several large power supplies for railgun experiments, including the 6.7-MJ REMGUN III homopolar generator and REMGUN VII, a 4-module 500-kJ capacitor bank. A large number of plasma railgun experiments employing these supplies and a variety of barrels testify to an experienced scientific staff.

France and Germany fund joint electrodynamic gun development through the French-German Research Institute Saint-Louis. ISL has been involved in small-scale experiments since the mid-1980s, and the staff have been active participants in professional meetings and visits to US laboratories. After several years of planning, this has culminated in the installation of the first module (2.77 MJ) of the planned 10-MJ Pegasus capacitor bank. Although experiments with the apparatus have begun only recently (May 1993), the launcher and projectiles are of relatively sophisticated design. Researchers have used a two-stage discharge to launch a 432-g

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[1] TNO is the acronym for the Netherlands Organization for Applied Scientific Research.

[2] Formerly, the Royal Armament Research and Development Establishment (RARDE).

"special design" titanium projectile-solid armature to 1.2 km/s. The experimental measurements are supported by detailed three-dimensional electromagnetic modeling and analysis. The stated goal of the ISL program is to accelerate long-rod projectiles with length-to-diameter (L/D) ratios up to 40.

In addition to the ISL work, there are a number of university-level railgun experimental activities in Germany. An innovative scheme to use the magnetic field of an inductive energy store to boost the railgun magnetic field was carried out at the Technical University of Braunsweig. The scale of this work was too small to address large-scale railgun issues. On the other hand, the long-term university programs in Germany serve as an important source of new ideas and of scientists trained in electromagnetic launch technology.

Researchers at the TNO facility in the Netherlands are also working toward tactical military applications of electromagnetic launchers. Their focus has been on solid armatures composed of many fine metallic fibers. This approach was tried briefly in the United States but was abandoned due to poor results. TNO has returned to this problem with a program dedicated to diagnosing the physical behavior of fiber armatures. Researchers have operated both copper and molybdenum fiber armatures up to 1.1 km/s. TNO has emphasized diagnostic measurements and possesses one of the most comprehensive diagnostic capabilities of any railgun laboratory in the world.

Railgun research in Japan is diverse, with a variety of research goals ranging from tactical guns and circuit breakers to space debris simulation and pellet injectors for fueling the next-generation experimental fusion reactor. The broad spectrum of experiments reflects the diverse interests of researchers located in universities, government centers, and industrial research groups. A hallmark of the Japanese work is the willingness to try innovative new concepts. Working at relatively small scale, Japanese researchers have built and tested a variety of devices, often based on ideas proposed but not implemented in the West. These include multiple Z-pinch discharges, segmented and fused rails, multi-turn augmentation, and ventilated bores. A few noteworthy Japanese achievements include work at the Institute of Space and Astronautical Science, Tokyo, which is routinely accelerating small (approximately 1-g) objects to about 6 km/s. The Japanese researchers employ a very high-current-density plasma armature, similar to the Russian work, and have achieved velocities as high as 7.45 km/s. Frozen hydrogen pellets measuring 4 mg have been accelerated to 1.4 km/s in work aimed at fueling an advanced Tokamak. Two laboratories, Japan Steel Works, Ltd., in Tokyo, and the National Chemical Laboratory for Industry, in Ibaraki, have described transformer coupling schemes that provide a better match between power supply and railgun, resulting in improved efficiency.

Beginning in 1991, two research groups in China have reported railgun experiments. In strong contrast to the diverse work in Japan and the hypervelocity orientation in Russia, the Chinese efforts are explicitly oriented toward tactical military applications. The first research group, at the Institute of Plasma Physics at Hefei, Anhui, has conducted experiments on long-rod penetration of steel and tungsten rods into test targets. The projectile is accelerated in a 25-mm square-bore, plasma armature railgun using a 3-MJ capacitor bank operating at 1.2 MA. A velocity of 3.2 km/s was achieved with a 30-g launch package. This group has plans to develop rotating machine power supplies and to test induction launchers. The relatively large size of the power system at the Institute of Plasma Physics suggests the program has strong support within the Chinese government. The second research group, at the Southwest Institute of Fluid Physics in Sichuan, is using a somewhat smaller capacitor bank (800 kJ) to work on hypervelocity plasma armature launchers. They report achieving 5.0 km/s with 1.3 g and 3.1 km/s with 5.1 g.

C. RAILGUN THEORY AND DESIGN

Theoretical research in railguns is concerned with three fundamental questions: How is the current flow distributed in the various conductors (and conducting plasmas)? How do the magnetic forces generated by current flow affect the moving and stationary parts of the railgun? How is the railgun affected by the inevitable heating that accompanies current flow? These questions are important for both solid armature and plasma armature railguns. However, because the physics is very different for solids and plasmas, the research methods and tools needed are quite different.

Solid armature research is dominated by (1) the need to solve for the current penetration into moving conductors and the resulting heating, and (2) the need to calculate the deformation of the solid armature and other railgun components subjected to the magnetic force.

Analytical techniques are of limited use in solid armature railgun research. The structure of railguns is inherently three-dimensional, and one is forced to use numerical methods to solve almost any practical problem. Finite element computer codes that can solve for mechanical deformation given the applied forces have existed for a decade or more. The important work of the past decade has been the development of three-dimensional codes to solve for the current distribution as a function of time in the presence of moving boundaries. Several codes now have this capability, and the focus is shifting toward coupling the electrical, mechanical, and thermal codes together into a useful design tool.

The principal findings of the assessment concerning railgun design codes for solid armature railguns are:

- The MEGA code, developed by the University of Bath in the United Kingdom, provides a unique capability for calculating the coupled, three-dimensional electromagnetic and thermal fields in electromagnetic guns.

- The Defence Research Agency at Fort Halstead in the United Kingdom has the most sophisticated non-US capability for performing electromagnetic gun design. The DRA has assembled a suite of codes to self-consistently solve for the electromagnetic, structural, and thermal response in railguns. This work appears to be more advanced than similar efforts in the United States.

- To a large extent, the electromagnetic gun design efforts outside the United States are taking advantage of codes available from the United States, including the structural codes DYNA and EMAS.

- Conspicuously absent are publications concerning theoretical railgun design work within the former Soviet Union, particularly in the area of solid armature modeling.

The questions facing plasma armature research are similar to those facing solid-armature researchers, but the problems are much more difficult. The plasma in a railgun armature is much more difficult to model than a solid conductor. In contrast to a solid armature that deforms slowly under applied magnetic forces, plasma armatures are fluid, and strong internal motion is created by the magnetic forces. In addition, the plasma electrical resistance, which determines diffusion of current into the plasma, is a sensitive function of the current. This leads to unstable behavior that is still poorly understood.

Although specialized computer codes, called magneto-hydrodynamic or MHD codes, have been developed for nuclear fusion research, they are not well adapted to the warm, dense plasmas used in railguns. During the past five years, several two-dimensional MHD calculations have been performed for railgun plasma armatures. These calculations have provided some insight, but a true design capability will require a three-dimensional MHD code with the capability to treat non-ideal effects such as turbulence, viscosity, and boundary mixing with neutral vapor. The first 3-D MHD codes are just becoming available today. It will take another three to five years of active theoretical and experimental research to refine these codes into design tools.

The principal findings of the assessment concerning modeling of plasma armature research (including solid-plasma hybrids) are:

- There is a surprising lack of activity outside the United States in the modeling of hybrid armatures.

- Russian researchers are applying their extensive capabilities in plasma physics to the problem of plasma armatures. This research does not appear to be directed at any particular application other than a desire to extend the velocity range of railguns beyond 6 km/s.

- Several groups in Russia are performing one- and two-dimensional MHD simulations of plasma armatures. While the computational capability is comparable to that in the United States, the Russians recognized earlier than US workers the need for full-bore simulations.

- If the economic situation in Russia were less severe, the Russians would clearly dominate in theoretical analysis of plasma armature, as almost no work is presently funded in the United States. Because of the economic situation, one of the key Russian researchers, Dmitri Kondrashov, is currently in the United States working on a three-dimensional MHD simulation code.

D. INDUCTION LAUNCHERS

Induction launchers are a type of electromagnetic launcher. The propelling force is created by the interaction of a current and a magnetic field. Induction launchers differ from railguns in one fundamental way. In a railgun, the same current flows in the rails (making the magnetic field) and in the armature (interacting with the magnetic field). In an induction launcher, the magnetic field is generated by an applied driving current. The force is exerted on an *induced* current in the moving armature. The major advantage of induction launchers is that the current does not have to pass through a moving contact from the external structure to the armature.

There are, of course, drawbacks to the induction launcher. One drawback is that the external magnetic coils have to perform two functions: generate the field and induce current in the armature. This makes the design of coils and power supplies more complex than the equivalent components of a railgun. Another issue is the difficulty of controlling the induced current distribution in the armature. Computational tools to calculate induction launcher currents and forces have evolved in the past two decades from one-dimensional analytical models to numerical methods based on finite-element solutions for the current distribution. As a result, the physical processes in induction launchers are understood with some confidence today. However, it is only recently that full three-dimensional current solutions have been practical. The final merging of finite-element field solvers with mechanical and thermal finite-element codes to obtain a true design capability is an active area of research.

Research on induction launchers started at the beginning of the 1970s with the seminal work of V. N. Bondaletov and colleagues at the Istra Division of the All-Union Electrical Engineering Institute near Moscow. This work, which began with simple single-stage, flat-ring accelerators, has evolved over more than two decades into a theoretical and experimental research program in multi-stage pulsed, synchronous accelerators. The initial work on flat coil accelerators was apparently motivated by the desire for high-velocity projectiles for penetration mechanics research. Theoretical and experimental results were published throughout the 1970s, suggesting that induction launching was not considered to be applicable to military problems. In the most advanced flat-ring experiments, velocities as high as 5 km/s were reported for masses of 1 to 2 grams.

By the early 1980s, the Soviet work had turned from flat rings to cylindrical conductors. The development of a two-dimensional finite difference scheme to solve the current penetration problem led to a careful study of design requirements for an optimum single-stage launcher. Multi-stage induction launcher development began with a study of single-stage launchers with the armature moving at an initial velocity. The limited number of publications from the Istra group since 1985 suggests that an expanded program has been in existence since the mid-1980s. A paper by G. Z. Ber on mesh-matrix methods for designing multi-stage induction accelerators mentions an 80-stage coilgun. Subsequent experimental papers report fragmentary information. The 80-stage coilgun has been described in detail by S. R. Petrov. It has been used to accelerate a 34-mm-diameter aluminum cylinder with a mass of 29 g to 1.56 km/s. This is substantially faster than the best US results and demonstrates convincingly that there is no barrier to the operation of induction launchers at tactical velocities. The large investment required to build an 80-stage launcher and power system is consistent with government investment in a militarily interesting technology. The intended application of this launcher development is not known.

In stark contrast to 25 years of Russian work on induction launchers, Western work began less than 10 years ago. During the period 1965 to 1985, there was little or no work on induction launchers in the West. In the past four years, there has been some work on single-stage launchers in the United Kingdom, Australia, France, and Germany. Most of the non-US work is patterned after US programs. None of the reported work exceeds the performance obtained in the former Soviet Union.

A joint research effort on pulsed induction launchers is being sponsored by the French and German ministries of defense. The work in Germany is primarily theoretical at this time, but there are plans to build several types of induction launcher systems. One study has concluded that it will be possible to build a 6-m launcher capable of launching a 1-kg projectile (approximately 3 kg total) to 2.5 km/s with 40-

percent conversion of stored energy to kinetic energy. Experiments in France with a three-coil launcher have accelerated a 5-kg wound armature to 0.4 km/s, a kinetic energy of 400 kJ.

All of the work discussed above was carried out on pulsed accelerators that apply power in sequence to each coil as the armature moves past. There is also ongoing work, mostly theoretical, on traveling wave induction launchers. Small projects in the United Kingdom, France, Austria, and South Korea are examining issues of design optimization, particularly the choice of excitation source for the poly-phase coil windings. A small experiment designed to verify theoretical calculations was reported by a group from Kangwon and Seoul Universities in South Korea. British work at Cambridge University and the University of Bath is in support of a modest experimental program sponsored by the Defence Research Agency.

One of the most pressing issues in induction launchers is high-current switching. Many of the practical design limitations in induction launchers are influenced by switching, including maximum velocity, efficiency, size, weight, and reliability. Continuing improvements in semiconductor switching increase the possibility of applying thyristor devices to induction launchers. A new thyristor structure has been reported by Asea Brown Boveri in Switzerland. Practical tests have demonstrated 110 kA, 750 A/µs, and 2 kV in a single device. The Russians have reported a potential revolutionary development in solid-state switching. Prof. Igor V. Grekhov of the Ioffe Physical Technical Institute reported a "reversibly switched-on dinistor" capable of switching 300 kA with a 100-kA/µs rise and a 30µs-long pulse. If the development of high-current, solid-state switches and high-energy density capacitors continues at its current pace, transportable launchers for heavy projectiles, for example, missile interceptors, should be technically feasible within the next five years. The technology needed for a mobile coilgun system will require substantially longer to develop.

E. ELECTROTHERMAL GUNS

Electrothermal launchers operate on a different principle than electromagnetic launchers. Instead of using the magnetic field to generate force, the electrical input energy is converted to heat, which may produce molecular dissociation. The pressure generated by this thermal energy input is used to accelerate a projectile, just as in a conventional gun. Performance increases are obtained either by operating at higher gas temperature than conventional chemical combustion can achieve, by using a lower-molecular-weight gas, or both.

Two forms of electrothermal gun are generally recognized, pure electrothermal (ET) and electrothermal/chemical (ETC). Pure ET uses only electrical energy to heat the propellant gases. Because the energy requirement for a tactical military gun is high, about 50 MJ, the power system for a pure ET gun is comparable in size, weight, and complexity to the power system for an electromagnetic (EM) gun. Offsetting this to some degree is the ability of the pure ET gun to operate with very low-molecular-weight gases such as hydrogen or helium. With these gases, velocities of 2.5 to 3 km/s are feasible. The ETC gun uses electrical energy to initiate a chemical reaction that provides a large fraction of the total energy. As the chemical energy fraction increases, however, the performance enhancement decreases, so there is a trade-off between reduced power supply size and enhanced performance.

Both ET and ETC, but particularly ETC, are considered "near-term" technologies because the gun tube and interior ballistics resemble those of a conventional gun. This makes ET technology particularly appealing to nations that currently manufacture large-caliber artillery. Electrothermal is an "upgrade" technology that promises somewhat better performance without the investment required to develop a whole new technology.

Significant non-US research in ET technology is taking place in France, Germany, Israel, the United Kingdom, and Russia.

In Russia, the principal laboratory for ET research is the Electrophysics Problems Institute[3] in St. Petersburg. When the Soviet Union dissolved, the Electrophysics Problems Institute was in the process of building a major new facility outside St. Petersburg. A large building, devoted to both EM and ET research had been completed and was operational. It houses four capacitor banks (0.5 MJ, 1.5 MJ, 4.5 MJ, and 20 MJ), various rotating machines, two firing stands, a 1.1m diameter by 70m long evacuable flight range and three electrothermal barrels (12.7 mm, 30 mm,

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[3] Until 1992, the Electrical Machine Building All-Union Scientific Research Institute (VNII Elektromash).

and 57 mm). In July 1993, the Director of the Electrophysics Problems Institute, F. G. Rutberg, described an extensive program of investigations concerning the hydrogen ET gun. F. G. Rutberg reported velocities of 6.2 km/s with 17 g, 4.5 km/s with 70 g, and 2 km/s with 200 g. Some of these masses were complex, saboted projectiles containing one or several "special rods" for ballistics research. In addition, he discussed extensive investigations of practical problems such as electrode erosion and generation of gaseous hydrogen from solid aluminum hydride. This program was largely supported by military funding that was "almost completely gone" as of July 1993. Recent visitors report no activity at this facility beyond critical repairs. There is no mention of ETC work at the Electrophysics Problems Institute (or elsewhere in the Russian technical literature).

The experimental ETC work in Israel is closest to demonstrating a practical capability. This is a well-organized effort, backed by the government, and supported in part by US funding. ETC firings with a 60-mm gun tube have been carried out for the past few years. Recently, this work has been extended to include firings using a 105-mm gun tube. One reason for the rapid progress of this program is a conservative choice of propellant. Using conventional propellants, no reduction in molecular weight is achieved and only a small performance improvement is realized from the extra electrical heating. This research approach has permitted the Israelis to gain a great deal of practical experience in ETC firing and diagnostics, most of which will be directly applicable to experiments with advanced propellants.

Germany and France are pursuing a joint ET program, through the Institute Saint-Louis (ISL), and several independent experiments. The joint program has two experimental facilities, a 6-MJ capacitor bank coupled to a 45-mm-bore gun at Technisches Zentrum Nord (TZN) in Germany and a 4-MJ capacitor bank with a 30-mm-bore gun at Commissariat à l'Energie Atomique (CEA)-Vaujours in France. Both of these facilities are of recent origin (the program began in 1991), and they have state-of-the-art diagnostic equipment. During the past year, both laboratories have been investigating plasma generators to learn how to optimize gun efficiency and survivability. The ISL program plan is aggressive. After less than two years of experiments at reduced scale, ISL is committed to building a 100+ mm test bed and operating it by mid-1994. Both the French and the Germans have reported substantial work on the development of numerical codes to model ET guns. Despite this work, their capabilities fall short of the US capability. In particular, they lack the integration of computer models needed to address reactive fluid-plasma instabilities in a dynamic chamber.

The most surprising feature of the ISL program is the apparent neglect of ETC. All of the experiments are on pure ET, as is the planned 100+ mm demonstrator. This appears to be a programmatic decision to demonstrate a working ET gun and to postpone the issues of power supply size and fieldability until more fundamental research has been performed. Although this approach lacks flexibility, it is providing program continuity and an experienced scientific staff with the tools to address ETC development in the latter half of the 1990s.

The Defence Research Agency in the United Kingdom is supporting a number of small activities in ET technology. Most of the work is being carried out in university and industrial laboratories and is concerned with modeling. Compared to the French-German effort, the activities in the United Kingdom appear disorganized and lacking in clear purpose. The DRA has a substantial resource for ET research in the newly opened Kirkcudbright facility. Judging from the published literature, the DRA has made little investment in developing the expertise required to undertake ET research at the Kirkcudbright scale (32 MJ).

The only Chinese publications related to ET technology are joint papers with Russian researchers from the Baltic States Technical University, St. Petersburg. It seems unlikely, however, that this is the only ET research in China. This conjecture is based on three observations:

- The Chinese have invested in a large capacitor bank for EM gun research at the Institute for Plasma Physics. This equipment and the IPP research staff could easily be used to perform ET/ETC work.
- China manufactures large-caliber munitions, so it passes the "self-interest" test.
- ET technology, being "near-term," is more likely to be subject to publication restrictions than the EM experiments that have been made public.

F. ENERGY STORAGE AND POWER SUPPLIES

Early in the US development of electrodynamic launchers, it was recognized that power systems would be a critical technology for any fieldable launcher system. As a result, a substantial portion of the US investment in electrodynamic technology has gone into improving the power and energy density of high-energy portable power systems. Judging from the published literature, this has not been the case outside the United States. Virtually every national program outside the United States is currently using conventional laboratory pulsed power supplies to carry out research on the physics and technology of the electrodynamic launcher itself. A majority of programs are using capacitor banks of 0.1- to 10-MJ stored energy with some type of conventional switching device (ignitrons, spark gap). Many of these capacitor banks were purchased from US suppliers.

Against this broad background, there is evidence that the major European nations are beginning to turn their attention to power system issues. Some of the evidence is as follows:

- In the United Kingdom, the DRA Combat Vehicle Department has recently reported two studies concerning power transmission and cooling issues in a tank environment.

- Rolls-Royce, a major supplier of turbine-driven power systems, has acquired International Research and Development Co., Ltd. (IRD), a developer of homopolar generators. IRD continues to support the laboratory homopolar generator at DRA and to perform studies for DRA on advanced generators. Rolls-Royce has expressed interest in developing dual-purpose power turbines for electric-vehicle propulsion and powering of vehicle-mounted electric guns.

- A recent upgrade of the DRA 1-MJ capacitor bank to 4 MJ was done with 50-kJ capacitors supplied by a UK vendor, Norfolk Capacitors, Ltd. This appears to be a deliberate move to reduce dependence on US suppliers.

- In France, ISL has announced plans for two new experimental facilities, the 10-MJ Pegasus capacitor bank and a facility to test coils for a 120-mm coilgun. Both systems will use high-energy capacitors from French suppliers, Haefley and Remy.

- A paper submitted to the Seventh Symposium on Electromagnetic Launch Technology describes a new design concept for the Pegasus capacitor bank. Instead of switching large blocks of capacitors (250 to 1000 kJ) with a conventional gas discharge switch, each 50-kJ capacitor will have an integrated pulse-forming unit consisting of a stack of solid-state thyristors for the main switch, a solid-state diode array for crowbar switching, and a compact inductor. While Pegasus is not a fieldable system, the integration of solid-state switching into high-energy modules is an important technology for future fieldable systems. This approach offers compactness, higher reliability, greater fault tolerance, and it simplifies the high-current interconnection problem.

- Researchers from two French companies, Haefley and LCC (Saint Apollinaire), have published detailed papers on optimization of dielectric systems for high-energy density capacitors. Energy densities of 0.67 MJ/m^3 have been demonstrated in a capacitor (about 50 percent greater than present 50-kJ units) and laboratory results of 2.8 MJ/m^3 have been achieved in a dielectric.

- In Germany, there is growing activity in inductive energy systems. Magnet Motor GmbH has developed an energy supply concept for electrodynamic launchers that integrates flywheel energy storage with an inductor and switch to deliver high peak power. The flywheel power system has been demonstrated at low power (150 kW) to store energy for an electric bus. A 2.5-MW unit is described without many details.

- There have been no reports of dedicated electrodynamic launcher power system development in Japan. However, the large Japanese investment in solid-state device development makes Japan a potential major competitor if future power systems move toward solid-state switching.

- A capacitor bank built by the Japan Steel Works employs an air core pulse transformer with an 8:1 turn ratio to match capacitor bank and railgun. This achieved an improvement in overall systems efficiency.

- Two Japanese companies, Fuji Electric and Nichikonn, are involved in power system research applicable to electrodynamic launchers. Nichikonn has achieved a capacitor energy density of 1 MJ/m^3.

- Russia has developed power system components that appear to be of considerable interest. Development of high-current solid-state switches was mentioned earlier. There has been a great deal of research on inductive energy storage in the former Soviet Union, both conventional and superconducting. A recent paper from the High Temperatures Institute in Moscow describes a technology for matching a power grid to a railgun accelerator through a Superconducting Magnetic Energy Storage system. While not practical for fieldable systems, this technology could be the key to large fixed installations, for example, for earth-to-orbit launching.

- Ukraine has developed the world's largest portable pulsed power system. Four homopolar generators driven by gas turbines and mounted on a single trailer store 60 MJ and can deliver 17 MJ to a 5-μH inductor. While this system does not have the energy density needed for a tactical electric gun, it represents a significant achievement using state-of-the-art components.

Despite decades of experience in high-energy storage systems and components, the published literature from Russia shows no evidence of an organized effort to minimize the size and weight of high-energy systems for fieldable applications. In view of the unstable economic and political situation, it is likely that Russian progress will be in component technology rather than power system development.

CHAPTER II
BACKGROUND

A. INTRODUCTION

This chapter is provided for the convenience of readers unfamiliar with electrodynamic launcher technology. After briefly defining electrodynamic launch, the presentation continues with a description of the physical operation of two principal types of electrodynamic launcher, electrothermal (ET) and electromagnetic (EM). Several examples are presented of each type of launcher, and the major strengths and weaknesses are summarized. Additional information concerning the history and development of electrodynamic launcher technology is presented in the introductory section of each Chapter. Readers familiar with electrodynamic launcher concepts and terminology may wish to turn directly to the relevant Chapter of this report.

The word "launcher" in this report denotes a device that provides the motive energy to accelerate an object to high velocity. In contrast to a rocket, the accelerated object provides no propulsion (except possibly steering). The classic example of a launcher is the barrel of a conventional chemical propellant gun. Most electrodynamic launchers have a form similar to a gun barrel; however, the internal structure may be much more complex. In the context of electrodynamics, the meaning of "launcher" differs, for example, from the usage in "rocket launcher," where the launcher is a passive guideway used only during the early period of motion. In an electrodynamic launcher, all of the velocity is imparted inside the launcher. Since the launcher length is generally short (about 10 meters or less), both the launcher and the object being accelerated are subject to very high pressure.

The term "electrodynamic launcher" is a catch-all name for a variety of launcher technologies that use electrical energy to provide a significant portion of the motive energy. Incorporating electrical power systems into any launcher complicates the design, construction, and operation. Some substantial benefit must accrue to justify this increased complexity.

The principal benefit sought with electrodynamic launch technology is higher velocity. Conventional chemical propellants can provide a velocity as high as 1800 m/s in a high-performance gun. Beyond this velocity, the benefit/cost ratio of chemical propellants decreases rapidly. For example, assuming the chamber pressure is at its maximum allowable value, then the options available to increase muzzle velocity are to increase the powder charge or the barrel length. Using a simple analytical model, one can calculate that a 75-percent larger powder charge or a three-times-longer barrel is required just to extend the velocity to 2 km/s.

The benefits of higher velocity are well established. Modest increases to 2500 m/s provide increased lethality, reduced transit time, and greater range. At higher velocity, 3000 to 4000 m/s, the combination of near-zero acceleration time and short fly-out time provide the possibility of close-in defense against theater missiles. At issue is the ability of electrodynamic launcher technology to reduce the cost of achieving higher velocity.

An electrodynamic launcher uses one of two physical effects to achieve increased velocity, the electrothermal effect or the electromagnetic effect. Because these effects are fundamentally different, they form the basis for a division of electrodynamic launchers into two categories, electrothermal launchers and electromagnetic launchers. The next two sections describe the physical operating principles of these two different launcher types.

B. ELECTROTHERMAL LAUNCHERS

The ET launcher is closely related to a conventional gun. The object being accelerated is pushed by the pressure of a hot gas contained in a long tubular barrel. Higher velocity is obtained by raising the sound speed in the propelling gas above the values achievable with chemical propellants. The speed of sound in a gas is a function of both the temperature and average molecular weight of the gas,

$$v_s = \sqrt{\frac{\gamma k T}{m}}$$

where γ is the specific heat ratio and k is the Boltzman constant. For conventional chemical propellants $\gamma \sim 1.3$, $m \sim 24$ atomic mass units, and $T \sim 2500$ K. The resulting sound speed is about 1 km/s. When the ratio of projectile velocity to sound speed in the propellant gas exceeds one, it is increasingly difficult for the gas to follow the projectile and exert an accelerating force.

An *ET launcher* uses both temperature and molecular weight to increase performance. Energy to heat the gas is provided by an intense electrical discharge rather than chemical reactions. Since electrical energy can be added almost without limit, the gas temperature can be much higher than the temperature of a chemical propellant that contains a fixed amount of chemical energy. In practice, however, the maximum temperature increase is limited to 30 to 50 percent because of thermal damage to the launcher barrel.

Reduced molecular weight provides most of the performance increase in a simple ET launcher. Using high-pressure hydrogen gas with a molecular weight of 2 increases the sound speed by a factor of $\sqrt{24/2} = 3.4$. Figure II.1 shows schematically the operation of a simple ET launcher. Laboratory devices of this type have produced velocities of greater than 5 km/s with objects of about 1-gram mass and over 3 km/s with sub-kilogram masses.

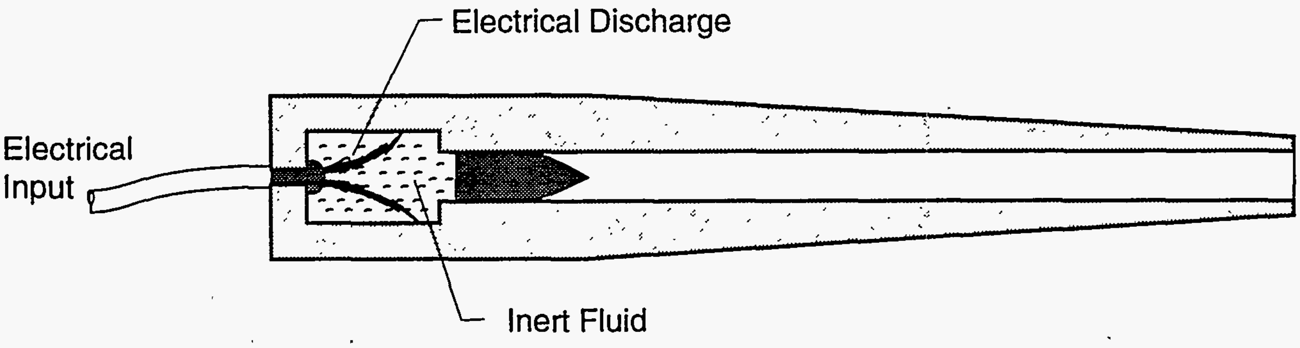

Figure II.1
Schematic of a Simple Electrothermal Launcher.
The inert fluid may be a high-pressure gas or liquid.

Hydrogen gas is not particularly practical for a fieldable launcher system because of the problems of storage and transport. Various liquids have been used in place of hydrogen, including water and isopropyl alcohol. These liquids offer modest performance gains, since their molecular weights are only modestly lower than conventional propellant gases. For example, water offers a sound velocity increase of only $\sqrt{24/18} = 1.15$. Any further increase must come from operating at higher temperature.

The principal drawback to the simple ET launcher is the large amount of electrical energy that must be provided. To accelerate a 3-kg projectile to 2.5 km/s requires greater than 30 MJ of electrical energy assuming the launcher efficiency is 30 percent. This energy has to be provided to the launcher in a few milliseconds. During this brief period, the electrical power input is several times the output of a large nuclear power plant.

An alternative to the simple ET launcher is the *electrothermal-chemical (ETC) launcher* illustrated in Figure II.2. In an ETC launcher, the inert, low molecular weight gas is replaced by reactive chemicals that provide some of the energy, thus reducing the amount of electrical energy that has to be provided. The benefit of the electrical energy comes from boosting the gas temperature and, in some cases, promoting the burning of chemicals that generate lower molecular weight products but will not react readily by themselves. ETC launchers can operate over the entire range from 100 percent electrical input to zero percent. The performance benefit, of course, decreases to zero as the electrical input goes to zero. From a system viewpoint an electrical input of 10 percent is very attractive because the power source is reduced in size and weight by a factor of 10. However, such a small addition of energy produces a rather small performance increase unless there is also a substantial decrease in average molecular weight.

Identifying the best applications for ET/ETC launchers and optimizing launcher performance is the subject of active research in the United States and in several European countries. The status of non-US electrothermal work is assessed in Chapter VI.

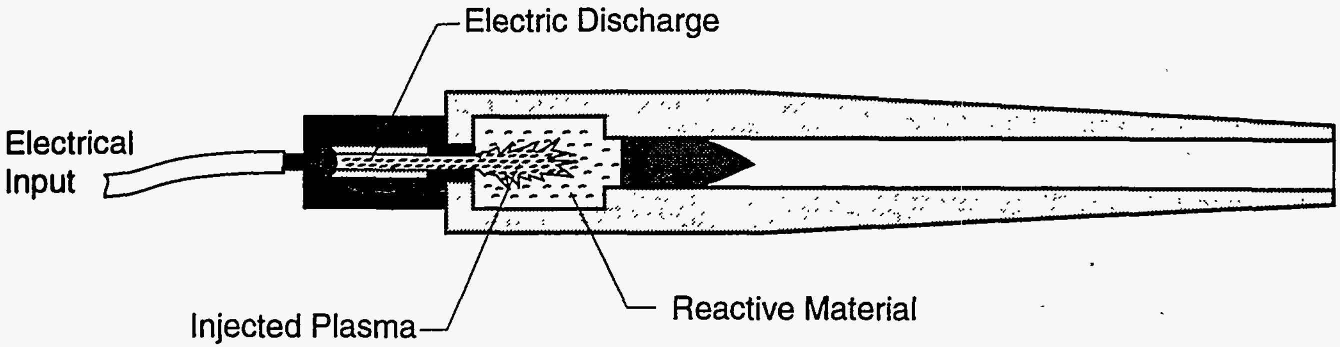

Figure II.2
Schematic of an Electrothermal-Chemical Launcher.
The reactive material may be liquid or solid propellant. In this example, the plasma is generated in an external capillary discharge.

C. ELECTROMAGNETIC LAUNCHERS

The other important electrodynamic launcher technology is electromagnetic propulsion. An EM launcher uses the force generated when an electric current flows through a conductor immersed in a magnetic field. A simple physical picture of EM acceleration is shown in Figure II.3. A strong magnetic field is provided by the launcher. The field lines are perpendicular to the desired direction of motion. The object to be accelerated, a wire in this figure, is placed in the field, and a current is caused to flow through the object. The direction of the current is perpendicular to both the magnetic field and the direction of motion. The interaction of the current with the magnetic field produces a force on the object that points in the desired direction of motion and causes the object to accelerate.

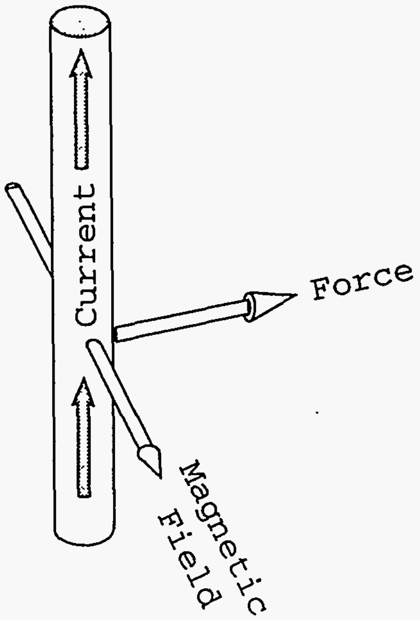

Figure II.3

The Fundamental Electromagnetic Interaction.

A current flowing perpendicular to a magnetic field produces a force per length proportional to the product B×I and acting in a direction perpendicular to both.

Unlike the propellant gas in a conventional or ET gun, the magnetic field has no physical mass, and the magnetic interaction is not limited by a "sound" speed. The only theoretical limit to the maximum velocity of an electromagnetically launched object is the velocity of light. The practical limits are, of course, much lower.

Starting from the fundamental interaction illustrated in Figure II.3, a bewildering array of EM launcher types can be designed depending on the manner in which the magnetic field is generated and the way that the current flow is provided to the object. Two of the most important types of EM launchers are the railgun and the induction launcher. The remainder of this section will examine the operation of these two types of EM launcher and explain some of the more important design variations for each type.

1, Railguns

Figure II.4 illustrates the geometry of the simplest EM railgun. The launcher consists of two parallel metal conductors, called "rails," surrounded by a rigid structure of insulating and metallic pieces that support the strong magnetic forces. The region between the rails is open so that the accelerated object can pass through. A strong electrical current is introduced at the rear end of one rail. This current flows along the rail until it reaches the object. At this point, the current leaves the rail, flows through the object to the opposite rail, and returns to the rear of the barrel.

The rear end of an electromagnetic railgun is commonly called the "breech" in analogy with a conventional gun. There is, however, no breech mechanism to seal the "magnetic pressure." The magnetic recoil forces are exerted directly on the electrical conductors that bring current into the rails. The breech end of the bore can be, and often is, left open during operation.

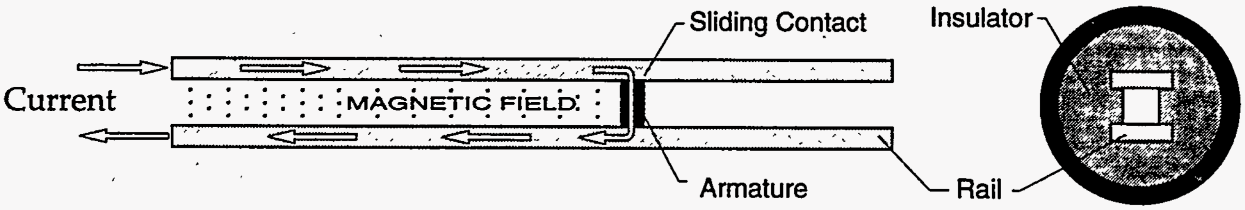

Figure II.4
Schematic of a Simple Electromagnetic Railgun

In this simplest of all EM launchers, the electric current plays a dual role. As it flows along the rails, the current creates a strong magnetic field between the rails that points perpendicular to the direction of motion. The same current, as it flows from rail to rail through the object, interacts with the magnetic field to provide the force that accelerates the object. The simple railgun is essentially a series connected DC motor. The current flows through the rails (stator winding) and then through the object (armature winding) producing a force that causes the object to accelerate (armature to rotate). Because of this close connection, the part of the accelerated object in a railgun that carries current is called the *armature*. The physical design of the armature and its interaction with the rails is one of the critical technologies in electromagnetic railguns.

2. Railgun Armatures

Railgun armatures are commonly divided into three categories: solid, plasma, and hybrid. A *solid armature* consists of a high-conductivity metal that carries the current from rail to rail. The metal armature must maintain sliding contact with the rail surface in order for current to flow without arcing. Maintaining sliding contact at high velocity is difficult. The combination of electrical heating and frictional heating causes the armature surface to wear rapidly. Solid armature railgun technology is currently limited to velocities of about 2000 m/s. Below 2000 m/s, solid armatures are generally the technology of choice based on their very low electrical resistance (about 10 μΩ) and the relatively small amount of damage a solid armature creates when it slides along the rail surface.

Above 2000 m/s, the solid armature presents a number of challenges. A momentary loss of contact due to dynamic effects can create an electrical arc that will not return to the sliding contact state. This results in increased electrical loss and substantial damage to the rails. Solid armatures can also exhibit a phenomenon called gouging above about 1500 m/s. Gouging creates severe rail damage, effectively ending the life of the barrel. All of these solid armature issues are the subject of on-going research.

A *plasma armature* conducts current from rail to rail through a gaseous plasma of ions and electrons that replaces the metal used in a solid armature. The plasma armature is much more complex than a solid armature. The primary (and possibly the only) virtue of the plasma armature is its ability to maintain electrical contact with the rails at high velocity. Plasma armatures routinely operate to 7 km/s and provide good contact to greater than 30 km/s in special laboratory experiments.

The list of plasma armature vices is lengthy:

- To maintain the plasma state requires a temperature of about 25,000°C. This high temperature creates intense visible and ultraviolet radiation from the plasma that damages both the rails and the insulating surfaces of the bore.

- The power source for this radiation is electrical power dissipated in the armature resistance. Since plasmas are about 1000 times more resistive than a metal, the power dissipation is large, typically hundreds of megawatts.

- The overall electrical efficiency of a plasma armature railgun is generally lower than the efficiency of a solid armature railgun, particularly at lower velocities.

- The plasma is a fluid being pushed by the magnetic interaction. The magnetic force is coupled to the object by the physical pressure of the plasma. To maintain this pressure, the object must be well sealed to the rail and insulator surface so that plasma cannot escape.

- Understanding the plasma armature requires experimental and theoretical effort in a number of different scientific fields, including magnetohydrodynamics, viscous flow, turbulent flow, and mixing.

- Only limited diagnostic measurement can be made on the plasma armature, because the intense radiation and high pressure preclude most standard plasma diagnostic techniques.

Finally, there is the *hybrid armature,* in which the armature is mostly solid metal but there is a thin layer of plasma between the metal and each rail. The hybrid armature is either the best of both worlds or the worst. The proposed advantage of the hybrid armature is the ability of its plasma layers to maintain contact at velocities greater than 2 km/s. By keeping the plasma layer thin, the total power dissipated is reduced, and the system efficiency approaches that of solid armatures. The disadvantage of the hybrid armature is that the thin plasma layer is still at a temperature of 25,000°C, and substantial damage can be done to the rail surfaces. In addition, all of the practical issues mentioned for plasma armatures (fluid sealing, diagnostic difficulties) apply equally to the thin plasma layer in a hybrid. Not much research and development are going into hybrid armatures at this time. Future activity will certainly be tied to the progress (or lack thereof) in extending the velocity range of solid armatures.

Before leaving the subject of armatures, a comment is in order on *transitioning armatures*. The label "transitioning" denotes a behavior rather than a type of armature. Transitioning refers to a change from one armature type to another during the launch, for example, from a solid armature to a plasma armature. When a solid-to-plasma transition occurs, it usually represents a failure, and substantial rail damage can result. It has been suggested that a controlled transition from solid to hybrid might be used to eliminate gouging at velocities greater than 1.5 km/s. Further work on this concept awaits development of a reliable hybrid armature.

3. Induction Launchers

An *induction launcher* uses the same magnetic force for propulsion as a railgun, but the means of generating the magnetic field and armature current are entirely different. Figure II.5 illustrates the operation of an induction launcher. The magnetic field is generated by a series of coils spaced along the length of the launcher. The armature is a metal cylinder that passes through the center of the coils. In operation, each coil is energized in sequence as the armature passes through. The coil generates a strong magnetic field that points along the direction of motion in the center of the coil and then bends outward to point in the radial direct as one moves away from the coil center. These two components of the magnetic field each play an important role. The field that points along the direction of motion passes through the center of the armature cylinder. However, the armature is a good electrical conductor, and when this field begins to increase, a current is *induced* in the armature that opposes the increase. This is the most fundamental difference between the railgun and the induction launcher. In a railgun, the armature current is supplied by the external power supply through a sliding contact. In an induction launcher, the armature current is induced by transformer action between the driving coil and the armature. There is no sliding electrical contact.

In the earlier discussion of electromagnetic interaction (Figure II.3), we saw that EM propulsion requires both the current and the magnetic field to be perpendicular to the direction of motion. Figure II.5 shows the induced current in the armature is perpendicular to the direction of motion. The magnetic field that induced the armature current, however, is parallel to the direction of motion and makes no contribution to the accelerating force. The accelerating force is generated by the radial component of the magnetic field interacting with the armature current.

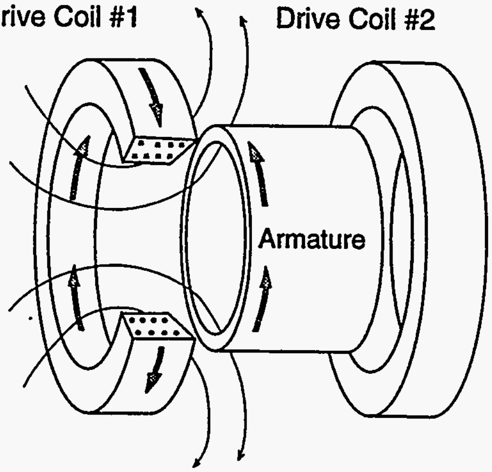

Figure II.5

Illustration of Synchronous Induction Launcher Operation.

The axial component of the magnetic field induces a current in the armature. The radial component of the magnetic field interacts with the armature current to produce an accelerating force.

Both the axial and radial components of the magnetic field decrease rapidly as one moves away from the coil. The force in an induction launcher is localized near the edge of each coil. Since the uniform field in the center of the coil does not provide propulsion, the optimum coils are relatively thin, usually less than the diameter of the armature. These physical considerations lead to efficient induction launcher designs that consist of a large number of closely spaced coils, each with its own power supply, switching, and timing electronics.

Although it is difficult to generalize about induction launchers as a class, there are several points worth remembering.

- The induction process is more efficient for large coils and armatures. Thus, small-scale demonstration experiments are always at a disadvantage and tend to produce pessimistic results. On the other hand, the power supply energy required to demonstrate a given velocity scales with armature mass or roughly as the cube of the armature diameter. Thus, economics weigh against demonstration experiments at large scale.

- The complex magnetic field geometry generates many parasitic forces that require structural strength yet do not contribute to performance. In particular, the axial magnetic field component produces a radial force that tries to crush the armature. Any extra armature mass added to resist this crushing force results in decreased performance.

- The risetime of the current in a coil becomes shorter as launch velocity increases and higher voltage must be applied to the coil. Switching devices and coil design become a major concern for induction launchers when the velocity exceeds 1 to 2 km/s.

- Compared to a railgun, the induction launcher is a complex device. Optimizing the design of an induction launcher requires sophisticated computational tools including a 2-D (or 3-D) electromagnetic field solver coupled with a stress analysis program that adequately models the properties of both the armature material and the heterogeneous structure of the coils.

This brief introduction to induction launchers has dealt with only one particular type, the synchronous induction launcher. For a more detailed description of the various types of induction launchers, the reader may turn to the introductory material in Section B of Chapter V, "Induction Launchers."

CHAPTER III
EXPERIMENTAL RAILGUNS

A. SUMMARY

Experimental railgun research around the world can be separated into two rather distinct groups: small-bore experiments using plasma armatures, and larger bore experiments using solid or transitioning solid armatures. The applications for the plasma armature work are usually for study of materials properties during high-velocity impact, study of the effects on spacecraft due to impact micrometeorites and space debris, and injection of hydrogen fuel pellets into fusion reactors. The solid armature work is oriented more toward military applications, most often the launch of long-rod projectiles at high velocity. The published literature related to the plasma armature research is more extensive, and the plasma armature papers usually give more detailed results than the papers related to the solid armature experiments.

The size of the experimental facilities is often related to the types of armatures used. Most of the plasma armature experiments are done using launchers with a bore size from 4 to 15 mm and stored energy from a few kilojoules to 1 MJ. Some fairly large, high-quality solid armature facilities with bore diameters to 90 mm and stored energy to 32 MJ have been constructed in China, Russia, and Europe. Diagnostic and analytical support of the experiments show great variation. Performance models range from the elementary electromagnetic force with no drag, to fairly sophisticated and comprehensive models including complete power supply simulation and models for friction, viscous, ablation, and aerodynamic effects. Standard diagnostic instruments to measure muzzle and breech voltage, and B-dot probes, are used on most experiments. In some laboratories, more sophisticated diagnostic methods have been developed. These include high-speed photography of transparent railguns, dynamic rail motion sensors, fiberoptic sensors and transducers, laser velocity interferometry (VISAR), X-ray cinematography, and time-resolved spectroscopy.

Compared with the US experimental railgun program, the major efforts in Europe appear to be more systematic and deliberate. The programs have shown incremental increases in size and complexity, based on many experiments and extensive analysis before commitment to larger and more expensive facilities. The large facilities that have evolved over the past two to five years are of high quality. The new 32-MJ Kirkcudbright facility in Scotland has a 2-km instrumented flight range, excellent diagnostics, and the flexibility to switch between two experiments, either electrothermal or railgun, very quickly. Diagnostic capabilities are at least as good as those in the United States. The more sophisticated diagnostic methods are generally scattered among different laboratories, but the TNO PML-Pulse Physics facility in the Netherlands has a comprehensive array of advanced diagnostics.

The central issue for plasma armature hypervelocity railgun research has been the 6-km/s velocity limit. The approach to solving this problem in other countries has not been the same as in the United States. The Japanese have been willing to build facilities to test a number of innovative approaches. These include the ablation mass driver (AMD) that uses a sequence of Z-pinch discharges, segmented and fused rails, multiturn augmentation, and ventilated bores. Neither the Japanese nor the Russians have reported attempts to improve performance using low-ablation bore materials, and their best performance of approximately 7 km/s has been obtained with copper rails and plastic insulators. The several Russian experimental groups have evolved a relatively consistent understanding of why the plasma armature does not work. Basically, this involves dynamic flow through the armature causing an inability of the rear of the armature to support adequate voltage without secondary formation. The Russian consensus is that it is unlikely that plasma armatures can be made to significantly exceed the 7-km/s limit.

The People's Republic of China has initiated a surprisingly large and aggressive program to develop weapons-related railgun technology at the Institute of Plasma Physics at Hefei, Anhui. The research papers describing this effort clearly indicate that the purpose is to develop a range of capabilities related to tactical military weapons. These include the launch of long-rod penetrators and a study of their effects, the use of erosion-resistant tungsten-copper alloys, development of an electrothermal gun preinjector, experiments with solid armatures and the development of rotating power supplies.

A notable "resounding silence" in the scientific publications has been the complete lack of any Russian literature related to these kinds of military applications. The first break in this silence occurred at the Seventh Symposium on Electromagnetic Launch (EML) Technology in April 1994. Two papers were presented by members of the Energy Physics Department of the Lyubertsy Scientific-Production Association "Soyuz," located near Moscow. "Soyuz" is a large facility that performs most of its work for military purposes, including the development and production of propellants and solid-fuel rocket motors. These papers revealed the existence of two large power supplies for railgun experiments, one utilizing a solid-propellant MHD generator power source. The research results reported included design calculations and experiments on solid armatures. The stored energy for railgun experiments is about one-fifth of the best Western facilities; however, the complexity of the systems and diagnostic systems reported suggest that this Russian work has been underway for at least five, possibly eight, years.

B. INTRODUCTION

The next sections provide a brief description of the experimental railgun research activities in various regions of the world. The coverage and papers cited are not meant to be comprehensive, but are representative of the nature and quality of the work reported for a given research group or highlight particularly different or interesting experiments. No particular significance should be attached to the order in which the work is presented. It is generally arranged alphabetically by country.

C. WORLD EXPERIMENTAL RAILGUN RESEARCH ACTIVITIES

1. Australia

The pioneering work of R. A. Marshall and his colleagues at the Australian National University (ANU) using a very large homopolar generator ushered in the modern era of railgun research. The seminal experiments of Rashleigh and Marshall showed that it was possible to accelerate gram-sized projectiles to a velocity of nearly 6 km/s. Although this work stimulated experimental programs worldwide, the work at ANU was terminated. Since that time, one other experimental activity has been conducted in Australia by The Defence Science and Technology Organisation, Materials Research Laboratories (MRL).

The work at MRL focused on the use of transparent railguns with high-speed streak and framing photography to better understand the nature of the plasma armature. A number of MRL and published reports detail the experiments and show the photographic data. Marshall was involved in some of this work and provided the idea of puff-switching for distributed energy store (DES) railguns that was tested experimentally by MRL. He also developed a physical model for the plasma armature based on the high-speed photographic data.

The railguns were constructed using copper or cadmium copper rails contained in clear polycarbonate bolted together with steel clamp plates. Barrel lengths from 0.5 to 2.4 m were used for different experiments. The projectiles were made of nested pyramidal segments of polyethylene and polycarbonate and used various fuse materials. Preinjection from 400 to 1200 m/s was provided by a powder charge. The motion of the plasma down the bore was observed using high-speed film cameras via a system of overhead mirrors. Details of the diagnostic methods used for the high-speed photography are given by Macintyre (1984). Stainsby and Bedford (1984) discuss the behavior of precursor arcs and their effects on muzzle voltage.

Marshall (1986) utilizes the high-speed photographic and muzzle voltage data together with microscopic examination of the rail surfaces to develop a physical model for the plasma armature and to estimate the plasma temperature. He estimated a plasma temperature of 50,000 K based on the time required by a rarefaction wave to propagate to the rear of the armature after projectile exit. The armature structure is described as a circulating plasma flow moving forward in the center and rearward along the walls. The current is carried through cold boundary layers by small constricted sub-arcs accounting for the excess voltage measured at the muzzle. He estimates that some 500 sub-arcs spaced approximately 4 mm apart each carried approximately 120 A. He concluded that plasma escapes from the back of the armature and is continuously replenished by rail material through the sub-arcs.

Sadedin and Stainsby (1987) describe an experiment to investigate R. A. Marshall's idea of triggering a DES railgun using a plasma "puff-switch" method. The 2.4-m-long 10-mm square-bore railgun used cadmium copper rails contained in a transparent polycarbonate containment to allow high-speed photography. A powder gun provided preacceleration of the nested pyramid-shaped polyethylene and polycarbonate projectile to approximately 1 km/s. The puff-switch used holes in the insulator at 900 mm to vent part of the armature plasma from the bore to trigger a spark gap that connected a second power supply upon projectile passage. The breech power supply had 72 kJ of stored energy, and the second power supply was fired with stored energy of 20 and 64 kJ.

The puff-switches fired early, probably due to blow-by past the projectile. Streak photographs were analyzed on an image processor and the armature length was found to increase with distance, even after the vent hole was passed. The armature separated from the projectile reducing the acceleration with or without the second power supply. Detailed diagnostic records are presented together with analysis. They evaluate the degree of electrothermal (ET) propulsion compared with electromagnetic (EM) and find it significant. They conclude that ablated mass is not all accelerated by the armature, and conclude that venting of the bore as proposed by Parker did not reduce the armature mass. They concluded that this implementation of the puff-switch was unsuccessful, but that a satisfactory design was possible.

2. China

Two groups are conducting railgun experiments in The People's Republic of China (PRC). The larger activity appears to be at The Institute of Plasma Physics (IPP), Academia Sinica at Hefei, Anhui. A second significant effort is underway at the Southwest Institute of Fluid Physics (IFP) in Sichuan. These efforts have relatively large capacitor banks, and the research appears to be oriented toward military applications. Only one small experimental effort was found in Taiwan.

The IPP research (Wang et al., 1991; Ren et al., 1991) is conducted using a 3-MJ capacitor bank that can provide currents to at least 1.2 MA. They have conducted experiments in 25 x 25-mm square-bore and 25-mm-diameter round-bore railguns of 3 to 3.5-m length. An electrothermal gun with a 200-kJ capacitor bank is used as a preinjector to achieve up to 700 m/s injection velocity. Both electrothermal gun and railgun structures have used copper–tungsten materials for better erosion resistance. The plasma from the preinjector is used to commutate the current into the rails. The best performance given for the square-bore gun was 3.2 km/s with a 30.2-g projectile and, for the round-bore gun, greater than 3 km/s with a 100-g projectile. Some experiments have also been conducted using segmented solid aluminum armatures on copper rails (Shi et al., 1991). Steel plate penetration tests have been conducted using both steel and tungsten long-rod penetrators with high-speed framing camera diagnostics. Their stated plans include the development of rotating power supplies and test of a coil launcher.

The IFP research seems more oriented toward hypervelocity using plasma armatures. They use an 800-kJ capacitor bank with a 1.9-m-long railgun of unspecified diameter (Gao et al., 1992). Secondary arc formation has been studied using transparent insulators and streak photography. A detailed one-dimensional plasma performance model is being developed. The highest velocity reported is 5.02 km/s with a 1.27-g projectile in a 1.9-m-long barrel with a peak rail current of 417 kA. A higher energy shot used a 5.14-g projectile with a velocity of 3.1 km/s at a peak current of 391 kA. The inverse relationship of projectile mass and launch efficiency was noted.

The Taiwan research is located at The Institute of Nuclear Energy Research at Lung-Tan, and started with a modified Mather-type launcher that accelerated a 0.8-g stainless steel disk to 1.2 km/s (Hou et al., 1987). The concept was modified to provide an ET preinjector for a small railgun experiment. This experiment uses a small (38-kJ) capacitor bank with a 3:1 transformer to provide 226-kA peak current. A velocity of 1.25 km/s was achieved using a 2-g polyethylene projectile. This work appears to be a small effort with unspecified objectives, in contrast to the relatively large experiments in the PRC.

3. Western Europe

The experimental railgun activities in Europe are more oriented toward tactical military goals than to hypervelocity. As a result, much of the work involves solid armatures instead of plasmas. Some hypervelocity work oriented toward spacecraft impact was done at Culham Laboratory in the United Kingdom, and similar work is still underway at the Technical University of Munich. From the published literature, it appears that some of the world's largest and best-equipped railgun laboratories are located in Europe. These include the large 32-MJ facility recently commissioned by the UK Defence Research Agency (DRA) in Kirkcudbright, Scotland, the 10-MJ PEGASUS facility at the joint French-German Research Institute Saint-Louis (ISL), France, and the 6.7-MJ homopolar generator facility at TNO PML-Pulse Physics Laboratory in the Netherlands. These facilities appear to be the culmination of careful step-by-step incremental research and planning, with careful attention given to good diagnostic capabilities and analysis.

Most of the experimental work has used conventional railguns with copper rails and glass fiber insulators. Conventional crowbarred capacitor-inductor power supplies or homopolar generators with an opening switch are used to power the experiments. Innovative approaches have been used for the solid armatures, for example, copper and molybdenum fiber bundles and front contact, inertially loaded titanium. Some sophisticated diagnostic techniques have been implemented, for example, VISAR optical interferometer measurement of in-bore projectile velocity and X-ray cinematography using image converter cameras at TNO.

a. United Kingdom

The largest and newest experimental facility in Europe is located at Kirkcudbright, Scotland, and began operation in the summer of 1993. This modern, large experimental electromagnetic gun facility built by DRA was described recently by Hammon (1993). With an energy storage capacity of 32 MJ, this is the largest known railgun facility outside the United States. The pulsed power system (PPS) was built by Physics International, and stores 32.2 MJ at 11 kV in 29 independently triggerable capacitor bank modules. This flexibility permits use of the power supply with both railguns and electrothermal guns in a range of sizes. The facility was specifically designed for testing of tactical systems and is situated on a 2-km instrumented flight range. A second firing stand fires into a 100-m stop butt. Primary power is provided by a 750-kVA, 415-V, 50-Hz diesel generator. Flexible buswork was designed to permit fast connection of the PPS to either of two gun positions. The 2-km range begins with a 3 m × 3 m concrete reinforced ballistic tunnel that is instrumented with several X-ray stations, high-speed cameras, and video cameras. The baseline railgun gun was built by Sparta. It is a conventional, 2-rail, 90-mm diameter round bore with an acceleration length of 7 m. It uses copper-chrome alloy rails and G-10 insulators backed with alumina ceramic contained in a graphite-epoxy containment tube with hydraulic pressurization. A recent (December 1993) firing produced a velocity of 1.6 km/s with a 4-kg projectile using a peak current of 3.25 MA, giving a muzzle kinetic energy of over 5 MJ.

The Kirkcudbright facility is the culmination of a continuing experimental railgun program at DRA (formerly RARDE). The experimental work from 1981 is reviewed by Atkinson (1989) and Bloyce (1989). Similar papers appeared in the 1989 Second European Symposium on EML Technology at ISL, St. Louis, France. The early experimental railgun program relied primarily on the REMGUN III 6.7-MJ homopolar generator (HPG) up to 1989. At this time, REMGUN VII, a four-module, 500-kJ capacitor bank was being developed. An explosive opening switch, LYNEX II was developed for the HPG and was used with a variety of launchers. These included: Utility Barrel, a 25-mm square-bore composite barrel that allows in-bore X-rays; ROSA/CE, a 2-m-long, 25-mm round-bore railgun combined with a conventional powder gun preinjector; HYPER 1, a 1-cm-round-bore, 1.2-m-long copper and G-10 railgun with a 600-mm conventional powder gun preaccelerator; and MARK IV, a four-conductor barrel.

Most of the experimental work at DRA was oriented toward solid armatures for use in tactical gun systems, and there is little detailed information on these experiments. HYPER 1 and MARK IV were operated as plasma armature guns, and more detailed performance data were reported. HYPER 1 achieved a velocity of 4.2 km/s with a 0.9-g projectile after a 2.4-km/s injection velocity using 150-kA peak current. Little bore erosion or damage were observed, perhaps due to the high preinjection velocity. The MARK IV experiments achieved a velocity of 270 m/s with a 10-g projectile. After these 1989 reports, there was an absence of literature on the experimental program. No experimental railgun papers were presented at the (US) Fifth Symposium on EML Technology or the Fourth European Symposium on EML Technology.

The other UK experimental railgun program was a hypervelocity program at Culham Laboratory. Putley (1991) reviews the experimental results of the first 26 shots on the Hypervelocity Test Facility (HTF) railgun. The best shot was 3.1 km/s with a 1.2-g projectile. Secondary arcs were blamed for the poor performance. The 1-MJ capacitor bank and railgun used for these experiments is described by Herring et al. (1993), in what are probably the last experiments done in the Culham railgun program. The experiment used a 1-MJ capacitor bank without crowbars. The five segments of the bank were staged to provide a slowly rising current pulse to investigate the effect on parasitic arc formation. The 1-cm square-bore railgun used both stainless steel and copper rails with 10G40 (G-10) insulators in a bolted metal containment. An explosive foil device was used to inject the projectile into the railgun with a velocity of approximately 50 m/s. Five shots were presented (27–31), two (accidental) free arc shots and three projectile shots. B-dot probes were calibrated and used to determine current distribution in the railgun. Secondary arcs formed on all shots, some resulting in stationary arcs. The best performance was 3.1 km/s at a peak current of 380 kA. The researchers conclude that the rising current did not produce better performance than shorter pulses, and that stainless steel rails were unsatisfactory due to excessive arc erosion.

Spikings and Oxley (1991) describe experiments conducted to test the concept of a projectile that contains the arc inside as a potential means of eliminating secondary arcs. A simple theoretical analysis was used to determine the optimal hole size and hybrid material. Both plasma (hole from rail-to-rail) and hybrid (metal insert with plasma brushes) were tested in a stationary fixture. None of the designs except a stainless steel hybrid withstood a small 50-kA, 26-C pulse, several times smaller than required for their railgun experiments.

b. France

The French-German Research Institute Saint-Louis is a joint military research establishment located at Saint-Louis, France, just outside Basel, Switzerland. The ISL experimental railgun program is oriented primarily toward the use of solid armatures to launch long-rod projectiles. ISL has systematically increased the size of its experimental facilities, and researchers have reported some experimental results using a 2.77-MJ subset of their planned 10-MJ PEGASUS facility. The experiments with the 2.77-MJ capacitor bank is considered the final step leading to the 10-MJ PEGASUS experiments.

Wey et al. (1993) describe the status of the facility and their most recent experiments. The 2.77-MJ, 10-kV capacitor power supply is divided into two identical modules, each of which can supply 1.5 MA over 2 ms into 0.7 μH. The launcher used pure copper rails and unspecified insulator material. It had a 50-mm round bore and was 2.5 m long with an acceleration length of 1.8 m. An unusual method was used to provide the initial prestress. The inner core, containing the rails and insulators, is conical, and prestress is obtained by forcing this conical kernel into a conical hole in the 160-mm-diameter glass-fiber-wound containment tube. The projectile-armature was made of titanium of a "special design" to enhance the electrical contact with the rails. (In keeping with earlier research, this was probably an inertially loaded front contact.) In addition to the usual electrical diagnostic measurements, rail voltage was measured at several locations along the bore using fiberoptic transducers. The velocity was measured using two flash X-ray tubes. The results are given for an experiment in which the two banks were fired 1 ms apart. The current maxima were 1.19 MA at 341 μs and 1.63 MA at 1.23 ms. A 432-g projectile was accelerated to 1173 m/s for a kinetic energy of 298 kJ. Muzzle voltage was used to determine the projectile resistance and was compared with that predicted from three-dimensional (3-D) electromagnetic models that neglected velocity skin effect and heating. The rail voltages were analyzed to determine rail resistance and gave a value of 0.16 mΩ/m compared with the 3-D model prediction of 0.03 mΩ/m. Analysis of the energy partitioning showed that projectile kinetic energy was 14.7 percent of stored energy and that 56.2 percent of the stored energy was dissipated in the energy source and connections. The researchers claim that excellent electrical solid contact was demonstrated to 1.2 km/s by use of the titanium projectile.

The first ISL experimental results with solid armatures are presented by Lehmann et al. (1993). Their stated goal is to accelerate long-rod projectiles with a length-to-diameter ratio (L/D) as high as 40. The strategy followed was to mitigate the velocity skin effect by using materials with large skin depth and high melting temperature and to inject the current into the front edge of the armature. The experiments were carried out in two facilities: EROC, a launcher powered by a 150-kJ capacitor bank, and the EMA-1 facility powered by a 500-kJ capacitor bank. Projectiles of copper, brass, and titanium were tested. An unsuccessful attempt was made to provide a liquid conducting layer between the rail and armature by filling the threads of a threaded copper projectile with tin. Brass and titanium projectiles were inertially loaded at the front to provide rail contact using tapered steel and tungsten rods. A 25.75-g titanium projectile and stainless steel wedge was fired in the EMA-1 facility to 1380 m/s. The muzzle voltage rose to approximately 175 V then dropped to approximately 25 V during the shot. X-ray photographs of the projectile showed that it was strongly eroded and was followed by metallic particles.

The early ISL experiments have been well documented by Wey and Peter (1991) and Wegner and Jamet (1989), and two papers in the Third European Symposium on EML Technology, London, England, April 1990. Experiments were performed on plasma, hybrid, transitioning, and solid armatures. The experiments were well diagnosed using fiberoptic light sensors and rail voltage measurements at several locations along the rail, and inertially loaded solid armatures were X-ray photographed in flight. Rail and plasma resistance was determined using the voltage measurements.

c. Germany

The German electric gun program (Witt and Newald, 1988) is primarily an electrothermal program. Rheinmetall administers the program, with the experimental facilities being built at Technology Center North (TZN) in Unterlüss. The German electromagnetic gun activities are located at the joint French-German ISL and the Technical University of Munich (TUM).

TUM has been involved in electromagnetic acceleration since 1971 for the calibration of space experiments (Igenbergs et al., 1986). The researchers extended their work into railguns in 1984. The initial small square-bore launcher reached a velocity of about 3.7 km/s with a 0.1-g projectile driven by a foil-initiated plasma armature. A new laboratory facility has been prepared at Garching to house all their electrothermal gun and electromagnetic accelerator activities.

Aigner and Igenbergs (1989) describe experiments to determine friction and ablation effects in a plasma armature railgun. A new round-bore facility was constructed using a crowbarred capacitor power supply with 16 modules and a total capacitance of 352-μF, voltage not specified (one plot shows 16 kV; this gives a stored energy of 45 kJ). The launcher was 6-mm in diameter, with copper rails and fiberglass-epoxy insulators contained in a bolted aluminum tube with an effective acceleration length of 420 mm. Optical fibers were used to detect armature position, and final velocity was determined by a magnetic pickup coil and an impact sensor at the target. The entire experiment was contained in a 1-m-diameter by 2-m-long vacuum tank. Experiments were compared with a performance model that incorporated projectile friction, ablation, and viscous drag. Good agreement with theory was shown for position-time data for a free-arc and a 250-mg projectile experiment. Final velocity was not given, but the researchers stated the ideal projectile velocity was reduced by about 28 percent, with 15 percent loss for electrode ablation, 9 percent loss for mechanical friction, and 4 percent loss for viscous arc drag.

A four-rail accelerator was constructed to reduce the rail forces in the launcher and focus the plasma armature towards the axis of the barrel (Igenbergs, 1991). Results were compared to a conventional two-rail launcher. The 6-mm-diameter barrel was 300 mm long with a 250-mg projectile. Fiberoptic light probes were used to obtain position-time data. The velocity was 1.33 km/s, and this was 15 percent higher than the conventional launcher experiment with the same parameters.

Wisken et al. (1993) describe a new facility that combines an ET preaccelerator with a railgun. The bore diameter is 6 mm with a 950-mm-long copper rail, fiberglass insulator railgun connected with an insulating section to the 52-mm-long ET preaccelerator. The entire system is placed in a 3-m-long vacuum tank. Capacitor energies of 25 kJ and 360 kJ were used for the preaccelerator and railgun, respectively. Results are given for an experiment in which 1.5 kJ was supplied to the preaccelerator to give an injection velocity of 1.5 km/s. The railgun capacitor was charged to 162 kJ, giving a current maximum of 160 kA. The 300-mg projectile was accelerated to a final velocity of 3.9 km/s.

One interesting experiment at the Technical University of Braunsweig describes several schemes to combine inductive storage with the railgun structure (Salge et al., 1985). The basic idea is to augment the magnetic field in the bore using the power supply inductor windings, and includes transformer coupling schemes to increase armature current. An experimental device was fabricated having a 10-mm × 10-mm square-bore railgun 0.7 m long together with two auxiliary windings, one above and one below the bore, with a total of 34 turns. These were contained in a steel tube filled with epoxy resin. The coil inductance was 178 μH, and the effective inductance gradient was 10 μH/m. The gun could be operated either series augmented or as an XRAM-gun, where the coils are charged in series and discharged in parallel to double the armature current. Experiments showed a linear increase of projectile velocity with charging voltage for both systems. The slope for the XRAM-gun was considerably larger. Details of the 7.3-g projectile were not given, but its mass decreased to approximately 5.9 g by contact erosion. The highest velocity was 500 m/s, achieved with a current of 25 kA.

Karasinski et al. (1991) describe a rather sophisticated time-resolved spectroscopic system developed at Diehl to determine the plasma temperature in a railgun or ET gun plasma. The system uses a mechanical chopper wheel to scan the spectrum across an optical multichannel analyzer (OMA) vidicon tube to obtain the time-resolved spectra. They demonstrate the method using Bartel's method to determine plasma temperatures of approximately 5000 K in a plasma arc initiated with a brass foil.

d. The Netherlands

The work at TNO is oriented toward tactical military applications, and this is the only research group known to be working in the Netherlands. Solid armature research has been the focus of their efforts, particularly the use of bundles of fine copper and molybdenum fiber for armatures. TNO has emphasized diagnostic measurements, and they may have the most comprehensive diagnostic capability of any railgun laboratory in the world. This group has been active in the formation of the European Electromagnetic Launch Society, and their experimental work is detailed in the four European Symposia on EML Technology.

Karthaus and Koops (1993) detail the status of TNO research and laboratory facilities. The work is characterized by especially strong diagnostic instrumentation. They have used VISAR optical measurements for in-bore velocity, and are currently using optical displacement sensors to obtain dynamic measurements of rail displacement, multiple X-ray units for three-station orthogonal shadowgraphs and X-ray cinematography using a high-speed image converter camera. The railgun experiments were powered by a 6.7-MJ homopolar generator used with a mechanical opening switch. Earlier experiments were carried out in a 15-mm square-bore 1-m-long railgun at current levels of 250 to 300 kA. A new accelerator 2.37 m long with a 20-mm square bore was used for the work reported here. The rails are copper alloy with G-10 insulators and are assembled into an aluminum V-block bolted structure.

The copper fiber armatures have a cross sectional area of 0.9 to 1.0 cm^2 made from insulated 0.1-mm copper wires packed to 70-percent copper density. The launch assembly consists of two glass fiber epoxy parts containing the copper armature. Similar launch packages have also tested armatures made of noninsulated 0.15-mm-diameter molybdenum wires. Copper and molybdenum armatures have been accelerated to approximately 1100 m/s. Specific parameters for these shots were not given, but it appears that the current maximum was about 300 kA.

Karthaus et al. (1991) give details on earlier solid armature experiments with a 3-m-long, 15-mm square-bore railgun that used monobloc aluminum armatures. Some multiple burst shots were fired in this railgun using the rotating mechanical opening switch. The aluminum armatures did not work well. They transitioned to a hybrid armature and then a plasma. The armatures broke up and lost significant mass, resulting in severe damage to the rails. This railgun did not have close bore tolerances and therefore, a 1-m, 15-mm square-bore gun was built with a maximum deviation of 0.01 mm. This new gun was successfully used with the solid copper fiber brush armatures detailed by Karthaus and Koops (1993).

Direct in-bore measurements of projectile velocity using the VISAR optical interferometer is described by Koops (1991). This is the only successful application of the technique to railguns. The method often has difficulty with plasma armature railguns because of plasma leakage past the projectile. It was successful here because of the solid copper fiber armatures. A commercial VISAR system, ATA Mod. 405/CLS was used with a single frequency argon ion laser operating at 514.5 nm. Excellent velocity data were obtained that helped to establish a value for static friction of the projectile. Reasonable acceleration data could be obtained by differentiation of the velocity data, but the data were "... not accurate enough to reveal the physical processes that occur at the rail-armature interface in detail."

4. Japan

Railgun research in Japan is rather diverse, with a variety of application goals from tactical guns to circuit breakers. Most of the systems are relatively small, less than 0.5 MJ stored energy, but one facility at the Tokyo Institute of Technology appears to have approximately 1 MJ. Most of the experimental efforts are oriented toward hypervelocity plasma armature railguns. Only one group appeared to have used solid armatures. Some impressive results have been achieved. The group at the Institute of Space and Astronautical Science has achieved a velocity of 7.45 km/s with a 0.87-g projectile, and claims to regularly achieve shots at over 6 km/s with the ability to predict performance to within ±3 percent.

The activities in Japan are characterized by a willingness to build experimental devices to test out a variety of innovative approaches to high velocity, often based on ideas proposed, but not implemented, in the West. These include the ablation mass driver (AMD) that uses a sequence of Z-pinch discharges, segmented and fused rails, multiturn augmentation, and ventilated bores or "spout holes." One interesting feature appears in several experiments: the use of transformer coupling to achieve better efficiency with relatively small stored energy. Another innovative feature of three of the groups is the use of laser induced breakdown to achieve plasma ignition.

There is some indication of military applications, but this is confined to the Japan Defence Agency (JDA—Kashii, 1989, 1990) and one reference to tactical guns at Mitsubishi Heavy Industries (Kobayashi, 1993). The activities at JDA appear to be on a small scale, although a drawing of a large facility (850-m-long, 1.5-m-wide rails) is shown without description. Researchers describe a five-turn augmented railgun that has accelerated a 1-g projectile to 1.2 km/s using a 60-kJ capacitor bank. The gun used copper-tungsten alloy rails, and the stated purpose was for armor testing. Another experiment used a two-section, distributed energy store, AMD (see Figure III.1) to accelerate a 14-g projectile to 560 m/s. The AMD combines the force due to projectile ablation with electromagnetic force due to the Z-pinch geometry for acceleration.

The largest experimental railgun facility, based on an energy storage of 1.2 MJ, is located at the Tokyo Institute of Technology Research Laboratory for Engineering Materials (Usuba et al., 1992). This group uses a two-stage helium light gas gun to inject projectiles at 2.5 to 3 km/s. They have fabricated barrels with brass rails contained in steel tubes filled with epoxy, but apparently without prestress. They have achieved 4 km/s with projectiles of 0.7 to 0.8 g and currents of 379 and 405 kA. The barrels failed during high-current experiments (1.2 MA). Their projectile is a two-piece sabot-fuse-projectile assembly with several aluminum rings and foil for the fuse.

The most impressive performance has been achieved by the group at the Institute of Space and Astronautical Science (Tokyo) using a 13-mm round-bore conventional railgun (HYPAC—Kawasima et al., 1993; Yamori et al., 1992). This work is oriented toward the study of impact with space debris. A 300-kJ capacitor bank was coupled to the railgun using a 4:1 transformer for better impedance matching. The conventional railgun uses copper rails and polycarbonate insulators, and is reamed before each shot. Earlier work was plagued with precursor arcs, and the projectile

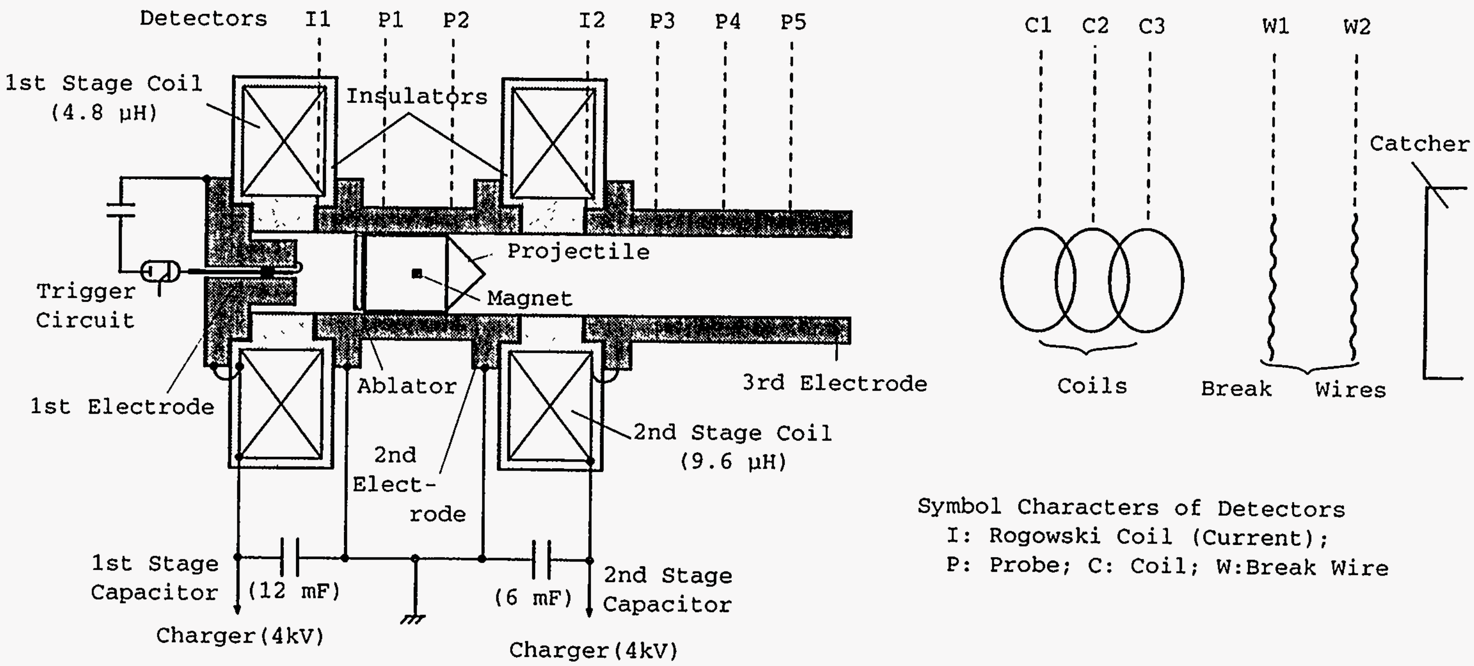

Figure III.1
Ablation Mass Driver

The AMD, a novel electromagnetic gun, uses two magnetically stabilized z-pinch discharges to generate plasma pressure. Mass for the plasma is ablated from the projectile base by energy radiated and conducted from the plasma.

diameter was increased to provide a 0.25-mm interference fit to reduce precursors. The researchers claim to be able to shoot routinely above 6 km/s and to be able to predict performance to within ±3 percent. Their best performance is 7.45 km/s with a 0.87-g projectile in a 13-mm-diameter bore 1860 mm long. The discharge current maximum was approximately 750 kA at 200 μs.

Three groups are working on small-bore railguns to use for hydrogen pellet injection into fusion reactors; one at the Tokyo Institute of Technology and two at Mitsubishi Heavy Industries. All these guns are conventional small-bore (3-mm) railguns and use either Nd:Yag or Ruby lasers to initiate the plasma armatures. The best velocity reported is 2.4 km/s using a 22-mg plastic projectile (Tamura et al., 1992). Solid hydrogen pellets of 4 mg have been accelerated to 1.4 km/s in a railgun that uses a pulse forming network (PFN) to power the railgun (Azuma et al., 1993).

Several innovative concepts have received experimental study. These include large augmentation, distributed energy store, and a ventilated bore. Japan Steel Works, Ltd., Tokyo, has achieved 4.3 km/s using a 200-kJ bank connected to a five-turn augmented railgun through an 8:1 transformer (Maruo et al., 1991a). They have also investigated the effects of different fuse materials on barrel erosion and find the least erosion using zinc (Maruo et al., 1991b). The National Chemical Laboratory for Industry, in Ibaraki, has conducted free-arc experiments in a distributed energy store (DES) railgun using fuses to uncouple the rail segments after armature passage (Usuba, preprint). This group also operates a 16:1 transformer-driven railgun and a railgun with an integral explosive flux compressor (Kakudate et al., 1992). Kobe Steel, Ltd., has performed experiments on a conventional railgun whose bore was vented with one or more sets of ventilating holes ("spout holes") to reduce secondary arc formation (Moyama and So, 1993). Researchers reached just under 4 km/s in one experiment using the ventilated bore.

5. Russia

The available publications on research in the former Soviet Union primarily describe research using plasma armature railguns for hypervelocity. There are three major centers for this work: Novosibirsk, Moscow, and St. Petersburg. Several groups are active in these locations. In Novosibirsk, there is one group at the Hydrodynamics Institute im. M. A. Lavrent'yev, and another at the Thermal Physics

Institute, both part of the Siberian Division of the Russian Academy of Sciences. In Moscow, there is a group at the High Temperatures Institute and another at the Atomic Energy Institute im. I. V. Kurchatov. In St. Petersburg, there appear to be two groups, both working under the auspices of the Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences. Most of the experiments have been done using conventional copper and fiberglass composite insulator railguns of nominal 1-cm bore size and modest energy storage of less than 1 MJ. However, there are mentions of larger systems to 5.76 MJ, explosive magnetic generators, explosive magnetohydrodynamic (MHD) generators, and augmentation. Very little work on solid armatures has been published. Recently, a group at the Lyubertsy Scientific-Production Association "Soyuz" described an extensive railgun laboratory and reported some work on solid armature projectile designs.

The Russian understanding of the behavior of plasma armatures and why they do not work is essentially consistent over these several groups. This understanding has come largely from diagnostic experiments and careful analysis of experiments, rather than detailed theoretical analysis or computational fluid dynamics (CFD) simulations. They differentiate between the H-compressed or current sheath (CS) discharge and the plasma dynamic discharge (PDD). The concept of the plasma piston where mass is completely trapped by the discharge is rejected in favor of a model where the plasma can flow in and out of the armature. Russian researchers do not accept that ablated material necessarily adds to the mass of the armature. In most plasma armature experiments, they observe that the breech voltage and muzzle voltage are relatively constant, and that if the railgun is to operate as an electromagnetic accelerator, these voltages must increase with velocity and pressure, respectively. The inability of the plasma to support a large electric field because of current shunting in the dynamic tail of the armature is cited as the primary reason for failure of the plasma armature railgun. They attribute a significant portion of projectile acceleration to fluid motion or electrothermal effects. In general, the consensus for breaking the 6 km/s barrier is pessimistic.

In Novosibirsk, the research railguns at the Lavrent'yev Hydrodynamics Institute and the Thermal Physics Institute share certain similarities. They both often use 11.7-mm bores contained in round, epoxy-filled steel or composite tubes. Both have used transparent insulators and high-speed cameras to understand the dynamic structure of the plasma armature. Most of the experiments at the Hydrodynamics

Institute used a capacitor bank of 255 kJ with a maximum available of 510 kJ. The work at the Thermal Physics Institute used capacitor banks of 100 kJ to 1.25 MJ. In addition to the capacitor bank, the Hydrodynamics Institute group did experiments with explosively driven magnetic flux compressors and MHD generators.

More detailed experimental papers were available from the work at the Lavrent'yev Hydrodynamics Institute. Shvetsov et al. (1987) describe experiments using conventional railgun designs with copper rails and polycarbonate or glass fiber insulators and steel or glass fiber laminate containment tubes. Bore diameters of 5.7 and 11.7 mm were used, with bore dimensions controlled to less than .02 mm. Barrel length varied from 0.3 to 1 m for the 5.7 mm diameter and 0.5 to 2.5 m for the 11.7-mm-diameter launchers. Projectiles were fitted undersized by 0.01 to 0.02 mm. Reasons for undersizing were not explained, and these experiments suffered from blow-by, precursor arcs and projectile fragmentation.

Brightness temperature was measured for a stationary arc at a wavelength of 453 nm using interference filters and high-speed cameras. The peak temperature observed immediately after initiation was approximately 25,000 to 30,000 K, but cooled, as the armature expanded and striations began to appear, to about 18,000 K near the end of the current pulse. In addition to the brightness temperature measurements, the structure of the plasma was observed using a streak camera. After 25 to 30 µs, irregular stratification was observed with durations from fractions of microseconds to several microseconds.

Experiments using a 510-kJ capacitor bank were conducted with current densities less than 350 to 400 kA/cm. They reached 5.3 and 5.5 km/s with intact projectiles of 0.2 and 1.3 g using the capacitor bank and the explosive driven magnetic compressor (MC). The maximum velocity with the capacitor bank was 6.0 km/s and with the MC generator 5.2 km/s, but with fragmented projectiles. (Perhaps this was because of the loose fit?) The maximum reproducible velocity was 5.0 km/s with intact projectiles, and the maximum attainable velocity with partial fragmentation was 7.4 km/s. During these experiments, the Russian researchers observed that acceleration due to fusing added approximately 0.5 km/s and that primary arc separation occurred at approximately 300 mm into the rails. The performance did not decrease in the small-bore gun when the length of the barrel was reduced to 0.3 m. They attribute shunting of the arc and loss of acceleration to metal evaporated from the rails behind the projectile. A catcher plate placed in front of the muzzle captured approximately 0.7 g of copper, significantly more than the 0.2-g projectile mass.

Anisimov et al. (1989) describe experiments carried out in a glass insulator railgun to observe the plasma structure using a high-speed (rotating mirror) camera and to measure its brightness temperature. Both blocked bore and accelerated projectiles were used. Framing camera sequences are shown for both stationary and accelerated discharges. Initial plasma expansion occurred over 25 to 30 μs without acceleration, and the plasma was separated from the projectile by 2 to 4 cm with the colder part near the projectile. Similar behavior was observed for the accelerated projectiles. Blow-by and precursor arcs were observed in all shots. Plasma current redistributed to extend over the entire bore, secondary arcs and primary arc separation from the projectile were observed, and arcs continued at the initial point of fusing.

The group at the Lavrent'yev Hydrodynamics Institute has also used explosive-powered generators to power railgun experiments. Shvetsov et al. (1984) describe a combination explosive-driven MHD generator and railgun. A schematic of the system is shown in Figure III.2. The railgun and the generator share a common set of rails (3). Initial acceleration of the projectile (4) is provided by conventional EM acceleration powered by the circuit L_0, R_0, C. At peak current, the explosive charge (1) is detonated, generating a flow of ionized gas into the railgun through the tube (2). When the ionized gas interacts with the magnetic field in the railgun, the current (I) is amplified and energy is transferred from the gas to the projectile. The efficiency of the transfer process is a sensitive function of the initial generator dimensions (d_1, d_2, l), the initial position (l_0) of the projectile and fuse (5), and the amount by which the gas velocity (V) exceeds the projectile velocity (v). The rail accelerator was similar to that used in the explosive-driven magnetic generator (EMG) experiments. The barrel was 11.7-mm diameter with copper electrodes 1.8-m long. The containment was an epoxy-filled steel tube. The 20.4-mF capacitor at 5 kV (255 kJ) was used to initiate acceleration of the 1.3-g plastic projectile using a copper foil fuse. Starting the projectile at the mid-point of the rails (0.9 m) and with an initial current of 400 kA, they achieved 4.5 to 5 km/s. No detailed experimental data (current profiles, voltages, B-dots, etc.) are given. Increase of the current to 500 kA did not increase performance, and it appears that the projectile failed.

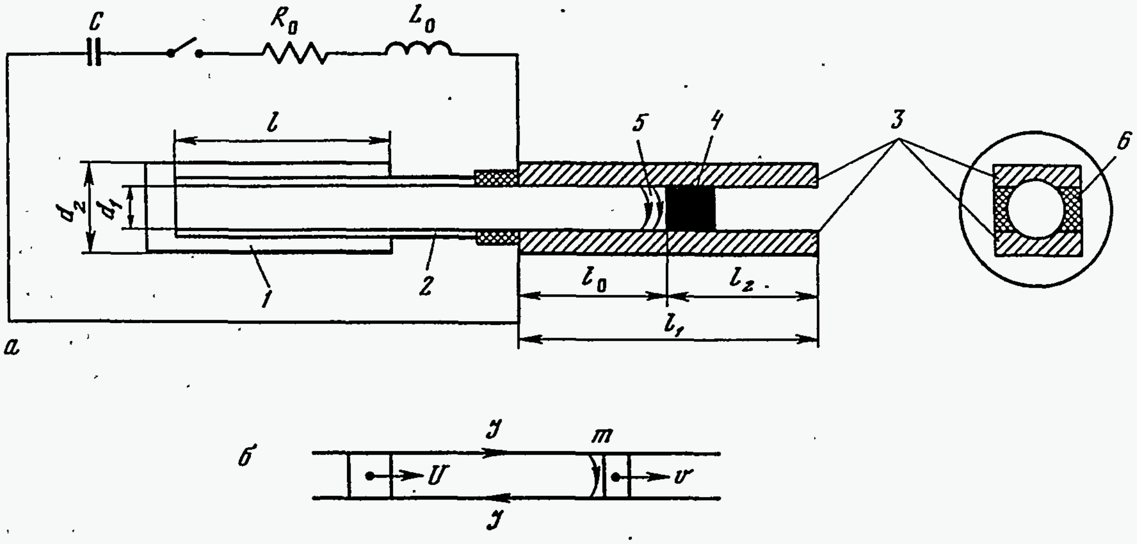

Figure III.2
(a) Schematic of Railgun Powered by Explosive MHD Generator
(b) Operation of Explosive-Powered MHD Generator on Railgun

Anisimov et al. (1986) describe experiments with a similar railgun using an EMG to provide power. The paper includes theoretical design calculations for cylindrical, spiral, and plane generators. The 11.7-mm-diameter generator/railgun had brass or copper rails 900 mm long with an acceleration section 800 mm long. The 1.2- to 1.3-g projectiles were made of caprolon. Aluminum or copper foils were used to initiate the plasma. The initial current was supplied by a 20.4-mF capacitor charged to 5 kV (255 kJ). A plane EMG with varying linear inductance was fabricated. The generator busbar was 50 mm wide by 1.4 m long. The distance between the busbars varied from 30 mm at the initial section to 40 mm at the end, with an initial inductance of 0.54 µH. The generator provided constant current of approximately 350 kA from 170 to 310 µs. A velocity of 4.5 km/s was achieved using a 1.2-g projectile. Experiments using explosives having low (3.7-km/s) detonation velocity were also described. The researchers concluded that these explosives can be used effectively to supply railgun accelerators of solid projectiles.

The group at the Lavrent'yev Hydrodynamics Institute has also conducted experiments on bimetallic rails (Shvetsov et al., 1991). An 8 × 8 × 100 mm discharge chamber was used with currents of 150 to 400 kA and a total charge transfer from 5 to 30 C. Electrodes were weighed to determine mass loss and examined microscopically for surface and internal melting, cracking and chemical changes. The mass loss was found to be directly proportional to action ($\int I^2$ dt). The resistance of the discharge was constant, equal to 0.75 mΩ for copper and 0.9 mΩ for molybdenum (Mo) and tungsten (W). Many molten droplets were found on the copper surfaces, while the refractory metals displayed surface cracking. Tungsten and molybdenum sheets 0.5 mm thick were explosively bonded to copper substrates. Surface cracking of the tungsten turned to dust after firing, leaving a plane surface, but cracking was pronounced at the interface. Explosively bonded Mo gave 30 percent less mass loss than other bonding methods. X-ray analysis revealed that the refractory alloys dissociated into their individual components and then reacted chemically. Their numerical analysis showed that the critical current density could be 30 to 40 percent higher using bimetallic electrodes as compared to monolithic electrodes. This is due to current redistribution in the surface and an increase in heat transfer to the substrate.

The experimental work of the group at the Thermal Physics Institute has been summarized in a review published in response to the pessimistic views expressed at Megagauss V in the papers by Parker and Hawke (Zheleznyy et al., 1992). This very interesting paper does not detail specific experiments, but presents insights gained by the Russian researchers from their experimental program over a period of time. The experiments were carried out for free-arcs and projectiles using various electrode and insulator materials with currents of 10 kA to 1 MA, self and external fields of 0.5 to 20 T, accelerator lengths of 0.3 to 3 m, bore size of 1 to 5 cm, capacitor voltage of 0.5-7 kV and energy storage of 0.1 to 1.25 MJ. In addition to the usual diagnostic measurements, they have used photo diode probes and fast-framing cameras with transparent insulators, and have measured emission spectra. One unusual experiment was described that used an accelerator with electrodes that increased in size toward the muzzle and a linearly increasing current to develop a true compact (CS) armature whose voltage increased with current. Some of the experiments achieved velocities of 6.8 to 7.2 km/s for an accelerated object with a mass approximately 1 g. The voltage across the arc in these experiments reached values of approximately 1.8 kV, which limited the current in the plasma conductor.

The Russian experiments and others were analyzed to evolve a physical understanding of plasma armatures. The authors note that the motion of the current peak cannot be identified with the motion of the center of mass of the projectile plus plasma. Experiments tend to show constant values (300 to 400 V/cm) of the electric field, while it should increase with pressure to the power 1/2. Several data sets are shown for electric field as a function of current to contrast the observed behavior with that for an ideal compact discharge. They object to the common neglect of the flow structure and dynamics of plasma expansion during initial times when the rate of change of current is large. The distributed discharges that develop operate similarly to an electric discharge (ET) gun with only a small contribution due to the EM component. They take exception to the notion of a "plasma piston" and the concept that the armature mass must increase due to ablation. A table of bore material vapor pressures is presented, and the authors argue that vaporized material cannot leave the wall until the armature has passed and the pressure drops below the vapor pressure. The emitted vapor does not increase the armature mass, but should be considered as a loss of momentum into the boundary layer. They conclude that it is very difficult to ever achieve the current sheath or magnetically compressed discharge that is needed for good EM acceleration when starting from a condition where the gasdynamic pressure exceeds the magnetic pressure.

A similar paper was presented by the group from the High Temperatures Institute at Megagauss VI (Ostashev et al., 1992). No experimental details are considered, but a physical understanding of the plasma armature is presented based on their analysis of their own and other experiments. Two regimes of plasma armatures are defined: current sheath (CS) and plasma dynamic discharge (PDD). The notion of an impermeable armature is rejected,"... PDD in railgun has no connection with the mass of gas it drives," and the authors suggest that more, not less, wall erosion may help to maintain the desirable CS type of discharge. Great importance is placed on the maximum voltage developed by the armature, and they state that the plasma tail in a PDD is absolutely unstable to secondary arcs. The increase of instability with current is due to a reduction of density in the PDD tail due to higher velocity, not increased erosion. They point out that if the breech voltage does not rise with velocity, then the railgun is not operating as an electromagnetic accelerator. This corresponds to reaching a maximum resistance of the plasma where the CS transitions to the PDD by breakdown at the tail. They conclude that the railgun is a gasdynamic converter and is limited by the velocity at which armature gas can be directed against the projectile base. Various limiting processes are shown on a velocity versus magnetic flux plot (Figure III.3 below). Regions above 10 km/s are excluded. They conclude that the problem of stabilizing the CS seems "... a hypothetical and unrealizable one."

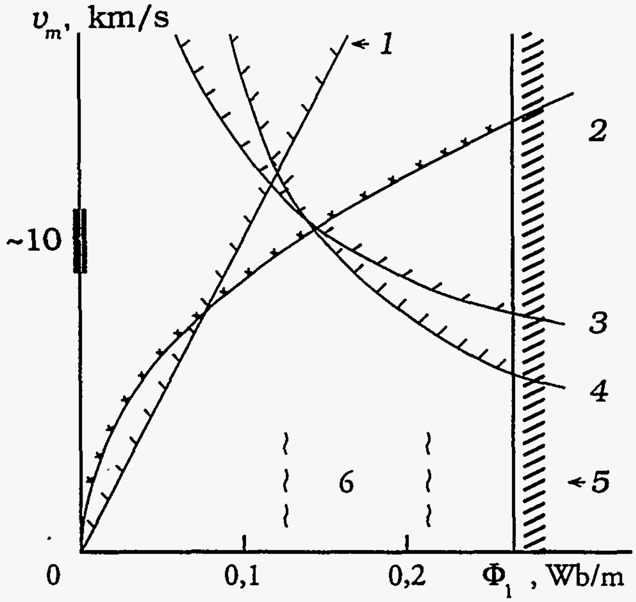

Figure III.3

Calculated limits on projectile velocity for a plasma armature railgun considering the effects of: 1 – flow velocity; 2 – plasma dynamic instability; 3 – turbulent friction; 4, 5 – exceeding the electrical strength and mechanical stiffness of the railgun bore. The area labeled 6 indicates typical railgun parameters (Ostashev et al., 1992)

Kondratenko et al. (1987, 1988) detail the High Temperatures Institute experiments in a short (to 1 m) 10×10-mm square-bore railgun with copper and glass epoxy bore materials. Initially, they suffered from precursors caused by leakage, but were able to eliminate them by stiffening the structure and projectile. They were able to achieve 600 to 700 kA without precursors. Velocity of 6 km/s was achieved repeatedly with 0.9-g polycarbonate projectiles and 0.5-m-long rails. Diagnostic measurements included high-speed photography in-bore and at the muzzle in addition to the usual array of electrical diagnostics.

A small railgun experiment at the Kurchatov Atomic Energy Institute to determine the ablation coefficients in glass fiber laminate insulators and copper rails was described by Alekseyev et al. (1990). The gun was 0.47 m long and "similar to that developed at LLNL," with 10 × 10 mm and 4 × 4 mm square bores. It was assumed that the ablated mass is proportional to the energy dissipated in the arc, and the rail and insulator parts were weighed to determine the mass loss. Both projectiles of 0.1 to 1 g and free arcs were used in the experiments. Precursor arcs formed in some of the experiments complicating the data analysis. Few details were given for the power supply except that the total capacitance was 32 mF separated into four modules. The researchers found a linear relationship between ablated mass and total energy dissipated in the arc. The maximum dissipated energy in the arcs shown in the plots was 16 kJ. Two insulators, steklotekstolit and caprolon, had ablation constants of 80 and 28 g/MJ and copper had an ablation coefficient of 75 g/MJ. Ostashev et al. (1993) describe experiments that relate the ability to form a current-plasma armature (CPA—similar to the CS armature discussed above) to the method of initiating the plasma armature. They mention experiments that use a foil sandwiched between the projectile and a massive (20 g) pusher injected with a conventional powder gun, and describe experiments in which the armature is initiated with a 1.5-mm-diameter copper wire. They conclude that initiation using a massive conductor results in a more stable quasi-stationary CPA initial state.

The group at the Ioffe Physical Technical Institute in St. Petersburg has also conducted small-bore railgun experiments and arrived at similar conclusions with respect to the plasma armature (Drobyshevskiy et al., 1991). The rationale for their experiments was based on observations of constant breech voltage and analysis. They also reject the notion of an impermeable plasma piston, and relate performance limits to the internal breakdown voltage of the plasma. They do not believe that restrike is the limiting mechanism.

This group has achieved 7.1 km/s with a 1-g Lexan projectile in a 60-cm-long railgun with a 10 percent efficiency, using a pulse forming network to obtain nearly constant current (Drobyshevskiy et al., 1993). The capacitance was 25 mF with a stored energy of 250 to 300 kJ. This result culminated several years of experiments, diagnostics and original analysis. The final results were obtained using a breech design incorporating thick mineral grease to cool the plasma armature and raise the armature voltage (Drobyshevskiy et al., 1994a). This prevented the formation of secondaries and longitudinal streamers.

The gun was operated just below the current limit at which the rail surface explodes. The researchers have increased this current limit from 45 to 60 kA/mm by the use of a conducting shield behind the main rail (Drobyshevskiy et al., 1994b). This shield reduced the L′ value of the rail, but the higher operating current overcomes this decrease and produces a higher total force. The shield also reduces the transverse force on the rail, thus the stress in the rail support insulators. The acceleration (4.5×10^7 m/s^2) exceeds the theoretical static strength limit of the projectile by a factor of 7. The researchers verified experimentally that the maximum velocity is proportional to the inverse square root of mass and that velocity was independent of L′. This approach, operating at the explosion limit of the rails, has also been applied to a very small-bore railgun with success. A velocity of 4 to 4.5 km/s is reported for a 1-mm, 1-mg plastic cube in an augmented railgun only 10 cm long (Drobyshevskiy, 1994c). The objective of this work is fusion pellet injection, but no experiments are reported for frozen hydrogen pellets that may not be able to survive such high acceleration.

A second group at the Ioffe Institute includes Rutberg and Levchenko on all papers. The latest experimental railgun work is described by Zakharenkov et al. (1993). They use a high-pressure helium ET gun for a preinjector. Some 50 experiments have been done on the ET gun and they achieved 2.3 to 3.6 km/s with projectiles of 1.8 and 4.15 g. The best specific energy for the ET preinjector was found at about 25 kJ/g. They have used a simple railgun barrel design consisting of half cylinder rails separated by a 6-mm insulator. This gives low (0.17 to 0.25 μH/m) L′. Performance of the combined system was not presented explicitly, but Figure 9 in their paper shows two experiments. Apparently this was for a 1.8-g projectile. The ET gun injected at 2.0 and 2.9 km/s. The final velocities were approximately 2.8 and 3.7 km/s. A large (20 MJ) electric gun facility and range is being assembled at the Electrophysics Problems Institute of the Russian Academy of Sciences (Bystrov et al., 1993). The 20-MJ capacitor power supply is divided into 12 separately controlled modules under computer control. The range includes a sabot and exhaust gas stripper, a 50-m vacuum flight range and catchtank.

Two Russian papers presented at the recent EML Technology Symposium (San Diego, April 1994) revealed the existence of a large railgun facility at the Lyubertsy Scientific-Production Association "Soyuz" near Moscow. The "Soyuz" facility is a large (approximately 8,000 personnel) installation working primarily for the military in the fields of solid rocket motors, propellants, and energetic materials.

Yu. P. Babakov, head of the Energy Physics Department at the "Soyuz" facility, presented a description of their power supplies and railgun apparatus (Babakov et al., 1994). One of the power supplies, "Mustang," is a unique system driven by a solid-propellant MHD generator, a pulse transformer, and an elaborate switching system employing seven explosively driven closing switches and two explosively driven opening switches. The MHD generator charges the primary of the transformer to a current of 20 to 25 kA in a period of 6 seconds. Operation of the explosive switches interrupts the primary current and generates a secondary current of up to 1 MA in about 1 ms. The other power supply is a modular capacitor bank, designated "EMMU-10," with a total stored energy of 6 MJ and a peak current capability of 2 MA.

Babakov et al. (1994) also describe two railguns. T2M is a 2-m-long device with a bore that can be configured for both round and square operation up to 15 mm. The railgun MK is a 4.5-m device with a nominal bore diameter of 30 mm. Both railguns are built of high-strength steel and appear to be built for multi-shot use rather than the "fire once and rebuild" philosophy that has dominated other Russian research. Both railguns employ an injector that uses chemical propellants to achieve injection velocities of 400 to 1200 m/s.

The experimental results described by Babakov and his coworkers are "typical," intended to show capability, not to establish any scientific result. Using "Mustang," a 3-g, 10×10-mm object was accelerated to 4.85 km/s at a peak current of 400 kA. It should be noted that the Mustang system exhibited very poor efficiency in this experiment. The MHD generator produced about 9.6 MJ of inductive energy and 10 MJ of resistive energy in the primary of the transformer. The kinetic energy of the accelerated object was only 35 kJ, an efficiency of about 0.2 percent.

Six typical experimental results are presented for the EMMU-10 system powering a variety of railguns with lengths from 2 to 4.2 m and diameters from 17.5 to 30 mm. The velocities achieved are comparable to results obtained in the United States and elsewhere. The highest velocity reported, 6.8 km/s with a 3.8-g object, is comparable to the 7-km/s velocities reported by other Russian groups and by

Japanese researchers. No information is given on the operating current or the damage done to the bore during an experiment. The heaviest mass reported, 150 g, reached a velocity of 2.9 km/s, a respectable but not exciting result.

A second paper from the same research group at the "Soyuz" facility reports on numerical and experimental results for metal armatures (Khandryga et al., 1994). A 2-D finite element calculation of the radial deformation of an aluminum cylinder shows that large friction forces can be developed when the cylinder rubs against the bore. The suggested solution is to neck down the cylinder so that only a fore body and the armature rub against the walls. A reduction of friction loss by a factor of 3 is predicted.

Six experiments using the MK railgun powered by a 5-MJ modular capacitor bank (presumably EMMU-10) are reported. The projectiles were aluminum cylinders with conventional "C" armature configuration. The special necked-down projectiles carried a payload mass of some type that increased the total mass to about 320 g. The efficiency of energy transfer from energy into the barrel to kinetic energy of the projectile is only 10 percent. The researchers attribute this to a friction force equal to about 50 percent of the driving force. This conflicts with US experience, where higher efficiencies are achieved routinely and friction is not a dominant factor.

The primary importance of these papers is the confirmation that there has been a military interest in railgun technology in Russia at least since the mid-1980s. The distinguishing features of this research include the following factors:

- Is carried out at an institution funded primarily by the military;
- Uses technology (solid propellant MHD generator) that provides large energies and is potentially feasible for tactical applications;
- Experimental work on solid armature, generally recognized as necessary for tactical railguns.

If this is the principal research activity addressing military objectives, then the Russian work is at least five years behind the US work in railgun technology and possibly further in power systems. There is evidence that the military funding for this program has been sharply curtailed in the past two years so the technology gap is unlikely to close in the next few years.

D. PROJECTIONS FOR THE FUTURE

Projecting the future course of experimental railgun work is difficult in light of the rapidly changing government support both in Russia and in the United States. It seems clear that research into plasma armatures and hypervelocity performance will decrease significantly, since this activity was largely driven by space defense applications. The Russian consensus that velocities above 6 km/s were unlikely was based on an approach that was, in any event, not usable for practical applications other than to launch small polycarbonate projectiles. This is because the average acceleration in their short experimental devices was four to five million times the acceleration of gravity, considerably more than any practical payload can withstand. It is likely that US research in this area will be virtually nonexistent after the current fiscal year, and the research in Russia will probably experience a similar decline. Work on plasma armature railguns as a means to supply frozen hydrogen pellets for fusion reactor fueling will probably continue at a low level in the United States, Japan, and Germany. Plasma armature railguns are being used today in Japan to provide a testing capability for satellite collisions with space debris. This ongoing application will probably result in continued Japanese development of plasma armature railgun technology.

The situation for lower velocity solid and hybrid armature railgun research is quite different. The application for this technology is largely to improve military gun performance in the areas of anti-tank guns, deep-strike artillery, and missile defense systems. The Chinese program appears to be moving aggressively to develop military railgun technologies and, given their stated goals and the organization and resources available, they could achieve parity with Western capabilities within a few years. The European experimental railgun facilities for research related to military applications are currently as good as or better than those in the United States. This is partly because of the partial US funding and the transfer of technology that has occurred in the past. If US support decreases in the future, the continued success of the European program will depend on the extent of the financial commitment of the European governments and industry.

It is difficult to predict the evolution of military railgun research in Russia, since so little relating to these applications has been published. In the current economic environment, it would seem unlikely that a large program will be sustained. However, the situation in Russia could change rapidly if the European or Chinese programs matured sufficiently to be near weaponization, particularly for the anti-tank application.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Table III.1 lists key non-US experimental railgun researchers, their affiliations, and areas of expertise.

TABLE III.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—EXPERIMENTAL RAILGUNS

Researchers	Facilities	Areas of Expertise
	Australia	
Richard A. Marshall	Australian National University, Maribyrnong, Victoria (This program was terminated; R. A. Marshall now conducting railgun research at IAT, Austin, Texas.)	Experimental railguns
D. F. Stainsby	Defence Science & Technology Organisation Materials Research Laboratory (This program has been terminated.)	Experimental plasma armatures
	China, People's Republic of	
Zhaoxing Ren	Institute of Plasma Physics, Hefei, Anhui	Tactical railguns
Shunshou Gao	Southwest Institute of Fluid Physics, Chengdu, Sichuan	Plasma armature railgun
	China, Republic of (Taiwan)	
W. S. Hou	Nuclear Energy Research Institute, Lung-Tan	Small railgun

TABLE III.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—EXPERIMENTAL RAILGUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	France	
Francis Jamet Hilmar Peter Volker Wegner Joseph Wey	French-German Research Institute Saint-Louis (ISL), Saint-Louis	Military railgun systems, solid armatures
	Germany	
T. Karasinski	Diehl GmbH	Spectroscopic diagnostics
Francis Jamet Hilmar Peter Volker Wegner Joseph Wey	French-German Research Institute Saint-Louis (ISL), Saint-Louis, France	Military railgun systems, solid armatures
Eduard B. Igenbergs	Department of Space Technology, Technical University of Munich (TUM), Munich (München)	Small railguns, four-rail accelerator
Jürgen G. H. Salge	High-Voltage Technology Institute, Braunschweig Technical University, Braunschweig	Small innovative EM launchers
Markus Löffler Thomas Weise	Technical Center North , R&D Center, Unterlüss	Small innovative EM launchers (Mostly involved with ET systems, but collaborate on experiments with J. Salge at Braunschweig Technical University)
	Japan	
Akira B. Sawaoka H. Tamura	Ceramics Research Center, Engineering Materials Research Laboratory, Tokyo Institute of Technology, Yokohama	Laser preignition, plasma armature railguns, microparticle plasma accelerator
Akira B. Sawaoka Shu Usuba	Engineering Materials Research Laboratory, Tokyo Institute of Technology, Yokohama	Hypervelocity, plasma armatures, light gas gun preinjectors
Kazunari Ijuta	Institute of Plasma Physics, Nagoya University, Nagoya	Ablation mass driver

TABLE III.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—EXPERIMENTAL RAILGUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Japan (cont'd.)	
Nobuki Kawashima Akira Yamori	Institute of Space & Astronautical Science, Kanagawa	Space debris simulations, hypervelocity plasma armature railguns
Hideaki Kashi	Japan Defence Agency, Meguro, Tokyo	Augmented railgun, ablation mass driver
Toshiaki Maruo Koji Nemoto Akihiro Okamoto	Japan Steelworks, Ltd., Tokyo	Augmented railguns, fuse materials
K. Moyama	Kobe Steel, Ltd.	Railgun "spout holes"
K. Kobayashi	Mitsubishi Heavy Industries, Ltd., Sagamihara Machinery Works, Kanagawa	Augmented railgun, tactical gun systems
K. Azuma	Mitsubishi Heavy Industries, Ltd., Takasago R&D Center, Takasago	Hydrogen pellet injection, laser-induced plasma armature
K. Koyama	Mitsubishi Electric Corporation, Hyogo	Plasma armature diagnostics
Yozo Kakudate Shu Usuba	National Chemical Laboratory for Industry, Ibaraki	Segmented electrode railgun, magnetic flux compressors
	Netherlands	
Willem Karthaus W. J. Hans Kolkert	TNO PML Pulse Physics Laboratory, Delft	Military railgun systems, solid-fiber armatures, advanced diagnostics
	Russia.	
Yu. A. Alekseyev	Atomic Energy Institute im. I. V. Kurchatov, Moscow	Small railguns, fusion reactor fueling
B. P. Levchenko F. G. Rutberg A. F. Savvateyev	Electrophysics Problems Institute, Russian Academy of Sciences, St. Petersburg	Combined ET and railgun
V. E. Fortov Ye. F. Lebedev V. Ye. Ostashev	High-Energy Density Research Center, High Temperatures Institute, Moscow	Hypervelocity railguns, plasma armatures

TABLE III.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—EXPERIMENTAL RAILGUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
A. G. Anisimov Yu. L. Bashkatov Gennadiy A. Shvetsov I. A. Stadnichenko V. M. Titov	Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, Russian Academy of Sciences, Novosibirsk	Hypervelocity railgun, explosive magnetic flux compressors, bi-metallic rails
Yuriy P. Babakov Dmitriy V. Khandryga Aleksandr V. Plekhanov Anatoliy N. Tereschenko V. B. Zheleznyy	Lyubertsy Scientific-Production Association "Soyuz," Moscow Region	Large railguns, MHD power, solid armatures
E. M. Drobyshevskiy R. O. Kurakin S. I. Rozov V. A. Sakharov V. M. Sokolov S. V. Yuferev B. G. Zhukov	Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences, St. Petersburg	Hypervelocity railguns, plasma armatures
A. D. Lebedev Valeriy B. Zheleznyy	Thermal Physics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk	Plasma armature analysis
	United Kingdom	
Derek Putley	AEA Industrial Technology, Culham Laboratory, Abingdon, Oxon	Plasma railgun
David Haugh	Defence Research Agency (DRA), Fort Halstead, Sevenoaks, Kent (The major experimental facility is located at Kirkcudbright, Scotland.)	Military railgun systems, modeling

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CHAPTER III: EXPERIMENTAL RAILGUNS

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CHAPTER IV
RAILGUN THEORY AND DESIGN

A. SUMMARY

This review of theoretical railgun research focuses on the areas of railgun design and armature modeling. The term railgun design, as used here, refers to the coupled electromagnetic (EM), structural, and thermal analysis of the launcher and launch package (projectile, armature, and sabot). Our principal conclusions in the area of railgun design are as follows:

- The MEGA code, developed by the University of Bath in the United Kingdom, currently represents a unique capability for calculating the coupled, three-dimensional EM and thermal fields in railgun geometries. Executable versions of MEGA, available through lease agreements, are used at several US railgun facilities. EMAP3D, currently being developed by the Institute for Advanced Technology (IAT), should provide the United States with a comparable and independent modeling capability.

- The Defence Research Agency (DRA) at Fort Halstead in the United Kingdom has the most sophisticated capability of all foreign countries for performing railgun design. The DRA group has assembled a suite of codes, including MEGA, with the intent of achieving a self-consistent coupling among the EM, structural, and thermal solutions for the railgun system. This research, which is intended to support the development of railgun weapon systems, appears more advanced than similar efforts in the United States.

- Other notable, but somewhat less comprehensive, efforts in railgun design include the work at the French-German Research Institute Saint-Louis (ISL), in France, in support of weapons development; the collaborative effort between the University of Catania and the University of Pisa, in Italy, for fusion pellet injection systems; and the joint effort between Mitsubishi Heavy Industries and the Japan Atomic Energy Research Institute, also for fusion pellet injection.

- To a large extent, the railgun design efforts in foreign countries are taking advantage of codes available from the United States, including the structural analysis codes DYNA and EMAS, and the fluids codes CALE and HAMEX.

- Conspicuous by its absence is any evidence in the published literature of significant activity in railgun design by the members of the former Soviet Union. On the other hand, there are indications that most of the railgun work dealing with the acceleration of large masses was classified.

Our principal conclusions in the area of armature modeling are as follows:

- The principal expertise in modeling of solid armatures, outside the United States, is represented by the work of James in the United Kingdom and Schoolderman and his co-workers in the Netherlands. The focus of this research is primarily to extend the transition velocity of solid armatures. The James work is particularly noteworthy in that it is funded, at least in part, by the DRA at Fort Halstead.

- Survey of the published literature in the former Soviet Union revealed only limited and narrowly focused efforts in modeling of solid armatures. However, it appears that most of the work related to acceleration of large masses was classified.

- There is a surprising lack of evidence of non-US activity in the modeling of hybrid armatures.

- Researchers in the former Soviet Union are applying their extensive capabilities in plasma physics to the problem of plasma armatures. The key facilities supporting this research are the Russian Academy of Sciences' Physical Technical Institute im. A. F. Ioffe (St. Petersburg), Theoretical and Applied Mechanics Institute (Novosibirsk), and High Temperatures Institute (Moscow).

- The research for acceleration to ultra-high velocities in the former Soviet Union does not appear to be directed at any particular final application;

rather, the focus is on understanding and overcoming the shortfall in performance that plagues plasma-driven railguns at velocities in excess of 4 or 5 km/s.

- Several groups within the former Soviet Union are performing one- and two-dimensional, magnetohydrodynamic (MHD) simulations of plasma armatures. While the computational capability appears to be comparable to that of researchers in the United States, the researchers in the former Soviet Union appear to have recognized, at a somewhat earlier stage, the need for full-bore simulations that extend from the breech of the gun to the back of the projectile.

- Two noted researchers in railgun modeling from the former Soviet Union are currently working in the United States. One is Yuri Dreizin, now at DYUAR, Inc. in Minneapolis, Minnesota, whose expertise lies in the area of novel launcher concepts and solid armature design. The other is Dmitri Kondrashov, who is currently a doctoral candidate at the University of Tennessee Space Institute, where he is extending his work to a three-dimensional MHD simulation of the plasma armature. Such a model would provide a unique capability for investigating the dynamics of plasma armatures.

- Applications of MHD models to study the stability of plasma armatures are also evident in the work of researchers in the United Kingdom and Sweden.

B. INTRODUCTION

This chapter reviews the status of non-US technology in the area of theoretical railgun research. The review, which is limited primarily to the launcher and armature, focuses on two areas: (1) railgun design and (2) armature modeling and development. Here, we employ the term railgun design to refer to the electromagnetic, structural, and thermal analysis of the launcher and launch package. The two areas of focus represent the disciplines where theoretical research plays a prominent role in advancing the technology.

Lumped parameter models of railguns, which consist principally of the electric circuit equations for the launcher, some form of Newton's law for projectile acceleration, and associated auxiliary relations such as might be required, for example, to treat ablation drag, are not specifically addressed because they are relatively straightforward and prevalent among virtually all railgun research facilities. We consider them here only when they contain a particularly unique feature or are important in providing insight into the over-all capability of a facility.

This assessment of theoretical railgun research is limited to the past five years and is based primarily on information available in the published literature. Principal sources of information include the *Proceedings of the Electromagnetic Launch Symposia*, which are published in the *IEEE Transactions on Magnetics*, the *Proceedings of the European Electromagnetic Launch Symposia*, and the Soviet journals.

C. DISCUSSION

1. Railgun Design

Railgun design pertains to the calculation of the time-dependent distributions of magnetic fields and currents in the launcher and to the thermal and structural analysis of the launch package and launcher. These calculations are particularly important for the design of weapon systems where the pressure to minimize system mass and maximize launcher efficiency and lifetime requires an ability to model, in detail, the electromagnetic, structural, and thermal response of the launcher and launch package.

Such an analysis is not straightforward for several reasons. First, the computation of the EM fields requires the solution of the transient magnetic field equations in three dimensions subject to boundary conditions, some of which must be applied at infinity. Second, the calculations are inherently coupled. For example, ohmic dissipation is an important source term for the thermal analysis. Accurate characterization of this source term requires that the current distribution in the launcher be resolved in both space and time. On the other hand, the temperature rise in the launcher and armature significantly influences the electrical conductivity and, therefore, the current distribution. Likewise, the launch package and rails of the launcher are subjected to magnetic loads, as well as mechanical loads, and these magnetic loads depend on the distributions of currents and magnetic fields in the railgun system. Furthermore, the characteristic time scales for the EM, thermal, and structural solutions can be quite different.

A recent US survey highlights the difficulties of analyzing railgun designs and assesses the status of the modeling capability.[1] At best, the approach taken by most researchers, both in the United States and abroad, is to solve the thermal and EM equations together self-consistently. The magnetic loads from these computations are then used as inputs to a material response code to derive the structural reaction of the launcher and launch package. The final step of coupling the deformation of the structure back into the EM and thermal analysis typically is not taken, with the exception, of course, of the motion of the launch package. Real and important phenomena, such as the presence of plasma conductors, less than perfect electrical contact, multi-phase materials at the interface between the rails and armature, friction, and balloting, are seldom accounted for in the coupled analysis except in possibly the most rudimentary manner.

Within the context of non-US work, researchers in the United Kingdom appear to have the most advanced capability for performing railgun design, both in terms of having the computational tools and their application to obtain a coupled and self-consistent solution. Of particular note is the development of the MEGA code by Rodger and his coworkers at the University of Bath (Rodger et al., 1991; Rodger and Leonard, 1993). MEGA uses a finite-element approach to calculating the transient electromagnetic fields in systems with three-dimensional, moving conductors. Applications of MEGA to railgun geometries have provided detailed simulations of the fields, currents, and magnetic pressure distributions. The original version of MEGA assumed constant values for the thermodynamic and transport properties of the conductors, but more recent versions include a coupled solution to the thermal diffusion equation and account for the temperature dependence of the thermodynamic and transport properties. It should be noted that executable versions of the MEGA code are available through lease and, indeed, MEGA is used at several US railgun research facilities. On the other hand, there does not appear to be much application to railguns except in the United Kingdom and United States.

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[1] M. W. Lewis, D. A. Rabern, and R. W. Meier, (LANL), "Electromagnetic, Structural, and Thermal Modeling for Solid Armature Projectiles and Railguns," *MEE13-92:628, Nov, 1992,*

No capability comparable to and independent of MEGA exists within the United States, although several two-dimensional, transient codes have been developed and applied to railgun geometries. The Institute for Advanced Technology is currently developing a three-dimensional model, EMAP3D, which should rival MEGA in terms of modeling capability.[2]

It is not surprising that the Weapon Systems Group of the Defence Research Agency at Fort Halstead has provided much of the recent support for the improvements to MEGA (Leyden et al., 1993; Bisson et al., 1993; Atkinson, 1989). The Weapon Systems Group has assembled a suite of codes for performing railgun design (Critchley and Leyden, 1993) with the objective of achieving a self-consistent coupling between the electromagnetic, thermal, and structural solutions for the railgun. Their codes include, in addition to MEGA, CALE and HAMEX, which are 2-D MHD codes for treating material flow and heating, and DYNA, which is a finite-element structural mechanics code with both 2-D and 3-D options. Both DYNA and CALE are codes developed by Lawrence Livermore National Laboratory.

Italy is also actively developing a capability for performing railgun design. The Italian effort consists of a collaboration between Azzerboni and his coworkers at the University of Catania and Cardelli and Raugi at the University of Pisa (Azzerboni et al., 1993a-c). Their approach employs a nonlinear, 3-D equivalent network to simulate the mechanical, magnetic, and thermal behavior of the system. By approximating the current distribution in the railgun as a network of elementary-shaped conductors, each with a uniform current, they are able to exploit analytic solutions to the Biot-Savart Law, thereby simplifying the analysis. A test of their model against a MEGA calculation yielded favorable results although the comparison was performed at low velocities (20 m/s) and for constant electrical conductivity (Azzerboni et al., 1993c). The Italian effort does not appear to be part of a major railgun development program. No acknowledgment of support or reference to application is provided in their railgun design papers, although an earlier paper describes a lumped-parameter analysis of a railgun for fusion pellet injection (Azzerboni et al.,

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[2] K. T. Hsieh and M. D. Driga, "Multiple Traveling Wave Electromagnetic Rotating Power Supplies: FEM Modeling," *IEEE Trans. Magn., 29,* 1(1993), 997-1002.

1990). Rather their railgun design work seems to represent but one example of several applications of their equivalent-network analysis technique.

Kienner and Kitzinger at the French-German Research Institute Saint-Louis are also investigating the magnetic and mechanical coupling of railgun designs (Kienner and Kitzinger, 1993; Kienner, 1993). To a large extent, the ISL work exploits capabilities developed in the United States. For example, their model for the EM calculations is EMAS, a 3-D, transient, finite-element code developed by MacNeal-Schwendler Corporation of the United States, and their structural response model is DYNA. The modeling capability of ISL lags behind that of the United Kingdom in that EMAS cannot handle moving boundaries. Furthermore, their analysis does not include coupling of thermal effects to the EM solution. The ISL work is directed towards structural analysis of railgun bores and of projectiles and sabots. Specific calculations are reported for the 3-m-long, 3-MJ, 50-mm, PEGASUS railgun (Kienner, 1993).

In Japan, researchers at the Mitsubishi Heavy Industries and the Japan Atomic Energy Research Institute are collaborating to perform EM, thermal, and structural analyses of plasma-driven railguns for high-speed pellet injection into fusion reactors (Oda et al., 1993). The EM field calculations are performed with a finite-element code developed by Mitsubishi. The model is 2-D, limited to the plane containing the gun cross section, and therefore does not account for the moving boundary represented by the projectile. Heating arises from ohmic dissipation in the rails and plasma heating. The structural analysis is obtained from the commercially available ABAQUS code.

Little evidence was found of attempts at developing a major railgun design capability within the former Soviet Union. Rather, most of the literature consists of studies of limited scope, such as analyses of transient current diffusion in the rail cross section (Bodrov, 1987: Yuferev and Yuferev, 1991) and work on the analysis of the melt layer at the interface of the solid armature and the rails (Lebedev et al., 1993).

2. Armature Modeling and Development

The armature is an integral part of the railgun system in that it completes the electrical circuit of the railgun and serves as the medium through which the EM force is transferred mechanically to the launch package. Armatures are generally classified as being solid/transitioning, hybrid, or plasma.

True solid-to-solid contact between the armature and the rails results in a voltage drop of only a few volts. However, this level of performance is rarely achieved in hypervelocity railguns. A more representative voltage drop is on the order of a few tens of volts, probably reflecting a mostly solid armature in contact with the rails through a thin molten or vaporized region. For the purpose of this review, we shall use the term "solid armature" to encompass both operating modes. As the vaporized region between the rails and armature grows, through a combination of ohmic and friction heating, the voltage drop increases about a hundred volts, representing the transition to a hybrid armature. Under some conditions, the solid armature may disappear altogether so that the current from rail to rail is carried entirely through a plasma arc, leading to voltage drops in the armature of several hundred volts.

a. Solid, Transitioning, and Hybrid Armatures

Solid armatures are attractive from the point of view of their relatively low resistance and low bore ablation. However, current designs are limited to velocities on the order of 2 km/s; beyond that velocity, the armature rapidly transitions to a hybrid or plasma armature. Solid/transitioning armatures are the preferred alternative for a wide range of applications in the velocity range from 2 to 3 km/s, a regime that includes advanced tactical weapon systems.

The principal objective in the modeling of solid armatures is to develop the fundamental understanding necessary to support the extension of solid armature performance to high velocities. Such studies tend to focus on the mechanical and electrical interactions occurring at the interface between the rails and armature.

In the United Kingdom, the most significant modeling relative to velocity limits for solid armatures is that of James of JEM Systems (James, 1991; James and James, 1993). His model is based on transition due to ohmic heating of the rail/armature interface with particular emphasis on the role of the velocity skin effect (VSE). VSE is the tendency, at high velocity, for the current distribution to be shifted towards the trailing edge of the armature/rail interface. The James model provides scaling laws for determining the effect of material properties, gun operating conditions, and geometry on the transition velocity. Funding for this work has been provided, in part, by the USAFOSR/EOARD, Culham Laboratory, and the DRA at Fort Halstead.

Researchers at the TNO PML-Pulse Physics Laboratory in the Netherlands are actively engaged in the development of solid armatures in support of tactical military applications (Karthaus and Koops, 1993). Modeling efforts in support of that objective include coupled, 2-D, finite-element EM and thermal analyses of the armature/rail system that account for projectile motion, friction heating at the sliding interface and temperature-dependent properties (Schoolderman et al., 1993). The equations governing this system are solved using the computer code developed by Long as part of his dissertation at the University of Texas Center for Electromechanics.[3] Transition velocities are also computed based on the melting of the rail/armature interface to one thermal skin depth. Recently, the rail/armature analysis has been modified to include tensor, as opposed to a scalar, representations of the electrical and thermal conductivities (Schoolderman, 1993a). This change was made to support the analysis of multi-fiber solid brush armatures. In these designs the armature consists of a large number of electrically insulated fibers. The intent of the insulation is to increase the rate of diffusion of current in the direction normal to the current flow in the armature, thereby decreasing the localized heating that can lead to early transition. The improved performance of the multi-fiber armature over the solid monolithic armature, indicated by their analysis, appears to have been achieved in actual demonstrations (Schoolderman et al., 1993b) as indicated by a doubling of the value of the electrical action in the armature at which transition occurred.

Most of the published work in solid armature modeling in the former Soviet Union seems to be taking place at the New Physical and Applied Problems Institute of the Ukrainian Academy of Sciences in Kiev. Studies focus on characterizing the melt layer at the rail/armature interface and its effect on performance. The models

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[3] G. C. Long, *Fundamental Limits to the Velocity of Solid Armatures in Railguns*, PhD Thesis, The University of Texas at Austin, August 1987.

employed range from lumped-parameter performance models (Lebedev et al., 1993) to self-similar and numerical solutions (Uryukov et al., 1993) of the 2-D fluid dynamic equations describing the melt layer interface. On the other hand, much of the work related to the acceleration of large masses, which would certainly include solid-armature research, may well be classified. For example, Lebedev's work deals with the advantages of and techniques for restricting the melting at the rail/ armature interface to the armature. Since the armature is discarded after every shot, this technique for management of wear is preferable to eroding the barrel and thereby limiting its lifetime. Sources familiar with Lebedev's work state that this research is directed toward the development of a 30-mm, rapid-fire gun for air defense applications, although no reference to this application can be found in the literature.

The experience of Yuri Dreizin offers further indications that there may have been a larger research effort in solid-armature railguns than is indicated by the published literature. Dreizin spent 20 years at the Atomic Energy Institute im. I. V. Kurchatov, the last 13 as head of the Electrodynamics Laboratory, before coming to the United States in 1991. He now heads his own consulting company, DYUAR, Inc. in Minneapolis, Minnesota. Since coming to the United States, he has published theoretical articles related to solid armatures and innovative railgun concepts. The solid-armature research focuses on extending the transition velocity by the use of resistive layers on the rails and/or armature to counter the velocity skin effect.[4] His innovative design, called the busgun, entails the integration of a combustion-driven magnetoflux compression generator into the gun barrel to power the gun.[5] It is likely that these ideas build on the experience he gained and the work he performed at the Kurchatov Institute, yet his research in railgun physics does not appear in the Soviet literature.

This review of non-US research did not reveal any modeling efforts specifically addressing hybrid armatures. This lack of activity is somewhat surprising since

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[4] Yu. A. Dreizin (Dreyzin), "Solid Armature Performance with Resistive Rails," *IEEE Trans. Magnetics*, *29*, 1(1993), 798–803.

[5] Yu. A. Dreizin (Dreyzin), "The Electromagnetic Chemical Propulsion Concept," *VII EML Symp, San Diego, Calif., 19–24 Apr. 1994,* to be published in *IEEE Trans. Magn.*

Yu. A. Dreizin (Dreyzin), "A Busgun Design Example," *VII EML Symp., San Diego, Calif., 19–24 Apr. 1994,* to be published in *IEEE Trans. Magn.*

evidence to date suggests that solid armatures are likely to evolve to hybrid armatures in the important 2- to 3-km/s velocity regime.

b. Plasma Armatures

It has been the consensus of the railgun community that the plasma armature offers the best alternative for achieving ultra-high velocities (4 to 10 km/s) in railguns. Unfortunately, the potential of plasma-driven railguns has not been fully realized because of the dramatic, and not yet fully understood, loss in propulsion efficiency for velocities much greater than 4 or 5 km/s. The early promise of plasma armatures for a wide range of applications in the ultra-high velocity regime and the subsequent shortfall in performance both have served to attract the attention of a number of researchers, in the United States and elsewhere.

Researchers in the former Soviet Union have taken advantage of their rich heritage in the field of plasma physics in developing models for plasma armatures in railguns. The key facilities supporting this research include the Russian Academy of Sciences' Ioffe Physical Technical Institute in St. Petersburg, Theoretical and Applied Mechanics Institute and Thermal Physics Institute in Novosibirsk, and High Temperatures Institute in Moscow, and the Ukrainian Academy of Sciences' New Physical and Applied Problems Institute in Kiev.

There are three groups performing plasma armature research at the Ioffe Institute. The first group, consisting of Drobyshevskiy and his coworkers, is focusing on efficiency loss mechanisms in the hypervelocity regime, together with techniques for extending the velocity limit (Drobyshevskiy, 1991a-c). Most recently, they have focused on the role that compactness of the armature plays in achieving high velocity (Drobyshevskiy, 1993). Specifically, they claim to have achieved over 7 km/s in a small-bore railgun by quenching and cooling the trailing edge of the armature to ensure that it remains compact. Such work, while principally experimental and not noteworthy from the point of view of the sophistication of the model, is important nonetheless in that it provides insight into the processes that must be understood in order to model armature performance at high velocities. A second group, D'yakov and Reznikov (1988, 1989), also at the Ioffe Institute, have focused on bore ablation and its effect on railgun performance. Special emphasis is placed on deriving expressions for the limiting velocity in the presence of ablation drag. A third group

(Yuferev et al., 1992) has published an analysis of how the velocity skin effect influences the length of the plasma armature and the profiles of the armature thermodynamic properties within it.

At the High Temperatures Institute, researchers are combining experiments on a small-bore railgun with theoretical modeling to better understand velocity limits in plasma-driven railguns (Ostashev et al., 1993; Korovin et al., 1993). The analyses include one-dimensional, transient MHD studies of the armature, which are particularly noteworthy in that they are full-bore simulations (Anisykin et al., 1993). That is, the computational domain extends from the back of the projectile to the breech of the gun, thereby circumventing the need to create artificial boundary conditions at some defined armature-bore gas interface. The emphasis of the calculations is to determine the mechanisms that lead to secondary arc formation and extended plasma armatures.

One particularly interesting paper, co-authored by researchers at the Moscow State Technical University im. N. Ye. Bauman and the High Temperatures Institute, explores the stability of plasma armatures (Protasov et al., 1990). The paper describes two possible operating modes for plasma armatures—a current sheath (CS) mode in which the armature current is localized in a fairly compact zone near the back of the projectile and moves with the projectile; and the quasistationary plasma flow (QPF) mode in which the armature current is nearly motionless and gas essentially flows through the current distribution. From a perturbation analysis of the one-dimensional MHD equations for the armature, the researchers conclude that the armature is susceptible to instabilities, and that the CS mode will always evolve into the QPF mode if plasma exists in the region between the breech of the gun and the trailing edge of the armature. Techniques for limiting the growth rate of the instability are discussed.

At the Theoretical and Applied Mechanics Institute in Novosibirsk, Zagorskiy and Katsnel'son have developed a suite of computational models for studying the effects of bore erosion, drag, and the formation of secondaries on the efficiency of plasma armatures. These models range from lumped-parameter or integral analyses (Zagorskiy and Katsnel'son, 1993a) to one-dimensional (Zagorskiy and Katsnel'son, 1991, 1993b) and two-dimensional (Zagorskiy and Katsnel'son, 1993c) transient MHD analyses of plasma armatures. The two-dimensional analyses focus on variations from rail-to-rail, as well as in the direction of acceleration. Multi-dimensional simulations are useful in that they can account more accurately for friction, mass, and heat transfer in the directions transverse to the acceleration direction. Furthermore, some potentially important MHD instabilities, for example, the Rayleigh-Taylor instability, can not be treated in one dimension. Finally, multi-dimensional simulations are required to resolve the variation of the magnetic field strength in the region bounded by the rails and insulators. These researchers also allow for the possibility that the computational domain may extend to the breech of the gun (or to a contact surface between the armature and the pre-accelerator gas). Yet, in most of their calculations, the armature quickly separates from the breech or contact surface, and the trailing-edge boundary condition is modeled as a vacuum interface.

Also at Novosibirsk, Zheleznyy et al. (1992) have investigated the limitations of achieving high velocities with plasma-armature railguns. This work, which is primarily experimental, focuses on how the initial dynamics of the formation process of the armature influences the extent to which a compact armature can be maintained. The researchers argue that compact armatures are evidence of true electromagnetic drive, whereas extended armatures are evidence of thermal acceleration. Both free-running arcs and armatures accelerating projectiles with masses up to a few grams are considered. Zheleznyy and his coworkers contend that compact armatures can be maintained under conditions where the current density in the armature is high, where the current at early times has a rapid rise, and where the rails are flared such that the plasma resistance decreases with distance from the breech. They achieved velocities of 6.8 to 7.2 km/s "for an accelerated object with a mass m* >>1 g," with the velocity being limited, they state, by the capability of the power supply.

A full-bore, transient, two-dimensional MHD simulation of the plasma armature is also reported by researchers at the High Temperatures Institute in Moscow (Zatelepin and Kondrashov, 1992). The second dimension in this simulation is in the insulator-to-insulator direction, in contrast to the rail-to-rail dimension modeled by Zagorskiy and Katsnel'son. While this modeling capability is noteworthy, the application of the model that is reported is of only limited interest since it treats the problem of a free-running arc (that is, no projectile) at low currents and for very short acceleration times (0.134 ms). Kondrashov is presently at the University of Tennessee Space Institute, where, as part of his doctorate, he is extending his work to a three-dimensional simulation of the plasma armature. Such a model would represent a unique tool for investigating the dynamics and stability of plasma armatures.

Lebedev et al. (1992a), at the New Physical and Applied Problems Institute in Kiev, have published a comparison of an approximate, analytic integral solution with a numerical solution of the one-dimensional, time-dependent MHD equations for a free-running arc. The comparison indicates that the integral solution provides reasonable estimates for arc parameters such as length, velocity, average temperature, and average density. While the specific application for the model is not specified, Lebedev is associated with an experimental research group whose objective is to extend the velocity of plasma armatures (Lebedev et al., 1992b).

The United Kingdom and Sweden also have developed notable MHD modeling capabilities for plasma armatures. The UK research is a collaborative effort between researchers at Fluid Gravity Engineering and British Aerospace Defence, Ltd. (Taylor et al., 1993). This work is two-dimensional (rail-to-rail and acceleration directions) and transient, but not full-bore. The computational domain is fixed at some finite length behind the moving projectile. The objective of their simulation has been to study instabilities at the rear boundary of the armature that could contribute to the development of secondary arcs. The Swedish effort (Witalis and Gunnarsson, 1993) is also two-dimensional and focuses primarily on the potential contribution of the Hall effect on the generation of secondary arcs.

D. PROJECTIONS FOR THE FUTURE

Modeling of railguns has the potential of contributing to a number of important areas, particularly,

- design of railgun systems;
- delay and control of transition in solid armatures;
- improving plasma armature performance at velocities greater than 4 km/s.

The first problem represents basically a coupling of available design codes, while the last two areas require an improved fundamental understanding of the physics of armatures in railguns.

The significance of the work in railgun design must be viewed within the context of the overall development and application of the technology. The most significant work in design is driven by the development of railgun weapon systems. The UK research, centered at Fort Halstead, reflects a logical and well-organized effort to assemble the modeling tools necessary to support the design of a railgun weapon system capable of firing at velocities of 2 to 3 km/s. While the same or equivalent modeling tools are available to US researchers as well, the Fort Halstead group has progressed further in developing the logic for coupling the computations to obtain a self-consistent EM, thermal, and structural solution for the launcher and launch package. Presumably, the US Army's Focused Technology Program, whose goal is to develop a tactical railgun weapon system capable of firing at 3 km/s, will spur the development of a comparable capability within the United States

The United Kingdom appears to have embarked on a sound and comprehensive program that incorporates both modeling and experiments to resolve the technical issues related to the development of railgun weapon systems. White the US Army's Focused Technology Program has an objective similar to that of the UK program, the commitment of the United States to develop railgun technology appears to be wavering. The joint French-German effort in railgun weapon design lags behind both the UK and US programs in scope. Consequently, the United Kingdom is well poised to take the lead in the application. If the UK commitment to the technology remains firm, it is reasonable to project that the United Kingdom will develop and actually deploy the first tactical railgun weapon system.

The Japanese modeling effort in support of railgun design focuses primarily in the area of high-speed pellet injection into fusion reactors. The modeling is less comprehensive than that being performed in the United Kingdom and the United States in support of weapons development. The equivalent-network analyses in Italy, though noteworthy, do not appear to be part of an integrated effort to design railguns for any particular application. Rather, they are better viewed as the application of an analysis technique to a specific problem. Therefore, it is doubtful that the Japanese and Italian efforts, in and of themselves, will lead to any breakthroughs in railgun design.

The principal design issues for solid armatures revolve around techniques for minimizing the parasitic mass of the armature, delaying armature transition, managing hybrid armature performance after transition, and integrating the armature with the projectile and the sabot. Delay and control of transition in solid armatures is particularly important for tactical weapons applications. From a theoretical point of view, the major problem is developing sufficient understanding of armature transition phenomena to support armature design. Consequently, modeling of armature transition is of major interest to both US and non-US researchers.

Noteworthy theoretical research into solid armature transition and control is being performed in the United Kingdom and the Netherlands. This assessment revealed limited information on solid armature design in the former Soviet Union, indicating either a low level of interest or tight classification of the technology. The understanding of solid armature performance, particularly as it relates to transition, is rather limited at this time. Indeed, there is disagreement among researchers as to the phenomena that influence transition. Therefore, the non-US research in this area is best viewed as contributing to the overall knowledge base rather than being competitive with US efforts. The understanding gained from the accumulated research in solid armature design may well lead to reliable and reproducible non-transitioning solid armature performance at velocities of 2 km/s or somewhat higher, but without any single country providing a major technological breakthrough.

Funding for railgun research in the United States has decreased dramatically within the past year, and those funds that remain are directed primarily towards systems with velocities of 3 km/s or less. Consequently, little experimental or theoretical effort is currently being expended in the United States to solve the problems that plague plasma-driven railguns at velocities in excess of 4 km/s. Researchers in the former Soviet Union have been very active in studying plasma armatures, and their work appears to have led to some success, in that they claim to have achieved a velocity of 7 km/s in a small-bore gun (Drobyshevskiy et al., 1993). However, the current economic climate there is also threatening to reduce support for their work. For example, Drobyshevskiy has been aggressively pursuing funding in the United States to support his research. The theoretical work on plasma armatures in the United Kingdom and Sweden is probably too limited in scope to lead to significantly improved performance at high velocities. Under these conditions, the problems associated with hypervelocity railguns driven by plasma armatures are likely to remain for the foreseeable future.

The potential applications for railguns that can achieve velocities in excess of 4 km/s make the plasma armature problem of more than theoretical interest. These practical applications and the funding problems in both countries suggest that this may be an opportune time for the United States to consider a joint research program with the former Soviet Union to resolve and eliminate the problems associated with plasma armatures at hypervelocity. Otherwise, both countries are likely to see researchers, facilities, and equipment diverted to other programs prior to a satisfactory resolution of this important problem.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Table IV.1 lists key non-US theoretical railgun researchers, their affiliations, and areas of expertise.

TABLE IV.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—RAILGUN THEORY AND DESIGN

Researchers	Facilities	Areas of Expertise
	France	
P. Kienner K. Kitzinger	French-German Research Institute Saint-Louis (ISL), Saint-Louis	EM, thermal, and structural analyses of railguns
	Italy	
F. Canavero	Polytechnic of Turin, Turin (Torino)	EM and thermal analyses of railguns
B. Azzerboni G. Tina	University of Catania, Catania	EM and thermal analyses of railguns; lumped-parameter circuit models
Ermanno Cardelli M. Raugi A. Tellini	University of Pisa, Pisa	EM and thermal analyses of railguns; lumped- parameter circuit models

TABLE IV.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— RAILGUN THEORY AND DESIGN (cont'd.)

Researchers	Facilities	Areas of Expertise
	Japan	
K. Hasegawa S. Kasai	Japan Atomic Energy Research Institute, Naka-gun	EM, thermal, and structural analyses of railguns
K. Azuma Y. Oda M. Onozuka T. Satake	Mitsubishi Heavy Industries, Kobe	EM, thermal, and structural analyses of railguns
	Netherlands	
Willem Karthaus M. Koops Arnold J. Schoolderman W. A. de Zeeuw	TNO PML–Pulse Physics Laboratory, Rijswijk, Delft	Solid armature design
	Russia	
E. V. Anisykin V. E. Fortov V. Ye. Ostashev A. A. Zubkov	High Energy Density Research Center, High Temperatures Institute, Russian Academy of Sciences, Moscow	MHD analyses of plasma armatures; armature stability requirements
A. Yu. Bodrov	High Temperatures Institute, Russian Academy of Sciences (IVTAN). Moscow	EM analyses of railguns
Dmitri Kondrashov V. Zatelepin		MHD analyses of plasma armatures
E. M. Drobyshevskiy R. O. Kurakin Ye. V. Nazarov S. I. Rozov M. A. Savel'yev V. M. Sokolov S. V. Yuferev B. G. Zhukov	Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences, St. Petersburg	Analysis of plasma armatures and their impact on efficiency

TABLE IV.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—RAILGUN THEORY AND DESIGN (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
B. B. D'yakov B. I. Reznikov		Analysis of bore ablation from plasma armatures and its influence on performance; lumped-parameter circuit models
N. Yu. Gnedin M. L. Gnedina (S. V. Yuferev) V. S. Yuferev		MHD analyses of plasma armatures; transient analysis of field penetration in conductors
Saveliy S. Katsnel'son Aleksandr V. Zagorskiy	Theoretical & Applied Mechanics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk	MHD analyses of plasma armatures
A. D. Lebedev Aleksandr V. Plekhanov Valeriy B. Zheleznyy M. F. Zhukov	Thermal Physics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk	Analyses of plasma armatures
	Sweden	
P. Gunnarsson Erik A. Witalis	National Defence Research Establishment, Sundbyberg	MHD analyses of plasma armatures
	Ukraine	
A. D. Lebedev C. C. Milyayev B. A. Uryukov	New Physical & Applied Problems Institute, Ukrainian Academy of Sciences, Kiev	Analysis of melt layer at solid armature-rail interface; MHD analyses of plasma armatures

TABLE IV.1
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— RAILGUN THEORY AND DESIGN (cont'd.)

Researchers	Facilities	Areas of Expertise
	United Kingdom	
S. H. Le G. Bisson J. F. Eastham P. J. Leonard David Rodger	Bath University, Bath	EM and thermal analyses of railguns
Derrick Hewkin	British Aerospace Defence Ltd., Nottingham	MHD analyses of plasma armature stability
A. P. J. Argyle S. P. Atkinson R. Critchley C. Leyden	Defence Research Agency (DRA), Fort Halstead, Sevenoaks, Kent	EM, thermal, and structural analyses of railguns; MHD analyses of plasma armatures
A. M. Milne S. Taylor	Fluid Gravity Engineering, Ltd., Surrey	MHD analyses of plasma armature stability
David C. James Trevor E. James	JEM Systems, Abingdon	Armature transition theory; solid armature design

CHAPTER IV: RAILGUN THEORY AND DESIGN
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CHAPTER V
INDUCTION LAUNCHERS

A. SUMMARY

The induction launcher has been studied analytically and experimentally in the following countries: Russia and Ukraine (former Soviet Union), United Kingdom, France, Germany, Italy, Australia, and South Korea.

Most of the work on induction launchers has been carried out at the Istra division of the All-Union Electrical Engineering Institute based in Moscow, Russia. Starting from the beginning of the 1970s under the direction of V. N. Bondaletov, researchers studied and then built a few types of single-stage accelerator. Their interest shifted gradually from very light flat-ring projectiles to more massive cylindrical projectiles. Velocities of about 1 km/s were achieved with 10- to 30-g projectiles with an electro-mechanical efficiency of 43 percent. Higher velocities up to 5 km/s with masses of 1 to 2 g were reported in 1975 and 1977. Interest in cylindrical projectiles was first evidenced in two theoretical papers published in 1983 and 1984. The 1983 paper concluded that the cylindrical projectile would better utilize the materials than the flat-ring launcher. Also, it introduced a new researcher, Stanislav R. Petrov, who later became the team leader. The 1984 paper deals with a massive cylindrical projectile, and concluded that the system can be studied with sufficient accuracy by using equivalent circuits where the conductor thickness is equal to the depth of penetration of the magnetic field.

The work on single-stage induction accelerators performed by the Istra group over a period spanning two decades is of high-quality and demonstrates an enviable continuity of support. It was adequately and comprehensively reported in the published literature, so that it is unlikely that additional work of a classified nature was performed at the same time within the group. This is not the case with the work published later about the multi-stage induction launcher.

Three recent papers, in 1989, 1991, and 1992, that carry the signature of S. R. Petrov from the Istra division, deal with multi-stage pulsed-induction accelerators. They operated in a pulsed synchronized mode from a precharged capacitor bank using ignitron switches. All three papers provide normalized values for system parameters, but fail, perhaps deliberately, to provide their base values. One cannot use data given in one paper as a base for the others, because the papers do not describe the same coilgun system. The 1992 paper does provide a few technical details of its launcher setup: 35-mm bore diameter, 12 stages (stationary coils), 0.5-km/s muzzle velocity. The 1989 paper deals with an 80-stage launcher. It states that researchers achieved 78 percent of the maximum theoretical velocity, and an attempt to employ data from the 1991 paper leads to a muzzle velocity of 1.6 km/s. However, as was mentioned above, it is not clear that this is a valid conclusion.

The Russian researchers used a simple solution for synchronization between the firing times of the main ignitrons and the projectile location. This system, first described in a 1989 paper, uses electrodes inside the barrel, permitting the electric connections needed to provide the trigger pulses for the ignitrons to be made by the projectile itself. It proved to be reliable in many launching shots. It is important to note that the excitation for their multi-stage launchers is strictly synchronized with the position of the projectile. As a result, the Russian guns have a very high concentration of current and, therefore, of mechanical and thermal stresses at the back of the projectile. By carrying to the extreme this aft-pushing characteristic of the propelling force with the total absence of a centering force, the Russian guns would be extremely prone to balloting; that is, rocking of the head (and tail) end of the projectile from side to side inside the barrel. Another problem associated with the strictly synchronous excitation is the decay of the DC component of projectile current with time. To overcome this problem, the polarity of the excitation current is reversed after a number of barrel coils. This results, however, in a strong skin effect leading to a reduction in the efficiency and to an enhancement of the temperature rise in the material of the projectile. The acuteness of the heating problem in the guns justifies the Russian preoccupation with finding the thermal limitation in the muzzle velocity and their consideration of precooling the projectile with liquid nitrogen.

In a recent letter, S. R. Petrov from Istra provided one of the authors of this assessment with the dimensions of the 80-stage Russian coil launcher and stated that the velocity of a 29-g projectile actually achieved in the experiments was 1.56 km/s. The Istra group stopped the launcher experiments in 1992 because of a lack of funds.

The power conditioning units in all the Russian coilgun tests consisted mainly of precharged capacitor banks and ignitron switches. But in an unrelated research activity that started at the beginning of the 1980s, a group headed by I. V. Grekhov at the Physical Technical Institute im. A. F. Ioffe in Leningrad (St. Petersburg), has been working on the improvement of fast high-power semiconductor switches. They developed a thyristor with a new switch-on mechanism, and named it a "reversibly switched-on dinistor" (RSD). They tested a 20-cm^2 RSD at a current peak of 300 kA and at a rate-of-rise of 100 kA/µs. These values are much above the capability of off-the-shelf thyristors available today. It is a relatively slow turn-off device (hundreds of microseconds). A few Ioffe devices are now under test at the US Army Pulsed Power Laboratory in Fort Monmouth, New Jersey. The group at the Ioffe Institute also developed semiconductor opening switches that they call "drift step recovery diodes" (DSRDs). These switches can turn-off a 3- to 4-kA anode current in 0.5 to 3.0 ns at operating voltages of 0.7 to 3.5 kV.

The Asea/Brown Bovery (ABB) semiconductor division in Switzerland also has developed high-voltage thyristors with very high peak current capabilities and with high rate of rise of anode currents. They call it a "high-current thyristor," or HCT. These devices are now available with peak currents up to 150 kA, di/dt ratings up to 20 kA/µs and voltages up to 4500 V. A few of those devices are also now under test at the US Army Pulsed Power Laboratory in Fort Monmouth, New Jersey.

A joint French-German research effort on induction launchers began in the mid-1980s and is being sponsored by the respective ministries of defense. A coaxial coil-gun effort has been carried out at GEC Alsthom, Belfort, France. Researchers tested a pulsed synchronous launcher having a wound projectile of 5 kg at 400-m/s velocity. Flat channel launchers were built by Magnet-Motor GmbH, Starnberg, Germany. Those are synchronous-type accelerators in which the current is fed into the moving part by drag wires. A muzzle velocity of 55 m/s was achieved with a 50-g projectile. A higher velocity launcher is now under construction. The flat-channel launcher is used as a "jumping board" and a learning tool for a more advanced concept called the toroidal accelerator that is now under study.

The work on induction launchers in the United Kingdom began in 1983, and has been sponsored by the Defence Research Agency (DRA) at Fort Halstead, Kent, England. On coilguns, the DRA has no significant in-house work, but they are using two universities, Cambridge and Bath, to get a basic understanding of the parameters required for coilgun design. Following the original work of Williamson in 1986 on mesh-matrix approach to the analysis of traveling-wave launchers, finite-element models have been investigated. Their relatively low budget allowed only limited theoretical studies and a few experimental tests at very low muzzle velocities. Their traveling-wave launcher was tested at a 20-m/s velocity for a 1.5-kg projectile, and their pulsed induction launcher was tested at a 211-m/s velocity for a 0.5-kg projectile.

Additional studies of induction launchers, involving mainly theoretical work, were carried out in five countries. At the Electrodynamics Institute in Kiev, Ukraine, a group, headed by V. T. Chemeris, dealt with considerable mathematical sophistication in predicting velocity, losses, and magnetic flux penetration of a single-stage launcher. Their study was aimed mainly at civilian applications such as electromagnetic impact motors of the solenoid type. Two groups at the Universities of Catania and Pisa, Italy, did work on the analysis of electromagnetic launchers by using current filament models. They evaluated the errors of the system solutions that are found by carrying out approximate calculations using the lumped parameter approach. In another effort, at the Grenoble Electrotechnic Laboratory (Laboratoire d'Electrotechnique de Grenoble), France, a theoretical study has been carried out by using a finite element method to calculate forces and currents of an induction traveling-wave launcher using a US experimental prototype. Additional work from Australia addresses aspects of propulsion of a single-stage launcher. It presents simple relationships between the various parameters that may help in the preliminary design of a larger accelerator. Other work from South Korea deals with an optimization design procedure for a traveling-wave launcher. This work reproduces the analytical and experimental results of a US effort.

The relative complexity of the coil launcher technology prompted the investigators, in all countries involved, (1) to assign an electrical engineer to head the project, and (2) to obtain, prior to construction, a thorough analytical and physical knowledge of the system mechanics. Although some important engineering and economic problems remain, the understanding of the theory, operation, and design of the coilgun has progressed sufficiently that its engineering/development is the next logical step. Of all coilgun concepts, the coaxial traveling-wave launcher has the edge mainly because, it has uniform distribution of propelling and centering (that is, levitation) forces along the complete armature surface during acceleration, as opposed to aft pushing. The weak point of all coilgun concepts remains the complex and bulky power supply. Since switching elements and capacitive storage are developing at a fast pace, the launching of heavy projectiles at high velocity, for example, missile interceptors, is within reach in the next five years. Applications range from penetration mechanics research, anti-armor and anti-missile defense, to earth-to-orbit (ETO) launch. Promising spin-offs of coilgun research are also foreseeable.[1, 2] Having gained the lead, the United States should try to maintain it by encouraging development in this field.

B. INTRODUCTION

The induction launcher has been studied analytically and experimentally in the following countries: Russia and Ukraine (former Soviet Union), United Kingdom, France, Germany, Italy, Australia, and South Korea.

An induction launcher consists of two main parts: a stationary part, which consists of one or an array of drive coils, and a moving coaxial part (projectile) that is made of conductive material. In principle, the drive coils generate a rapidly varying magnetic field, which induces azimuthal currents in the projectile. The interaction between the magnetic flux density and the induced currents in the projectile creates an axial (propelling) force as well as a radial (centering) one. The launcher can be realized either in a coaxial configuration or in a flat-channel configuration. Work has been done on two basic types of induction launcher: pulsed induction launcher, and traveling-wave launcher.

1. Coaxial Configuration

In the coaxial configuration, both the drive coil assembly and the projectile have a circular cylindrical shape, and their central axes coincide, as suggested in Figures V.1, V.2, and V.3.

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[1] US Patent No. 5,270,593, "Air-Cored Linear Induction Motor for Magnetically Levitated Systems."

[2] F. A. Wyczalek, "American, European, and Japanese Coaxial Maglev Technology," *STECH'93 Int'l. Maglev Transit Conf., Yokohama, Japan, 22–25 Nov. 1993.*

a. Pulsed Induction Launcher.

Pulsed induction launchers are of two types: single-stage and multi-stage. The latter may operate either in a synchronous or in an asynchronous mode.

(1) Single-Stage Launcher

This pulsed induction launcher consists of only one drive coil and one moving conductive ring (Figure V.1). The stationary and the moving parts are coaxial. The drive coil is fed by a pre-charged capacitor C through a switch S. When the capacitor is discharged through the stationary coil, a magnetic field pulse is produced, and this in turn induces a current in the conductive ring. This induced current generates its own magnetic field that opposes the original pulsed field. In Figure V.1, the direction of the two fields is designated by North poles. Since like poles repel, the ring tends to move away from the stationary coil. The force F is given by the product of the currents i_1 and i_2 in the drive coil and in the ring, times the gradient of the mutual inductance M between the two coils:

$$F = i_1 i_2 \frac{dM}{dx} \tag{1}$$

where x is the axial distance between the two coils. This gradient peaks when the distance between the two coils is about 10 percent of the coil diameter. The larger the energy stored in the capacitor C, the larger is the force F, because both currents i_1 and i_2 are larger. Maximum achievable velocity is limited by the melting of the materials in the drive coil and in the ring.

In a slightly different configuration, the diameter of the moving part is made somewhat smaller than the bore diameter of the stationary coil. This allows the flat ring to be replaced by a short cylinder.

The main advantage of this device is its simplicity, its low fabrication cost, and its relatively low power requirement. It has been used mainly in penetration mechanics research and to validate theoretical and computer simulation results.

The major limitation arises from the rapid decay of the force as the distance between the stationary and the moving parts increases.

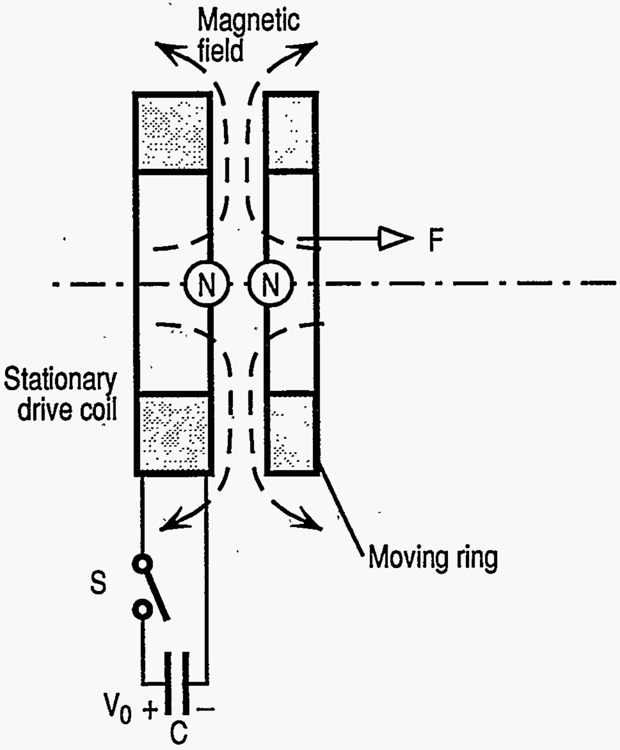

Figure V.1
Single-Stage Induction Launcher

(2) Multi-Stage Launcher

A more advanced version of the pulsed induction launcher consists of many stationary drive coils, which constitute the barrel of a gun. As shown in Figure V.2, the projectile is a hollow cylinder whose outer diameter is slightly smaller than the inner diameter of the drive coils in order to allow relative motion.

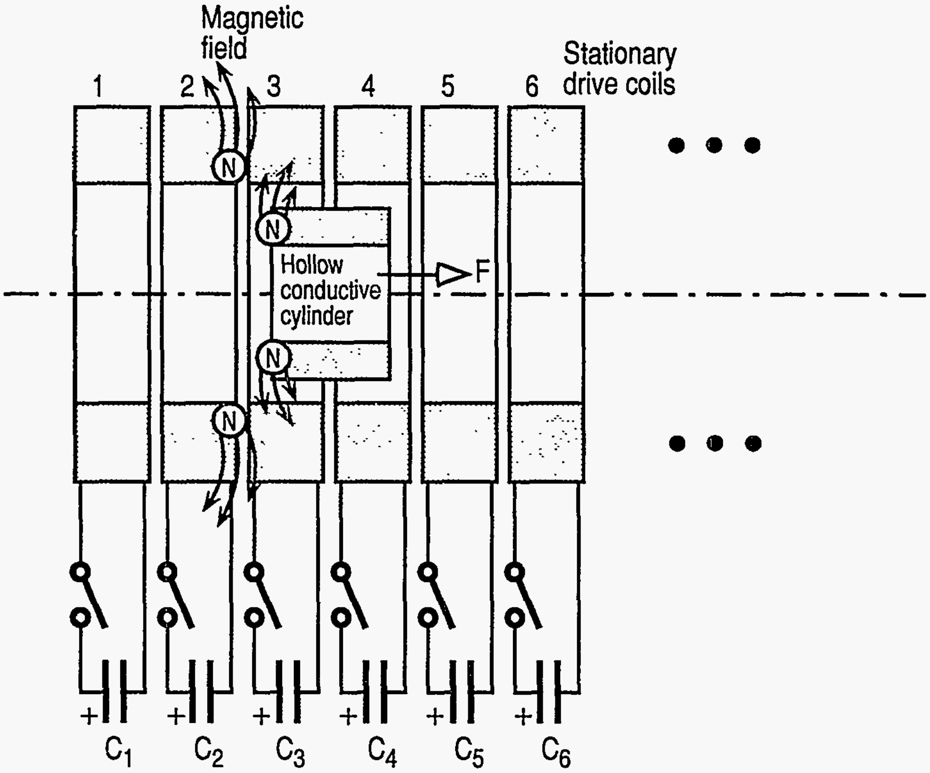

Figure V.2
Multi-Stage Induction Accelerator

Synchronous Mode of Operation:

The operation of the synchronous multi-stage launcher is similar to that of the single-stage accelerator. In principle, only one drive coil is energized at a time. The capacitors are discharged successively with the aid of switches, and in synchronism with the movement of the accelerated cylinder. When coil no. 2 is energized, its current generates a pulse of magnetic field (Figure V.2). This field induces an azimuthal current at the back of the hollow conductive cylinder (projectile), which, in turn, generates its own magnetic field. The direction of both fields is designated in Figure V.2 by North poles. Since like poles repel, the projectile accelerates in the direction shown. In addition to the longitudinal component, there exists a radial component of the force that acts on the back of the projectile and tends to keep it centered during the acceleration. However, since the induced current and, therefore, the force are concentrated at the back of the projectile, the latter is prone to balloting.

For optimal operation, the length of the projectile and of a drive coil must be approximately equal to the inner diameter of the drive coil.

To maintain unidirectional azimuthal current in the back of the projectile, the current in all drive coils must flow in the same direction. Therefore, a crowbar switch must be added across the terminals of every drive coil. This crowbar closes prior to current reversal in the coil. Strictly synchronous excitation of the drive coils causes the DC component of the projectile current to decay with time. To overcome this problem, the polarity of the currents must be reversed after a number of barrel coils. This results, however, in a strong skin-effect that causes a reduction in the efficiency and an enhancement of the temperature rise in the material of the projectile.

Asynchronous mode of operation:

A modified version of the synchronous multi-stage launcher of Figure V.2 energizes the drive coils in sequence, but somewhat more rapidly than the movement of the projectile. This asynchronous mode of energization generates a magnetic wave that travels faster than the projectile.[3] The difference in velocity is called slip-velocity. Feedback information regarding the relative position of projectile and drive coils is still required, but the interval between firing of succeeding drive coils is somewhat shorter than the transit time. This creates a situation where the next drive coil is energized before the first coil is crowbarred. Since the energized section of the drive coil array is now wider than in the synchronous case, the active surface of the projectile is slightly longer, with consequent reduction of the mechanical and thermal stresses. But, if the magnetic wave generated in the barrel travels much faster than the projectile, it may pass it by. Therefore, the length of the projectile must be at least equal to the product of that slip velocity times the transit time of the projectile within the barrel. This mode of operation alleviates the need for current reversal that is required in the synchronous mode, as was described before.

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[3] US facility: Sandia National Laboratories, Albuquerque, NM. R. J. Kaye, E. C. Cnare, M. Cowan, B. W. Duggin, R. J. Lipinski, B. M. Marder, G. M. Douglas, and K. J. Shimp, "Design and Performance of Sandia's Contactless Coilgun for 50-mm Projectiles," *IEEE Trans. Magn. 29*, 1(1993), 680-685.

The main advantage of multi-stage launchers is their simplicity, that is, their straightforward adaptation of the single drive coil concept. Also, they utilize less expensive unidirectional power capacitors, and unidirectional power switches.

Their main limitation is the need for a complex feedback mechanism to provide accurate synchronization between the movement of the projectile and the switching sequence. If, by mistake, a drive coil in front of the projectile is energized (for example, coil no. 5 in Figure V.2) an opposing force will act on the projectile as a brake. Also, because of the aft pushing, it is necessary to restrain the front of the projectile from hitting the walls and creating a hot plasma inside the barrel.

b. Traveling-Wave Launcher

This version of the induction launcher also involves an array of stationary drive coils that constitutes the barrel of the gun (as with the multi-stage pulsed launchers described above). But here, alternating (AC) currents are separately fed to a number of drive coils. The energized section of the barrel is longer than the projectile, and therefore encompasses the back, the body, and the front of the projectile.[4] With the aid of switches, the drive-coil currents simulate a balanced three-phase set, Ph1, Ph2, and Ph3, and produce a magnetic field pattern indicated by the curved arrows in Figure V.3. This field pattern (magnetic wave) is equivalent to the set of North and South poles shown near the drive coils. The magnetic wave travels to the right with a predetermined linear velocity v_0 that is given by the product of its wave length (two pole pitches, 2τ), and the frequency f of the currents flowing in the drive coils:

$$v_0 = 2\tau f \tag{2}$$

The frequency f depends on the value of the capacitor C and the inductance of the drive coil.

The traveling magnetic wave generated in the barrel by the drive coils induces azimuthal currents in the conductive cylinder. These currents, in turn, produce their own magnetic field pattern that is similar to the one generated by the drive coils, but

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[4] US facility: Polytechnic University, Brooklyn, NY. X. N. Lu, E. Levi, Z. Zabar, and L. Birenbaum, "Behavior of Azimuthal Currents Induced in the Projectile of the Linear Induction Launcher (LIL)," *IEEE Trans. Magn.*, *29*, 1(1993), 696-700.

is displaced a short distance to the right of it. The projectile (the conductive cylinder) field pattern is also represented in Figure V.3 by a set of North and South poles. Since like magnetic poles repel, and unlike poles attract, the projectile is propelled to the right. As a result, the projectile is "dragged" by the magnetic traveling wave at a velocity close to v_0. The difference between this velocity v_0 and the velocity of the projectile is called the slip-velocity.

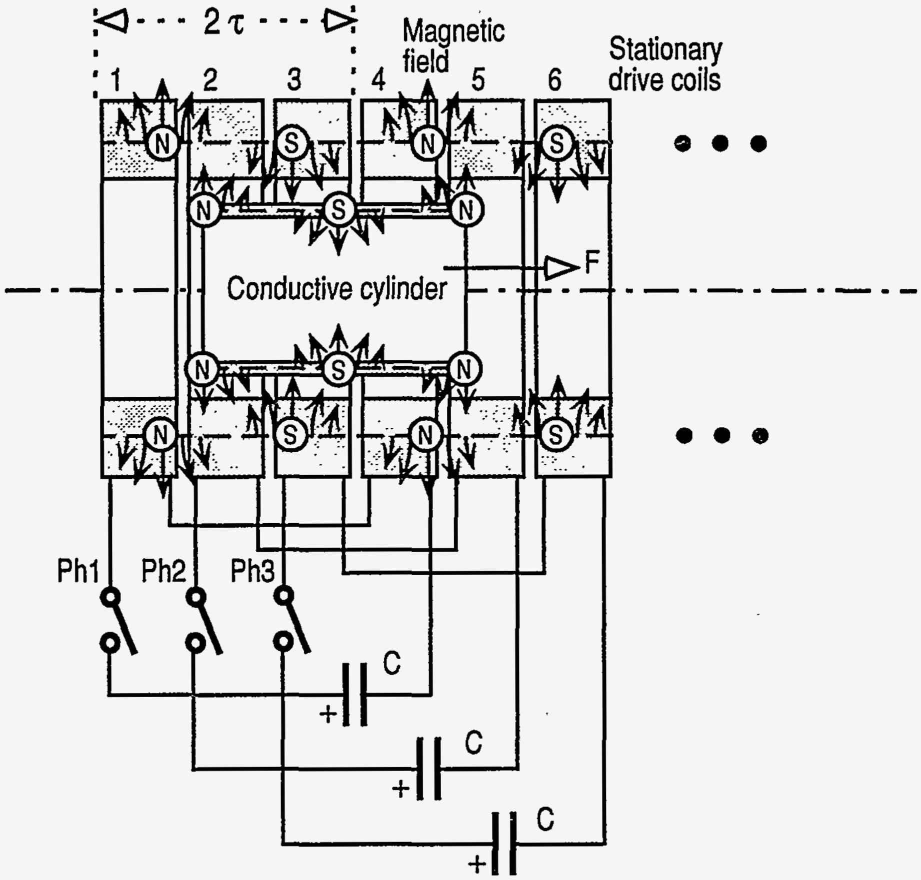

Figure V.3
Traveling-Wave Accelerator

In addition to the longitudinal component of the magnetic force, which causes acceleration of the projectile, there exists a radial component that acts on the projectile to keep it centered during the acceleration.

The main advantages of the traveling-wave accelerator are:

- The propelling force acts over the complete surface of the projectile (not just at the back, as with the other two concepts). This even distribution of stress allows for a reduction of the barrel length by at least one order of magnitude.
- The centering (levitation) forces act over the complete surface of the projectile during acceleration, thus keeping the projectile centered in the barrel.
- The need for exact synchronization between projectile and drive coils is eliminated.

One disadvantage with respect to the previous launchers is the need for alternating current capacitors and switches, which are more expensive than the corresponding uni-directional versions. A second drawback is the additional complexity, caused by the need to divide the barrel into sections energized in sequence at successively higher frequencies, in order to reduce the slip-velocity in each section, and, as a consequence to reduce the heat losses.

2. Flat-Channel Configurations

In a flat-channel configuration, the arrangement is planar, rather than coaxial. In this case also, the projectile is driven by a set of stationary drive coils.

a. Flat-Channel Launcher

A simplified diagram of a flat geometry launcher is shown in Figure V.4.

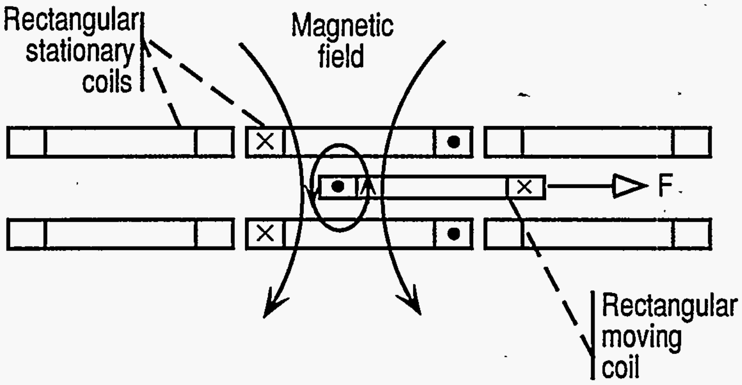

Figure V.4
Sketch of a Flat-Channel Launcher

The flat geometry launcher consists of several pairs of rectangular stationary coils (drive coils) arranged above and below a flat acceleration channel. Inside this channel, there is a rectangular coil that is free to move. As before, the drive coils are sequentially energized through a switched capacitor bank. In Figure V.4, the middle pair of drive coils is energized to generate a magnetic field. The current in the moving coil also generates its own magnetic field. Since the flux lines that are in the same direction create a repelling force, and those in the opposite direction create an attractive force, the inside rectangular coil tends to move to the right. Just after the left edge of the moving coil has passed into the space between the next pair of drive coils, those drive coils are energized, and the current in the preceding drive coils is extinguished.

The flat-channel launcher can operate in single-stage, multi-stage, and traveling-wave arrangements, as can the coaxial launcher, and has the same advantages and limitations. Added limitations are:

- The asymmetry of its structure, as compared with that of the coaxial launcher. This may add in-bore flight dynamic problems.

- The addition of currents in the lateral edges of the coils that cause **losses but** do not contribute to the generation of propelling forces.

- The absence of centering forces.

b. Toroidal Launcher

The toroidal launcher consists of several flat channels arranged in a **circumferen**tial structure as shown in Figure V.5.

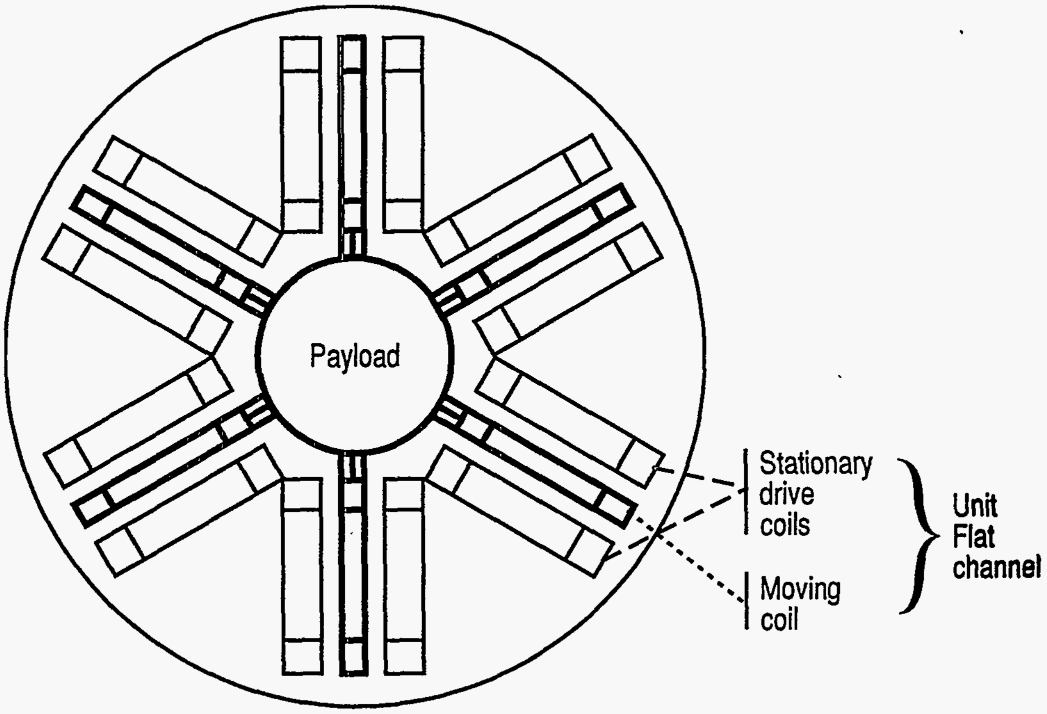

Figure V.5
Sketch of a Toroidal Launcher

The payload (see above) is accelerated by means of several (six in Figure **V.5)** moving coils, affixed to it, forming a rigid assembly, and arranged in a **star-shaped** geometry. The direction of movement of this assembly—the payload **with its six** moving coils—is intended to be directly into the page (that is, away from **the reader).** In each separate section of the assembly (that is, in each flat-channel **unit), the** moving coil operates in synchronism with the switching sequence of its own set of stationary drive coils. For the entire unit to function, all six flat-channel units must operate in synchronism with each other.

The toroidal launcher can operate in single-stage, multi-stage, and traveling-wave arrangements like the flat-channel launcher. It operates in a similar way, and has similar advantages and limitations. An advantage of the toroidal configuration over the flat-channel configuration is its better utilization of the magnetic flux. Since the drive coils are arranged around the circumference of the cylindrical payload, a combined toroidal magnetic field is generated in the stationary part. This reduces the flux leakage. A limitation is the complexity required by the need for synchronization of the several flat-channel units.

C. DISCUSSION

The discussion of the work performed on induction launchers outside the United States is divided into five sections. The pulsed induction launchers are discussed in the first section in two parts: single-stage and multi-stage launchers. The traveling-wave launchers are discussed in the second section. Switching and power conditioning systems are discussed in the third section, and analytical procedures are discussed in the fourth section. The fifth section compares US capabilities with those reviewed in previous sections. The discussion concentrates on the work done in each individual country separately.

1. Pulsed Induction Launchers

Work has been done on two types of pulsed induction launchers: single-stage and multi-stage.

a. Single-Stage Launchers

Most of the work on the single-stage type of launcher has been carried out at the Istra division of the All-Union Electrical Engineering Institute based in Moscow, starting from the beginning of the 1970s and under the direction of V. N. Bondaletov. From a survey of their literature, it appears that their interest shifted gradually from very light flat-ring projectiles to more massive cylindrical projectiles.

Only from the mid-1980s is there evidence of work done in England, Australia, and France-Germany on single-stage launchers.

The major limitation in the velocity range that has been achieved with single-stage accelerators is the rise in the conductor temperature up to the melting point. Since this rise is the result of Joule losses, maximum utilization of the source energy is the major consideration. This involves optimization of the geometry and of the parameters of the electrical circuit. As was noted in the Introduction (Section V.B), the repelling force is

$$F = i_1 i_2 \frac{dM}{dx} \qquad \text{so that} \qquad F \cong -\frac{M}{L_2} i_1^2 \frac{dM}{dx} \quad [N]$$

because, when the projectile losses are relatively small, the flux linkage with the projectile ring is nearly constant, so that $L_2 i_2 + M i_1 \cong 0$. Here, i_1 and i_2 are the currents in the drive coil and in the projectile, respectively, L_2 is the self inductance of the projectile coil, M is the mutual inductance and dM/dx is its gradient. This gradient peaks when the distance between the two coils is about 10 percent of the coil's average diameter. It follows that maximum acceleration is obtained when the current in the drive coil peaks, and the projectile has, simultaneously, reached the distance of maximum gradient. Consequently, the lighter the projectile, the faster must be the rise time in the induction current.

The radial forces are negligible when the drive and driven coils have the same diameter (Figure V.1).

Considering the Russian effort, performance predictions based on lumped circuit analysis were presented by Bondaletov (1967) in a seminal paper. Experimental results were first reported by Bondaletov and Goncharenko in 1971. Velocities of about 1 km/s were achieved with 10- to 30-g projectiles with an electromechanical efficiency of 43 percent. Higher velocities up to 5 km/s with masses of 1 to 2 grams were reported by Bondaletov and Ivanov in 1975 and 1977. These papers also indicate that the main application of these accelerators was penetration mechanics research.

Methods of measuring hypervelocities were described briefly in an early paper from the Istra division (Bondaletov and Ivanov, 1975). Two methods were used: high-speed photography, and a contact method called the capacitor-probe method. In the first, a spark light source was used as a synchronized light source with photographic recording. The projectile and the catcher were captured on every frame. Based on the distance between the two, and the time between adjacent frames, the speed could be obtained. In the second method, the magnetic wave generated by the current in the projectile was used to affect an antenna rod located in the catcher. The time of flight was determined from the voltage signal captured on an oscilloscope screen. Knowing the distance between the drive coil and the catcher, and the time of flight, the average speed could be calculated. An error of 5 to 10 percent was reported with the two methods. These methods were used to measure velocities on the order of 5 km/s (Bondaletov and Ivanov, 1977).

Restrictions on the maximum rate at which the energy of the source may be introduced into the inductor (drive coil) system is the subject of a theoretical investigation reported by Gal'yetov and Ivanov (1979). Studied in terms of lumped parameters is a circuit in which, initially and until the current reaches its peak, the capacitor is discharged through an exploding wire that bypasses the inductor. In order to reduce the Joule losses and hence to increase the allowable temperature rise, precooling of the projectile in liquid nitrogen was proposed. In spite of these measures, thermal limitation (due to heat losses) of the velocity remained a major concern. This prompted a study of the heat dissipation process published by Baltakhanov and Ivanov in 1982. Whereas earlier theoretical investigations had been based on a lumped parameter description of the system, and the equations had been solved on analog computers, this study was based on a field description and the resulting integro-differential equations were solved numerically.

Interest in cylindrical projectiles was first evidenced in two papers by Bondaletov et al. (1983) and Ber et al. (1984). The first uses a lumped parameter analysis of the system to reach some important conclusions:

- For zero initial velocity, the maximum acceleration efficiency of the projectile is obtained for (1) values of the length of the inductor and projectile approximately equal to the inner diameter d_1 of the inductor, (2) an initial displacement of the center of the projectile with respect to the center of the inductor less than the distance at which the gradient in mutual inductance is maximum, and (3) values of the normalized mass σ between 0.1 and 0.01 where:

$$\sigma = m \frac{d_1^2}{C^2 V_0^2 L_1}$$

with d_1 – inner diameter of the inductor (drive coil)
m – projectile mass
C – capacitance of capacitor bank
V_0 – initial voltage on the capacitor
L_1 – inductance of the drive coil.

- When the resistive losses in the discharge circuit increase, the optimum values of the axial dimensions of the inductor and of the projectile are reduced, and the optimum initial displacement increases, approaching the value at which the gradient in mutual inductance is maximum.

- For an initial conductor velocity different from zero, the optimum initial position is displaced toward the entrance to the inductor; for optimum initial velocity, it is zero.

- For the same normalized parameters for the cylindrical and flat-ring projectile launchers, one can obtain similar values of efficiency. But, in a cylindrical projectile, the relative mass of the projectile is 100 to 200 times smaller than for a flat-ring launcher.

This last conclusion is an indication that interest of the Russian group was switching toward multi-stage accelerators. In fact, more recent papers deal exclusively with this type, as will be discussed in the next section.

Ber et al. (1984) deal with a massive cylindrical projectile and take into account the penetration of the field into the inductor and into the projectile. The analysis, which is based on the magnetic vector potential, makes use of a finite difference scheme. The major conclusion is that the system can be studied with sufficient accuracy (approximately ±5 percent) by using equivalent circuits where the conductor thickness is equal to the depth of penetration of the magnetic field, and if the velocity obtained for an ideal system with zero source impedance is multiplied by 0.9.

The work on single-stage induction accelerators performed by the Istra group over a period spanning two decades is of high quality and demonstrates an enviable continuity of support. It was adequately and comprehensively reported in the published literature, so that it is unlikely that additional work of a classified nature was performed at the same time within the group.

Outside Russia, but still within boundaries of the former Soviet Union, a group headed by V. T. Chemeris at the Electrodynamics Institute of the Ukrainian Academy of Sciences in Kiev focuses its theoretical effort on single-stage induction generators and accelerators. This work, which is mainly theoretical, started with the development of basic relations between drive and the moving coils (Chemeris et al., 1978, 1979, 1981). A computer simulation code modeled the velocity, heat losses, and the diffusion of the magnetic field into the projectile (Chemeris et al., 1982); and a small-scale experiment was conducted to verify the analytical predictions (Chemeris et al., 1986). A 1.1-kg projectile of 7-cm diameter was accelerated up to 3 m/s. Later work deals with modeling thermal and electromagnetic processes in the design and study of cylindrical and flat single-stage induction coil systems (Chemeris et al., 1988). The announced motivation of the Ukrainian work was the study of electromagnetic impact motors of the solenoid type for civilian applications (Chemeris et al., 1975; Kucheryavaya et al., 1986).

Outside the former Soviet Union, research on single-stage induction accelerators has been performed more recently at:

- The Optic and Laser Technology Department, Sowerby Research Centre, British Aerospace PLC, achieving a velocity of 4.0 km/s with a projectile mass of approximately 0.7 g (Thornton and Seddon, 1989).

- The CSRIO Division of Manufacturing Technology in Preston, Australia. In a theoretical study, four aspects of propulsion of a disk were considered: (1) an overall equation that relates all the main parameters including the mass of the accelerated disk; (2) the effect of resistance; (3) the importance of the initial induction into the disk; and (4) the effect of the shape of the magnetic field. The simple relationships between the various parameters may help in the preliminary design of the accelerator (Sadedin, 1991).

- The French-German Research Institute Saint-Louis (ISL) in France. Experiments were performed under sponsorship of the Ministry of Defense of the Federal Republic of Germany on a drive coil provided with a flux concentrator to enhance its mechanical strength. Flux densities up to 24 T were achieved, and a 10-g projectile was accelerated to 122 m/s with an efficiency of less than one percent (Nett and Gernandt, 1991). The work done at ISL on electromagnetic acceleration is concentrated on railgun studies. Only a small part of the budget is designed for electrothermal and coilgun studies (Nett, 1994). This ongoing effort is now concerned with the synchronization mechanism between drive and projectile motion (Nett and Gernandt, 1994).

b. Multi-Stage Launchers

Bondaletov et al. (1983) demonstrated the efficiency gains that one can achieve when the projectile enters a drive coil with a finite velocity. This probably motivated the shift of interest on the part of the Russian group from single-stage (Figure V.1) to multi-stage (Figure V.2) accelerators. Also, a new investigator, Stanislav R. Petrov, joined the group, and later he became the group leader in the development of the multi-stage launcher. All the papers on multi-stage coilgun by the Istra group carry his signature.

A theoretical investigation of multi-stage accelerators by Vasil'yev and Petrov (1989) began with the set of integro-differential equations developed earlier (Ber et al., 1984), but instead of using a finite difference scheme for the solution, employs the mesh-matrix approach[5] and a Runge-Kutta iteration scheme. The researchers also mention experiments performed with an 80-stage coilgun.

In a more recent paper, Bashun and Petrov (1992) confirm that the drive coils of these accelerators are excited strictly synchronously with the position of the projec-

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[5] D. G. Elliot, "Mesh-Matrix Method for Electromagnetic Launchers," *IEEE Trans. Magn., 25,* 1(1989).

tile. The drawbacks of this scheme were mentioned in the Introduction (Section V.B). Although multistaging solves the thermal problem of the stationary drive coils, it does not solve the more serious problem of the temperature rise at the back of the projectile. In view of their constant preoccupation with the thermal limitation, and in view of the availability of US literature on linear induction launchers, it is strange that the Russian group should not have adopted a scheme that distributes the mechanical and thermal stresses over the whole cylindrical surface of the projectile.

What was the maximum velocity actually achieved by the Istra group with their multi-stage launcher? This is a question that requires some technical discussion. The reason is that, perhaps intentionally, there is no straight-forward statement in any Russian paper, except in one (Bashun and Petrov, 1992), that gives the actual muzzle velocity in meters per second obtained in their tests. Bashun and Petrov report that a 0.5-km/s muzzle velocity was achieved from a 12-stage launcher of 35-mm bore. Vasil'yev and Petrov (1989) state that, in an 80-stage coilgun, the measured muzzle velocity was 78 percent of the velocity attainable before melting of the projectile occurred. Vlasova and Petrov (1991) state that, ideally, this thermally limited velocity is in the range of 14 to 16 km/s. The theoretically derived magnetic field patterns shown in Figure 4 of the Vasil'yev and Petrov paper and Figure 4 of the Vlasova and Petrov paper (for $v^* = 0.5$) are almost identical. This suggests that both papers refer to the same coilgun. One is therefore tempted to conclude that a velocity in excess of 10 km/s was actually achieved experimentally. But close examination of the papers raises serious questions about the validity of this conclusion. A few examples of inconsistencies follow:

- An indication that Vasil'yev-Petrov and Vlasova-Petrov do not refer to the same coilgun system can be inferred from a comparison of the current waves in Figures 3 of the two papers. The current in the projectile is alternating in the former, but unidirectional in the latter. Also, Vlasova-Petrov indicate a decay of the DC component of projectile current with time. To overcome this problem the polarity of the excitation current was reversed after a number of barrel coils. This would be expected to result, however, in a strong skin effect, which would lead to a reduction in the efficiency, and to an enhancement of the temperature rise in the material of the projectile. The above discrepancies indicate that the two multi-stage launchers were used in different modes of operation.

- In Figures 4 and 5 of the Vasil'yev–Petrov paper, the projectile is shown having the shape of a cup, similar to the Sandia projectile (footnote 3, p. V-9). In contrast, in the Vlasova-Petrov paper, it is shown as a hollow cylinder with a uniform thickness, stated to be 75 percent of the bore diameter. (The maximum muzzle velocity of 14 to 16 km/s was calculated by Vlasova-Petrov for a 1-cm -thick cylinder-type projectile.)

- Concerning the 78-percent statement: On page 869 of the Vasil'yev-Petrov paper, it is stated that

  > According to the calculations, when the number of cascades is increased above 80, the limit velocity corresponding to the destruction of the conductor as a result of melting would amount to $v^* = 0.18$. Thus, experimentally we reached an acceleration velocity amounting to 78 percent of the maximum velocity in terms of the melting conditions.

  One would conclude that, experimentally, the Russian team achieved a relative velocity of $v^* = 0.78 \times 0.18 = 0.14$. This value agrees with the experimental graphical data given in Figure 3 of the Vasil'yev-Petrov paper.

  The relative velocity is defined as: $v^* = v\sqrt{C'L'}$, where v is the actual velocity in m/s, and C′ and L′ are the average capacitance and inductance per unit length of the barrel, respectively. These two values, C′ and L′, are not given in the paper.

  In the Vlasova-Petrov paper, substituting the values given on page 20 into Equation 7, one gets for the maximum limiting velocity v_* (note that $v_* \neq v^*$):

  $$v_* \cong \left\langle \begin{array}{l} 14.7 \text{ km/sec (for } x = 0.16) \\ 18.4 \text{ km/sec (for } x = 0.20) \end{array} \right.$$

  where x is the differential ideality coefficient that relates to the rate of change of energy losses per heat losses. When this is compared with $v_* = 14$–16 km/s as quoted in the paper (p. 20), it is clear that the paper is internally consistent. Now, introducing a maximum relative velocity of $v^* = 1.6$ (as suggested by Vlasova-Petrov) and the maximum velocity of $v = 18.4$ km/s (from the equation above) into the defined value (p. 18) of relative velocity

$v^* = v\sqrt{C^o L^o}$, one obtains $\sqrt{C^o L^o} = 0.0868$. Here, C^o and L^o were defined as per unit length of a drive coil. If this is the same gun as in the Vasil'yev paper, and assuming practically that $C' = C^o$ and $L' = L^o$, one would get for the muzzle velocity (with $v^* = 0.78 \times 0.18 = 0.14$): $v = \frac{0.14}{0.0868} = 1.6$ km/s (but not 10 km/s).

- These two papers (Vasil'yev and Petrov, 1989; Vlasova and Petrov, 1991) provide normalized values for the gun dimensions, components and velocities, but both fail to give the values that serve as bases for the normalization. The third paper (Bashun and Petrov, 1992) does provide a bore diameter of 35 mm; but this value cannot be used as a base diameter for the other two papers because, to begin with, the two gun systems employed two different synchronizers. In the first (Vasil'yev and Petrov, 1989), the firing pulse to the main ignitron switches was provided through the moving projectile that shorted a pair of electrodes mounted inside the barrel. In the third paper (Bashun and Petrov, 1992), an added amplifier allows a much lower current through those electrodes, preventing the ejection of plasma into the gap and the subsequent misfire of adjacent electrodes. Secondly, when one extrapolates the quoted result of 0.5 km/s in a 12-stage gun (Bashun and Petrov, 1992) to an 80-stage one (Vasil'yev and Petrov, 1989), assuming the same projectile and equal energy gain per stage, one obtains for the muzzle velocity only $v = 0.5\sqrt{\frac{80}{12}} = 1.3$ km/s (but not 10 km/s).

- A fourth paper (Baltakhanov et al., 1991), written by researchers of the same Istra group, discusses a power conditioner that has 20 identical modules, each having capacitors and ignitron switches. The total energy of the storage device is 2.5 MJ for a voltage of up to 10 kV. This power conditioner was developed at the Istra Branch and put into operation at the Leningrad/St. Petersburg Scientific Industrial/Production Organization "Soyuz." Again, one cannot draw any conclusion that this power conditioner is in any way connected with the 80-stage induction launcher because 2.5 MJ (in 20 modules) is not adequate for energizing the 80-stage gun.

In a recent letter from Dr. Stanislav R. Petrov (1994) in reply to our inquiries, he describes the current status of his research laboratory. In addition, he provides very specific information about the 80-stage induction accelerator (see Table V.1) built by him and his colleague, Dr. Igor A. Vasilyev. An experimental muzzle velocity of 1.56 km/s was achieved with this accelerator.

Table V.1
RUSSIAN 80-STAGE INDUCTION LAUNCHER SYSTEM

Barrel	Number of coils (stages)	$N = 80$
	Radial thickness of each coil	$d = 0.038$ m
	Axial length of each coil	$l_k = 0.067$ m
	Number of turns per coil	$N_1 \dots N_{10} = 14$ $N_{11} \dots N_{40} = 9$ $N_{41} \dots N_{80} = 4$
	Fiberglass-insulated conductor	4 × 2 mm
	Magnetic flux density	30 tesla
	Number of sections (each: 16 coils)	5
	Total length of launcher	$l = 6.64$ m
Sleeve (projectile)	Average radius	0.017 m
	Length	0.045 m
	Weight	0.029 kg
	Material	aluminum B95
Pulsed power supply	Capacitance per coil	$C_k = 64\ \mu F$
	Initial voltage per capacitor	$U_{o,k} = 10$ kV
	Main switches	Ignitrons

The energy utilization ratio η_{energy} of the 80-stage launcher was:

$$\left.\begin{aligned} E_{stored} &= 80\,\frac{1}{2}\,64\cdot 10^{-6}\left(10^4\right)^2 = 256\ kJ \\ E_{kinetic} &= \frac{1}{2}\,0.029\left(1.56\cdot 10^3\right)^2 = 35.3\ kJ \end{aligned}\right\} \quad \eta_{energy} = \frac{E_{kinetic}}{E_{stored}} = \frac{35.3}{256} = 0.14$$

The accelerator consists of five modules (sections) having 16 stages (drive coils) in each. Those drive coils were wound with fiberglass insulated 4×2-mm rectangular copper bus on a plastic-glass epoxy tube (Figure V.6). Groups of coils were centered in a steel bandage, and the empty spaces were filled with polyurethane. The electrodes of the spark synchronizer (Bashun and Petrov, 1992) were inserted into holes between the drive coils. In order to make the projectile as light as possible, it was shaped in the form shown in Figure V.7 (Vasil'yev and Petrov, 1989), and was made of B95 (possibly V95), an aluminum alloy used by the aviation industry in Russia.

The "capacitor batteries" in the power supply were mounted on shelves and were connected to the drive coils through current-sharing transformers. The terminals were arranged in such a way as to allow reversal of polarity of the capacitors feeding the drive coils. The Russian scientists calculated that, with additional stages, a speed of 2 km/s could be reached before melting. The actual velocity achieved, 1.56 km/s, represents 78 percent of this speed limit. The velocity was measured using the synchronizer discharges within the barrel, and also by the rupture of two wires at the muzzle end. Altogether, 60 shots were made with different numbers of sections, and with different values of initial voltage across the capacitors.

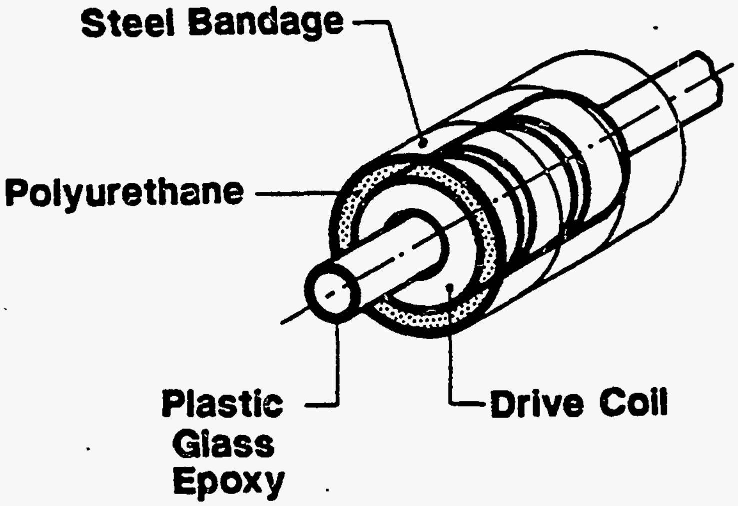

Figure V.6
Portion of 80-Stage Russian Launcher
(the projectile accelerates inside the plastic glass epoxy tube)

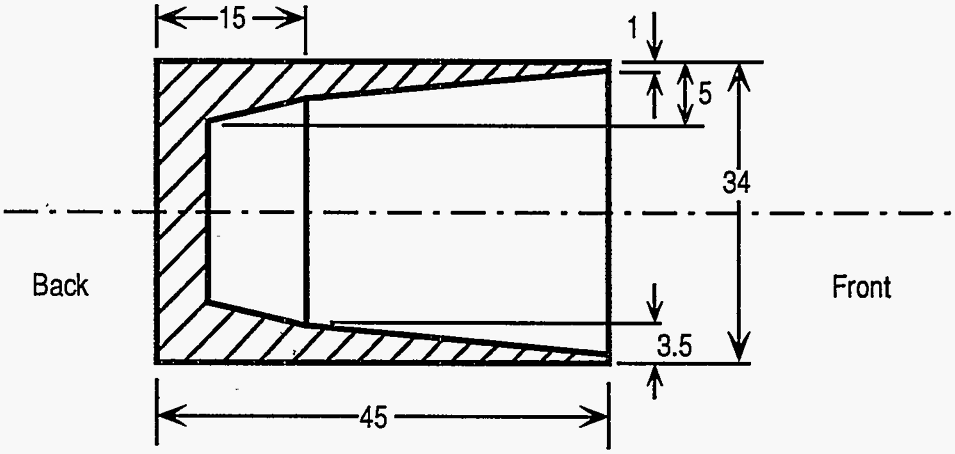

Figure V.7
Cross-Section of the Aluminum Projectile
(dimensions in mm)

Figure V.8 shows the complete 80-stage gun. The ignitron switches and the capacitor bank are located to the right of the accelerator. The catcher is positioned in front of the launcher (where the man stands). Details of one module (section) that holds 16 stages (drive coils) is shown in Figure V.9. The projectile (after a 950-m/s shot) and elements of the projectile (after a 1.56-km/s shot) can be seen in Figures V.9, and V.10, respectively. Erosion of the back of the projectile was probably caused by the heat generated there. The nearby rectangular case is probably a match box for scaling purposes.

As a next step, the launcher system was updated with the intention of reaching 2 km/s with double capacitance in the power supply. But, at the beginning of 1992, the Russian government support was cut, and eventually the research work stopped. Subsequently, the launcher laboratory (as well as some others) was closed.

Figure V.8
The 80-Stage Russian Coil Launcher

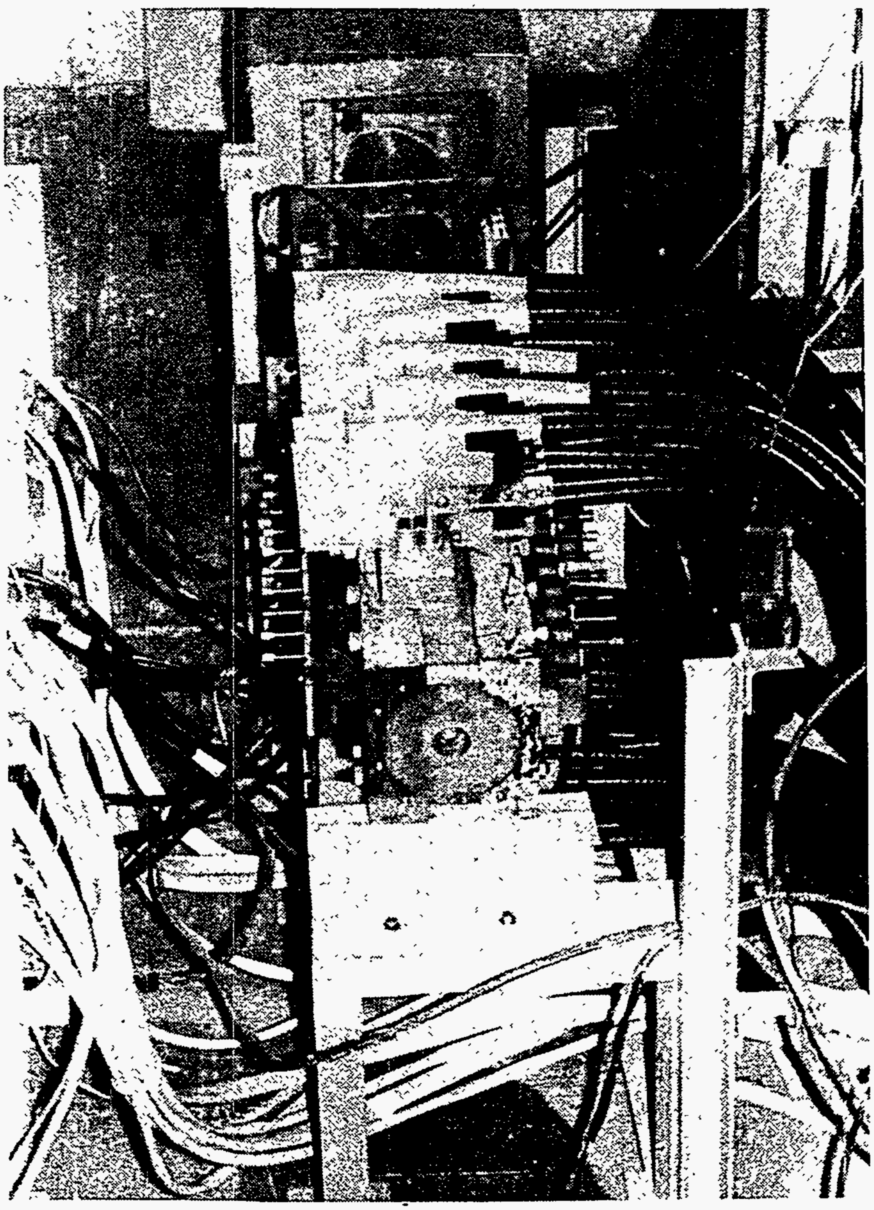

Figure V.9
One 16-Stage Module of the Russian Coil Launcher

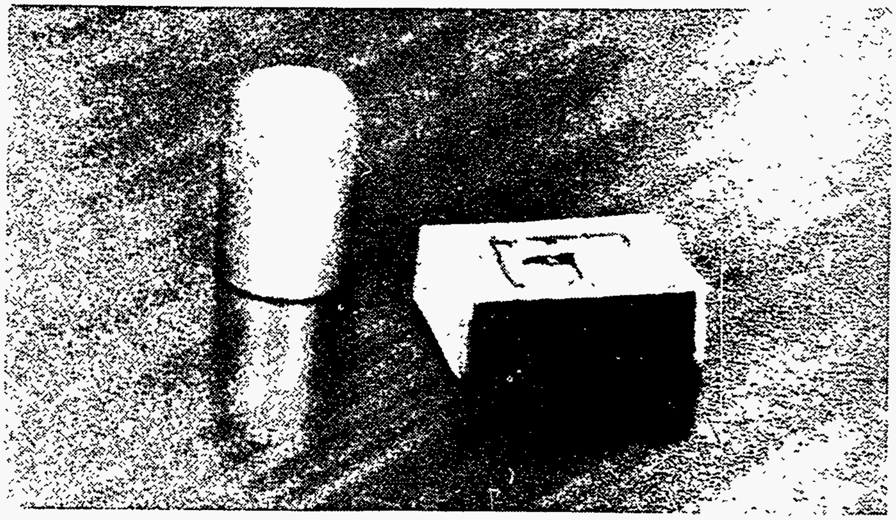

Figure V.10
The Projectile after a 950-m/s Shot

Figure V.11
The Elements of the Projectile after a 1,560-m/s Shot

A joint French-German research effort on pulsed-induction accelerators is being sponsored by the respective ministries of defense. Three principal configurations are being investigated: (1) the flat channel of Figure V.4 (see Introduction/Section V.B) in Magnet-Motor GmbH, Starnberg, Germany; (2) the toroidal coilgun of Figure V.5 in Magnet-Motor GmbH, Starnberg, Germany; and (3) the circular or coaxial coilgun of Figure V.2 in GEC Alsthom, Belfort, France. This effort is being conducted under the direction of H. Weh, and its output up to this point has been mainly analytical with a few experiments. It is reported in a series of five papers that were presented at the Fourth European Symposium on Electromagnetic Launch (EML) Technology, Celle, May 1993. The first two papers (Weh et al., 1993; Mailfert et al., 1993) can be classified as tutorial. The third (Loffler, 1993) deals with scaling laws that are used to establish thermal velocity limits and concludes that there are no basic restrictions to obtaining velocities of 10 km/s or more. A fourth paper (Loffler and Grundl, 1993) presents a computer demonstration model, and the fifth (Tran et al., 1993) describes the present and future experimental effort.

One experiment was carried out with the flat-channel coilgun in Germany. It had only three stationary coils having a total length of 0.3 m. It had a wound projectile that weighed 50 grams. The muzzle velocity achieved was 55 m/s, which translates into 76-J kinetic energy. This demonstrator operated as a synchronous motor in which the direct current was fed into the moving part using drag wires. A faster version, up to 1000 m/s, is now under construction. Two other experiments were carried out with coaxial coilguns in France. The first setup had five stationary coils with a 2-cm bore diameter, and a total barrel length of 1.27 m. The wound projectile had 34 turns and weighed 128 grams. The muzzle velocity achieved was 300 m/s, which translates into 5.7-kJ kinetic energy. The second setup had three stationary coils with a 12-cm bore diameter, and a total length of 1.8 m. There were 10 turns in the wound projectile and it weighed 5 kg. The muzzle velocity achieved was 400 m/s, which translates into 400-kJ kinetic energy. In both cases, the current was injected into the projectile as follows: the projectile coil first contacted the stationary injection source. Then, the winding was short-circuited as soon as it started to move. All three experimental setups above were operated in the pulsed synchronous mode (see Figure V.2 in the Introduction/Section V.B).

Of particular interest are the use of niobium-titanium wires embedded in the copper (normally used for superconducting windings) to strengthen the drive coils, and the topology of the toroidal launcher being developed by Magnet-Motor GmbH, Starnberg, in Germany. As was shown in Figure V.5 (see Introduction/Section V.B), the latter consists of several flat channels. The projectile substructure is a rectangular plate. The projectile coils are fixed on these plates like conductor tracks on a printed circuit board. These coils are short-circuited aluminum loops that are fed from the stator coils by asynchronous induction. The toroidal geometry confines the magnetic field to the stator (producing low flux leakage), when it operates at a relatively higher power factor. Preliminary tests show that it is possible to construct a launcher of about 6-m length capable of accelerating a payload of 1 kg, as part of a projectile with a total mass of about 2.3 to 3 kg, to 2500 m/s, with a ratio of kinetic to stored energy of 40 percent or more.

Interesting as the flat-channel coilgun of Figure V.4 and the toroidal coilgun of Figure V.5 may be, it is noted that any departure from the cylindrical symmetry of the coaxial coilgun of Figures V.2 and V.3 is likely to create serious problems with regard to mechanical stresses and in-bore and flight dynamics of the projectile.

Two papers from Cambridge University in England on design requirements for the multiple-stage coilguns (Williamson and Horne, 1993, 1994) evidence continued interest in the subject by the Defence Research Agency (DRA), Fort Halstead. A computer simulation, based on the coupled-coil model, shows that the offset of timing errors is more severe than that of positional errors when firing each stage of the coilgun. Also, an optimization procedure provides the design of a multi-stage coilgun to suit a given power supply. Experimentally, a peak velocity of 211 m/s (11.1-kJ kinetic energy) was achieved from a four-stage launcher with a 66.5-mm bore diameter.

2. Traveling-Wave Launchers

Most of the work done on the traveling-wave type of accelerator (Figure V.3) has been of a theoretical nature. It has been performed by Williamson's group in Cambridge, England, by Rioux's group at Orsay, France, by Aichholzer's group in Graz, Austria, and by Kim's group in Seoul, South Korea. In 1986, Williamson published a seminal paper that first used the mesh-matrix approach for the analysis of both the steady-state and the transient operating conditions (Williamson and Leonard, 1986). Good agreement was found between theoretical predictions and experimental results obtained from two low-velocity, (20 m/s) launchers, one with constant pitch and one with variable pitch, excited at 50 Hz. Constant frequency with variable pitch was also discussed in two more recent papers (Williamson, 1989, 1991). Although this solution for creating an accelerating traveling wave simplifies the power supply, it creates a mismatch between the length of the projectile and the pole pitch, so that it can be applied only when the range of velocities between the breech and the muzzle is limited. In fact, in Williamson's examples, the projectile is introduced into the breech with a velocity (500 m/s) that is a significant fraction of the muzzle velocity (1000 m/s). In both studies (Williamson and Leonard, 1986; Williamson, 1991), the barrel was designed as a single-stage that operated at a constant frequency.

The main research thrust (and funding) of the UK DRA is on railguns centered around the Kirkcudbright facility. The DRA is using (at a relative low budget) the two universities at Cambridge and Bath to acquire a basic understanding of the parameters required for coilgun design (Haugh, 1993). For that reason, Williamson first studied the traveling-wave launcher and later studied the pulsed induction launcher. Royal Armament Research and Development Establishment (RARDE—now the DRA) involvement with coilgun technology began in 1983. Two types of launcher design have been investigated and constructed: a pure linear induction motor design fed by a synchronous generator at a constant frequency; and a switched DC power supply fed from a battery bank.

Optimization of the length of the projectile and its dependence on the other parameters of the launcher is one of the objects of a parametric study by Rioux's Group in France (Desesquelles et al., 1989a-b). A simple model derived directly from the equation of the vector potential in cylindrical coordinates leads to a comprehensive set of normalized curves that provide excellent guidelines for the design of induction launchers. A critical comparison, based on closed-form relations, between the DC commutator and AC induction coil launcher is presented in another paper (Aichholzer et al., 1991). The main conclusion is that while the DC launcher suffers from commutation problems, the AC one suffers from low power factor. Although this results in heavier supplies and storage systems, the AC launcher will achieve higher muzzle velocities.

Kim et al. (1993) at the Kangwon and Seoul Universities, South Korea, presented work on a capacitor-driven traveling-wave launcher. The electric circuit equations were solved together with the equation of motion by using the Runge-Kutta method. Optimization was achieved by employing a genetic algorithm. Experimental results of a single-section launcher, 6-cm bore, 76-g aluminum projectile, 5-m/s muzzle velocity, showed good agreement with the computer predictions. This work is patterned after that done at the Polytechnic University, Brooklyn (see footnote 4, p. V–10) on their first prototype.

3. Power Supplies and Conditioners

Coilguns can be supplied by generators or by a combination of energy storage elements and switches. The requirements of extremely large power and of rapidly increasing frequency have proven so far to be an insurmountable hurdle for generators and for most power conditioners consisting of capacitor banks and switches. Baltakhanov et al. (1991) provide some details about the capacitor banks used by the Istra group in Moscow, although not necessarily for application to a coilgun. The total energy of the storage device is 2.5 MJ for a voltage of up to 10 kV. It consists of 20 identical modules located in separate rooms. Each unit contains five storage modules and a control module. One storage module contains 50 capacitors (40 µF at 5 kV) that are connected by sections of cable, 0.8 m long, to two 1RT-6 ignitrons, one used for the start-up mode and one for the crowbar mode.

In an earlier paper, Bezuglov et al. (1981) described a switch capable of discharging 100 kJ at 50 kV. It consists of a spark gap with electrodes made of special erosion-resistant materials, and operates at 6×10^5 Pa.

The continuing development of semiconductor switching elements suitable for very high-power applications creates the possibility of applying thyristor devices in the power conditioners of electromagnetic launchers. The advantages of the semiconductor switch over the ignitron or the spark-gap are higher reliability, lower internal losses, smaller size (volume), and much shorter recovery time.

A new thyristor structure, called a "high-current thyristor," or HCT, which has an improved gate/cathode structure, was introduced by ABB in Lenzburg, Switzerland (Ramezani and Wellemen, 1993). This device is now available with peak currents up to 150 kA, di/dt ratings up to 20 kA/µs and voltages up to 4500 V. Practical tests were done at 110 kA, 750 A/µs, and 2 kV; also, at 7 kA, 15 kA/µs, and 2 kV. The turn-off capabilities of the HCTs are now under investigation. A few of those devices are now under test at the US Army Pulsed Power Laboratory in Fort Monmouth, New Jersey.

Prof. Igor V. Grekhov (1992), head of the Power Electronics Division of the Ioffe Physical Technical Institute, St. Petersburg, has announced a potentially revolutionary advance in solid-state switching devices. These solid-state switching devices, which promise improved characteristic performance in the micro-, nano- and picosecond ranges, are now being tested at the Power Laboratory in Fort Monmouth, New Jersey. The switching capability of semiconductor devices, power thyristors, and bipolar transistors is limited mainly by the turn-on process localization near the gate electrode, because of the spreading resistance of the base layer. To avoid this limitation, the use of a thin electron-hole plasma layer, instead of the gate electrode, is suggested. This layer is uniformly distributed over the whole device area in the collector plane and plays the role of a distributed gate electrode that initiates the uniform turn-on process over this area. In the microsecond range, such a device is called a "reversibly switched-on dinistor" (RSD) and consists of a large number of interchanging thyristor and transistor sections. An RSD with 20-cm^2 operating area is capable of switching about 300 kA with a di/dt about 100 kA/µs for a 30-µs-long pulse. This fast current rise permits the series connection of RSDs without the need for dynamic voltage dividers. The turn-off time of the RSD is a few hundred microseconds. The development of MA-range pulse generators with operating voltages of 30 to 50 kV and frequencies of 0.1 to 1 Hz seems to be feasible.

Turning now to the nanosecond range, the problem of high-power switching has been solved by using the effect of superfast recovery of high-voltage power diodes. A typical value of voltage rise rate is 10^{12} V/s (1 kV/ns). The diode for superfast switching is called a "drift step-recovery diode" (DSRD); it is an opening switch that can cut off the current from 0.5 to 3.0 ns, depending on the operating voltage (0.7 to 3.5 kV). The operating reverse current density depends on the voltage, and for 2 kV is 10^2 A/cm^2. The operating area of such a device can be as high as 30 to 40 cm^2, so that the current pulse may be as high as 3 to 4 kA. With series connected DSRDs, one can design nanosecond generators with operating voltages up to 100 kV and pulse powers of 10^9 W.

High-power switching in the picosecond range cannot be based on the same principles, associated with the motion of carriers in semiconductors, as in the micro- and nanosecond ranges. So, new physical phenomena are needed. One such phenomenon is the high displacement current passing through a reverse-biased diode, when an overvoltage pulse with a rise time of more than 10^{12} V/s is applied by means of a DSRD generator. It produces in the neutral part of the base a field high enough for lattice impact ionization by majority carriers. The holes produced here drift, and in a few nanoseconds reach the super-high-field region near the pn-junction. These holes initiate an extremely intensive breakdown in this region; the ionization time is less than 10^{-11} s. At about this time, the super-high-field region is filled by electron-hole plasma, the field in it drops, increasing in the nearby region where the breakdown begins, and so on. Diodes based on this phenomenon are called avalanche shapers (AS). The shortest switching time obtained up to now in silicon diodes is 50 ps. Series connection of AS's has made it possible to build generators up to 20-kV voltage.

A new fast vacuum switch for electromagnetic launchers has been developed by Rioux's group at the Orlay Electrotechnical Laboratory (Laboratoire d'Electrotechnique d'Orlay), France (Bauville et al., 1989). The interruption ability of a fast triggered vacuum switch was tested with a pulse duration of 27 μs and a recovery time of 20 μs. A breaking capacity of more than 1.3 GVA was obtained with a 44-kA current pulse and a 32-kV recovery voltage. New research is designed to increase the performance by using a pseudo-spark discharge in which the product pressure × gap distance is located on the left branch of the Paschen curve, or a magnetic field. Also a new switch with shorter times of conduction (1.7 μs) and recovery (3 μs) is being tested.

These latest achievements in switches are very important, because opening switches will permit transfer of energy from one section of the barrel to the next and lead to significant enhancement of the efficiency of the launchers.

4. Analytical Procedures

These procedures have undergone an evolutionary process that parallels the increasing sophistication of the computer codes.

Starting with the work of the Istra group in Russia, the first papers (Bondaletov, 1967; Bondaletov and Goncharenko, 1971; Bondaletov and Ivanov, 1975, 1977; Bondaletov et al., 1983) model the accelerator system in terms of lumped circuit parameters and solve the differential equations using, first, electronic analog computers (Ber et al., 1984), and later on the Runge-Kutta method with variable step (Gal'yetov and Ivanov, 1979) in digital ones. Approximate closed-form, design-oriented formulas are presented in a subsequent paper (Petrov, 1987).

The need for determining the current distribution and the heat flow in massive conductors prompted the use of the field approach that led to a set of integro-differential equations. The problem is then reduced to the solution of a linear integral Fredholms equation of the second kind at each time interval by means of substitutions of the integral with finite sums (Vasil'yev and Petrov, 1989) or of numerical algorithms based on finite difference or elements methods (Baltakhanov et al., 1989). A comparison of the finite difference and integral equations method in the analysis of two-dimensional pulsed magnetic fields is presented in another paper by Bondaletov et al. (1982). The conclusion is that, when analyzing the fields with moving conductors, the finite-difference method requires less memory and computer speed. When analyzing a system with stationary conductors, the integral equations method is more advantageous.

In another effort at the Electrodynamics Institute of the Ukrainian Academy of Sciences in Kiev, a group of scientists, headed by V. T. Chemeris, has been studying the single-stage launcher. In a list of 15 papers produced by this group, the first seven deal with pulse generators,[6] and the remaining eight with induction accelerators,[7] indicating a change of interest. A significant evolution is noticeable in the group's analytical approach, which reflects the increased availability of modern

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[6] Chemeris et al., 1978a-d, 1979a,c, 1981.

[7] Chemeris et al., 1979b, 1982, 1984, 1986, 1988a-b; Podol'tsev and Chemeris, 1983; Kucheryavaya et al., 1986.

computing equipment and algorithms. The earlier papers dealt with the simplest geometry, planar and one-dimensional, and a lumped parameter description. Later came the field approach with numerical solutions of integro-differential equations and, finally, the use of current-filament model. In parallel with computational evolution in the papers is a visible trend toward becoming more application oriented.

A problem that arises in unbounded systems is the large amount of computation required to find the field at parts far removed from conducting bodies that are not of much interest. Titkov (1991) of the Polytechnic University of Leningrad (St. Petersburg), Russia, developed a hybrid scheme that uses a combination of the boundary integral equation method to calculate the field in the nonconducting region and the finite difference method to solve the field equations in the conductor.

Of the work performed in the United Kingdom, two papers present a scheme for modeling coilguns using finite elements (Williamson and Leonard, 1986; Leonard et al., 1993). The stationary and moving bodies are modeled using Lagrange multipliers that depend on the relative position of the two meshes. This scheme allows the inner mesh to slide during the transient simulation without the need to remesh the problem. Mesh matrix analysis with solutions based on Adams-Moulton and Runge-Kutta fourth-order algorithms are used by the group at the Loughborough University of Technology (Gregory et al., 1993). The capabilities of their modeling techniques were demonstrated with a single-stage experimental 80-gram ring-accelerator at velocities up to 100 m/s (Gregory et al., 1994). A comparison between finite-element and mutual-inductance models of coilguns is addressed in work by the group at the University of Bath (Hainsworth et al., 1993). Good agreement is demonstrated between the two methods, but the finite-element method enables many effects to be examined that would not be possible using the mutual-inductance method. In a later paper, Hainsworth et al. (1994) demonstrated the use of optimization techniques to obtain gun dimensions, switching requirements, and power supply specifications.

Computation by the finite-element method is the object of two papers by the Grenoble Electrotechnical Laboratory (Laboratoire d'Electrotechnique de Grenoble), in France. In the first, new mesh generation at each step and introduction of speed terms due to the movement is avoided by performing the simulation in the reference frame of the induced part, which appears to be "fixed," while the supplied part appears to be "moving" (Jarnieux et al., 1993a). In the second paper, a coupling between electric and magnetic equations makes it possible to model all kinds of conductors as well as connections with electrical circuits (Jarnieux et al., 1993b). A local remeshing around the moving part is applied at the beginning of each step in order to take into account the conductor displacement. Moreover, a thermal coupling permits consideration of variations of the main characteristics of the material. Both papers present an application to the LIL launcher at Polytechnic University in Brooklyn.

Current filament models have been widely used for the electromagnetic analysis of induction launchers. A paper by two groups at the Universities of Catania and Pisa, Italy, presents two functions of the eigenvalues of the filament parameter matrix (Azzerboni et al., 1993). They serve to evaluate: (1) the errors of the system solutions, induced by approximate calculations of the matrix parameters, and (2) the influence on the solution of a variation of the filament number of the discretizations. These estimates were found avoiding the numerical or analytical integration of the set of differential equations of the system.

Assessment of the research literature leads to the conclusion that modeling of the accelerator is reaching adequate maturity, that all aspects of their performance are well understood, and that their design can be approached with confidence.

5. Comparison with US Capabilities

The Istra group near Moscow took an early lead in the development of coilguns. As was mentioned in Section V.C.1.2 above, the Russian researchers did not adopt a scheme that distributes the mechanical and thermal stresses over the whole cylindrical surface of the projectile, although a US paper describing such a system had appeared as early as 1982,[8] and a British paper appeared in 1986 (Williamson and Leonard, 1986). With regard to the multi-stage induction launcher, it is important to note that the excitation of the Russian guns is strictly synchronized with the position of the projectile. This makes them different from their US counterparts, Sandia's "reconnection" gun and Polytechnic's LIL. Sandia's gun (see Section V.B.1.a.(2)/

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[8] T. J. Burgess, E. C. Cnare, W. G. Overkampf, S. G. Beard, and M. Cowan, "The Electromagnetic θ Gun and Tubular Projectile," *IEEE Trans. Magn.*, *18*, (1982), 46-59.

Multistage Launcher—*Asynchronous Mode of Operation*) takes advantage of the forward diffusion of the currents induced in the projectile, and excites the barrel coils with a predetermined slip velocity ahead of the projectile, albeit with a unidirectional pulse limited in spatial extent. Polytechnic's LIL (see Section V.B.1.b/ Traveling-Wave Launcher) is a true linear induction motor with an open-loop polyphase AC excitation largely independent of the projectile position and velocity. These considerations suggest that the Russian guns have the highest concentration of current and, therefore, mechanical and thermal stresses at the back of the projectile. Sandia's projectiles have a slightly larger active surface, whereas in Polytechnic's LILs the whole cylindrical surface of the projectiles carries induced currents, so that, for equal forces, the local stresses are significantly reduced.

Another problem associated with strictly synchronous excitation is the decay of the DC component of projectile current with time. To overcome this problem, the polarity of the excitation current is reversed after a number of barrel coils. This results, however, in a strong skin effect leading to a reduction in the efficiency and to an enhancement of the temperature rise in the material of the projectile. The acuteness of the heating problem in the Russian guns justifies their preoccupation with the determination of the thermal limitation in the muzzle velocity, and their consideration of precooling of the projectile with liquid nitrogen. On the other hand, the much reduced thermal stress in the US guns holds promise that in time they will achieve much higher muzzle velocities.

Because of the aft-pushing nature of the propelling force, and because of the absence of the type of centering force that characterizes the LIL, the Russian guns are believed to be extremely prone to balloting. In a personal communication to a member of this panel, S. R. Petrov (Istra) stated that he had evaluated the traveling-wave launcher by conducting his own simulations and studying the results. He concluded that the capacitor-driven, polyphase launcher had decreased sleeve heating, a high coefficient of efficiency, and a relatively uniform distribution of forces along the length of the projectile.

Recent research in France/Germany seems to orient itself toward the traveling-wave launcher (either with a coaxial or toroidal concept), after the US models, but as of now, it is mainly theoretical.

The work performed in Cambridge, England, at the end of the 1980s, and in Chuncheon and Seoul, South Korea, at the beginning of the 1990s, also demonstrates interest in the traveling-wave launcher. Their concept is similar to the Polytechnic LIL (footnote 4, p. V–10), but again, as of now, the work has been mainly theoretical, and their experiments were conducted at very low velocities.

Significant, because of its absence, is any published reference to work performed in Japan or China on induction launchers.

D. PROJECTIONS FOR THE FUTURE

A look into the technical future cannot ignore the likely political and economic atmosphere. Therefore, in Russia, although some relatively small projects may be carried out, large serious experimental efforts such as the construction and testing of a coil launcher in the 10-MJ range of kinetic energy are not expected. At this time, the Russians may be interested in a US-Russian collaboration on coil launcher development. On the other hand, and indicative of a general trend, the latest concentration of effort in the French-German group shows their growing interest in developing a heavy coil launcher, either of the coaxial or of the toroidal type. It is evident that the coaxial traveling-wave launcher is attracting increased interest. The main reasons are the absence of sliding contacts; the presence of full levitation (centering) and uniform distribution of propelling forces along the complete armature surface; no need of synchronization, and no apparent limitation in muzzle velocity, because cooling can overcome the thermal limitation. The weak point of the traveling-wave launcher remains the need for a complex and bulky power supply. Since switching elements and capacitive storage are developing at a fast pace, the launching of heavy projectiles at high velocities, such as missile interceptors, is within reach in the next five years. However, launching of very heavy objects at hypervelocities, such as for earth-to-orbit (ETO) applications, still remains beyond technical and economic feasibility (Deschamps and Glaser, 1991). Also, it is likely that the future will see increased concentration on imaginative schemes for energization that will make use of direct energy conversion from chemical form. The construction of the barrel will make increased use of techniques borrowed from the megagauss technology of force-free coils (Shneerson, 1992; Nett and Gernandt, 1991). As for the armature, no better material than aluminum is in sight.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Table V.2 lists key non-US induction launchers researchers, their affiliations, and areas of expertise.

TABLE V.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— INDUCTION LAUNCHERS

Researchers	Facilities	Areas of Expertise
	Australia	
D. R. Sadedin	CSIRO Division of Manufacturing Technology, Preston, Victoria	Single-stage launcher
	France	
J. Jacquelin R. Mailfert F. Moisson	Alcatel Alsthom Research, Marcoussis	Multi-stage launcher
P. Lombard	CEDRAT Research, Meylan	Modeling of coil launchers
G. Bauville A. Delmas P. F. Desesquelles C. Rioux	Electrotechnical Laboratory, University of Paris South, Orsay	Fast vacuum switches, traveling-wave launcher
L. Gernandt J. Nett	French-German Research Institute Saint-Louis (ISL), Saint-Louis	Single-stage launcher
P. Bonnet T. Tran	GEC Alsthom, Belfort	Multi-stage launcher
D. Grenier M. Jarnieux G. Meunier G. Reyne	Grenoble Electrotechnical Laboratory, Saint-Martin-d'Hères	Modeling of coil launchers
	Germany	
H. May H. Weh	Braunschweig Technical University, Braunschweig	Flat-channel and toroidal launchers
G. Aichholzer H. Köfler	Graz Technical University, Graz	Traveling-wave launcher

TABLE V.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— INDUCTION LAUNCHERS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Germany (cont'd.)	
A. Gründl B. Hoffman	Gründl & Hoffman GmbH, Starnberg	Flat-channel and toroidal launchers
P. Ehrhart M. Heeg G. Heidelberg G. Reiner W. Weck	Magnet-Motor GmbH, Starnberg	Flat-channel and toroidal launchers
Markus Löffler	Technical Center North–Research & Development Center, Unterlüss	Flat-channel and toroidal launchers
	Italy	
B. Azzerboni	Department of Electronics & Electric Systems, University of Cantania, Cantania	Modeling of coil launchers
Ermanno Cardelli M. Raugi A. Tellini	Department of Electric Systems & Automation, University of Pisa, Pisa	Modeling of coil launchers
	Russia	
S. A. Kalikhman	Chuvash State University, Cheboksary	Single-stage launcher
A. N. Andreyev G. K. Artimovich A. M. Baltakhanov A. P. Bashun G. Z. Ber V. N. Bondaletov V. P. Gal'yetov Ye. N. Ivanov S. R. Petrov I. A. Vasil'yev T. G. Vlasova	Electrical Engineering All-Union Institute im. V. I. Lenin, Istra (Moscow Region)	Single-stage and multi-stage launchers, capacitor discharge techniques
S. R. Petrov (since 1994)	High-Energy Density Research Center, High Temperatures Institute, Russian Academy of Sciences, Moscow	

TABLE V.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—INDUCTION LAUNCHERS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
I. V. Grekhov	Power Electronics Division, Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences, St. Petersburg	High-power, fast-operating semiconductor devices
	South Korea	
S. Y. Hahn	Electrical Engineering Department, Seoul University, Seoul	Traveling-wave launcher
H. K. Jung	Electrical Engineering Department, Kangwon National University, Chuncheon	Traveling-wave launcher
	Switzerland	
E. Ramezani	Asea/Brown Bovery Semiconductors AG, Lenzburg	High-power thyristor switches
	Ukraine	
V. T. Chemeris S. A. Gavrilko I. N. Kucheryavaya V. P. Petrovskiy A. D. Podol'tsev Yu. N. Vaskovskiy	Electrodynamics Institute, Ukrainian Academy of Sciences, Kiev	Single-stage launcher
	United Kingdom	
M. J. Edwards	British Aerospace Defence Ltd., Royal Ordnance Division, Nottingham	Modeling of coil launchers
N. Seddon E. Thornton	Optics & Laser Technology Department, Sowerby Research Centre, British Aerospace PLC, Bristol	Single-stage launcher
K. Gregory Ivor R. Smith V. V. Vadher	Loughborough University of Technology, Loughborough, Leicestershire	Modeling of coil launchers

TABLE V.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— INDUCTION LAUNCHERS (cont'd.)

Researchers	Facilities	Areas of Expertise
	United Kingdom (cont'd.)	
J. F. Eastham G. Hainsworth H. C. Lai P. J. Leonard David Rodger	University of Bath, Bath	Traveling-wave and multi-stage launchers
C. D. Horne S. Williamson	Department of Engineering, University of Cambridge, Cambridge	Traveling-wave and multi-stage launchers

CHAPTER V: INDUCTION LAUNCHERS
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CHAPTER VI
ELECTROTHERMAL GUNS

A. SUMMARY

For the purposes of this assessment, electrothermal (ET) gun research includes all electric gun research that is not specifically of the electromagnetic (EM) variety. Thus, we include the "pure" electrothermal gun, the electrothermal-chemical (ETC) gun, the electrothermal light gas gun (ELGG), and the plasmadynamic accelerator.

The research being performed can be divided into four major categories; military gun research, research on gun concepts, electric light gas gun research, and plasmadynamic particle accelerators. As always, there is some overlap. The last of the areas, plasmadynamic particle accelerators, is only marginally electrothermal acceleration, but is frequently considered such by authors or conference organizers. (Little of the plasmadynamic particle accelerator work is discussed below.)

By military gun research, we refer to experiments that are being performed in weaponized gun tubes with bore diameter of 60 mm or larger and that appear to have the potential of leading to a fielded gun system within the near term (before 2000). The work being performed in Israel clearly falls into this category.

By research on gun concepts, we refer to those efforts that, while showing positive results, are not in a position to be judged capable of weaponization nor yet proven to provide an improvement over conventional technology. Most of the ET and ETC (electrothermal-chemical) gun research falls into this category.

The electric light gas gun research refers to those efforts that either fill the chamber with a light gas at high pressure or use a propellant designed to produce a light gas working fluid. Some of these efforts may well be weaponizable in the intermediate (2000 to 2010) or long term (beyond 2010), and for specific applications.

Plasmadynamic particle accelerators accelerate small particles of mass 10^{-9} to 10^{-4} gm to velocities greater than 1 km/s to simulate micrometeorite impacts with spacecraft or to provide super-high-temperature "flame spraying" techniques.

In assessing non-US electrothermal gun research, we conclude that

- The ETC gun research being performed by the Israeli group from Soreq using first a 60-mm-bore-diameter gun tube and, more recently, a 105-mm-bore-diameter gun tube is close to weaponizable. How much of an improvement over conventional performance has been gained is not clear—perhaps none, because this program has not used advanced solid propellants. This is a well organized research program, supported by the Israeli Government and funded, in part, by the United States. Funding from the US Government during Fiscal Year 1994 is uncertain.

- The ET/ETC gun research program being conducted as a combined effort by France and Germany is a very broad-based and well orchestrated program, with strong backing from both governments. To date, most of the work seems to be exploratory in nature, investigating diverse techniques for potentially enhancing conventional gun performance by use of electric energy. We expect to see a focusing of this effort in 1994, with the selection of those techniques that seem most likely to be weaponizable. The program is well-balanced between experimental and theoretical efforts. There is a separate ET gun research program in Germany using the plasmadynamic accelerator to accelerate very small particles to simulate micrometeorite impacts with spacecraft.

- The ET/ETC gun research program conducted in the United Kingdom has been criticized as being disorganized, and some changes have been suggested. Most of this effort appears to be used to develop a theoretical understanding of the processes involved in the ET/ETC gun. The experimental program is presently devoted to small-scale (10- to 30-mm) ET/ETC guns, though the Electric Gun Facility at Kirkcudbright could readily power ET/ETC guns even larger than the 155-mm ETC cannons studied in the United States. The stated goal of the program is to develop military weapons, but it appears that perhaps UK researchers are waiting to see the results obtained in other countries before committing to large-bore experimental programs.

- No ET or ETC gun research efforts that suggest military application are reported in the literature in the former Soviet Union; and, given the level of dislocation in the former Soviet Republics at this time, it is unlikely that such a new effort will be started soon. There are ELGG research programs that have been supported in the past by military funding, and these could eventually see military application. There are also two research efforts with industrial application in the areas of Tokamak refueling and powder coating.

- Research in the area of ET guns is minimal in both China and Japan. However, given the substantial electromagnetic/rail gun programs that have been active in both countries for years, either country clearly has the power supplies and range facilities to launch a substantial ET/ETC gun research program at very short notice.

B. INTRODUCTION

Electric discharges have, of course, been known and studied for many years going back to the experiments of Benjamin Franklin with natural lightning in about 1750.[1] These discharges have been used to generate electromagnetic signals in the early telegraph systems (sparks); as light sources for spectroscopic analysis, cinematography, and eye surgery (arcs and sparks); in industry as welding and cutting tools (arcs and blown arcs) and as thermal sources (the arc furnace); and in the early fusion efforts (z-pinches, etc.). Electric discharges were soon found to be unstable and spectroscopists developed the so-called wall-stabilized arc and the capillary discharge to provide stable light sources with special characteristics. In particular, the high-current capillary discharge (confined high pressure discharge, or constricted arc) with current density $\geq 3\times10^4$ A/cm^2 was known as a source of "blackbody" radiation from the visible through the vacuum ultraviolet spectral regions.[2]

Electric discharges in the form of the plasma armature (rail guns) were applied to the acceleration of material objects in the late 1800s,[3] but electrothermal propul-

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[1] B. Dibner, *Lightning Volume 1: Physics of Lightning,* Ed. R. H. Golde, Chapter 2, New York: Academic Press, 1977.

[2] W. R. S. Garton, *J. Sci. Instrum., 36,* 11(1959) and *30,* 119(1953).

[3] Railgun patent (1895).

sion technology is a much more recent concept. In the United States, Tidman and Goldstein began working on the "electrothermal gun" in 1980, and formed their company GT-Devices to develop this technology. In those days, electrothermal gun technology implied the use of an inert propellant (typically water) whose only function was to provide a low molecular weight working fluid when heated to evaporation or decomposition by the electric discharge. Thus, the role of the electric discharge was to convert electric energy to thermal energy as efficiently as possible and to deliver this thermal energy to the propellant effectively, that is, in such a way that all of the propellant was heated uniformly to temperatures in the range of 3000 K. The propellants used were liquids or slurries, the latter being chosen to provide the low-molecular-weight working fluid and to require less electric energy to create the working fluid, for it was soon realized that a large amount of electric energy was consumed in just evaporating the water. Thus, it was gradually realized that "pure" ET gun technology was not weaponizable using near-term electric power supply technology.

In the late 1980s, and with significant encouragement from the US Army, the emphasis in ET gun technology was redirected to seek energetic propellants to replace the earlier non-energetic propellants, and the term "electrothermal-chemical" (ETC) was coined. With the majority of the energy to drive the ballistic cycle coming from chemical energy of the propellant, it was envisioned that the burden of the electrical power supply would become manageable. Two major companies initially led the US effort: General Dynamics Land Systems (GDLS) Division, which purchased GT-Devices (GTD) in 1989, and FMC Corporation, Naval Systems Division (now United Defense LP). Both companies continued to look for liquids or slurries as propellants, primarily on the basis of packaging and partially following encouragement from the US Army. A significant point in the evolution of the ETC technology occurred in the Spring of 1990, when both contractors ended their EEF-ETC firing programs at Green Farm.[4] It was concluded that

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[4] K. J. White, W. F. Oberle, I. C. Stobie, J. D. Knapton, C. D. Bullock, A. A. Juhasz, and W. F. Morrison, *An Analysis of the 120-mm Green Farm Electrothermal-Chemical Gun Firing Results*, ARL-TR-13, US Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066, Nov. 1992.

> The readiness of the ETC concept for advanced development was not demonstrated. ETC, however, does have potential for significant, up to 50 percent, increases[5] in muzzle energy. The control and predictability problems observed, however, indicate the need for developing a better understanding of the ETC process before its promise can be realized.

During the years 1991 through 1993, significant advances have been made in firing large-bore ETC guns in programs sponsored by the US Army (120 mm), Navy (60 mm), and DNA (5 in). This work has been performed by FMC, GDLS, Maxwell Laboratories, SAIC, and S-cubed.

In late 1990, under a separate US Army sponsorship,[6] the Olin Corporation, Ordnance Division began a search for "Alternate Propellants for ETC Guns." This effort involved extensive paper studies of potential propellant mixtures, laboratory testing of selected mixtures, and culminated in the firing of successful candidates in the 30-mm ET Gun Facility at GT-Devices. Liquids (gels), slurries, wet powders, monolithic (cast) solids, and granular solids were all included in these studies. As a baseline against which to compare these candidates, this program also undertook a series of firings[7] using a conventional Deterred BALL POWDER propellant (WC891). With these firings, the connection between conventional ignition and ET plasma ignition was clearly demonstrated; and it was shown that, in large measure, the understanding of conventional charge design applies equally to charge design for an ETC environment. At that time, three levels of "improvement" over conventional guns were envisioned:

- An ET igniter that replaces the conventional igniter system and thus improves survivability but not performance.

- An ET controller that provides sufficient control of performance to counteract the temperature dependence of present gun performance so that all firings could be as good as the "hot day" firing.

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[5] W. F. Oberle, "A Feasibility Study of Power Curve-Working Fluid Combinations for Optimal ET Gun Performance," *Proc. 25th JANNAF Combustion Meeting*, CPIA Pub. 498, Vol. IV, Oct. 1988, 269–293.

[6] *Electrothermal-Chemical (ETC) Gun Alternate Working Fluid (Propellant) Systems Investigation and Study Effort*, Contract DAAA15-90-C-1061, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005.

[7] H. A. McElroy, J. R. Greig, and A. A. Juhasz, "Plasma Augmented Ball Propellant Ballistics," *V Int'l. Gun Propellant and Propulsion Symp.*, ADPA/ARDEC, Picatinny Arsenal, NJ, Nov. 1991.

- An ET gun system with performance substantially above present conventional gun performance from the same gun tube.

The extensive work that has been done in recent years (since 1989) using solid propellants in ETC guns is summarized in a paper by Juhasz (Army Research Laboratory/ARL).[8] Work done in the United States concerning all forms of ET gun technology is collected in a series of reports issued through the ARL that are listed in Table VI.1. These "collected works" were first produced in 1988, when only six papers were published. In the latest collection, that for 1992, there are 41 papers, all of which represent work done in the United States.

TABLE VI.1
US ELECTROTHERMAL GUN EFFORTS

A. A. Juhasz, *Technology Efforts in ET Gun Propulsion,* Vol. 1, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005, December 1988 (6 papers).

A. A. Juhasz, *Technology Efforts in ET Gun Propulsion,* Vol. 2, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005, December 1989 (13 papers).

A. A. Juhasz, *Technology Efforts in ETC Gun Propulsion,* Vol. 3, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005, December 1990 (23 papers).

W. F. Oberle, *Technology Efforts in ETC Gun Propulsion,* Vol. 4, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD 21005, December 1991 (23 papers).

W. F. Oberle, *Technology Efforts in ETC Gun Propulsion,* Vol. 5, US Army Research Laboratory, Aberdeen Proving Ground, MD 21005, December 1992 (41 papers).

Work on electric-arc-heated light gas guns was conducted in the 1950s but essentially stopped by 1960 because the technology was not competitive compared

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[8] A. A. Juhasz, K. J. White, H. A. McElroy, J. R. Greig, and Z. Kaplan, "A Status Report on Solid Propellant ETC," *29th JANNAF Combustion Subcommittee Meeting, NASA Langley Research Center, Hampton, VA, Oct. 1992.*

to conventional light gas guns.[9] The technique was resurrected recently in the United States and Russia as the electrothermal light gas gun.[10] By using initial gas fill pressures up to 20,000 psi and minimizing the metallic content in the discharge plasma, ELGGs have succeeded in producing a low-molecular-weight working fluid and so achieving high projectile velocities. Though light gas guns are presently laboratory devices used for impact and equation-of-state studies, the emergence of the ELGG as a hypervelocity device provides the possibility of future development into a device with specific military application in the area of Terminal Defense.

Igenbergs introduced his plasmadynamic accelerator in 1973.[11] The purpose of this accelerator was specifically to accelerate small particles (20 to 2000 μ in diameter) to velocities of kilometers per second to simulate micrometeorites and space debris as they impact spacecraft. It has essentially no direct military application. To achieve these velocities, a plasma is created in a coaxial plasma gun and accelerated into a converging magnetic field to increase its density. Small dust particles are then injected into this plasma stream, where they are accelerated by the aerodynamic drag force.

ET gun research is ongoing in at least three countries in Europe (Germany, France, and the United Kingdom); in Israel; in Russia; in China; and in Japan. In these seven countries, the laboratories involved in such research number 33: three in Israel, 11 in Germany,[12] four in France,[12] seven in the United Kingdom, five in Russia, one in China, and two in Japan. We have reviewed the literature from 1987 through April 1994 (Seventh Symposium on Electromagnetic Launch Technology), and have assessed a total of 87 articles. A few conference papers are by abstract only, and one paper was presented but not published. These articles include 11 from Israel, 26 from Germany, 21 from France, 12 from the United Kingdom, 17 from Russia, two from China, and three from Japan. Five of the articles involved collaboration between two countries, and these are listed in each of the countries. A total of

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[9] A. E. Seigel, "Theory of High-Muzzle-Velocity Guns," from *Interior Ballistics of Guns*, Eds. H. Krier and M. Summerfield, Vol. 66, *Progress in Astronautics and Aeronautics, AIAA*, 1979, 135.

[10] D.A. Tidman and D.W. Massey, "Electrothermal Light Gas Gun," *IEEE Trans. Magn.*, 29, 1 (1993), 621–624,.

[11] E. Igenbergs, "Ein magnetogasdynamischer Beschleuniger für die Simulation von Mikrometeoriten," *Raumfahrtforschung, Heft*, 4(1973).

[12] The French-German Research Institute (ISL), in Saint Louis, France, has been listed in both countries.

139 researchers are involved as co-authors in the work retrieved: 22 from Israel, 28 from Germany, 19 from France (with another 10 from ISL), 16 from the United Kingdom, 34 from Russia, four from China, and six from Japan.

C. DISCUSSION

As noted above, electrothermal gun research is ongoing in at least three countries in Europe: Germany, France, and the United Kingdom; in Israel; in Russia; in China; and in Japan. In the following paragraphs, we examine the efforts within each laboratory in each country separately. The efforts in Israel and in Europe are perhaps closest in philosophy with those in the United States, and, as such, appear to be aimed at relatively near-term application in the tactical gun arena. The efforts in Russia are diverse, with the published literature leaning toward industrial applications. The efforts in China and Japan appear to be relatively new and somewhat immature. The Chinese effort is only apparent in joint publications with Russian colleagues.

1. Israel

Two Israeli institutions are involved in ET gun research: the Propulsion Physics Laboratory at the Soreq Nuclear Research Center and the School of Physics and Astronomy at Tel Aviv University (see Section VI.E/Key Research Personnel and Facilities). This work is coordinated and actively assisted by the Israeli Ministry of Defense.

The ET gun research at the Propulsion Physics Laboratory, Soreq Nuclear Research Center, is somewhat anomalous in this assessment. While this effort is performed by the staff of the Soreq Nuclear Research Center, it receives significant funding from the United States,[13] and some of the more recent gun firings have been performed in the United States at the Eglin Air Force Base, Florida. Research at Soreq began several years ago with small caliber firings but progressed rapidly to firings at 60-mm bore diameter (Juhasz et al., 1992; Kaplan et al., 1993), and is now well into a firing program using a modified 105 mm cannon. Results from the 105-mm firing

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[13] *Demonstration of HV Gun Technology for ATBM ET Augmented Solid Propellant Gun*, Contract SDIO84-89-C-0017, Strategic Defense Initiative Office, The Pentagon, Washington, DC 20301-7100.

program will be published in the *Proceedings of the Seventh Symposium on Electromagnetic Launch Technology (IEEE Transactions on Magnetics,* January 1995). In the highest performance shot, a 4-kg projectile was successfully launched from a 105-mm ET gun, with 9 m travel, at a velocity of 2032 m/s (Kaplan et al., 1995). The performance achieved in most shots represents an improvement of 5 to 6 percent over optimal conventional firings. In some of these firings, the projectile was the smart projectile known as D2, and the ET gun used a triple-base solid propellant manufactured by IMI, probably similar to M30.

The Israeli research has been thorough and balanced between the fundamental physics necessary to understand the ETC gun process and steady progress in firing ET guns at the different calibers (Loeb and Kaplan, 1989; Zoler et al., 1993).

The basic design of the ET gun used in the Israeli program is very similar to that used by Olin Ordnance.[7] The plasma generator is always a capillary discharge, and the capillary is positioned in the breech-nut of the gun, that is, behind the stub case of the round. This layout is shown in Figure VI.1, which shows the 60-mm cannon. This ETC cannon uses a conventional 60-mm gun tube and projectile and a conventional solid granular propellant (M3O) housed in a conventional cartridge case.

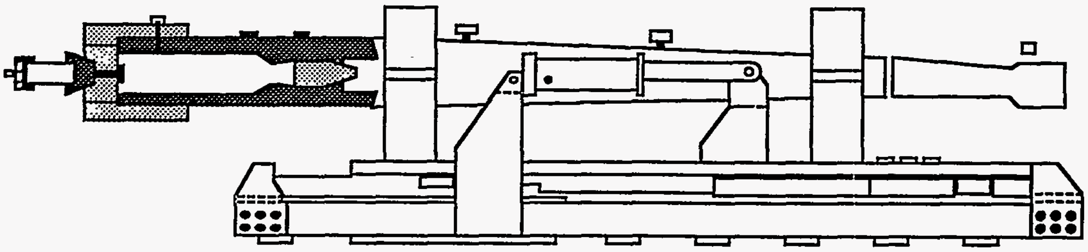

Figure VI.1
The Soreq 60-mm Electrothermal Cannon[14]

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[14] A. A. Juhasz, S. Smith, Z. Kaplan, D. Melnik, D. Saphier, and M. Blum, "Solid Propellant Electrothermal Gun Propulsion," *US Army Science Conference, Orlando, Fla., June 1992.*

The ET gun research at the School of Physics and Astronomy, Tel Aviv University, in Israel, appears to be theoretical work in cooperation with the Propulsion Physics Laboratory, Soreq Nuclear Research Center (Zoler et al., 1993).

2. Germany

Two quite separate ET gun efforts appear to be underway in Germany. The larger program, coordinated and assisted by the Federal Office of Defense, is directed toward the tactical gun and missile defense scenarios. The smaller program, centered at the Technical University of Munich (TUM), appears to be aimed at producing particle streams suitable for simulating micrometeorite or space debris impact with spacecraft.

The German ETC gun program was reviewed at the DEA-G-1060 ETC Workshop at the Weapons Technology Directorate, US Army Research Laboratory, Aberdeen Proving Ground, Maryland, 5–6 October 1993, by H. J. Maag of the German Federal Office of Defense. The German program, known as the Electric Hybrid Propulsion Technology program, is a highly organized national program aimed at improving the performance of conventional guns by the use of electric power. Various approaches to the application of electric power are being systematically studied in eight different laboratories (see Section VI.E). Most, if not all, of this work falls under the French-German collaborative effort, and some is being pursued in French laboratories. In other cases, an ETC gun system developed initially in one laboratory will be sent to another laboratory for further testing, that is, where different pulsed power supplies are available. A lot of this work is already being done at large bore size, particularly the 120-mm tank cannon. However, it appears that most of the work is very "experimental," is a long way from weaponization, and is being studied "to see how it works." An earlier, less extensive review of the French-German ETC gun program was given by Weise and Noiret (1993).

Diehl GmbH has a conventional liquid propellant gun (RLPG) with electric arc heating of the burned propellant gases in the entrance to the barrel after the projectile has moved out. This gun has a 30-mm bore diameter.

At the Technical Center North (TZN), researchers appear to be looking at the TMD/Air Defense role with 45-mm and 50-mm-bore-diameter fixtures. Here, the electric arc is struck through the liquid propellant (presently isopropyl alcohol) in the propellant chamber (Weise, 1993). The intention is to use relatively large amounts of electric energy but to create a working fluid with significantly lower molecular weight (~10) than conventional barrel gases (~24). Using 4.5 m of projectile travel, they have accelerated a projectile of mass 404 g to 2.1 km/s with a charge of 180 g of isopropanol and 3.6 MJ of electric energy. The goal is a projectile mass of 3.2 kg to 2.5 km/s in a 105-mm barrel with a system efficiency of 20 to 30 percent. This program is supported by theoretical analysis and development of a pseudo one-dimensional code with the electric arc put in as a phenomenological model (Schmidt et al., 1993).

In another experiment at TZN, scientists have put an insulator section in the barrel of a 120-mm cannon approximately halfway through the projectile travel. The intention is to strike a discharge across this insulator after passage of the projectile, which will be launched with a conventional JA-2 charge. With this "electric boost" they believe they will see noticeable performance improvement. Presently, a 120-mm barrel with the insulator section has been fabricated and is being tested with conventional charges. Some work on this project is also being done at Meppen.

At the High-Voltage Technology Institute at Braunschweig Technical University, the projectile itself is one electrode of the electric discharge so that the discharge grows in length as the projectile moves (Weise et al. 1989). Therefore, the resistance of the discharge increases, and more energy is transferred to the gun as the projectile moves down the gun tube. The objective of this effort is to achieve a "flat topped" pressure profile and thus increase the ballistic efficiency. This technique has been incorporated into the research at TZN (Weise, 1993).

In a separate effort at the High-Voltage Technology Institute, an electrothermally driven light gas gun uses an electric discharge to evaporate a liquid propellant and pressurize a reservoir with gas at high pressure (Fien et al., 1993; Wisken et al., 1993). When the reservoir pressure exceeds a desired value, a diaphragm breaks and the projectile is accelerated.

At the Technical University of Munich (TUM), Department for Space Technology, an ET launcher is being used as an injector to a plasmadynamic accelerator to accelerate small particles (diameter 100 to 500 μm) to velocities of several kilometers per second (Rott, 1991, 1993). In the ET gun, these particles are packaged into a macroscopic (few-gram) projectile that disintegrates during the acceleration process. In other ET gun experiments, separate 28-mg particles have attained a maximum velocity of 5.5 km/s (Rott, 1995). The primary objective of this work has been to simulate space debris, but recent efforts with the plasmadynamic accelerator have used this acceleration technique to apply surface coatings (Igenbergs et al., 1995).

3. France

The French ETC gun effort is almost all included in the French-German collaborative program (Weise and Noiret, 1993) and is aimed at tactical guns, theater missile defense, or air defense. Experiments are performed at two laboratories. One laboratory, the French-German Research Institute Saint-Louis (ISL), in France, has been established specifically to house major parts of this collaborative effort and is staffed by both German and French nationals.

Results obtained with a 12-mm-bore ETC gun using a capillary plasma generator were reported by Zimmermann et al. (1989). More recent efforts describe a comprehensive model for the ETC gun including a two-dimensional transient description of the plasma arc, a 2-D two-phase interior ballistics module (the code AMI) and a preprocessor to provide plasma physical data (Silvestre et al., 1993; Hensel et al., 1995).

The other experimental site is the Vaujours Laboratories of the Atomic Energy Commission[15] near Paris. This facility was described in some detail at the 43rd Aeroballistic Range Association Meeting, Columbus, Ohio, September 1992 (Dormeval et al., 1992). The facility, which became operational in 1992, consists of a 4-MJ pulsed power supply and a 30-mm ET gun firing fixture. The pulsed power supply is made up of two separate lumped-parameter transmission lines, the main line (3 MJ) has a pulse duration of 1.2 ms, while the secondary line (1 MJ) has a pulse duration of approximately 400 μs. Interchangeable inductors allow extension of the main line pulse duration to 2.4 ms. The 30-mm ET gun uses a capillary as the plasma generator and has a large chamber to allow different cartridge designs to be tested. Prior to completion of this "new" facility, results were obtained using a 15-mm ETC gun with a capillary plasma generator (Aubouin et al., 1991). There is a parallel effort

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[15] Commissariat à l'Energie Atomique (CEA), Centre d'Etudes de Vaujours-Moronvilliers.

simple half-sine wave is probably the most cost effective considering the size and weight of the switches, etc., necessary to create an optimized power pulse.

At the RO Weapons Concept Group, Westcott, the major thrust seems to have been to develop an all-inclusive model (ROSETTE) for conventional, ET, or ETC guns that includes the power supply, interior ballistics, projectile design, flight dynamics, terminal ballistics, and vehicle integration (Locking et al., 1993). Since it is not specified, we presume that the interior ballistics are 0-D. By now, a 3-MJ, 30-mm ET gun system should be in operation, but no results have been published.

At the RO Guns and Vehicles Division, Nottingham, there is another modeling effort, based on a 2-D MHD code (Hewkin and Figura, 1993). Experimental data from ET gun firings at RO Sowerby and RO Westcott will be used for comparative analysis.

At the British Aerospace Sowerby Research Centre, Filton, experiments have been performed using 130-kJ and 500-kJ pulsed power supplies to drive a 10-mm-bore-diameter ET gun (Spiking and Thornton, 1993). Most of the effort has been directed to understanding the operation of the capillary discharge plasma generator.

5. Russia

Six Russian institutions have published articles in ET gun technology in recent years (see Section VI.E/Key Research Personnel and Facilities), but only one of these reports work that falls into the areas of tactical guns, theater missile defense, or air defense.

At the Electrophysics Problems Institute of the Russian Academy of Sciences, in St. Petersburg, the ET gun is a "light gas gun" in which the chamber is initially filled with hydrogen gas at 4 to 40 MPa (Rutberg, 1993; Budin et al., 1993, 1995). The hydrogen gas is separated from the barrel section (30-mm bore diameter, 4-m travel) of the gun by a metal diaphragm, and is rapidly heated by a high-current (400-kA to 1-MA) arc discharge. The electric power pulse is provided by a 4-MJ capacitor bank. With this gun, projectiles of mass 17 g have been accelerated to velocities of 6.2 km/s; 70 g to 3 km/s; 200 g to 2 km/s. No mention is made of barrel erosion, which has been a significant issue in similar US experiments. Future plans appear to at CEA to develop a comprehensive model of the capillary driven ETC gun (Aubouin 1993) that is presently concentrated on understanding the capillary discharge itself.

The effort at Giat Industries, the Research Center (CRET) and Giat Vecteur, supports the work done in both France and Germany under the French-German collaborative program (Nicolas, 1993a-b).

There is, in addition, a small effort at the Ecole Nationale Superieure de Mechanique (ENSM) that appears to be marginally related to ET gun technology. In this work, an exploding aluminum foil is used to accelerate flyer plates for impact studies (Cozic and Chiem, 1989).

4. United Kingdom

In the United Kingdom, the ET gun effort is split among four major laboratories. Three of these are divisions of the company British Aerospace PLC (Royal Ordnance [RO] Weapons Concept Group; RO Guns and Vehicles Division; and the Sowerby Research Centre). The fourth is the UK government laboratory, the Defence Research Agency (DRA). Three other organizations provide support to these laboratories. Fluid Gravity Engineering appears to have a small effort (one man) supporting the RO Guns and Vehicles Division. The Frazer-Nash Consultancy, Ltd., and the Mathematical Institute at Oxford University both support DRA with theoretical analysis. A new laboratory, an electric gun test range at Kirkcudbright in Scotland, has now begun operation. This laboratory was initially an EM (rail) gun test facility, but will probably be used to test all types of electric guns. No ET gun results have yet been released from Kirkcudbright.

At the DRA, Fort Halstead, basic research on ET gun technology at small scale has been undertaken with a strong modeling effort to provide understanding and evaluation (Snell et al., 1989; Woodley, 1991, 1993; Woodley et al., 1993). This ETC gun uses a capillary plasma generator. In support of DRA, Kennaugh and Woods (1995) have derived a simple, integrated, time-dependent model for the capillary discharge. Using interior ballistic codes developed with DRA, Guyott (1995) has examined the effect of power pulse shape on the Electric Enhancement Factor (muzzle kinetic energy/electric energy input) for an ETC gun, and concludes that a include moving to 40-mm bore diameter with 8 m travel to provide higher velocity with heavier projectiles. This work received substantial support from the military until recently. In private correspondence, Rutberg reported extensive work on the development of hydrogen gas generators using aluminum hydride, a key technology for field use of this technology.

At the Moscow Engineering Physics Institute, two avenues of research are being pursued. One objective is to launch fuel pellets for refueling Tokamak thermonuclear reactors (Shkolnikov et al., 1995a). These projectiles have mass from 2 to 15 g, and so far a 4.5 g projectile has been launched with a velocity of about 2.4 km/s. The other objective is to heat and launch powder particles of size 10^{-9} m to 10^{-4} m that will be used as a flame-sprayed coating (Shkolnikov et al., 1995b). A variety of materials are being considered: metals, carbides, nitrides, oxides, etc. Copper particles, 50 μm in diameter, have been accelerated to velocities of almost 400 m/s.

At the Experimental Physics Research and Development Institute, in Sarov (formerly Arzamas-16), the only published work concerning ET gun research has been in collaboration with the Moscow Engineering Physics Institute (Volkov et al., 1993), and was part of the effort on flame-sprayed coatings. No details of this work are available.

At the Applied Mechanics and Electrodynamics Research Institute at the Moscow Aviation Institute, the ET gun research involves accelerating particles of mass approximately 10^{-3} g to simulate space debris interaction with spacecraft (Aleksandrov et al., 1993). The working gas of this ET gun is helium, and particles of mass 2×10^{-3} g have been accelerated to 3.2 km/s in a gun with bore diameter 12.7 mm and travel 1.2 m. No details of the design of this gun are available, but it would appear to be an ET light gas gun.

At the Baltic State Technical University, Department of Applied Mechanics, or at the St. Petersburg Mechanical Institute, research appears to be being done in the area of tactical ET guns. This work was done in collaboration with Chinese authors from the East China Institute of Technology, Nanjing (People's Republic of China). Two papers were found. In the first, the researchers consider the design of an ET light gas gun with bore diameter of 8 mm, which uses helium gas as the working fluid and is intended to accelerate a 0.5- to 1.5-g projectile to 3.5 km/s (Zakharenkov et al., 1993a). In the second, the authors address the reduction of the heat flow to the bore surface in an ET gun with bore diameter of 14.5 mm and a projectile velocity of 940 m/s (Zakharenkov et al., 1993b). This could well indicate that other work is going on that has not been published. ET guns are relatively notorious for achieving high velocities through the use of high-temperature working fluids, which leads to significant bore erosion. Thus, protective coatings for the bore surface are of interest.

At the Theoretical and Applied Mechanics Institute of the Siberian Branch of the Russian Academy of Sciences in Novosibirsk, Zagorskiy and Katsnel'son (1995) have examined a hypothetical ET light-gas gun in which electric energy and working fluid mass (the light gas) were added throughout the ballistic cycle and distributed along the gun tube to optimize the system for accelerating heavy projectiles to velocities up to 3 km/s. An ablating projectile (similar to a traveling charge) was suggested as a means of implementing this proposal.

6. China

The only Chinese work found in the area of ETC Technology was that coming from the East China Institute of Technology in Nanjing. This work was done in collaboration with Russians from the Baltic State Technical University, St. Petersburg (Zakharenkov et al., 1993a-b). It appears from their previous work that the Chinese researchers are expert in two-phase flow problems and interior ballistics.

The concentration in the work by Zakarenkov et al. (1993b) on reduction of the heat flow to the bore surface could well indicate that other work is going on that has not been published.

7. Japan

At the Japan Steel Works, Ltd., ET gun research is based on using the aluminum/water reaction to create hot hydrogen gas at high pressure to drive a projectile through a conventional gun tube (Ikuta, 1992). This work is reminiscent of earlier work performed in the United States by GDLS/GTD. However, there are interesting innovations. An aluminum wire helix under water is heated electrically to cause the chemical reaction. The resultant pressure drives the projectile in a conventional gun tube. The paper suggests that solid by-products may be trapped in a "cyclone" at the breech and thus not be accelerated. This work appears very immature.

At the Research Laboratory of Engineering Materials, Tokyo Institute of Technology, the plasmadynamic accelerator is used to accelerate small particles to simulate micrometeorites and their impact on spacecraft (Thomas et al., 1993).

D. PROJECTIONS FOR FUTURE

In a recent review article,[16] Morrison et al. differentiate between two classes of ETC concepts. One class comprises ETC gun concepts that are not compatible with present gun technology, could be available in the intermediate (2000 to 2010) to far term (after 2010), and could provide a 10- to 50-percent improvement in kinetic energy over conventional weapons with some increase in velocity. The other class is solid propellant ETC (SPETC) concepts that may be compatible with present gun technology, could be available in the intermediate term, and could provide a 10- to 35-percent improvement in kinetic energy over conventional weapons with some increase in velocity.

Clearly, the Israeli ET gun efforts, and perhaps some of the French-German effort, would fall in the category of SPETC and could be available even in the near term (before 2000). The Israeli effort has been funded, in part, by the US Government, and this funding has not been forthcoming in FY94.

The greater part of the French-German efforts are exploratory and will not lead to weaponization in any discernible time frame. We expect to see a focusing of this effort in 1994, with the selection of those techniques that seem most likely to be weaponizable.

The UK effort is developing a solid theoretical base with comprehensive code capabilities, but presently has only small-scale experimental efforts. Perhaps in the coming year, as more results become available from other programs, the UK

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[16] W. F. Morrison, A. W. Horst, I. W. May, and J. J. Rocchio, "Trends in Gun Propulsion for Tactical Army Application," *Military Technology*, 3(1993), 10–23.

research community will commit to a large-bore firing program. The facility is already in place at Kirkcudbright.

No ET or ETC gun research efforts suggesting military application have been reported in the literature of the former Soviet Union although facilities clearly exist that could support such research. ELGG research has been the subject of active research programs and these might eventually lead to military applications. ELGG technology appears most suitable for small-caliber weapons. The large electrical energy requirements argue against its use for mobile systems with multi-megajoule kinetic energy projectiles.

Only minimal Chinese and Japanese efforts have been seen in the published literature. However, given the substantial electromagnetic/rail gun programs that have been active in both countries for years, either country clearly has the power supplies and range facilities to launch a substantial ET/ETC gun research program at very short notice. Of course, such programs could be already underway but not released for publication.

E. KEY RESEARCH PERSONNEL AND FACILITIES

Table VI.2 lists key researchers, their affiliations, and areas of expertise for the non-US electrothermal gun research. The facilities are separated by country in alphabetical order. Particularly in Germany, a number of researchers continue to appear on publications from different laboratories, and these have been listed at each laboratory.

TABLE VI.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ELECTROTHERMAL GUNS

Researchers	Facilities	Areas of Expertise
	China, People's Republic of	
Zhou Yanhuang Chang Yin Wang Pufa Chen Tong	East China Institute of Technology, Nanjing	Two-phase flow/interior ballistics; heat flow and bore erosion
	France	
P. Aubouin P. Benetruy S. Bouquet J. Buchet O. Caillou Richard Dormeval M. Durand Emmanuel Jacob D. Maillot Pierre Noiret C. Patou S. Paul J. Reynaud S. Roux B. Tortel L. Véron	CEA–Atomic Energy Commissariat, Vaujours-Moronvilliers Research Center, Courtry	ET gun/small-bore firings; interior ballistics modeling
C. Y. Chiem R. Cozic	Ecole Nationale Superieure de Mechanique (ENSM), Nantes	
K. Darée D. Grune Dieter Hensel Francis Jamet H. Mach P. Noiret Hilmar Peter J. Raupp Nicolas Silvestre Volker Wegner T. H. G. G. Weise K. Zimmermann	French-German Research Institute Saint-Louis (ISL), Saint-Louis	ET gun/large-bore applications
Christophe Nicolas	Giat Industries Research Center (CRET) and Giat Vecteur	ET closed bomb/mechanical design in support of French-German program

TABLE VI.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ELECTROTHERMAL GUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Germany	
S. Bleickert T. Karasinski D. Zwingel	Diehl GmbH, Röthenbach	
G. Klingenberg G. Zimmermann	Ernst-Mach-Institute (EMI), Ballistics Division, Weil-am-Rhein	
H. J. Maag	German Federal Office of Defense	
H. Thuenemann	German Liaison Office, WTD/Army Research Laboratory, Aberdeen Proving Ground, Maryland (United States)	
U. E. Braunsberger H. W. Fien J. G. H. Salge T. H. G. G. Weise	High-Voltage Technology Institute, Braunschweig Technical University, Braunschweig	ET guns
H. G. Wisken		Electrothermal light gas gun (ELGG)
K. Gruber H. Hilgendorf W. Romhild	IABG, Ottobrunn	
J. K. Biele	Ministry of Defense, Weapons Test Center, Meppen	ETC gun/large-bore applications
W. Witt	Rheinmetall GmbH, Düsseldorf	ETC gun/large-bore applications
Kh. G. Schmitt-Thomas	Technical University of Munich (TUM), Raw Materials in Machine Building/Mechanical Engineering Department, Munich	
Eduard Igenbergs Martin Rott Josef Spörer Peter Thomas	TUM, Space Technology Department, Munich	Plasmadynamic accelerators/with ET injector
Uwe H. Bauder	TUM, Technical Electrophysics Department, Munich	

TABLE VI.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ELECTROTHERMAL GUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Germany (cont'd.)	
H. Haak M. J. Löffler K. H. Reineit B. Schmidt H. Stüwe T. H. G. G. Weise	Technology Center North, Unterlüss R&D Center, Unterlüss	ELGG (isopropanol)/large-bore applications
	Israel	
M. Blum	Ministry of Defense, State of Israel, Tel Aviv	
Roger Alimi Gabriel Appelbaum J. Ashkenazy B. Brill M. Caner R. Cerny Z. Gorelic M. Kanter Zvi Kaplan David Kimhe J. Levinson A. Loeb David Melnik Lior Perlmutter Daphne Plotnik D. Saphier N. Spector Morris Sudai	Propulsion Physics Laboratory, Soreq Nuclear Research Center, Yavne	ETC guns/theory and experiment/direct military application
S. Cuperman D. Zoler	Tel Aviv University, School of Physics & Astronomy, Tel Aviv	Theoretical support to Soreq Nuclear Research Center

TABLE VI.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ELECTROTHERMAL GUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Japan	
A. B. Sawaoka H. Tamura	Engineering Materials Research Laboratory, Tokyo Institute of Technology, Yokohama	Plasmadynamic accelerator/impacts with spacecraft
Y. Aso K. Fujioka K. Ikuta T. Maruo S. Nakamura Y. Uehara	Japan Steel Works, Ltd., Yotukaido, Chiba	Aluminum/water propellant
	Russia	
V. A. Aleksandrov Yu. N. Ivanov S. A. Leonov A. V. Panshin V. K. Tyutin A. S. Voynovskiy M. I. Zaytsev	Applied Mechanics & Electrodynamics Research Institute, Moscow Aviation Institute, Moscow	ELGG/space debris and micrometeorite impact in spacecraft
A. V. Budin A. E. Bystrov A. M. Glukhov V. L. Goryachov V. A. Kolikov A. I. Kulishevich A. G. Kuprin V. V. Leont'yev B. P. Levchenko I. P. Makarevich F. G. Rutberg A. F. Savvateyev N. A. Shirokov A. M. Voronov S. V. Zakharenkov	Electrophysics Problems Institute, Russian Academy of Sciences, St. Petersburg	ELGG (hydrogen); combined ELGG and railgun (see also railgun section)
M. I. Kaymovich	Experimental Physics Research & Development Institute, Sarov (formerly Arzamas-16)	Plasma-sprayed coatings

TABLE VI.2
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ELECTROTHERMAL GUNS (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
A. V. Chebotarev A. E. Ignatovich I. L. Kolenskiy Yu. A. Kulikov A. V. Melnik E. Ya. Shkolnikov S. V. Volkov	Moscow Engineering Physics Institute, Moscow	Tokamak refueling/plasma-sprayed coatings
A. V. Belov V. F. Zakharenkov	St. Petersburg Mechanical Institute im. D. F. Ustinov, St. Petersburg	
S. S. Katsnel'son A. V. Zagorskiy	Theoretical & Applied Mechanics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk	
	United Kingdom	
I. Cullis S. Fuller Chris Leyden A. W. Snell Clive R. Woodley	Defence Research Agency (DRA), Fort Halstead, Sevenoaks, Kent	Basic research/small-scale/comprehensive modeling
Edward Figura	Fluid Gravity Engineering, Ltd., Godalming	2-D modeling of ETC gun
C. C. H. Guyott	Frazer-Nash Consultancy Ltd., Leatherhead, Surrey	
Richard J. Kennaugh Leslie C. Woods	Mathematical Institute, Oxford University	Basic theoretical analysis/modeling
Derrick Hewkin	Royal Ordnance PLC, Guns & Vehicles Division, Nottingham	2-D modeling of ETC gun
T. Harling A. J. Howson M. Johnson P. M. Locking	Royal Ordnance PLC, Weapons Concept Group, Aylesbury	Basic research/small-scale ETC gun/end-to-end modeling
Christopher R. Spikings E. Thornton	Sowerby Research Centre, British Aerospace PLC, Bristol	Basic research/small-scale ETC gun

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CHAPTER VI: ELECTROTHERMAL GUNS
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CHAPTER VII
ENERGY STORAGE AND POWER SUPPLIES

A. SUMMARY

In the last 10 years there has been considerable growth in electric gun programs around the world. While no systems have yet been fielded, it now appears that this *could* happen within the next 10 years. Work on compact energy storage and power supplies since the mid-1980s has shown that, although significant improvements have been made, progress towards miniaturization has been more difficult than originally expected. This technology, perhaps more than any other, is a limitation for the development of fieldable electric guns.

As a result of their rather poor efficiency (muzzle energy versus stored energy is typically 25 to 30 percent), the input energy needed for high-velocity *electromagnetic (EM) railguns* is high. For a typical ordnance muzzle energy of 20 MJ, 60 to 80 MJ therefore has to be provided to the gun breech for each shot. Even for a single-shot gun, this is a major requirement; for a rep-rated gun, the corresponding power and thermal management requirements for railguns are even more demanding. Coilguns may be more efficient than railguns, but it is unlikely that the energy and power requirements will decrease substantially, because, although efficiencies over 50 percent may ultimately be achieved, the parasitic sabot/armature mass needed to carry the payload may be substantially heavier than the projectile itself.

Much of the technical effort in the development of energy and power sources has been led by the United States. Two major avenues have been followed: capacitors and rotating machines. Although significant improvements have been made with the energy density of capacitors, it seems unlikely that they will be capable of supporting a fieldable (that is, mobile or easily transportable) rep-rate large-bore EM railgun in the near future. Despite substantial investments in rotating machine technology, the same appears true of homopolar generators (HPGs) and compulsators at present.

In contrast, the prospects for *electrothermal chemical (ETC) guns* are much better, since the energy requirements are much smaller, perhaps a megajoule or less per shot, because the electrical energy input is substantially augmented by the chemical energy stored in the associated fuel. In this case, the development of a mobile system appears to be viable, and an ETC system should be regarded as the most likely candidate for the first application of electric gun technology provided performance improvements over advanced conventional propellants can be demonstrated.

Although there have been some significant contributions from the United Kingdom, France, Germany, Japan, and Russia in specific technology areas, in general, the United States is still the leader in developing this technology. Russia has demonstrated considerable expertise in explosive magnetohydrodynamic (MHD) and magnetocumulative generators (MCGs), but the applicability of these to fielded ordnance systems (other than very special one-shot devices) has yet to be shown. A notable (1993) disclosure from Ukraine was a recent description of a transportable 60-MJ pulsed power system on a trailer that consisted of four 15-MJ HPGs driven by helicopter gas turbines. At present, there is no comparable system elsewhere in the world.

For the future, our perception is that Europe and possibly Japan will make steady, and perhaps accelerating, technical progress in this area and, as a result of close cooperative links between their respective National Ministries of Defense (MODs) and their defense industries, may be more successful in making future progress than the United States. Research and development in France and Germany are being conducted cooperatively through a Memorandum of Understanding that has been in place since 1992. The Netherlands has now joined this agreement, and negotiations are being conducted with the United States on further cooperation. In the present era of shrinking defense budgets, such cooperation may become the standard approach.

A German objective is to develop an all-electric tank with an electric gun for anti-armor applications. The present strategy is to maximize the available stored energy that can be fitted in the tank, depending on available power/energy technology, and then choose the gun type and size to match. Key decision points are 1995 for the choice of gun type, and 2002 for the type of power supply technology.

A notable development is the technology and products from the former Soviet Union that have recently become available for sale to Western (and other) countries. For example, triggered vacuum switches from Moscow are being distributed in the

West for use in capacitor banks and pulsed forming networks. In addition, Germany has contracted with an institute in St. Petersburg to undertake research on hydrogen-fueled 50-mm-caliber electrothermal (ET) guns that have reached velocities of 3.5 km/s. It is believed that Russia has had an all-electric tank under development, although the present status of this is unknown.

B. INTRODUCTION

Power supplies for the three main types of electric guns (railguns, coilguns, and electrothermal guns) have similar fundamental requirements: voltages of a few to tens of kilovolts, currents of hundreds of kiloamperes to megamperes (for large railguns), and total pulse lengths of a few to about 10 ms. The specific requirements depend on the mission, but for military applications, generally stem from the desire to accelerate masses of practical significance (from a few up to tens of kilograms) to velocities of 1500 to 3000 m/s, that is, significantly higher than conventional powder guns. The total energy needed depends on the type of electric gun, but typically ranges from a megajoule or less (for ETC guns) to many tens of megajoules (for large rail guns). With acceleration times of a few milliseconds, the instantaneous power requirements to the breech of the gun are generally 1 to 10 GW.

Electric gun applications fall into two categories: (1) laboratory test facilities, and (2) fieldable weapons. In both cases, the energy requirements are similar. For laboratory programs, there is seldom a weight or size constraint, and system reliability is the major concern. Almost all laboratory tests to date have been single shot. In contrast, the ultimate fieldable weapon will need to be rep-rated, compact, lightweight, and mobile or transportable.

Repetitive firing necessitates a prime power supply that can be used to recharge the energy storage system, whether a capacitor bank or a rotating machine. Depending on the firing rate, the gun type and size, the power supply may be trivial or may be a major component. At one extreme, a small-caliber ETC gun may only require an energy input of 200 kJ, so that with a firing rate of one round per second, the power supply would have to furnish 200 kW (excluding losses). In contrast, a large-bore EM railgun that requires a breech input of 60 MJ every five seconds would need an average power of 12 MW to recharge the energy source (excluding losses).

Of necessity, this assessment focuses on laboratory energy supplies, while keeping in mind the future weaponization issues. Relatively little has been published, even in the United States, on future weapons systems.

C. DISCUSSION

In the following discussion, efforts in the countries shown in Table VII.1 are described. The number of organizations that are known to be, or to have been, involved in each country is summarized in Table VII.1 in alphabetical order, together with the number of key personnel.

TABLE VII.1
SUMMARY OF WORLD INTEREST IN ELECTRIC GUNS OUTSIDE THE UNITED STATES

Country	No. Organizations	No. Key Personnel†	Page in This Chapter
Australia	2	1 or 2 (?)	5
China	3	34	5
Europe (other) *	5	12	7
France	12	57	8
Germany	7	38	15
India	1	2	20
Israel	3	13	21
Japan	18	53	22
Netherlands	1	11	27
Romania	1	4	29
Russia	21	250	29
Ukraine	1	17	42
United Kingdom	17	51	45

* Italy, Spain, Sweden, and Switzerland.

† Estimated number based on published papers. See Tables at the end of this chapter.

Some countries clearly have decided to invest much more effort than others; the countries with larger efforts are those with the largest defense budgets. These investment decisions lead to the development of a relevant national infrastructure of industrial and university organizations that support the national defense establishments. The discussion below is focused on the efforts of these large countries in power and energy storage technologies. The same alphabetical order is followed as in Table VII.1.

1. Australia

To a large extent, the growth of interest in electric guns during the last 15 to 20 years can be traced to the work of Richard Marshall and John Barber at the Australian National University in Canberra (Barber, 1972). Their experiments used a large (550-MJ) HPG to power a 0.5-inch square-bore railgun with which they achieved velocities of almost 6 km/s (Rashleigh and Marshall, 1978). These experiments used high-pressure plasmas created by exploding fuses as armatures to drive gram-sized projectiles.[1] Marshall and Barber are now both in the United States, and, following their pioneering experiments, only a rather modest effort was subsequently undertaken in Melbourne (see, for example, Sadedin, 1984; Clark and Bedford, 1984; Richardson and Kowalenko, 1984). Following the publication of a major report on railguns and their power sources by the Materials Research Laboratories of the Australian Defence Science and Technology Organization (Sadedin and Bonwick, 1987), there is little work in Australia, and Sadedin has recently worked at the Institute for Advanced Technology in Austin, Texas.

2. China

Relatively few efforts on electric guns have been reported from China, although it is likely that there will be a growing Chinese interest in this area. Early descriptions of work undertaken at the Electric Launch Laboratory (ELL) at the Academia Sinica (Institute of Plasma Physics), Hefei, in the People's Republic of China, were given at the IEEE Conference in Williamsburg, Virginia, and at the Third European Electromagnetic Launch (EML) Technology Symposium (Ren et al., 1991a–b; Wang

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[1] I. R. McNab, "Electromagnetic Macroparticle Acceleration by High Pressure Plasma," J. *Appl. Phys.*, *51*, 5(1980).

et al., 1991). The facility contained a 25-mm square-bore gun powered by a 3-MJ capacitor bank that accelerated a 30-g projectile to over 3 km/s in a 3.5-m railgun barrel with a peak current of 0.72 MA. In the first gun, the EMG 303, a 30-g projectile was pre-accelerated to about 750 m/s, using an ET preinjector that operated at 200 kA and 23 kV. The 3-MJ capacitor bank was divided into four electrically independent 5-kV modules. With pre-acceleration of the 50-g projectile to 700 m/s in the ET gun, the "503" railgun accelerated it to 3.1 km/s (Ren et al., 1994). Substantial diagnostic capability is employed on this system, including 20 fiber optic detectors or magnetic probes, laser/X-ray detectors, a high-speed camera, and 60 channels of diagnostics. The ET preinjector and ET gun research are undertaken with a 240-kJ capacitor bank that has a 200-kA peak current capability. Wang et al. (1991) described details of the barrel construction and noted that particular attention was paid to high-voltage insulation. After assembly, the entire barrel was maintained at 8 kV for five to 10 minutes for test, during which the insulation resistance was maintained above 10 MΩ. Eight shots had been completed successfully without bore disassembly by April 1991. Plastic, aluminum, steel, and tungsten rod penetrators were used for hypervelocity penetration experiments. A tungsten long rod penetrated a 40-mm-thick steel plate at 1.4 km/s, as illustrated with high-speed camera photographs (Ren et al., 1991b).

Several researchers from the Institute of Plasma Physics have also studied theoretically and experimentally the performance of a solid armature with currents of 600 kA in the 3-m-long, 25-mm-caliber ELL barrel (Qiang et al., 1991). A comparison of the muzzle voltages measured with solid and plasma armatures was given by Ren et al. (1991b), who noted that further work was being undertaken on solid armatures.

This same institute has four large rotating generators that were installed more than 10 years ago in anticipation of the construction of a large fusion reactor experiment. Researchers may also have previously used a large submarine battery assembly to power a 60-MJ inductive storage system to drive flashlamps for a large glass laser. No details of the energy density or other relevant parameters of the capacitors used in the above-mentioned ELL facility were provided, although they are believed to be physically much larger than equivalent US technology. Solid-state switches have been used, but switching is likely done with explosive devices.

At the Southwest Institute of Fluid Physics in Sichuan, capacitor banks of 50 kJ, 600 kJ, and 800 kJ have been used to conduct railgun experiments. Ignitrons or explosive switches have been used for the closing switch, and a metallic closing switch as the crowbar. An 800-kJ capacitor bank has been used to provide currents up to 417 kA to launch gram-sized projectiles in a 1.9-m railgun (Gao et al., 1992), although the capability to reach 700 kA was mentioned.

A researcher from the East China Institute of Technology in Nanjing (Zhou Yanghuang) co-authored a paper on ET guns with two Russian scientists from the Mechanical Institute in St. Petersburg (Zakharenkov et al., 1993).

The Institute of Nuclear Energy Research in Lung-tan in the Republic of China (Taiwan) undertook research on railgun plasmas using a 19-kV, 86-kJ capacitor bank in which small (millimeter-size) plasmas were accelerated to velocities up to 150 km/s (Hou et al., 1988). Impact of plasmas of this type onto an 0.8-g projectile gave velocities up to 1.2 km/s. A small (38-kJ) railgun powered by six 25-kV capacitors and an air-cored pulse transformer, with gas-filled sparkgaps used for switching was described by Hou et al. (1991). However, it is reported that Hou has left the organization (to become a monk), the effort has ended, and the equipment is not in use at present.

3. Europe

Although the widely used Bofors gun is manufactured in Sweden, relatively little Swedish interest in electric guns has been evident until recently. An effort on ETC research is starting, but no details are yet available, although a Request for Proposal for two 300-kJ pulsed power supplies (capacitor banks) was issued in mid-1994, with an anticipated order placement date of late 1994. The only published Swedish work so far has been theoretical investigations undertaken at the National Defense Research Establishment, Sundbyberg. These include studies on the influence of the Hall Effect and recoil on railgun performance (see, Witalis and Gunnarsson, 1993, and Witalis et al., 1994, respectively). The latest studies suggest that the main reason researchers have been unsuccessful in reaching high railgun performance is the lack of recoil and lack of attention to Hall Effect currents. Concerning recoil, this appears contrary to most experience, in that recoil is a *result* of gun performance, not a *cause*. However, one of the remedies suggested (improved rail materials) may be beneficial, if it results in reduced rail erosion and ablation.

ABB in Switzerland is a major electrical and electronics company and is engaged in the production of large (75-mm-diameter) solid-state devices that could be of considerable use for switching in future electric guns (Ramezani et al., 1993). These are being investigated at the French-German Research Institute Saint-Louis in France (see below) and in laboratories in the United States. The Swiss military is aware of electric gun potential to upgrade existing guns in the Alps, for both extended range defense artillery and improving lethality for fixed-position anti-tank guns.

A significant experimental effort on electric guns in Italy has not yet occurred, although the gun manufacturer Oto Milera has had contacts with Rheinmetall and Technical Center North (TZN) in Germany. However, theoretical analyses of several aspects of power generation for electric guns have been undertaken, including explosive magnetic flux compressors (Becherini et al., 1991), explosively driven linear HPGs (an "inverse railgun" or a momentum transformer—Esposito et al., 1994a), and an MHD-generator-driven railgun for fusion pellet injection (Esposito et al., 1994b).

The only known interest in topics related to electric guns in Spain is that presented in a paper on Rayleigh-Taylor instabilities in plasma arcs by Huerta from the University of Miami, who had a co-author from UNED, Madrid.

4. France

Several government and industrial organizations in France are involved in electric gun research or component development, as shown in Table VII.2. The main organizations are the French-German Research Institute Saint-Louis (ISL) in Saint-Louis and the Commissariat à l'Energie Atomique (CEA) in Vaujours-Moronvilliers. A Memorandum of Understanding between France and Germany covering research and development in this field has been in place for two years. The Netherlands is now a part of that agreement, and discussions with the United States on extending the scope of the cooperation are presently underway. France appears to have sole responsibility for coilguns, ISL is researching railguns, and TZN in Germany (and CEA in France) are studying ET guns.

A variety of efforts have been undertaken at ISL, which is funded jointly by France and Germany. The efforts primarily cover railguns and coilguns, but also include some ET gun work (Hensel et al., 1994). The energy source for the 15-mm railgun EMA-1 was a 500-kJ, 10-kV, 10-mF capacitor bank switched by spark gaps and crow-barred with semi-conductor diodes (Jamet et al., 1990). During experiments, a peak current of 420 kA was reached with this bank, with an exit current of 200 kA.

TABLE VII.2
FRENCH ORGANIZATIONS ACTIVE IN ELECTRIC GUNS RESEARCH

Organization Type	Organization Name
Government	French-German Research Institute Saint-Louis (ISL), Saint-Louis
	Commissariat à l'Energie Atomique (CEA), Vaujours
	Etablissement Technique de Bourges (ETBS), Bourges
Industry	Haefley
	Thomson LCC (Saint Apollinaire)
	Compagnie de Guerre Electronique (CGE) Marcoussis
	GEC-Alsthom
	Thomson
	Matra
	Groupement des Industriel des Armaments Terrestres (GIAT)
	Remy
	Electrotechnical Laboratory, National Telecommunications Research Center, National Center of Scientific Research (CNRS), Grenoble
University	University of Paris

The energy source for a larger railgun, PEGASUS, is a capacitor bank of 2.77 MJ divided into two modules that give peak currents of 1.4 MA and 1.2 MA, respectively, with a switching time difference of 350 µs. The efficiency for a railgun of 50-mm caliber and 3 m in length, which will accelerate 100-g projectiles to 4 to 5 km/s, was predicted as 30 percent. With a pre-accelerator that combines ET and

EM principles, an energy input of 150 kJ is expected to be capable of accelerating a 100-g projectile to 400 m/s in a 0.3-m length (Peter et al., 1994). Experiments with a DES (distributed energy store) railgun have been conducted with this bank in which the second part of the capacitor bank is triggered by the passage of the projectile, which has a special design to achieve good electrical contact with the rails. Good agreement with model predictions was observed (Wey et al., 1994).

There are plans to increase the energy level of PEGASUS to 10 MJ. In this proposed arrangement, 200 identical current pulse forming units (PFUs) will be used, each of which will consist of a 50-kJ, 10-kV capacitor, a thyristor stack as the main closing switch, a semi-conducting diode stack as the crowbar switch, and a compact pulse forming inductance. The current pulse amplitude for each PFU will be 60 kA with a rise time of 250 µs. One such unit has been built (Spahn et al., 1994). The primary circuit inductance (capacitor, main switch, and crowbar switch) was less than 150 nH, so that the reverse voltage was limited to 4 percent, and electrical power dissipation was negligible. Since the main switch consisted of thyristors, the operating voltage could be varied continuously from 0 to 10 kV. The parallel operation of several PFUs is considered feasible when each unit is decoupled by an inductance of 30 µH. In general, this seems to be an excellent direction for future electric gun systems, although not necessarily always the optimum arrangement for all applications; in some cases, the use of fewer (lumped) inductances may be more efficient or less costly.

Fast switching thyristors have been investigated for several years at ISL, as described by Spahn et al. (1993). The preferred type has an interdigitated gate structure that allows fast switching (greater than 700 A/µs) by ensuring uniform turn-on. Since the blocking voltage is limited to 3 kV, four thyristors have to be used in series to operate at 10 kV. A special gate unit with a dispersion of less than 30 ns has been built to provide the gate current pulse. Such a device has been built and tested successfully as a main switch for a 50-kJ capacitor (Spahn and Buderer, 1994).

The capacitor manufacturing plant owned by Haefley is very close to ISL in Saint-Louis, and it has therefore been the traditional supplier of capacitors for ISL electric gun experiments, although a few capacitors have been provided by the United States. A 90-kJ plastic-cased can has been supplied by Haefley. Optimization of the dielectric system for a high-energy storage capacitor has been discussed, in detail, by Hafeley (Bonigen et al., 1990). Aspects such as paper characteristics, including dielectric strength for different densities, number of conducting points in paper as a function of paper thickness, choice of electrode, relative price, etc., were included. However, at present, the future of Haefley in the development of high-energy-density capacitors is in doubt.

Initial work on ET guns at CEA at Vaujours-Moronvilliers was undertaken using a 600-kJ capacitor bank purchased from the United States (Véron et al., 1994). More recently, the program has scaled up to use a 30-mm gun, powered by a 4-MJ, 22-kV capacitor bank that was also designed and built in the United States (Dormeval et al., 1992). The bank uses two separately triggerable banks of 3 MJ and 1 MJ, each built up with 250-kJ modules. Gas-filled rotating arc gap switches switch the current, and 30-kV diodes prevent voltage reversal on the capacitors. Pulse lengths of 1.5 ms at a peak current of 220 kA can be achieved with the 3-MJ load and about 2 ms when an extra 500-µs pulse from the 1-MJ module is added. The 30-mm gun used for these experiments was built by GIAT and has a 1.4-m-long by 0.48-m-diameter high-strength breech capable of withstanding a peak pressure of 7 kbars. Two barrel lengths have been used: 0.7 m and 3 m. A polyethylene capillary was used for ET work. The pressure attained in the cartridge was about 5 kbars, and velocities of 1200 to 1600 m/s were achieved with an energy of 300 to 500 kJ, corresponding to a global efficiency of 12 to 16 percent (Roux et al., 1994).

In a discussion of energy storage in capacitors, researchers from CNRS and ATESYS concluded that greater than 1 MJ/m^3 can be achieved using two-layered insulation and possibly exceeded in multi-layer systems (Coelho and Neufeld, 1990). The proposed capacitors would be made of impregnated paper and mylar. Specific data were included for impregnated paper with a relative permittivity of 4.5 and a relaxation time of 10^{10} sec and mylar with effective permittivity of 3.2 and relaxation time of 5×10^{10}. The respective electric stresses in these two materials were given as 120 and 440 V/µm. With these conditions, a device was built that had an energy density of 1.15 MJ/m^3 and operated for 1000 discharges with good reliability at peak current levels up to 10 kA. Comparable or greater performance has been achieved in the United States. The authors point out that putting a rectifier in parallel with the capacitor limits internal losses by preventing voltage reversal; this was already known.

The state-of-the-art technology as it applies to 50-kJ capacitors was described by Bramoullé (1990) from Thomson LCC. It was noted that high reliability with a paper-based capacitor can be ensured by choosing a high-density paper dielectric having a very narrow spread of physical characteristics (density from 1.30 to 1.38 g/cc). The effect of electrode construction on capacitance and stress was discussed, and it was pointed out that 5 MJ/m^3 could be achieved with a permittivity of 10 to 20 and an electric field of 300 to 420 V/µm. Edge effects were identified as limiting the dielectric thickness to 10 to 20 µm, which result in potential reliability problems. Data on various dielectric combinations and impregnants were given. Funding for a program to develop new liquid impregnants was provided by the French Ministry of Defense (DRET) with a view toward achieving a new dielectric system that is closer to the theoretical limit of the film, since most impregnants reduce the energy density of the total system. This work was carried out as a joint exercise between LCC and PRODELEC. An energy density of 2.8 MJ/m^3 was achieved in the *dielectric*, with a corresponding *capacitor* energy density of 0.67 MJ/m^3. The formation of "a consortium of all principal parties" to reduce and optimize the cost of developing a new generation of capacitors was mentioned, but it is not known whether this has actually occurred.

Authors from CGE-Marcoussis and GEC-Alsthom have suggested that a 50-MJ superconducting transformer with a superconducting primary and a normal secondary could provide currents of hundreds of kiloamps to megaamps for an EM launcher (Mailfert et al., 1990). A reduced scale-level system of a few kilojoules was built in which the load inductance was also superconducting so as to model a purely inductive launcher. Experiments with available equipment gave a primary current of 100 A and a secondary current of 1000 A. An air-core solenoid transformer was used with a maximum magnetic field of 2 T and an outer transformer diameter of 150 mm. A multi-filament NbTi conductor made by GEC-Alsthom was used. The transformer coupling coefficient was 0.846. Slow charging of the superconducting primary was achieved, and the experiment successfully demonstrated the principles on a reduced scale. The researchers conclude that a scaled-up transformer could be designed with storage on a kiloamp scale and pulsed discharges in the (normal) secondary coil of hundreds of kiloamps. The main challenges identified are the replacement of resistive switches by superconducting loss-free switches and the optimization of the superconducting cables by the use of multi-filament strands of small diameter, which will reduce losses under fast transient conditions. The work was sponsored by DRET.

Laser-activated solid-state switches that have pulse lengths of several tens of nanoseconds and voltages above 10 kV, have been evaluated by researchers at Thomson-CSF, since they could replace spark-gaps and thyrotrons (Becle and Vinter, 1990). These switches have fast rise times (down to 100 ps), negligible jitter and potentially high repetition frequency. Details of three types of such switches—linear, lock-on, and extrinsic—are given. Linear silicon switches can have conducting lifetimes greater than 100 µs, but the voltage hold-off is limited to a few microseconds. In contrast, GaAs linear switches have a much better voltage hold-off, but are limited to nanosecond pulses. The lock-on switch uses a specific (as yet not understood) property of GaAs that, if an electric field greater than 4 kV/cm is applied, it remains in the conducting state, thereby combining good voltage hold-off properties with lifetimes greater than microseconds. The extrinsic switch may offer the possibility of operating with non-optical wavelengths. Applications for laser-activated switches include electromagnetic pulse (EMP) simulators, copper-vapor lasers, and induction accelerators in which several photo-conductive power switches (PCPS) can be operated in parallel to overcome the thermal constraints imposed by the high-frequency requirements. A program at Thomson-CSF on PCPSs for EMP simulators was supported by the Centre d'Etudes de Gramat (CEG).

Explosive-driven magnetic flux compression generators (MFCGs) to drive railguns were studied by Matra (see, for example, Deneuville et al., 1989, and Jaquelin and Mantel, 1990). The Matra design used a strip-line geometry, divided into two parts, the first having an explosive ignition system. Although having a lower efficiency than a helical MFCG, the device was simple, adjustable, and easy to set up. The researchers stated that the measured performance agreed very well with the design predictions. The design was optimized to achieve a high-efficiency railgun launch with a fast initial current rise, followed by a slower rise in current as the projectile accelerates. The initial speed required (50 km/s) was much higher than any existing explosive detonation speed and was achieved by an angled plate-projection system driven by the explosive. Experiments were undertaken at CEA-DAM using a 600-kJ capacitor bank to create the initial magnetic field. The total length of the generator was less than 2.5 m, and copper electrodes with different widths and gaps between 50 and 75 mm were used. The selected phase velocity for the first stage was 30 km/s; the detonation speed for the second stage was between 5.5 and 8.6 km/s. The first stage gave a rise in current from 330 to 660 kA in 50 μs. In the second stage, using common cast PBX explosives, and a "slow cruising" compression, the current rose up to 1.9 MA. With a "fast cruising" compression, the current was higher, 2.2 MA, although less than calculated because of non-linear losses. The researchers claim that the system could launch an 8-g projectile to 3700 m/s in a 1-m barrel. It is believed that this work has been discontinued.

The Etablissement Technique de Bourges (ETBS), in collaboration with GIAT and GEC-Alsthom, is planning to install a 120-mm-caliber coilgun test rig in 1995. This is expected eventually to be a 30-MJ system, but the first phase may be limited to 10 MJ because of funding limitations at DRET. Capacitor banks for evaluating prototype coils for this system have already been built by Remy, although not yet delivered. In the next phase, 40 coils out of an ultimate total of 140 are expected to be built. The eventual objective is to accelerate a 1-kg *projectile* to 2500 m/s. However, the total *package* mass to be accelerated may be as much as 5 kg.

Researchers from the Laboratoire Electrotechnique at the University of Paris have undertaken experiments on the concept of non-dissipative inductive energy transfer between two coils at low-energy levels of about 500 J (Delmas et al., 1990). The concept is similar to that suggested by Zucker in which turns of an inductor are progressively short-circuited.[2] In this case, the energy usually dissipated in the thyristor switches was transiently stored in a capacitor. With a five-stage system, an approximate 2:1 increase in current was achieved in the load coil. Further work to be undertaken with a 100-kJ system in which vacuum switches would be used was mentioned.

Also at the University of Paris, Bauville et al. (1989) tested the interruption capability of a fast-triggered vacuum switch with a pulse duration of 27 μs and a recovery time of 20 μs for a current of 44 kA and a voltage of 32 kV. This switch used two fixed-plate electrodes with diameters in the range from 5 to 80 mm enclosed in a stainless steel arc chamber at a pressure less than 10^{-4} Pa. Triggering was accomplished with a molybdenum auxiliary electrode with an energy of less than 1 J. The

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[2] See, for example, D. Giorgi, J. Long, T. Navapanich, K. Linder, A. Griffin, and O. Zucker, "New High-Current Meatgrinder Experiments," *IEEE Trans. Magn., 22, 6(1986), 1485–1488.*

best performance was obtained with small gaps when a uniform diffuse discharge spread over the entire anode surface. No erosion of the anode was observed. The highest current density was obtained with the smallest electrodes. Slight improvements were observed with Inconel-over-copper electrodes. Some work was done to investigate the effect of applying external magnetic fields, and up to a 16-percent improvement in voltage recovery was achieved.

Two other switches were also studied by the same group: (1) a pseudo-spark switch, in which a recovery voltage of 25 kV was attained for a current of 25 kA at a gap distance of 1 mm; and (2) a faster triggered vacuum switch especially designed for induction EM launchers (Delmas and Bauville, 1993). The best results with the vacuum switch (although not reproducible) were 1 kA for a recovery voltage of 6.5 kV.

5. Germany

Effort on electric gun research and development in Germany is focused at relatively few locations (see Table VII.3), with TZN being the focal point for much of the work.

TABLE VII.3
GERMAN ORGANIZATIONS ACTIVE IN ELECTRIC GUNS RESEARCH

Organization Type	Organization Name
Government	BWB, Meppem Test Range
Industry	Technisches Zentrum Nord (TZN)
	Magnet Motor GmbH
	Messerschmitt Bolkow Bohm (MBB)
	Diehl GmbH & Co.
	Industrie Anlagen Betreibs Gesellschaft (IABG)
University	Technical University, Braunschweig
	Karlsruhe University
	Technical University, Munich (TUM)

TZN is a research organization located in Unterlüss, formed in the 1980s, and jointly supported by a "troika" of funding sources composed of Rheinmetall, the local state government, and a consortium of local industries in the area. Rheinmetall, the supplier of large-caliber guns to the German Ministry of Defense, is the major influence on TZN's research and development program for military systems. Rudy Romer, developer of the smooth-bore 120-mm tank gun, led Rheinmetall efforts to develop electric guns for the dual roles of anti-armor and air defense, which he described as a modern 88-mm gun, as used by Germany in World War II for both purposes. Most of the other organizations in Germany are associated with the TZN effort, with the exception of the TUM, which is following independent studies into very high-velocity impacts with micro-particles. The French-German Research Institute (ISL) exchanges information with TZN as part of the French-German cooperative electric launcher program. In May 1993, TZN hosted the Fourth European Conference on EM Launchers.

Several years ago, TZN purchased a 6-MJ capacitor bank and a matching 50-mm railgun from the United States which first demonstrated >3 km/s with >100-g projectiles. The system was a copy of the CHECMATE system built by Maxwell for the US Defense Nuclear Agency and Strategic Defense Initiative Organization. Based on available capacitors when the design was undertaken in 1985, the system had an operating voltage of 44 kV. Subsequently, TZN stopped work on railguns and focused on electrothermal guns. Since the same capacitor bank was used, the ET plasma burner for their 50-mm gun was therefore optimized for operation at 44 kV (Weise and Kloppenburg, 1994). Bank energies up to 5.7 MJ have been used to power ET guns in a specially designed enclosed building.

More recently, TZN built a 1-MJ transportable bank system in cooperation with Physics International (PI) from the United States, and installed it in a transportable container (Weise et al., 1993a). This bank voltage is also 44 kV, and maximum normal- and short-circuit currents are 52 kA and 180 kA, respectively. A simple LCR circuit provides an overdamped sinusoidal pulse shape. Aerovox metallized-film capacitors were used, with spark gap output switches. TZN is currently building a 30-MJ bank, also in collaboration with PI, that uses Aerovox metallized-film capacitors and PI spark-gap switches (Weise et al., 1993b, 1994). This bank will be used to power a 105-mm ET gun at the Unterlüss range. The bank is basically 22-kV (and can therefore be used to test the French CEA electrothermal cartridge concept) but can be marxed to 44 kV to match the TZN electrothermal cartridge concept. At 44 kV, short-circuit currents up to 1.6 MA can be generated, and power levels in the ET load up to 20 GW are planned for pulse lengths up to 3 ms. The objective of this program is to demonstrate the acceleration of 3.2-kg projectiles to 2.5 km/s on a 2000-m range by 1995.

Following work in Germany as early as 1968, TZN has restarted efforts on exploding switches for crowbarring the 30-MJ bank (Schmuck et al., 1993). An exploding wire will be used to blast an aluminum conductor into a sharpened cutter to interrupt the circuit. The required switch specifications are a current of 25 kA, a DC voltage of 30 kV, and a pulse voltage of 100 kV for 1 µs. To achieve the desired jitter time of less than 5 µs, the wire will be exploded with a 50-µF capacitor switched by a small spark gap.

TZN is now starting to consider the system implications of tank-mounted electric guns. Issues such as the reaction time for firing, silent watch operation, and recharge time are being evaluated for different technologies, such as advanced capacitors, superconducting inductors, and rotating energy storage systems. The application of such technologies to an all-electric tank, which could be electrically driven, have EM armor, and use electric weapons such as lasers and guns, is the objective.

An energy supply chain that could be used for EM and ET launchers has been proposed by Magnet Motor GmbH (Ehrhart, 1990). The concept is that main energy storage is provided by the magnetic-dynamic storage (MDS) system, which is a flywheel generator, while peak power storage is provided by an inductor or capacitive pulse power network. The inductive storage system may be a normal conducting current transformer with an explosive opening switch or a super-conducting inductor with an integrated opening switch. The peak power storage system is necessary because the flywheel cannot deliver the instantaneous power needed by an electric gun launcher, while the energy storage in the rotating machine is necessary because a fielded system has to be able to fire a number of shots without recharging the primary energy storage system. A prototype 10-MJ MDS used to power a public trolley bus in Basel, Switzerland, had a power rating of 150 kW; 12 of these systems have been bought. A 10-MJ, 3-kW unit has been used to power an inductor for railgun research (Heeg et al., 1993), and a 78-MJ, 5-MW unit has now been built (Reiner et al., 1993; Heeg et al., 1994). The Magnet-Motor concept for a superconducting pulsed power supply consists of many small modules that are discharged in parallel, with the charging, storage coil and switch all being immersed in liquid helium. The energy storage capability of rotating machines is attractive, but the problem is the efficiency of energy extraction and the low generator voltage—the 78-MJ machine mentioned above has an output voltage of only 500 V. While such a low voltage may be acceptable for charging an inductor, an opening switch is then required that, at least for a railgun, is a significant concern when used for a current of several megaamperes, although less critical for the lower currents required in an ET gun. Charging a high-voltage capacitor bank will require either a transformer-rectifier system or a Marx arrangement in which the capacitors are charged in parallel and then switched into a series connection.

Although the development of these machines is interesting in its coordinated application to electric guns, our judgment is that the specific technologies being applied are some years behind the capabilities of the US National Laboratories such as Oak Ridge (high-speed flywheels) and Argonne (superconductivity). The use of a superconducting system for a fieldable weapon system does not seem likely any time in the near future unless revolutionary changes in superconductivity occur.

Pfisterer (1990), from MBB, described the design and construction of a pulse-shaping solenoidal coil for a 750-kJ ET gun . The peak current was 500 kA, and the peak voltage was 100 kV. The coil inductance was variable between 10 and 40 μH. Ten turns were used with two taps for setting the inductance to 20 and 30 μH. The maximum dissipative resistance was 2 mΩ at 1 kHz, and the coil volume was less than 1 m^3 with a coil diameter of 0.6 m. The author discussed extending the operating current to 1 MA; however, it not clear whether that was with this coil or with another of a similar design. It is known that this coil proved to be very expensive, and that it has never been operated to the full original design level of 6 MJ.

The Technical University of Braunschweig has been involved in many aspects of high-voltage and high-current electrical engineering for many years. Professor Jurgen G. H. Salge is a respected advisor to the Ministry of Defense in Bonn on electric gun research. Rheinmetall funded work at Braunschweig on several doctoral theses on ET guns prior to 1985.

Recent papers include one on the benefits of metallic contact switches, namely, that they have very low resistance prior to opening (Schade et al., 1990). Such switches were first applied in nuclear fusion research where the switches were used to short circuit ("crowbar") capacitor banks after the delivered current had reached its maximum. The main problem was to get small switching and jitter times despite the necessary movement of the contact system. Three driving methods were tried: explosives, electromagnetic forces, and electrothermal techniques. Electrothermally driven switches use the pressure generated by exploding foils to establish metal-to-metal connection. Such switches have been used at several places, including Jülich, where 2-MA switch ratings were achieved with a jitter of 0.1 μs (Dokopoulos, 1968). Similar switches have been built and used in the United States for railgun facilities, including at Westinghouse,[3] at the University of Texas Center for Electromechanics[4] (both using homopolar-inductor arrangements), and at Eglin Air Force facility using a battery-inductor system.[5] Electromagnetically driven switches have also been operated in France to switch currents of up to 1.3 MA.

Also at Braunschweig, a 500-kJ inductive storage coil using commercially available circuit breakers was used for studies on high-pressure discharges (Salge et al., 1989). Current pulses up to 10 kA of nearly rectangular shape were created for pulse lengths of 1 to 10 ms.

Since at least 1987, there has been a continuing effort at the Technical University of Munich (TUM) in which electromagnetic accelerators are used to accelerate particles of 10^{-10} to 10^{-4} gm to velocities up to 20 km/s. The objective is to simulate micrometeorite damage to spacecraft, although there may be some commercial spin-off in coating material surfaces by the impact of small glass beads at hypervelocities

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[3] E. Aivaliotis and M. Peterhans, "Explosive Opening Switch Work at Westinghouse," *IEEE Trans. Magn., 25,* 1(1989), 40–45.

[4] D. R. Peterson, J. H. Price, J. L. Upshaw, W. F. Weldon, R. C. Zowarka, Jr, J. H. Gully, and M. L. Spann, "Heavy-Duty Explosively Operated Pulsed Opening and Closing Switches: Reducing Cost and Turnaround Time," *IEEE Trans. Magn., 27,* 1(1991), 369–373.

[5] R. B. Klug, R. D. Ford, D. J. Jenkins, and W. H. Lupton, "Ten Megacoulomb Switching Operation for the Air Force battery-Powered Inductive Storage Launcher Research Facility," *IEEE Trans. Magn., 27,* 1(1991), 380–383.

(Igenbergs et al., 1994). The TUM system uses a gas gun to preaccelerate a sabot containing small particles prior to the creation and acceleration of an aluminum plasma in a converging coil geometry (the "compressor coil") in which the particles are further accelerated. Then current and new facilities at the TUM were summarized by Igenbergs and Rott (1990). A flat-coil EM accelerator, driven by a portable pulsed power supply, was used to accelerate dust particles on metallic discs to 500 m/s to generate shock waves in metals and to generate short magnetic pulses. The accelerator velocity was reproducible to less than 1 percent for a given bank voltage. The ET accelerator was powered by a 8-kV, 50-kA capacitor bank and switched by an ignitron. It was used to accelerate projectiles of 43 mg and 28 mg to velocities of 3 km/s. A plasma accelerator, consisting of a coaxial accelerator with a compressor coil, has been used to accelerate microparticles to velocities up to 17 km/s. A summary of the work with the small-caliber ET accelerator was given by Rott (1994). EM railguns have also been investigated at TUM, and the work is continuing with a 300-kJ bank in cooperation with Salge at the Technical University of Braunschweig. A combined 6-mm-diameter railgun barrel with an electrothermal preacceleration was discussed by Dirr (1994). A cooperative effort was conducted with Sawaoka of the Tokyo Institute of Technology, where a 300-kJ plasma accelerator powered by a Maxwell capacitor bank has been installed. A new laboratory using a (Maxwell-supplied) 300-kJ, 10-kV capacitor bank is currently being installed at TUM (Rott, 1993). This will be used to power a railgun and a larger coaxial plasmadynamic accelerator.

The University of Karlsruhe has undertaken a wide range of pulsed power studies, some in support of the Kernforschungs Zentrum Karlsruhe, where nuclear effects simulations are undertaken.

6. India

The use of exploding foil-driven hypervelocity liners has been investigated at the Bhabha Atomic Energy Research Center in Bombay (Shyam and Srinivasan, 1984). The technology was based on that developed in the United States by Lawrence Livermore National Laboratory, although the application was different—conical target compression. In preliminary experiments, the plasma created by a small aluminum foil (6 mm × 6 mm × 25 μm thick) was ejected from the barrel of the electric gun at about 6 km/s at a voltage of 15 kV. The energy was supplied by a

20-kJ, 50-kV capacitor bank called HEXA. Conical targets were investigated, and it was calculated that, with flyer disc velocities of 10 km/s, neutron yields above the detection threshold would be obtained with cones of less than 1 mm if D-D or D-T were used. At present, to our knowledge, there is no similar work in this country, following efforts in the early 1980s in which it was estimated that impact velocities on the order of 100 km/s were needed to achieve impact fusion.

7. Israel

Studies on electric guns in Israel are undertaken at the Soreq Nuclear Research Center and are focused on electrothermal techniques to augment the velocity achievable with conventional propellants. Financial support has been received from the United States and Germany to augment the Israeli investments, although there is no present funding. Until recently, the US Army Ballistic Missile Office was supporting studies related to terminal missile defense, in which the emphasis was on attaining high projectile velocities (>2.5 km/s), but this has now stopped. Experimental work in Israel has used an electrical power system based on several E-type PFNs developed by Soreq. The system provided a two- or three-part pulse shape that matched the need of their particular ET gun concept. This had an initiation phase, in which an arc was established, followed by a two-level pulse with power levels of about 1 GW and 3 GW (Sudai and Melnik, 1993). Early experiments achieved velocities up to 1670 m/s with a 60-mm gun with a 130-g projectile using the M30 as the solid propellant for the ETC (SPETC) approach. Higher velocities, up to 2.5 km/s, are believed to have been subsequently reached.

Initial experiments were undertaken with a 60-mm SPETC gun and have been scaled up to 105 mm. Kaplan et al. (1994) reported that 50 successful laboratory and 22 field firings were carried out at the 105-mm scale with no failures of the ET fixture. These experiments used hitherto untried US M-30 propellant formulations. Experiments were undertaken at the Hellfire range at Eglin Air Force Base, Florida, in the summer of 1993, using a long-barreled (9.24 m) gun mounted on a tank chassis (Aden et al., 1994). Velocities in the range from 1800 to 2030 m/s were achieved with masses from 3.8 to 5.2 kg using stepped power pulses up to 1.9 MJ obtained from a capacitor bank on loan from FMC. Subsequently, a small mobile capacitor bank was built. The use of a pulsed inductor mounted in a tank turret to power an ET gun has been proposed. The main focus of these studies is most likely for modest increases in the launch velocity of anti-armor projectiles.

Kanter et al. (1991, 1993) described the design of a four-stage XRAM (inverse Marx) generator that was used to amplify current for studies on ET gun capillaries. An 800-V battery bank was used to charge four coupled inductors in series to 25 kJ at a peak current of 2.5 kA. The current in the load was amplified to 10 kA through solid-state switches that connected the inductors in parallel. The stored energy was transferred at an efficiency of 84 percent, and the current rise time was from 100 to 2000 μs.

Rafael, a company owned and operated by the Israeli Ministry of Defense, has some interest in electric guns and has obtained a US Patent on a combined ET and railgun accelerator that is described as follows:

> A device for accelerating a projectile to an extremely high velocity includes a launch tube having electrodes engageable with the projectile assembly for applying a large electrical voltage to it, the projectile assembly includes a pair of traveling electrodes fixed to the rear end of the projectile and engageable with the launch tube electrodes during the travel of the projectile assembly through the launch tube. The traveling electrodes define a spark gap which, under the high voltage applied from the launch tube electrodes, forms a high-temperature plasma arc traveling with the projectile and effective to increase its acceleration. [Rosenberg, 1993]

In about 1987, the Israeli Aircraft Industries contracted with Westinghouse in the United States to undertake a preliminary conceptual study of electric guns for an ATBM. However, Israel chose the missile solution and developed the "Arrow" missile.

8. Japan

Work on electric guns in Japan is undertaken at many locations, each of which has facilities of modest size. Although no major breakthroughs have been reported, the work undertaken is generally of high quality. The organizations involved are listed in Table VII.4.

In 1989, the Japan Defence Agency (JDA) reported that it had a railgun powered by a 60-kJ, 450-V capacitor bank at the Shimokita Test Center located on the northern end of Honsyuu Island (Kashii, 1989). The 1.4-m-long five-turn augmented gun used tungsten-copper alloy segmented rails and accelerated 1 g to 1.2 km/s. The studies were intended for armor tests. At the 41st ARA Meeting, a new type of accelerator, the ablation mass driver (AMD) that combines ET and EM acceleration mechanisms was described (Kashii, 1990). It used two pairs of cylindrical electrodes connected to a DC power supply to create a plasma that ablated material from the back of the projectile. A small two-stage experimental system was powered by two small capacitor banks of 6 mF and 12 mF. A 14-g projectile was accelerated to 563 m/s at an efficiency of 1.6 percent and multi-staging was demonstrated. A similar concept was studied earlier at Nagoya University (Ikuta, 1987).

TABLE VII.4
JAPANESE ORGANIZATIONS ACTIVE IN ELECTRIC GUNS RESEARCH

Organization Type	Organization Name
Government	Japan Defence Institute, Technical R&D Institute
	National Institute for Fusion Science, Nagoya
	NIMCR, National Institute of Materials and Chemical Research (formerly, NCLI, the National Chemical Laboratory for Industry)
	Institute of Space and Astronautical Science
Industry	Japan Steel Works (JSW)
	Ishikawa-Harima Heavy Industries (IHI)
	Kobe Steel
	Mitsubishi Heavy Industries
	Kawasaki Heavy Industry
	Fuji Electric Company
	Nichikon Company
	Mitsubishi Electric Company
	Hitachi Company
	Sumitomo Electric Company
University	Tokyo Institute of Technology, Yokohama
	Osaka City University
	Shonan Institute of Technology, Kanaga
	Kumamoto University

Authors from NCLI (now NIMCR) recently provided an excellent detailed description of the design and experimental performance of a 200-kJ capacitor bank and 8:1 to 16:1 pulse transformer and a magnetic flux compression generator that were used to power a small (30-mm square bore) railgun (Kadudate et al., 1992). The advantage of the pulse transformer was that a relatively low-current (tens of kiloamps) ignitron could be used to switch the current. Researchers from NCLI cooperated with personnel from Fuji Electric, Asahi Chemical, and Nichikon to develop an explosive switch for high-current commutation (Usaba et al., 1993). It was shown that 40 kA could be switched in 30 µs. In both of these studies, good technology is described that could, with additional funding, be scaled up to the level of US technology.

Researchers from the Institute of Space and Astronautical Science have accelerated metal projectiles to high velocities using a 300-kJ-capacitor-powered railgun to study high-pressure shock waves in a target for the study of space debris (Kawashima et al., 1994). A velocity of 7.6 km/s is believed to have been achieved with a Lexan projectile of less than 1 g.

The Japan Steel Works used a 200-kJ capacitor bank to undertake experiments with a 0.5-m-long 25-mm round-bore launcher and a 1-m-long 10-mm square-bore bolted launcher using plasma armatures (Maruo et al., 1988). The 4-mF, 10-kV capacitor bank employed a pulse transformer with an 8:1 turns ratio to supply currents up to 1 MA to the rail launcher. Both the main and crowbar switches were ignitrons. A velocity of 3.81 km/s was achieved with the 10-mm square-bore launcher at currents in excess of 600 kA. The same bank was also used to energize a conventional and an augmented railgun at voltages of 7 kV and 10 kV to study the effect of initial injection velocity on final velocity in a railgun, and to evaluate the effect of bore and armature materials on erosion (Maruo et al., 1991).

Japan Steel Works is also investigating an ohmic ignition chemical (OIC) launcher, which is an ETC gun based on the aluminum-water reaction triggered by the ohmic heating of an aluminum filament in water (Ikuta, 1992). The objective was to replace the compressor stage of a light gas gun with a smaller system. A cyclone was used to separate out the alumina ash from the resulting reaction, thereby permitting higher sound speed and projectile velocities. These experiments were powered by one module of a five-module, 2-MJ capacitor bank bought from, and originally used by, General Atomics in the United States.

Research on two small EM accelerators, powered by 26-kJ PFN and 150-kJ crowbarred PFNs, respectively, has been undertaken by IHI (Ohtsuka et al., 1988). Studies to evaluate foreign object damage (FOD) against high-temperature materials, such as ceramic turbine blades, was described by Uematsu and Ochi (1992). Since the exhaust from a conventional gun can contaminate the testing environment, it was suggested that an EM or ET gun may be a cleaner source of high-velocity projectiles. A new ET launcher for launching a 1-mm steel ball from a sabot was operated at currents of about 25 kA and 9 kV. Particle velocities of 1.6 km/s were achieved with a 58-mg steel ball and 1 km/s with a 120-mg ball. More recently, a 1-MJ capacitor bank designed and built by Maxwell has been installed.

A research program for the development of EML technology started at Kobe Steel in 1988 (Koide and Kitagawa, 1990). For this program and the development of armor materials, impact physics facilities were constructed and began operation in 1989. A 1-MJ capacitor bank (built by Maxwell in 1989) was used to power a 2.4-m long, 13.5-mm round-bore barrel with a 1-m-long pre-accelerator section in which 2.5-g projectiles were accelerated to 4.5 km/s. The capacitor bank was divided into two 500-kJ modules that used inductors for pulse-shaping; at least 178 shots have been reported. With the same bank, velocities of 3.2 km/s were achieved with deuterium pellets 1.8 mm in diameter and 3 mm long in studies on refueling magnetic fusion reactors. Experiments have also been conducted with a railgun in which the bore was not reamed after each shot, as is common in many cases (Ikeda, 1994). This is a necessary prerequisite for a repetitively fired fieldable railgun.

Several Japanese companies are involved to some extent in research and development on systems that could be used to power electric guns, notably Fuji Electric and Nichikon (the others are Mitsubishi Electric, Hitachi, and Sumitomo). Nichikon has achieved a capacitor energy density of 1 MJ/m^3 and was the supplier of a capacitor bank to the Institute of Space and Astronautical Science.

Mitsubishi Heavy Industries has focused their studies on the development of repetitive railgun pellet injectors for refueling fusion reactors, in cooperation with the Japan Atomic Energy Institute and Tokyo Institute of Technology. The objective is to reach 5 km/s and 2 Hz (Oda et al., 1993; Azuma et al., 1993). A 500-kJ capacitor bank has been used for these studies, and augmented railguns are under investigation.

The Tokyo Institute of Technology has accelerated micro-projectiles in a gas gun to 4.2 km/s using a plasma accelerator that is modeled on the helical design of Igenbergs at the Technical University of Munich (Tamura et al., 1989). A Maxwell 6-mF capacitor bank with an inductance of 57 nH was used to power the coil, with ignitrons for switching. Glass particles of 300-µm diameter were accelerated to 10 km/s. The projectiles were pre-accelerated by an 8-m-long gas gun and then boosted in a coaxial plasma accelerator, which consisted of concentric electrodes 20 and 48 mm in diameter, separated by a 350-mm axial gap. Projectile velocities were linearly dependent on the capacitor charging voltage: velocities up to 12 km/s were achieved with 100 to 112-µm particles and 10 km/s with 300 to 350-µm particles at 8 kV (Usaba et al., 1992).

A railgun with a helium gas gun pre-injector was developed at the Tokyo Institute of Technology to simulate the injection of a solid hydrogen pellet into a fusion reactor using a small nylon pellet (Tamura et al., 1990). The energy source was a 9.6-mF capacitor bank that was charged to 3 kV, yielding a ringing current with an initial peak of 60 kA and a second peak of 30 kA. Researchers from Osaka City University and the Shonan Institute of Technology collaborated in these studies.

Researchers from Kumamoto University collaborated with K. N. Sato, from the National Institute for Fusion Science, in studies on railguns. In one case, a permanent magnet was used to augment the railgun, and it was found that the plasma armature was more compressed (Katsuki et al., 1994). In a second study, a technique known as PISP—plasma initiation separated from the plasma—was used to provide initial acceleration of the plasma before it entered the railgun breech (Sueda, 1994). The initial plasma was produced by exploding a thin copper wire near the gun breech, followed by its acceleration to 10 km/s before it collided with the projectile. Since the current increased during the acceleration of the plasma alone, the driving force on the projectile just after acceleration was increased.

9. Netherlands

Interest in electric guns in the Netherlands started in the mid-1980s, when Hans Kolkurt, from TNO, was a visiting scientist at the US Army Research, Development, and Engineering Command (ARDEC), Picatinny. At ARDEC, the 16-MJ EMACK homopolar-generator-powered railgun system had been installed in which, during commissioning tests at Westinghouse in 1982 and subsequently at ARDEC, fiber brushes were used as the solid armature.[6] Kolkurt became involved in these experiments at ARDEC,[7] and, subsequently, TNO has maintained an interest in this approach (see, for example, Karthaus and Koops, 1993, and Schoolderman et al., 1994).

In the mid-1980s, TNO obtained a refurbished HPG from the United States, courtesy of SDIO. This machine, manufactured by Parker Kinetic Devices in Austin, Texas, was originally installed at the General Dynamics railgun laboratory in Pomona, California, but when that effort was terminated, and after repair of damage caused by a machine short circuit, it was provided to TNO and used for rep-rate railgun experiments at modest energies and velocities (see Karthaus et al., 1991). The machine was designed to deliver currents up to 1 MA when the inductor was cryogenically (LN_2) cooled; the peak current was 700 kA with an uncooled inductor. Its capability is comparable to the Westinghouse-built HPG located at Eglin Air Force Base.[8]

A fast-discharge bipolar battery-driven pulsed power supply for opening switch and rail accelerator research has been developed at TNO (see, for example, Tuinman, 1991). A detailed description of the Kapitsa facility at TNO, which consists of a 100-kJ, 172-V fast-discharge 80-cell bipolar battery, was given by Kaanders (1993).

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[6] D. W. Deis and D. P. Ross, "Experimental Launcher Facility—ELF-1: Design and Operation," *IEEE Trans. Magn.*, *18*, 1(1982), 23–28.

D. P. Deis, D. W. Scherbarth, and G. L. Ferrentino, *"EMACK Electromagnetic Launcher Commissioning,"* *IEEE Trans. Magn.*, *20*, 2(1984), 245–251.

[7] G. L. Ferrentino and W. J. Kolkurt, "On the Design of an Integrated Metal Armature and Sabot for Railguns," *IEEE Trans Magn.*, 22, 6(1986), 1470–1474.

[8] B. D. McKee and I. R. McNab, "A 10-MJ Compact Homopolar Generator," *IEEE Trans. Magn.*, 22, 6(1986), 1621–1622.

Although such a battery provides excellent compact *energy* storage (perhaps reaching 440 kJ/kg by the year 2000 in some versions), its maximum achievable *power* density (perhaps reaching 400 kW/kg by the year 2000) is not sufficient to power a railgun directly. To increase the power density, it is therefore necessary to combine the battery with an inductor or capacitor. At TNO, the inductor has been judged to have a higher energy density, and the Kapitsa facility therefore used a battery with a pulse transformer. The first-generation Kapitsa facility used a silicon-controlled rectifier (SCR) and a gate turn-off thyristor as an opening switch, which could switch off 1.2 kA in 72 μs and withstand 1.7 kV. To develop a switch with higher capability, a 10-kA/10-kV semiconductor opening switch has been studied. Thyristors performed the opening and closing switch functions, aided by a resonant counterpulse circuit (see below). Both the counterpulse and main circuit consisted of SCRs placed in series. The 10-kA/10-kV semiconductor opening switch consisted of three thyristor stacks; two 5-kA/-10 kV stacks contained six SCRs in series, while the opening function was performed by a third stack with three SCRs in series. The main problem identified with this arrangement was the difference in the reverse current risetimes of the two main stacks, because, when the first one was turned off, the second still conducted reverse current. When it snapped off, it did so at a higher dI/dt, causing higher induced voltages across the switches than with symmetrical turn-off. This effect was confirmed by P-Spice calculations. To reach the 25-kA/25-kV level, saturable inductors may have to be placed in series with each stack; in addition, more thyristors will have to be placed in parallel and in series. This may not be an attractive solution for a future fieldable weapon system.

Counterpulse techniques for high-current (up to megampere) opening switches have been discussed by van Dijk and van Gelder (1994). Such techniques utilize an auxiliary capacitor to provide a rapid counterpulse that lowers the current in the switch to near zero immediately before it is opened, thereby greatly reducing the arc damage that would otherwise occur when a high-current switch is opened in the high-current circuit of, for example, a homopolar-powered inductor for a railgun. This principle is not new but remains of interest for laboratory systems.

Considerations of benefits that might accrue from the higher muzzle velocity of EM guns compared with conventional guns were examined by researchers from TNO and the Royal Netherlands Navy. Hit probabilities were calculated for a Close-In Weapons System (CIWS), and it was concluded that the higher velocity caused considerable improvements (de Reus and van der Weijden, 1993).

10. Romania

One paper from the Institute of Physics and Technology of Radiation Devices, Bucharest, described theoretical and experimental work on the energy transfer efficiency between magnetic flux compression generators and inductive loads (Zoita et al., 1993). The work was not specifically related to electric gun studies, but similar devices have been used by others in the United States and Russia.

11. Russia

In the former Soviet Union, there has been a substantial Russian effort on power and energy technologies that are relevant to electric guns. The electric gun research does not appear to have progressed as far as in the United States, based on references obtained from the published literature, but the technology related to power system components is of considerable interest. Many organizations have been involved; the major ones are listed in Table VII.5.

One conclusion derived from the published literature is that, apart from one or two specific areas, relatively little Russian research or development is taking place (or is being *published*) on energy source miniaturization. We found no Russian papers on compact homopolars or on compact capacitor development, and evidently there has been little Russian investment in the compulsator type of rotating machine, although some pulsed alternator effort was reported.

TABLE VII.5
RUSSIAN ORGANIZATIONS ACTIVE IN ELECTRIC GUNS RESEARCH

Organization Name	Location
Applied Mathematics Institute im. M. V. Keldysh, Russian Academy of Sciences, Moscow State University im. M. V. Lomonosov	Moscow
Applied Scientific Problems Institute, Russian and Ukrainian Academies of Sciences	Moscow
Astrofizika Corporation	Moscow
Chuvash State University	Cheboksary
Electrical Engineering (All-Union) Institute im. V. I. Lenin	Istra, Moscow Region
Electrical Engineering Institute	Novosibirsk
Electrophysical Apparatus Scientific Research Institute im. D. V. Yefremov	St. Petersburg
Electrophysics Institute, Russian Academy of Sciences	Yekaterinburg
Electrophysics Problems Institute, Russian Academy of Sciences (formerly, the Electrical Machine Building All-Union Scientific Research Institute)	St. Petersburg
Experimental Physics (All-Union) Scientific Research Institute	Sarov/Arzamas-16,
General Physics Institute, Russian Academy of Sciences	Moscow
High-Energy-Density Research Center, High Temperatures Institute	Moscow
Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Branch, Russian Academy of Sciences	Novosibirsk
Krasnoyarsk State University	Krasnoyarsk
Lyubertsy Scientific-Production Association "Soyuz"	Moscow Region
Mechanical Institute im. D. F. Ustinov	St. Petersburg
Moscow Aviation Institute im. Sergo Ordzhonikidze	Moscow
Moscow Engineering Physics Institute	Moscow
Moscow (State) Technical University im. N. Ye. Bauman	Moscow
NOVIK Research & Production Corporation, St. Petersburg State Technical University	St. Petersburg
Physical Technical Institute im. A. F. Ioffe	St. Petersburg
Polytechnic Institute im. M. I. Kalinin	St. Petersburg
Russian Research Center/Atomic Energy Institute im. I. V. Kurchatov	Moscow
St. Petersburg State Technical University (formerly, Leningrad Polytechnic Institute im. M. I. Kalinin)	St. Petersburg

TABLE VII.5
RUSSIAN ORGANIZATIONS ACTIVE IN ELECTRIC GUNS RESEARCH
(cont'd.)

Organization Name	Location
Technical and Applied Mathematics Institute	Siberia
Theoretical and Applied Mechanics Institute, Siberian Branch, Russian Academy of Sciences	Novosibirsk
Thermal Physics Institute, Siberian Branch, Russian Academy of Sciences	Novosibirsk
Tomsk Polytechnic Institute im. S. M. Kirov	Tomsk
Troitsk Innovation and Fusion Research Institute (TRINITI)	Troitsk, Moscow Region

A method for designing PFNs to optimally match railgun requirements has been developed by the High-Voltage Research Center of the Electrical Engineering All-Union Institute im. V. I. Lenin in Istra near Moscow (Alekseyev and Baltakhanov, 1990, 1992; Alekseyev et al., 1992). Capacitor modules are characterized and operated as groups to give the required pulse shapes, I=I(t). To our knowledge, no similar explicit approach has been followed in the United States, although specific design choices are made in the case of each custom-built capacitor bank, generally with similar results. The Russian approach shows how the optimization can be applied in several cases, but no details are given that would permit the approach to be followed by others. The fact that this problem is being studied at all is an indication of a considerable degree of sophistication in the design and optimization of railgun power supplies. Examples are given of flat-topped pulses of 600-kA and 5-kV for 1000 μs.

The capabilities of this facility in high-voltage electrical engineering is reflected by the design and test of items such as an experimental 1.15-MV on-off switch that was used for protection of electrical transmission lines. The switch consisted of two series-connected open spark gaps with inter-electrode gaps of 1.0 and 1.5 m (Rul'skaya and Pertsev, 1985). In addition, this center has developed a range of triggered vacuum switches that are now being marketed in the West by Maxwell Laboratories under an exclusive licensing agreement. The largest of these switches is rated for 50 kA and 50 C with long life, although substantially higher values can be achieved for shorter times. These switches act as diodes to prevent reverse current flow for certain values of dI/dt and dV/dt of interest for electric gun applications (Alferov al., 1990; Vozdvizhenskiy and Siderov, 1992). Also from the same institute, V. N. Bondaletov and his colleagues have developed pulsed inductive accelerators since at least 1966, initially with single coil devices but more recently with multi(80)-stage systems (see Chapter V).

Emelin et al. (1993, 1994) provided a detailed description of a large capacitor energy storage unit that was built at the Electrophysics Problems Institute of the Russian Academy of Sciences in St. Petersburg, under F. G. Rutberg's direction. It is a new facility housed in a 30,000 square-meter building with access to a 200-MW power station for charging current. The facility has two firing pads, a 70-m evacuable flight tank, and a 12.7-mm railgun, plus 30- and 56-mm ET guns. The capacitor bank used 23 modules, each having eight capacitor cells of 94-kJ 25-kV, for a total energy of 17.2 MJ. (It is not clear whether the full 17.2 MJ was actually completed.) The facility was intended for investigations into high-voltage discharges in compressed gas, as well as for ET and inductive launchers. The output current from each cell was brought to the cable collector by four coaxial cables. The collector comprised two massive copper plates, held in place by steel slabs with a total weight of six tons. The total collector impedance was less than 6 nH, and the peak current capability was 10 MA. The individual modules could be programmed to discharge in different ways by triggering the spark gaps appropriately. Examples were shown of experimental discharges at 10 kV into a 1-μH load at up to 1.02 MA at 250 μs with simultaneous discharge, of an extended peak current of about 650 kA for 500 μs, and a flat-topped current pulse of about 300 kA for 750 μs. Although this capacitor bank was nominally rated for 17 MJ, the useful output energy may be much less because of the high internal impedance. This facility has been used to drive ET, EM, and combined ET/EM guns at currents up to 600 kA and voltages up to 10 kV (Rutberg et al., 1989; Rutberg 1993; Budin et al., 1993). It is clear that a very aggressive program has been pursued. This research group is at present undertaking contract research for Germany (TZN) on hydrogen-fueled ET guns. At the 50-mm-caliber, velocities up to 3500 m/s have been achieved with a system efficiency of 15 percent.

Large power supplies that are used for Tokamak research are also located at the Electrophysics Problems Institute. Bobrov et al. (1993) described a 242-MVA system that provides 5-s pulses for this work through inductive storage systems. It is said that up to 5-GW can be drawn off the local power line for this application.

Andriyanov et al. (1987, 1990), from the High Temperatures Institute in Moscow, described circuit designs for matching normal or superconducting (SMES) inductive energy storage systems to a utility grid and to a railgun accelerator. Inductance control can be implemented by sequential switching in current multiplication circuits. It was shown that, with three to five multiplication stages, the 15-kA initial current in an SMES could be increased to 500 kA. The main disadvantage is the appearance of overvoltages due to mutual inductance between the windings. Although these papers provide considerable theoretical detail, they do not include any experimental data for comparison. It is apparent that the superconducting nature of the SMES will make such a system difficult to consider as a fieldable device. For many applications of railguns, currents much larger than 500 kA will be required—typically 3 MA or more for large guns. In this case, the number and complexity of the required current multiplication stages will be greatly increased, perhaps to the point of impracticality. It is clear that the High Temperatures Institute has a vigorous research program on railguns and plasma armatures, as shown by the papers given at the Fourth European Symposium on EM Launcher Technology in Celle, in 1993, and the Seventh EML Symposium in San Diego, in 1994. A recent abstract from the High-Energy Density Research Center at the High Temperatures Institute mentions a new PFN for railguns, although no details are given (Ostashev and Yankovskiy, 1994).

Shishkov et al. (1990), from the Tomsk Polytechnic Institute, described explosive switches and a sectional inductor that could be used to drive a railgun. Two-, three- and eight-section inductors were tested, in which all switching elements were in one housing and operated from a single charge of explosive material (up to 10 g). Each switch section was designed for a primary current up to 100 kA; the total switching time was ≤ 100 μs. At Tomsk, considerable research also has been carried out on pulsed power generation using electromechanical energy conversion in different machines, including rotary flux compressors (Sipaylov et al., 1990). The production of millisecond flat-topped output pulses has been considered and compared with the compulsators under development at the University of Texas Center for Electro-Mechanics.

Gandilyan (1988), from the Radiophysics and Electronics Institute (Yerevan) and the Yerevan Polytechnic Institute, described inductive-capacitive energy converters in a broadly based review of such technology. In an earlier paper from the High Temperatures Institute, Lebedev et al. (1982) described explosive MHD generators. Magneto-cumulative generators and explosive MHD generators were compared, and it was noted that the MCG equipment is largely destroyed during an experiment, but not the MHD generator. However, this undoubted benefit is accompanied by a reduction in the energy density achievable with the system, from 100 MJ/m^3 and 10 MW/m^3 with the MCG to 2 to 5 MJ/m^3 and 10 to 100 kW/m^3 with the MHD generator.

Early work on explosively driven railguns at the Hydrodynamics Institute im. M. V. Lavrent'yev, in Novosibirsk, analyzed system performance in detail and referred to earlier work undertaken by Western researchers (Shvetsov et al., 1984). A 250-kJ, 5-kV capacitor bank was used as the initial energy source for these experiments and a 1.3-g projectile was regularly accelerated to 4.5 to 5 km/s in air in a 0.9-m railgun at 400 kA. At 500 kA, the projectile broke up on exiting the barrel, and the researchers noted the need for improved materials for the projectile. In a subsequent theoretical paper from the same institute, Burenin and Shvetsov (1977) analyzed the energy characteristics of a self-excited coaxial explosive MHD generator. An aggressive program of research into high-velocity railguns and explosively driven flux compressors has been conducted at the Lavrent'yev Institute for more than 10 years. An excellent survey of flux compressors as of 1982 was given by Lebedev et al. (1982). A more recent description of the explosive electromagnetic facility at the Lavrent'yev Institute was given by Shvetsov et al. (1989). The facility was comprised of a 50-kJ capacitor bank and a 10.5-m chamber in which 20 kg of high explosive can be detonated.

Considerable research on the acceleration of small particles in railguns has been undertaken at the Physical Technical Institute im. A. F. Ioffe in St. Petersburg. With a 200- to 250-kJ capacitor bank that provides constant current, gram-sized Lexan® projectiles were accelerated to over 4 km/s in a 450-mm barrel (Drobyshevskiy et al., 1991).

I. V. Grekhov at the Ioffe Institute has developed a new type of solid-state switch, the reversibly switched dynistor (RSD) that uses a controlling plasma layer and a retarded shock wave to develop three new classes of devices in a thyristor-type unit (Tuchkevich and Grekhov, 1987; Grekhov, 1989). The devices are reverse switched dynistors (RSDs), reverse controlled transistors (RCTs), and drift step-recovery diodes (DSRDs). The highest-power microsecond-range RSDs switch 300-kA single-pulse current, and 50 kA at 100 Hz. High-power DSRDs generate current pulses of 1000 A in a few nanoseconds at frequencies greater than 10 kHz. Compared with conventional devices, these units have increased switching powers of almost an order of magnitude in the microsecond range, by three orders of magnitude in the nanosecond range, and by four orders of magnitude in the picosecond range. Manufacturing technology for microsecond-range RSDs was developed by the Ioffe Physical Technical Institute and industrial enterprises. Experimental lots of these devices could switch 250 kA in a 56-mm-diameter unit, and 80-mm-diameter units were built. A 250-kA, 10-kV rep-rated switch of 80-mm diameter was built that had a pulse length of 60 µs. Several applications for such switches are described. Grekhov has visited the United States in recent years with a view to selling such devices here.

Although not directly related to electric guns, but employing similar pulsed power technologies, a compact 500-kV, 45-kJ high-repetition-rate (10 Hz) seven-stage Marx generator has been developed by the Astrofizika Corporation, of Moscow (Klyuyev et al., 1992). This is interesting, in that there are very few Russian organizations in this field that are styled as corporations.

Research undertaken by Kalikhman and his colleagues from the Chuvash State University has focused on theoretical and experimental studies on the acceleration of conductors to high velocities by pulsed magnetic fields. A maximum velocity of 10.5 km/s was achieved as early as 1973 (Agarkov et al., 1974), and Kalikhman (1985) states that "it is possible to bring cylindrical conductors up to velocities exceeding 12 km/s ... using separate sources for the accelerating magnetic field and the current in the conductor." More recently, experiments have been undertaken with a three-module 4-kV capacitor bank that stored 202.5 kJ and used solid-state switches (Kalikhman et al., 1990). Calculations showed that a 500-kJ, 30-kV supply could enable velocities of over 15 km/s to be reached (Kalikhman and Khorev, 1987).

Babakov et al. (1994), from the "Energy Physics (Energofizika)" Department of the Lyubertsy Scientific-Production Association "Soyuz," described diagnostics and instrumentation for a 10-MJ capacitor bank. The technology described would be well accepted in the West, and it was noted that the single-stage and multi-stage EM railgun complex was able to undertake two to three experiments daily. The researchers also mentioned that the control system was applicable to an energy storage system based on capacitor and inductive energy storage. In a companion paper, Babakov and Zheleznyy (1994) described an inductive energy storage system, "Mustang," powered by a solid energy propellant MHD generator in which a pulse transformer is used to convert the MHD generator output current (25 kA) to the high value needed by the railgun (1000 kA). The capacitor bank system, "EMMU-10," is based on the pulse-forming network principle and uses four modules that can be triggered independently. The source parameters are shown in Table VII.6. The results obtained with these systems are summarized in Table VII.7. In another paper on solid armatures, Khandryga et al. (1994) also mentioned experiments with a 5-MJ 4.3-kV capacitor bank that was used to power a 30-mm-bore diameter, 4.2-m-long railgun.

Table VII.6
PARAMETERS OF POWER SOURCE "EMMU-10"

Parameters	Moduls			
	KU-1	KU-2	PIAF-2.5	New (project)
Capacity, F	0.036	0.048	0.05	0.01
Voltage, kV	to 8.5	to 8.5	to 10.0	to 20
Possibility to switch on with time delay	Yes	Yes	Yes	Yes
Main switch	Spark gap	Spark gap	Mercury ignitron	Vacuum gap

Table VII.7
RESULTS OF EXPERIMENTS ON SET-UP "MUSTANG"

Macroparticle Mass (g)	Muzzle Velocity (km/s)	Railgun Length (m)	Railgun Caliber (mm)
3.8	6.8	3.0	17.5
10.0	6.2	2.0	23.0
20.3	4.85	3.0	17.5
50	3.85	2.0	23.0
100	3.2	4.2	30.0
150	2.9	4.2	30.0

Volkov et al. (1994a), from the Moscow Engineering Physics Institute, mentioned the use of a small capacitor bank (100 kJ) that was used to accelerate projectiles of 2 to 15 g to 2.5 km/s in a 15-mm-diameter electrothermal launcher with a total efficiency of 20 to 30 percent. The acceleration of small powder particles in an ET launcher with the object of creating coatings on metals and ceramics was discussed by Chebotarev and Shkolnikov (1993) and Volkov et al. (1994b).

It is evident that, for more than 20 years, Russian researchers have had a strong interest in homopolar generators for the acceleration of liners and projectiles. Examples of this interest include a book on machines with liquid metal collectors and air-cored (non-ferromagnetic) machines (Bertinov et al., 1966), and papers on the theory of non-linear HPGs (Aliyevskiy, 1984) and the design and testing of a 125-kA, 12-V prototype machine that was built for the electrolysis of nickel (Lukina and Yantovskiy, 1989).

A major reference work in this area is the book *Shock Unipolar Generators* by Glukhikh et al. (1987). This book was based on investigations carried out in the Electrical Apparatus Scientific Research Institute im. D. V. Yefremov in St. Petersburg. The authors pointed out that with HPG armature velocities in the range of 200 to 500 m/s, the stored energy densities are in the range from 18 to 112 MJ/m^3 and 2.3 to 14.5 kJ/kg. A GP-8500 generator was referenced in which 140 MJ was stored in a mass of 115 tons, that is, 1.21 kJ/kg. Of course, because of the low voltage of homopolar generators, inductors, switches, and other auxiliary components are needed that substantially reduce the *system* energy density, compared with the above values. To our knowledge, there is not a homopolar machine of similar size to the GP-8500 in the West, although similar energy densities have been achieved. (The 1500-ton homopolar machine at the Australian National University is the largest that has ever successfully operated, and it has now been scrapped.) However, it is not clear whether the GP-8500 was actually built or was just a design.

Much of the first portion of this book consists of theoretical calculations on the detailed machine design; however, in the later chapters, several experimental machines are described. One novel idea mentioned is the possibility of combining an integrated step-up transformer in the HPG to increase the output voltage. Reports are given on brush tests using solid and liquid metal brushes and US and UK work on plated fiber brushes are referenced. Much of the work reported is conventional, although an unusual "blade-type impeller" is mentioned that is said to help to retain liquid metal in the contact zone. Following pioneering work at IRD in the United Kingdom in the early 1970s, researchers at the Yefremov Institute built a disk-type superconducting generator with a sodium-potassium alloy liquid metal current collector. At 2850 revs/min, the machine generated 17 V, and it was noted that vibration of the cryostat of 0.1-mm amplitude led to an increase of about 10 percent in the evaporation rate of liquid helium. Machines with gas bearings were also built and tested to reduce losses due to bearing friction; rotational speeds of 12,000 revs/min were mentioned.

Considerable detail was provided on a 40-MJ homopolar that was initially brought into operation at the Yefremov Institute in 1981. The rotational speed was 4500 revs/min, and copper-graphite brushes were used. The rotor was run up to 2960 revs/min in about 30 sec with an 800-kW induction motor. A clutch disconnected the drive motor from the homopolar rotor during discharge. The generator was used for charging inductors, high-voltage switch testing, and for testing conductors for thermonuclear installations. The open circuit voltage was 120 V at 2950 revs/min, and currents up to 600 kA were achieved. Closing switches using liquid metals and brushes were also mentioned. This relatively conventional generator apparently operated reliably for several years with simple servicing.

A more innovative self-excited double disk machine was also built at the Yefremov Institute in 1981. This machine used two 1.08-m-diameter bronze disks arranged 1.25 m apart on one shaft. Between these two was a centrally mounted flywheel, which stored 40 percent of the rotational energy. A rotational speed of at least 1950 revs/min was needed to achieve self-excitation. At 2730 revs/min, the stored energy was given as 8.2 MJ in one reference, and as about 1 MJ in another. This machine has no iron in the field circuit, that is, it is air-cored. In the self-excited state, the rotor is spun up with a homopolar motor, which remains connected to the main shaft during discharge. Solid copper-graphite brushes are used to transfer current. Although the use of two rotors on the same shaft is unusual (and not necessarily optimum mechanically), the machine appears to owe much to the work of Robson and others at the US Naval Research Laboratory in the 1970s, including the design of explosive switches.

The design of high-current (>1 MA) contactors made at the Yefremov Institute, using liquid metals, was also described in the above book. Indium-gallium-tin was used as the liquid metal, covered with an inert gas (argon or nitrogen) to prevent oxide film formation. Not mentioned in this reference is the considerable work on inductive energy storage and opening switches with stored energies greater than 100 MJ that has been undertaken at the Yefremov Institute. Dashkina et al. (1981) mention the creation of high magnetic fields with single turn solenoids at the Yefremov Institute.

Substantial inductive energy storage systems have been designed and manufactured by the Yefremov Institute for use on high-magnetic-field tokamak experiments at the Kurchatov Atomic Energy Institute. Doynikov et al. (1992) described a 90-MJ toroidal transformer-type of inductor that was manufactured in 1988. Three different pulse power systems using inductive energy storage were compared by Druzhinin et al. (1992).

A "kilometer-long" railgun powered by HPGs is rumored to exist at Troitsk, but we have found no direct reference to such a device. A paper by authors from the Troitsk Innovation and Fusion Research Institute (TRINITI) mentions topics that could be of relevance to such a device, but only in general terms (Grabohak et al., 1992).

The Atomic Energy Institute im. I. V. Kurchatov in Moscow has been involved in the research and development of MHD generators since at least 1962 (Velikhov, 1962). However, such generators are generally not well suited to match the electrical demands of railguns because of their relatively high internal impedance and, hence, high-voltage and low-current characteristics. Experiments with small-bore railguns have been conducted at the Kurchatov Institute using a four-module capacitor bank connected with a ring-like vacuum switching tube through a cable bridge to the gun electrodes (Alekseyev et al., 1989). An application of interest to the Kurchatov Institute is for the refueling of a fusion reactor by the injection of small solid hydrogen pellets at high velocity (Alekseyev et al., 1992).

Researchers at the Moscow Aviation Institute have studied some aspects of electric guns and associated power supplies for many years. Bertinov et al. (1966) have built homopolar generators for pulsed power applications for at least 25 years. Vassyukevich (1993) presented a paper at the 1993 Pulsed Power Conference on iron-core compulsators describing work that he undertook at the Defence Laboratory of the Institute. He designed and constructed a four-pole machine having a rotor diameter of 150 mm and a length of 320 mm. Other researchers from the same institute have interest in the impact of orbital debris on spacecraft and have simulated such effects with electrothermal light gas guns. Experiments used currents up to 400 kA to accelerate 2-g masses to over 3 km/s in a 1.2-m barrel; theoretical calculations for currents up to 1000 kA were reported (Aleksandrov et al., 1993).

The Applied Scientific Problems Institute of the Russian and Ukrainian Academies of Sciences was created in Moscow recently. Several papers from this institute discuss railgun studies, including a discussion of the energy necessary to launch a 30-kg mass into orbit at 13 km/s (Lebedev et al., 1993).

The NOVIK Research and Production Corporation at St. Petersburg State Technical University has developed capacitors and high-voltage generators for eximer lasers (Komin et al., 1991a-b, 1993; Belogorskiy, 1993). Komin et al. (1991a) described the effect of pulse repetition frequency of charge-discharge cycles on the life of polypropylene capacitors impregnated with castor oil. They found that, at frequencies greater than 1 Hz, the probability of edge breakdown exceeded that of bulk dielectric failure. The worst conditions were at a frequency of 50 to 100 Hz for an applied electric field of 125 V/μm. Komin et al. (1991b) reported the development of capacitors for large pulsed power systems. The capacitors manufactured by NOVIK as described by Komin et al. (1993) were low-inductance, fast-rise units made from paper and film insulation. Voltages ranged from 30 to 130 kV and stored energies from 19 to 250 J. The authors claimed repetitive operation at up to 1 kHz with lifetimes up to 10^8 pulses. Severyukhin et al. (1991) of the "Girikond" Scientific Research Institute discussed the benefits of using metallized dielectrics compared with foil electrodes for energy-intensive monopulse capacitors with kilovolt ratings. Reduced thickness and weight, and self-healing capability were identified as the primary benefits, and an analytical relationship between the critical (breakdown) current density, pulse duration, and electrode conductance was derived. Vekhoreva et al. (1991) also discussed ways to increase the specific energy of pulse capacitors, including improved insulating materials and impregnating liquids, optimization of the dielectric structure, and reduced operating life. Pereselentsev et al. (1989), from the Synthetic Rubber (All-Union) Scientific Research Institute, investigated seven liquid dielectric insulating compounds for high-voltage film-paper capacitors. Their results indicated that compounds based on aromatic rings without lateral chains were superior to compounds based on aromatic rings with lateral chains, as well as aliphatic compounds, such as the widely used castor oil.

G. A. Mesyats and his colleagues at the Electrophysics Institute in Yekaterinburg (formerly, Sverdlovsk) have been involved in many aspects of high-power engineering for many years, particularly in connection with very high-power (TW) short-pulse (μm) systems using plasma opening switches. So far as we know, there has not been any direct application of this technology to electric guns, although the general areas of interest are similar. For example, Kotov et al. (1993) described a semiconductor opening switch capable of operating in the GW-range at voltages up to a few hundreds of kilovolts for nanoseconds. A 30-ns opening phase duration, 45-kA interrupted current and 450-kV opened voltage have been achieved with a three-stage Marx generator as the driver. Some of this type of technology has been applied to portable systems that can be used for mineral identification using electron beams.

The Experimental Physics All-Russia Scientific Research Institute at Sarov (Arzamas-16) is a nuclear weapons design and research establishment that, until recently, has been relatively unknown to the West. In capability, it appears to be similar to the Los Alamos and Livermore National Laboratories in the United States. There is substantial expertise in the design and construction of large explosive magnetocumulative generators, and, during 1993, scientists from Los Alamos cooperated in experiments at Arzamas. Explosive generators of this type have provided currents in excess of 100 MA and energies of 10 to 100 MJ (Pavlovskiy, 1993b-c). In view of the typical current-risetime of 5 μs, such devices are not directly applicable to electric guns, although this technology capability could serve as a useful base for similar technology, if appropriate. Pavlovskiy (1993a) notes that the maximum energy concentration is achieved with axisymmetrical compression of magnetic flux. The magnetic energy cumulation stabilization has achieved 1 MJ/cm^3, with the possibility of 10 times higher energy. The conceptual feasibility of 5×10^{11} J/cm^3 was discussed.

A few papers that show Russian interest in pulsed rotating machines other than HPGs have been published. These include papers on compulsators (But and Koneyev, 1991), on a comparison of cylindrical versus disc pulse generators from the Tomsk Polytechnic Institute (Chuchalin, 1990), in which the multigap disc generator was considered preferable, and an examination of several types of pulse generators (Chuchalin, 1989).

12. Ukraine

Several important contributions have been made by researchers at the New Physical and Applied Problems Institute, Ukrainian Academy of Sciences, in Kiev. Perhaps the most important was a truck-mounted 60-MJ portable pulsed power system built with four HPGs and driven by helicopter gas turbine (Petukhov et al., 1993). There is no similar system anywhere else in the world. Its performance is impressive and of interest for electric guns as well as for other stated applications: electrical welding in the field; test of powerful equipment at site; and geophysical investigations of the earth's crust by electromagnetic or impact sounding. A summary of the performance is given in Table VII.8. The system has undergone initial testing up to 60 MJ and 18,000 rpm with a pulse duration of 0.9 s and peak current of 1.2 MA. It was noted that the rotor has a limited lifetime of 1000 shots because of material fatigue.

TABLE VII.8
DESIGN PARAMETERS OF UKRAINIAN 60-MJ MOBILE PULSED POWER SUPPLY

Parameter	Value
Stored energy (four generators)	60 MJ
Peak discharge current (parallel/series connection)	2.6/0.65 MA
Voltage (parallel/series connection)	75/300 V
Inductive stored energy	17 MJ
Inductor voltage	10 kV
Gas turbine power (per unit)	350 hp
HPG rotor speed	18,000 rpm
HPG spin-up time	5 min
Rotor lifetime	1000 cycles
Total system dimensions	2.5x3x6 m
Total system mass	22,000 kg
Rotor length/diameter	400/400 mm
Current collector diameter	250 mm
Time to peak current after load switch closure	0.5 s
Number of toroidal inductor segments	24
Inductance	5 µH
Inductor mass	7200 kg

Several authors from the same institute have also discussed a linear electromechanical generator (LEMG), or linear magnetic flux compressor, as a power supply for a railgun (Kapustyanenko et al., 1993). This can be regarded as a momentum transformer in which a massive, relatively slowly moving armature is fired into a non-linear spiral winding. This compresses the magnetic flux previously established by a capacitor bank and generates a high current that feeds the railgun circuit. Table VII.9 summarizes the proposed design.

TABLE VII.9
DESIGN PARAMETERS OF UKRAINIAN LINEAR ELECTROMECHANICAL GENERATOR FOR RAILGUNS

Parameter	Value
Generator winding length	1.5 m
Number of generator sections	5
Generator armature mass	20 kg
Generator armature velocity	500 to 700 m/s
Initial generator current	15 to 25 kA
Launcher length	2 to 4 m
Projectile mass	0.05 to 0.2 kg
Muzzle velocity	2.1 to 4.8 km/s
Acceleration efficiency	0.2 to 0.3
Time to peak current	~3 ms
Time to peak velocity	4 to 5 ms

A theoretical paper by Pignastey (1993) from the same institute discussed a self-excited magnetic flux compressor in detail, but no practical data was provided.

A. D. Lebedev from the New Physical and Applied Problems Institute collaborated with two coworkers from the Lyubertsy Scientific-Production Association "Soyuz" near Moscow on an experimental study of plasma armatures in railguns (Lebedev et al., 1992). Their system used a three-module capacitor bank, storing 1.7 MJ, 2.0 MJ, and 2.5 MJ, which were connected together to the load with ignitron switches. The charging voltage was 2 to 8 kV. Capacitor types IM-5-140, K-41-47, and K-75-40 were used. A 2-m bolted barrel of 23 mm square bore was used with a 23-g projectile. Currents just over 1 MA were used for pulse durations of about 1 ms, and velocities up to about 4 km/s were achieved.

A detailed evaluation of an homopolar generator coupled to a storage inductor and used to power a plasma load was undertaken by Dubovenko (1991). A disk-type HPG and two-stage switching using a mechanical breaker followed by an explosive switch were assumed. The generator considered had a steel rotor with a diameter of 0.7 m and stored 1.24 MJ. The deceleration time of the generator was 35 ms, and 109 kJ was transferred to the inductor, which reached a peak current of 260 kA. Of this, 64 kJ was transferred into the discharge in the plasma channel. The application of the plasma discharge was not discussed.

Shikhal'yev (1991), from the Problems in Simulation in Power Engineering Institute in Kiev, discussed the thermal problems of brush and rotor surface heating in HPGs. The study was very mathematical, and only non-dimensional parameters were given, although mention was made of comparison with experimental data.

An evaluation of scaling effects in "impact solenoid motors," by researchers from the Electrodynamics Institute of the Ukrainian Academy of Sciences, revealed many similarities with coilgun technology, although no reference was made to such an application. For armature masses ranging from 0.1 to 12,500 kg, velocities of 401 to 465 m/s were mentioned with maximum current requirements ranging from 0.149 to 7.47 MA, respectively (Kucheryavaya et al., 1986). Podoltsev (1990) and Chemeris et al. (1991), also from the Electronics Institute, have evaluated and built rotary pulse generators.

13. United Kingdom

Significant work on electric guns is taking place in the United Kingdom (primarily England and Scotland), coordinated through the Defense Research Agency (DRA, formerly known as the Royal Armament Research and Development Establishment, RARDE)), based at Fort Halstead near Sevenoaks in Kent, England. Efforts are being supported within DRA and in industry or university on all three types of electric guns. In July 1993, DRA commissioned a major (32-MJ) capacitor bank system located at a tank gun firing range in southwest Scotland. This was built with the assistance of the United States. UK organizations known to be active in this field are listed in Table VII.10, and their work is summarized below.

TABLE VII.10
UK ORGANIZATIONS ACTIVE IN ELECTRIC GUNS RESEARCH

Organization Type	Organization Name
Government	Defence Research Agency (DRA)
	Culham Laboratories
	Royal Military College of Science (RMCS), Shrivenham
Industry	International Research & Development Co., Ltd. (IRD)
	Royal Ordnance (RO)
	British Aerospace (BAe)
	English Electric
	GEC-Marconi Radar and Control Systems
	Straughn and Henshaw
	Rolls Royce
	Norfolk Capacitors, Ltd. (NCL)
	Fluid Gravity Engineering
University	Loughborough University
	University of Bath
	Cambridge University
Consulting Companies	Aerobel
	JEM Systems
	Frazer-Nash Consultancy

The DRA has been the national focal point for all electric gun studies in the United Kingdom since the early 1980s. DRA's interests have focused on the application of high-velocity projectiles launched from EM railguns for the anti-armor mission, but there is now a growing interest in applications of ETC technology. DRA has a vigorous and well-coordinated effort in this area, with 16 engineers/technicians presently employed in this area alone. DRA interacts with the all the UK armed forces, but the principal interest to date has been from the British Army for the anti-tank mission.

The first experimental system at DRA was a railgun that used a 6.7-MJ (stored energy) HPG manufactured by IRD (Bloyce, 1993). This permitted DRA to obtain experimental experience with electric guns, but the pace of work was hampered by the relatively low current achievable with the system (about 400 kA) and the unreliability of the brush-gear. An explosive switch that used linear shaped-charge explosives to cut thin-section busbar material was developed for use with this system and demonstrated up to 320 kA (Reip et al., 1989). To replace this machine (which is no longer in use), the DRA railgun group now has in operation, or is planning, several other energy storage systems using capacitors for experimental purposes. An existing 1-MJ capacitor bank is being upgraded to 4 MJ for railgun operations at Fort Halstead.

Most importantly, DRA commissioned a 32-MJ capacitor bank at the tank test range in Kirkcudbright, Scotland, in July 1993 (Haugh et al., 1994). Two large-bore (90-mm) railguns, provided by the United States (built by Sparta and IAP), are part of this facility, together with a 40-mm laminated barrel built by DRA. GEC-Marconi was the prime contractor for the facility contract, and Physics International from the United States assisted with the design of the system. Capacitors and fuses were procured from Maxwell, and the system was assembled on site by Straughn and Henshaw. As of early 1994, the system has been assembled and over 10 shots fired at currents in excess of 3 MA with projectiles up to 6 kg, resulting in considerable damage to the Sparta barrel

Edwards (1994) refers to a DRA review of electrothermal, liquid propellant (LP), and solid propellant (SP) gun propulsion programs and notes that a decision was subsequently taken to increase funding in the ET area. DRA recently purchased a US-built flexible multi-modular 500-kJ capacitor bank for ETC experiments with guns and closed vessels in Fort Halstead (Augsburger et al., 1994a), together with a small 80-kJ, 80-kV system for ETC gun research.

Two recent papers by the DRA Combat Vehicles Department illustrated the growing interest by DRA in tank gun weapon applications. Gordon (1994) addressed the electrical power transmission issues, and Johnson (1994) discussed the effects of cooling and pulsed power system sizes on tank design and operation. Johnson concluded that, even if reductions in the size of the pulsed power system occurred, the size of the auxiliary systems (prime power generation, electrical power transmission and cooling) will become the principal concerns in the design of a future tank using a railgun. He also concluded that the cooling and power transmission systems are unlikely to be reduced in size, since they depend on fundamental physics. Gordon studied the design of busbars, cables, and connection devices, and their influence on the design of a tank using a railgun. He concluded that, while electrical power transmission within the tank can be practical, it will strongly influence the vehicle design. Such studies are very dependent on the starting assumptions—for example, if a high-efficiency ET gun were assumed in place of the EM railgun, substantially different conclusions might result.

Culham Laboratories, once part of the UK Atomic Energy Authority but now a laboratory primarily concerned with fusion experiments and diversification into industrial applications, has considerable experience in pulsed power systems. An excellent review of the pulsed power systems installed for fusion research by James et al. (1987) includes a description of 1- to 10-MJ capacitor banks with pulse lengths of 50 µs to 50 ms, a 125-ms 100-MJ inductive system, a 10-sec 100-MJ rectifier converter, and a 2.5-GJ rotating generator that delivered 2-sec 10-kV 100-kA pulses. For several years up to about 1992, Culham had some small-scale experimental work with a 10-mm-bore railgun driven by a capacitor bank, but this work is no longer active. Culham also undertook modeling and experimental research on compulsator-type machines (Spikings and Putley, 1991) and identified the current pulse requirements for railguns (Putley, 1991). A 9.2-kW AC Schrage motor that stored 40 kJ inertially at its maximum speed of 3500 revs/min was modified to operate as a four-pole machine with two separate windings on the rotor and six on the stator. Good agreement with theory was demonstrated when magnetic saturation effects in the rotor iron were considered. It was concluded that it would be possible to produce the required railgun pulse shape (flat-topped) using a selective passive compulsator.

At the Royal Military College of Science (RMCS), in Shrivenham, experimental work has been undertaken on explosive MHD generators (Crowley et al., 1993). Propellant combustion devices have been studied using a modified 105-mm howitzer, in which the propellant is loaded in the same way as in a conventional gun. A 50-mm throat diameter convergent-divergent nozzle, located in front of the combustion chamber, accelerates conducting gas into a 60-mm-diameter short duct, followed by an exit diffuser. The duct uses opposed or diagonal electrodes. With this equipment, experiments showed that hot gun propellants provided a reasonable propellant base, with aluminum and potassium nitrate being promising additives. Experimental studies were also undertaken with 5-mm-diameter shaped-charge jets at velocities up to 10 km/s (Fanthome et al., 1989).

In the 1960s and 1970s, IRD, located in Newcastle-upon-Tyne, developed room-temperature and superconducting HPGs for several applications, including ship propulsion. A 1500-hp superconducting motor and generator were built for installation in a naval mine-sweeper, but the project was never completed. A room-temperature HPG, originally built by IRD for another customer, formed the basis of the 6.7-MJ pulsed energy supply used for railgun experiments at DRA. Using the same approach as in US versions of the same technology, the current pulse from the HPG was shortened by storing energy temporarily in a room-temperature inductor, prior to switching it into the load with an explosive switch. The weak point of this system was the transfer of current from the generator rotor to the output circuit via brushes. As a consequence, the generator was limited to a current rating of about 400 kA and is no longer in use. More recently, IRD, now owned by Rolls Royce, assisted DRA with studies on pulsed power and energy technology, including an evaluation of high-current (2.5 MA) self-excited HPGs for use with railguns (Mitcham, 1988; Mitcham et al., 1989). Two machine designs were considered—one using a single rotor and one using two contra-rotating rotors. The use of liquid metal sodium-potassium (NaK) eutectic alloy current collectors were proposed for these machines, and it was concluded that they would be ideally matched to railgun requirements. Such studies followed similar studies by Westinghouse and the University of Texas Center for Electromechanics (UT-CEM) for the US Army.[9] To our knowledge, none of these machines was ever built.

British Aerospace (BAe) has used modular 150-kJ and 500-kJ capacitor banks at its Sowerby Research Center for experiments with ET guns (Thornton and Spikings, 1993; Spikings and Thornton, 1993). Both of these systems used Maxwell capacitors. In addition, Royal Ordnance (now owned by BAe) has procured a 2.4-MJ eight-module 11/22-kV capacitor bank from the United States for its test site at Faldingworth, Lincolnshire (Augsburger and Hewkin, 1994b). This is being used for ETC gun research.

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[9] See, for example, D. Ohst and D. Pavlik, "A Series-Wound Air Core Homopolar Generator," *IEEE Trans. Magn.*, *25*, 1(1989), 387–392.

The Tube Division of the English Electric Company, located in Lincoln, is one of the two leading manufacturers of mercury-filled ignitron switches in the West (the other is National in the United States). Ignitrons are widely used in laboratory pulsed power systems, although there are increasing indications that their manufacture and use may be phased out in the future because of environmental concerns associated with the use of mercury.

GEC-Marconi is a Division of the General Electric Company (not related to GE in the United States), which is the largest electrical manufacturing organization in the United Kingdom. GEC-Marconi was the integrating contractor for the Kirkcudbright electric gun facility but is not known to have any other activity in this area at present. However, other parts of GEC are developing solid-state switches that have promise for moderate current applications in electric gun systems.

Straughn and Henshaw, Ltd., assembled the pulsed power modules for the DRA Kirkcudbright facility, working as a subcontractor to Marconi and with guidance from Physics International. At present, they are not known to have any other work in this area.

Rolls Royce, Ltd., is the largest manufacturer of gas turbines in the United Kingdom and one of the largest in the world. It has shown interest in developing dual power level turbines for use with fieldable electric guns that could operate at about 1 MW to power the vehicle transmission, but which could provide a surge capability (up to a few megawatts) to charge up a capacitor bank or spin-up a rotating machine in readiness for gun firing (Reynolds, 1991). Because of its acquisition of IRD's parent company, Rolls Royce also participated in studies of the entire power train for a vehicle with an electric gun, from fuel to electrical input to the gun. Such studies point up the need for optimization of the entire vehicle system, not just a single component.

Norfolk Capacitors, Ltd., is the main indigenous manufacturer of pulsed power capacitors in the United Kingdom. Their 50-kJ units are being utilized by DRA to upgrade an existing 1-MJ bank to 4 MJ.

Loughborough University has recently undertaken studies on self-excited explosive MHD generators, possibly in support of the program at RMCS, Shrivenham (Senior et al., 1993). The proposed design used "meat-grinder" techniques to match the energy source (a battery) to the excitation coil, and the generator to the load impedance (Giorgi et al., 1986). Other work at Loughborough has centered on investigations of inductive coil launchers.

The main contribution of the University of Bath to electric gun research has been to develop a modeling code (MEGA) that can be used to evaluate electromagnetic effects. This has been sold and is used in the United States as well as the United Kingdom. However, recent papers have described the construction of a small iron-cored compulsator (Eastham et al., 1993, 1994). The objective of this work was to validate the numerical analysis describing the use of single- and multi-phase outputs and concentrically and sinusoidally distributed windings.

Aerobel Defence Technology, Ltd., is a small consulting company that has performed a number of electric gun studies on DRA applications, including a comprehensive study of main tank armament (Blackburn and Wroebel, 1991). In this study, the authors evaluated three options for the future Main Battle Tank (MBT), although the paper gives only a very superficial summary of the results. Stated assumptions were that the initial operational capability (IOC) is early next century, and the key design goals are increased armor penetration (by 50 percent) and reduced response time (by 50 percent). The required projectile muzzle energy was unstated, but was probably about 20 MJ. On the basis of Aerobel's simulation models, three concepts were down-selected for further study, namely:

(1) a hybrid railgun with a powder gun pre-accelerator, energized by two contra-rotating self-excited HPGs (through a multi-shot opening switch) and powered by a gas turbine;

(2) a hybrid ET gun energized by capacitors and powered by a diesel engine; and

(3) a pure ET gun energized by capacitors and powered by a gas turbine.

Option (1) required about 55 MJ of input energy per shot, of which 30 MJ is chemical and 25 MJ is electrical. The power supply has to deliver 2.5 MW to provide a shot approximately every 10 sec.

Option (2) needed a total of 80 MJ of energy, of which 16 MJ was electrical—delivered by four plasma generators—and 64 MJ was chemical energy released from the exothermic working fluid. With an uprated (2 MW) diesel engine, the energy store would be replenished in 8 sec with a 100-percent efficient system.

Option (3) used an endothermic working fluid (such as water), and much more electrical energy was therefore needed—100 MJ was mentioned.

Such studies are very dependent on the input assumptions, which change with time to reflect the state of the art. Given the present state of energy storage technology, it seems unlikely that systems with energy demands as high as those quoted above will be practical for fielded weapons within a reasonable future. More recent studies have been undertaken by Aerobel (Wroebel, 1993; Dickerson and Wroebel, 1993).

Frazer-Nash Consultancy, Ltd, has assisted DRA by performing analyses on various aspects of ETC gun operation. This includes the pulse shape requirements for an ETC gun (Guyott, 1994a), thermal and electromagnetic signature management (Guyott, 1994b), and spectroscopy on exploding wires. The system implications of installing a capacitor or compulsator power supply on board a ship for a medium-caliber indirect-fire ET gun were examined (Guyott, 1993).

D. PROJECTIONS FOR THE FUTURE

It is very difficult at present to predict the direction of research and development in Russia and the other countries of the former Soviet Union. Clearly, there are many talented and capable researchers who have produced excellent work in the past. Given the funding and infrastructure, there seems little doubt that they could continue to do so. However, those are two elements that can not be guaranteed. The apparently free and open interchange between Russia and the Western and Eastern countries indicates that Russian researchers are actively searching for funds and support for the technologies that were hitherto devoted almost entirely to defense efforts. One of many such examples is the agreement to make available the triggered vacuum switch for sale in the West. This is an important component that can improve the efficiency of pulsed power systems.

In Western Europe, the major efforts are taking place in the United Kingdom, France, and Germany, with the latter two countries having pooled their resources in a cooperative research program. Although these countries started their studies after the United States, they have steady efforts that are directed at the relevant technological areas. Less total funding is being applied to the electric gun programs than in the United States (before recent reductions in the United States), but more careful planning and execution seem to have made the programs more effective. In addition, all three countries appear well aware of efforts in the United States and Russia and have either bought complete pulsed power systems from US manufacturers or have utilized key US components (such as capacitors, fuses, switches) in many systems whose design and/or assembly has been provided or assisted by US companies.

There are signs that this approach is changing, with concerns being openly discussed about the dependence on US suppliers (for example, see IDR, 1993). Taken together with the improved technology being developed in Europe, it seems likely that the United Kingdom, France, and Germany will have much greater influence in this field in the future.

If we had to choose a few notable areas now, we would say that the work at ISL on solid-state switching offers the possibility of developing modular compact capacitor banks that will be of considerable interest for future large systems. The Rolls Royce studies on dual-power gas turbines offer the possibility of achieving a compact unit that could act both as the vehicle prime mover and as the power supply for the electric gun energy source. In Germany, the development of combined generator-flywheel assemblies specifically for powering rep-rated electric guns may also be important.

In the former Soviet Union, several significant laboratory systems have been built, but there is doubt as to whether these are still fully operational. The assembly of a 60-MJ portable system comprised of four HPGs powered by helicopter gas turbines exceeds anything that has been achieved in the West. However miniaturization of this technology has not been discussed in the published literature, either for rotating machines or for capacitors.

In Asia, Japan has been the leading research country until now in terms of the number of organizations involved. However, well-directed Chinese programs are beginning to emerge at a larger scale and with a clear focus on projectile penetration of armor. The Japanese effort has been widespread but on a small scale (perhaps limited by the relatively small defense budget); several innovative technical approaches, such as the use of current transformers, have been employed. To date, there have been no major technological breakthroughs in the energy storage area, although Japanese companies are known to be working on high-energy density capacitors.

E. KEY RESEARCH PERSONNEL AND FACILITIES

The key non-US research personnel in energy storage and power supplies and the facilities with which they are affiliated are listed in Table VII.11.

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES

Researchers	Facilities	Areas of Expertise
	China	
Yanhuang Zhou	East China Institute of Technology, Nanjing	Design of ET guns
J. Cheng Siyao Cheng Songyuan Dai J. M. Li Yahong Li Yanqin H. Liu L. X. Nie Zhaoyuan Y. Ning Zhaoxing X. Ren (Director, ELL) Keming M. Shen Q. Shi S. H. Sun T. S. Tang Y.ongchen C. Wang X. J. Wang Songtao Wu J. Z. Xu Damao Yao Shuquing Q. Zhang	Institute of Plasma Physics, Academy of Sciences (Academia Sinica), Hefei	Capacitor banks; railgun experiments; solid armatures
W. S. Hou Y. Y. Juo P. S. Song C. C. Tzeng C. K. Yeh T. R. Yeh M. Yen T. Z. Yu	Nuclear Energy Research Institute, Lung-tan, Taiwan	Capacitor banks; railgun experiments; plasma guns
Quihua Chen Shunshou Gao Xinggen Gong Zongyi Li Xinping Long Jianxun Shi Chenwen Sun Zikui Zhou	Southwest Institute of Fluid Physics, Sichuan	Plasma armature; railgun experiments; capacitor banks

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	France	
J. Jacquelin R. Mailfert F. Moisson	Alcatel-Alsthom Research	Coilguns
P. Aubouin Jacques Bouchet S. Bouquet Richard Dormeval Emmanuel Jacob Pierre Noiret S. Roux P. Seytor-Benetruy L. Véron	Atomic Energy Commissariat (CEA), Vaujours-Monronvilliers, Courtry	ET guns–theory and experiments; modeling
P. Mailfert F. Moisson	Compagnie de Guerre Electronique (CGE)	Superconducting transformers
P. Coelho	CNRS–National Telecommunications Research Center	Capacitor development
Guenther Buderer R. Charon K. Darée D. Eckenfels C. Gauthier L. Gernandt F. Hatterer Dieter Hensel Francis Jamet Philippe Kienner Pascale Lehmann Johann Nett Hilmar Peter Nicolas Silvestre Emil Spahn Volker Wegner W. Wenning Joseph Wey	French-German Research Institute Saint-Louis (ISL), Saint-Louis	Railgun experiments; armature development, ET gun research; code development for railguns; semiconductor switching
J. L. Sabrie	GEC-Alsthom	Coilguns

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	France (cont'd.)	
J. M. Bonigen G. Marguet M. Steiger	Haefley	Capacitor development
Michel Bramoullé	LCC-St. Apollinaire	Capacitor development
M. Jarnieux P. Lombard G. Meunier G. Reyne	Grenoble Electrotechnical Laboratory, CNRS	Modeling of coilguns
P. Jaquelin H. Mantel P. Deneuville	Matra	Explosive MHD generators
O. Becle B. Vinter	Thomson-CSF	Light-activated switches
G. Bauville A. Delmas P. F. Desesquelles N. Haddad P. Lequitte J. C. Luchet M. Omeich G. Quichaud C. Rioux	University of Paris South, Orsay	Vacuum switches; pseudospark switches; meat-grinder circuits; pulsed alternators
	Germany	
D. Britting G. Eyring T. Karasinski K. P. Zocha C. D. Zwingel	Diehl GmbH	Semiconductor switches; optical gun techniques; ET gun concepts
H. Hilgendorf K. Gruber	IABG	

TABLE VII.11

KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Germany (cont'd.)	
Peter Ehrhart Manfred Heeg G. Heidelberg G. Reiner W. Weck	Magnet Motor GmbH	Rotating machines; inductive coils; coilguns; superconducting coils
M. Pfisterer	Messerschmitt Bolkow Bohm (MBB)	Inductor design and fabrication
Sigmund Jungblutt	Rheinmetall	E-gun facilities and components
A. Arndt H. D. Block C. Hoppe T. Kloppenberg Markus Löffler F. Podeyn B. Schmidt F. Schmuck H. Stuwe H. G. G. Thomas Weise	Technology Center North (TZN)	ET gun research; capacitor banks; pulsed power applications; coilguns; modeling; control systems
Ulrich E. Braunsberger Dieter W. Schade Jurgen G. H. Salge H. G. Wisken Harald W. Fein	Technical University of Braunschweig	Aerophysics; ET gun concepts; metal-to-metal switches; inductive power supplies
K. Barkawi Uwe H. Bauder Bernhard Dirr A. Hudepohl Eduard Igenbergs W. C. Reschauer Martin Rott Josef Sporer Peter Thomas	Technical University of Munich (TUM)	Microparticle acceleration; ET plasma accelerators; railguns; metal coatings by impact; MHD codes
	Israel	
Alfred Frohlich	Israeli Aircraft Industries (IAI)	EM gun studies
Gideon Rosenberg	Rafael	ET/EM gun patent

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Israel (cont'd.)	
R. Alimi R. Hareuveni M. Kanter Zvika Kaplan David Melnik L. Perelmutter Daphne Plotnik D. Saphier M. Shaked Morris Sudai S. Wald	Soreq	ET gun development; XRAM circuits
	Italy	
Ermanno Cardelli	University of Perugia	Solid-armature analysis
G. Becherini Nunzio Esposito M. Maffei M. Raugi A. Tellini	University of Pisa	Plasma armature modeling; linear homopolar generators; magnetic flux compression generators
	Japan	
Nobuki Kawashima Akira Yamori	Institute of Space & Astronautical Sciences (ISAS)	Railgun experiments
Masao Ochi Takenori Ohtsuka Shigeru Sato K. Uematsu	Ishikawajima-Harima Industries Co. (IHI)	Small railgun experiments
K. Kasawi K. Hasegawa	Japan Atomic Energy Research Institute	Railgun pellet injector for fusion reactors
H. Kashii	Japan Defence Agency (JDA)	ET/EM gun theory and experiments

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Japan (cont'd.)	
K. Fujioka K. Ikuta T. Maruo K. Nagaoka S. Nakamura K. Nemoto A. Okamoto R. Tsukamoto Y. Uehara	Japan Steel Works (JSW)	Railgun erosion and materials; railgun pre-acceleration; augmented railguns
Shushi Ikeda Masahiro Kanno Kenji Koide Yoshikawa Kitagawa K. Moyama T. So	Kobe Steel	Railguns for reactor refueling; impact physics; spout holes in railguns
Hidenori Akiyama N. Eguchi Sunso Katsuki S. Maeda M. Soejima T. Sueda	Kumamoto University, Department of Electrical Engineering & Computer Science	Plasma armatures in railguns
K. Azuma S. Kuribayashi Y. Oda M. Ogino M. Onozuka T. Satake K. Shimizu T. Tsujimura	Mitsubishi Heavy Industries	Railgun injectors for fusion reactors
K. N. Sato	National Institute for Fusion Science	Fusion reactor refueling with railguns
Katutoshi Aoki Shyuzo Fujiwara Yozo Kadudate Katsumi Tanaka Shu Usaba Masatake Yoshida	National Institute of Materials & Chemical Research (NIMCR—formerly, the National Chemical Laboratory for Industry/NCLI)	Railgun experiments; explosive switches

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Japan (cont'd.)	
Migiwa Kohno	Shonan Institute of Technology	
K. Dan T. Fushida Ken-ichi Kondo Akira B. Sawaoka H. Tamura T. Tohyama K. Ueda	Tokyo Institute of Technology	Microparticle acceleration; plasma accelerators; railgun development
	Netherlands	
N. M. de Reus M. A. M. Kanders Willem Karthaus W. J. Hans Kolkurt M. Koops W. H. P. Mosterkijk J. Nowee Arnold J. Schoolderman E. Tuinman Edwin van Dijk Peter van Gelder	The Netherlands Organization for Applied Scientific Research (TNO), Prins Maurits Pulse Physics Laboratory (PML)	HPG railgun system; solid-state switch development; bipolar battery development; fiber armatures; counterpulse switching; naval CIWS evaluation
	Romania	
A. Ludu B. Novac V. Zambreanu V. Zoita	Institute of Physics & Technology of Radiation Devices, Bucharest	Magnetic flux compression generators

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia	
M. P. Galanin V. P. Ignatko S. S. Khramtsovskiy S. I. Muchin Yu. P. Popov	Applied Mathematics Institute im. M. V. Keldysh, Russian Academy of Sciences, Moscow	Mathematical modeling
V. A. Aleksandrov Yu. N. Ivanov I. G. Krivonosov S. A. Leonov M. M. Orlov A. V. Panshin G. A. Popov V. K. Tyutin A. S. Voinovskiy P. V. Vassyukevich M. I. Zaytsev	Applied Mechanics & Electrodynamics Research Institute, Moscow Aviation Institute im. Sergo Ordzhonikidze, Moscow	Iron-core compulsator; high-frequency pulse generator; ET macroparticle accelerator; plasma accelerators; spacecraft damage effects
V. D. Belik A. D. Lebedev C. C. Milyayev B. A. Uryukov	Applied Scientific Problems Institute, Russian & Ukrainian Academies of Sciences, Moscow	Wall friction in EM launchers; EM launch to space
A. V. Klyuyev Yu. S. Mityakov S. Yu. Nekipelov Yu. L. Sidorev	"Astrofizika" Corporation, Moscow	Marx generators
V. F. Agarkov A. A. Blokhintsev V. N. Bondaletov V. N. Fomakin S. A. Kalikhman A. V. Khorev V. I. Kuznetsov V. A. Lots V. N. Pichugin A. A. Tsarev	Chuvash State University im. I. N. Ul'yanov, Cheboksary	Pulsed magnetic field acceleration

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
Aleksey V. Alekseyev D. F. Alferov A. M. Baltakhanov A. P. Bashun G. Z. Ber Vladimir N. Bondaletov V. A. Derevtchikov V. P. Gal'yetov I. M. Gavrilov G. M. Goncharenko A. A. Gusarev Ye. N. Ivanov A. I. Kapustin A. F. Kharchenko A. V. Lovenetskiy Yu. V. Markitanov M. G. Nikiforov A. A. Pertsev S. R. Petrov M. I. Ral'chenko L. A. Rul'skaya I. O. Sibiryak V. A. Siderov S. E. Svyatenko V. A. Tyut'kin R. I. Valeyev I. A. Vasil'yev T. G. Vlasova V. A. Vozdvizhenskiy V. S. Yeremenko V. I. Zherigin	Electrical Engineering All-Russia Institute im. V. I. Lenin, Istra, Moscow Region	PFNs for railguns; megavolt switches; pulsed coil accelerators; 2.5-MJ capacitor bank assembly; high-voltage pulse generators; vacuum switches
I. S. Gerasimov V. I. Ikryannikov	Electrical Engineering Institute, Novosibirsk	Current flow in metal at high-current densities
G. A. Baranov S. I. Dashkina A. S. Druzhinin V. A. Glukhikh	Electrophysical Apparatus Scientific Research Institute im. D. V. Yefremov, St. Petersburg	Pulsed HPGs; high-field solenoids

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
A. L. Filatov Yu. A. Kotov S. K. Lyubutin G. A. Mesyats S. N. Ruykin	Electrophysics Institute, Russian Academy of Sciences, Yekaterinberg	Megavolt semiconductor opening switch
V. M. Bobrov A. V. Budin A. E. Bystrov P. Yu. Emelin B. E. Fridman A. M. Glukhov V. L. Goryachev Ye. G. Kasharskiy A. M. Khodakovskiy V. A. Kolikov A. I. Kulishevich A. G. Kuprin B. P. Levchenko V. V. Leont'yev I. P. Makarevich M. Y_. Platonov F. G. Rutberg A. F. Savvateyev N. A. Shirokov S. V. Tomp A. M. Voronov S. V. Zakarenkov	Electrophysics Problems Institute, Russian Academy of Sciences, St. Petersburg	Pulsed flywheel generators; arc-heated light gas launchers; 4-MJ capacitor bank; HPG/inductive power system; energy balance in ET launcher; 17.2-MJ capacitor bank; launcher test stand; plasma generators; EM/ET launcher; high-pressure arcs
A. Ya. Brodskiy V. K. Chernyshev V. A. Demidov A. N. Demin I. V. Ivanov V. I. Kargin Y_. P. Korchagin A. S. Kravchenko R. Z. Lyudayev G. F. Makartsev P. V. Mironychev M. V. Musatova	Experimental Physics All-Russia Scientific Research Institute, Arzamas-16/Sarov, Nizhniy Novgorod Region	Explosive opening switches for helical EM generators; disk explosive generators; magnetocumulative generators; 10- to 100-MA complex; 10- to 100-MJ complex

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
A. S. Pikar N. F. Popkov V. A. Shvetsov V. I. Shpagin A. I. Pavlovskiy E. A. Ryaslov Yu. P. Vlasov G. I. Volkov Yu. V. Volkov A. S. Yuryzhev	(cont'd.) Experimental Physics All-Russia Scientific Research Institute, Arzamas-16/Sarov, Nizhniy Novgorod Region	Explosive opening switches for helical EM generators; disk explosive generators; magnetocumulative generators; 10- to 100-MA complex; 10- to 100-MJ complex
G. A. Askar'yan I. V. Gosudarev I. D. Klebanov	General Physics Institute, Russian Academy of Sciences, Moscow	Plasmas in railguns
V. V. Andriyanov E. V. Anis'kin V. P. Bayev A. Yu. Bodrov V. E. Fat'yanov O. V. Fat'yanov V. E. Fortov N. A. Kazantsev M. M. Kondrashenko Dmitri Kondrashov N. S. Korovin Ye. F. Lebedev G. A. Mesyats V. Morozov V. Ye. Ostashev M. B. Parizh A. Rakhel V. I. Safonov V. S. Sheynkman A. V. Shurupov V. Skvortsov A. N. Uchvatov A. V. Ul'yanov B. D. Yankovskiy V. Zatelepin A. A. Zubkov	High-Energy Density Research Center, High Temperatures Institute, Russian Academy of Sciences, Moscow	Plasma armature simulation; material explosion by pulsed currents; capacitor PFN; plasma railgun experiments; variable inductor for SMES; numerical codes for MHD flow; magnetic field diffusion; explosive MHD generators

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
A. G. Chervyakov V. L. Korol'kov A. A. Shishkov	High-Voltage Scientific Research Institute, Siberian Branch, Russian Academy of Sciences, at Tomsk Polytechnic Institute im. S. M. Kirov, Tomsk	Explosive switches
A. G. Anisimov Yu. L. Bashkatov Yu. A. Burenin V. P. Chistyakov V. I. D'yachenko N. V. Gubareva V. D. Kurguzov V. I. Maly A. V. Orgov Genadiy A. Shvetsov T. M. Sobolenko I. A. Stadnichenko Sergey V. Stankevich G. A. Titov V. M. Titov V. M. Yermolenko	Hydrodynamics Institute im. M. A. Lavrent'yev, Russian Academy of Sciences, Novosibirsk	Flux compression generators; plasma railguns; explosive MHD generators; electrode erosion
S. V. Kukhtetskiy A. D. Lebedev V. A. Lyubochko	Krasnoyarsk State University, Krasnoyarsk	High-current gas discharges
Yuriy P. Babakov A. I. Kapustin Dmitriy V. Khandryga A. V. Kudravtsev S. A. Perkov Aleksandr V. Plekhanov Anatoli N. Tereschenko Valeriy B. Zheleznyy	Lyubertsy Scientific-Production Association "Soyuz," Dzerzhinskiy, Moscow Region	Metal armature acceleration; railgun experiments; railgun control systems; hybrid armature experiments; 6-MJ capacitor banks; three-stage EM launchers; solid propellant MHD generator
Yanhuang Zhou	Mechanical Institute im. D. F. Ustinov, St. Petersburg	ET gun design

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES— ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
A. V. Chebotarev I. L. Kolenskiy Yu. A. Kulikov A. V. Melnik E. Ya. Shkolnikov S. V. Volkov	Moscow Engineering Physics Institute, Moscow	ET experiments for pellet injection; powder acceleration and coatings
Ye. V. Lukina Ye. I. Yantovskiy	Moscow Institute of Agricultural Production Engineers im. Goryachkin, Moscow	HPG optimization
V. E. Fortov V. Ye. Ostashev Yu. S. Protasov S. N. Tchuvashev	Moscow (State) Technical University im. N. Ye. Bauman, Moscow	Plasma dynamic discharges
V. V. Belogorskiy A. A. Dublov V. S. Fedorova S. N. Komin V. A. Ledomtsev E. A. Morozov I. Sharenkov T. G. Sokolova V. I. Tselisheva	NOVIK Research & Production Corp., St. Petersburg State Technical University, St. Petersburg	Capacitor development and production; high-voltage generators for lasers
E. M. Drobyshevskiy B. B. D'yakov M. I. Gnedin I. V. Grekhov R. O. Kuryakin Ye. V. Nazarov S. I. Rozov B. I. Reznikov	Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences, St. Petersburg	Plasma armatures; superfast impact craters; electrode ablation; railgun accelerators; computer modeling; skin effects in railguns; conducting shields in railguns; millimeter projectile launch
V. A. Sakharov M. A. Savel'yev V. M. Sokolov V. M. Tuchkevich S. V. Yuferev B. G. Zhukov	Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences, St. Petersburg (cont'd.)	Plasma armatures; superfast impact craters; electrode ablation; railgun accelerators; computer modeling; skin effects in railguns; conducting shields in railguns; millimeter projectile launch

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Russia (cont'd.)	
Yu. A. Alekseyev A. A. Belikov V. V. Gorev O. A. Kalugin M. N. Kazeyev I. V. Sadof'yev	Russian Research Center/Atomic Energy Institute im. I. V. Kurchatov, Moscow	Electrostatic particle accelerator; hydrogen pellet acceleration in a railgun; wall ablation effects
A. N. Semakhin G. A. Shneerson V. V. Titkov	St. Petersburg Technical University, St. Petersburg	Electrostatic capacitance calculations; stresses in conductors in fields
Vladislav P. Fomichev Saveliy S. Katsnel'son Sergey S. Pravdin Aleksandr V. Zagorskiy	Theoretical & Applied Mechanics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk	Modeling plasma armatures; modeling multistage railguns; segmented railguns; experiments with Rogowski induction coils
N. V. Kudryavtsev A. D. Lebedev R. B. Luban K. V. Malevinskiy V. I. Nazaruk S. A. Perkov A. V. Plekhanov A. P. Plyushkin V. B. Zheleznyy M. F. Zhukov V. P. Zinov'yeva	Thermal Physics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk	Plasma railguns; electrode erosion
N. N. Grabohak Yu. A. Kareyev M. K. Krulov A. P. Lototskiy R. M. Zayatdinov	Troitsk Innovation & Fusion Research Institute (TRINITI), Troitsk, Moscow Region	Novel railguns; distributed railguns
	Sweden	
Sten Andreasson Sten Hugo Risland Erik A. Witalis	National Defense Research Establishment, Sundbyberg	Plasma armature modeling

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	Ukraine	
V. T. Chemeris I. N. Kucheryavaya A. D. Podoltsev	Electrodynamics Institute, Ukrainian Academy of Sciences, Kiev	Impact solenoid motors
Konstantin V. Dubovenko	Electrohydraulic Design & Development Office, Ukrainian Academy of Sciences; IIPIT	HPG/inductor systems
G. G. Kapustyanenko V. A. Krupko A. D. Lebedev C. C. Milyayev V. S. Mischenko S. S. Pignastey I. P. Petuhov G. V. Sandrakov S. N. Shevyakin A. I. Syusyukin B. A. Uryukov T. V. Vishtak	New Physical & Applied Problems Institute, Ukrainian Academy of Sciences, Kiev	Magnetic flux compressor; 60-MJ mobile pulsed power; plasma armatures; plasma calculations; metal armatures; solid-armature experiments
S. Z. Shikhaliyev	Problems in Simulation in Power Engineering Institute, Ukrainian Academy of Sciences, Kiev	Thermal problems in HPGs
	United Kingdom	
W. I. C. Blackburn A. D. Dickerson Nicholas Wroebel	Aerobel	System analysis
M. J. Balchin J. F. Eastham R. J. Hill-Cottingham David Rodger	Bath University, School of Electronic & Electrical Engineering	Finite element code (MEGA); compulsator modeling; coilgun modeling
Trevor Bearpark Chris Spikings Ted Thornton	British Aerospace (BAe), Sowerby Research Centre, Bristol	Small capacitor banks; ET gun research
C. D. Horne Alexander C. Smith Stephen Williamson	Cambridge University, Cambridge	Coilgun modeling

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	United Kingdom (cont'd.)	
Malcolm Kear Derek Putley	Culham Laboratories	Capacitor-powered railguns; compulsators
A. R. P. Bloyce R. Critchley David Edwards D. J. Gordon David Haugh Steve Gilbert S. F. Nigel Johnson Douglas Kirkpatrick Chris Leyden Clive R. Woodley	Defence Research Agency (DRA)	EM/ET guns; 6.7-MJ HPG-powered railguns; armature modeling; 32-MJ capacitor bank; 1-MJ capacitor bank; composite railgun barrels; design of vehicles with E-guns; explosive switches
Hugh Menown	English Electric	Switching
Edward Figura A. M. Milne S. Taylor	Fluid Gravity Engineering	EM/ET gun modeling
C. Christou Christopher Guyott	Frazer-Nash Consultancy Limited, Surrey	ET gun systems studies
John Timbers (retired) Frank Whitby	GEC-Marconi	Kirkcudbright program management
Alan Mitcham Hugh Prothero	International Research & Development Co., Ltd. (IRD)	HPGs; current collection
D. C. James Trevor E. James	JEM Systems, Abingdon, Oxfordshire	Solid-armature modeling
P. Butterfield K. Gregory P. Senior Ivor R. Smith H. R. Stewartson V. V. Vadher	Loughborough University of Technology	Coil launchers; pulsed MHD generators
John Murfitt	Norfolk Capacitors, Ltd. (NCL)	Capacitor manufacture
Graham Reynolds	Rolls Royce	Gas turbine development

TABLE VII.11
KEY NON-US RESEARCH PERSONNEL AND FACILITIES—ENERGY STORAGE AND POWER SUPPLIES (cont'd.)

Researchers	Facilities	Areas of Expertise
	United Kingdom (cont'd.)	
Anna Crowley R. D. Green D. W. Leeming	Royal Military College of Science (RMCS), Shrivenham	Explosive MHD generators
Derrick Hewkin Kim Vance	Royal Ordnance PLC, Nottingham	ET and LP gun experiments
Malcolm Burton	Straughn & Henshaw	Kirkcudbright module assembly

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CHAPTER VII: ENERGY STORAGE AND POWER SUPPLIES

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Andriyanov (Andrianov), V. V., V. P. Bayev (Baev), N. A. Kazantsev, V. Ye. Ostashev, and M. B. Parizh, "Energy Conversion Efficiency of a Regulated Inductive Store," *Power Eng. (Izvestiya Akademii Nauk SSSR, Energetika i transport, 25,* 6(1987), 41–48.

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APPENDIX A
ABOUT THE AUTHORS

Jerald V. Parker *(Panel Chairman)*. Dr. Parker is Technical Director for Electromagnetic Launchers at the Institute for Advanced Technology (IAT), University of Texas at Austin. He received a BS and a PhD in Physics from the California Institute of Technology in 1960 and 1964, respectively. He is recognized internationally for his contributions to understanding the physical processes in plasma armature railguns—in particular, for his experimental and theoretical work on the role of ablation and viscous drag in limiting the performance of plasma armature railguns. He has served on several Department of Defense (DOD)/Defense Nuclear Agency (DNA) advisory panels to assess the status of electromagnetic launcher research projects in the United States. In 1989, he developed and presented a two-day short course on railguns in cooperation with the University of New Mexico. Prior to joining IAT in December 1993, Dr. Parker worked for 18 years at Los Alamos National Laboratory, where he performed research on high-energy gas lasers, electron beam-plasma interactions, electromagnetic launchers, and high-energy density plasmas. From 1987 to 1993, he was technical leader of the Pulsed Power for Weapons Physics program, where he directed the application of both high-explosive and conventional pulsed power to the generation of intense soft X-ray sources. He has published over 30 journal papers in the fields of gas lasers, railguns, plasma physics, and pulsed power. In 1994, he was awarded the Peter Mark Medal in recognition of his contributions to electromagnetic launch technology.

Jad H. Batteh. Dr. Batteh is the Manager of the Advanced Concepts Division of Science Applications International Corporation (SAIC), and an Adjunct Associate Professor in the Department of Mechanical Engineering at the Georgia Institute of Technology. His formal education is in Aerospace Engineering, having received a BS from the University of Florida in 1967, an MS from the Georgia Institute of Technology in 1971, and a PhD from the University of Florida in 1974. Prior to joining SAIC, Dr. Batteh was a Research Physicist at the US Army Ballistic Research Laboratory. He has over 20 years of experience in advanced weapons development, electromagnetic and electrothermal propulsion, and laser technology. He currently leads a research group performing analyses of hypervelocity railgun and electrothermal gun systems and serves as a lecturer for a short course in electric gun technology. Dr. Batteh has authored or co-authored 86 technical publications, including 34 in refereed journals. Twenty-two of his refereed publications are directly related to hypervelocity launcher technology.

Joseph R. (Bob) Greig. Dr. Greig is a Senior Research Scientist with GT-Devices, Inc. He received a BSc in Physics (1959) and a PhD in Plasma Physics (1965) from Imperial College, London. Before joining the Naval Research Laboratory (NRL) in 1973, Dr. Greig was a Research Officer at the Central Electricity Research Laboratories, Leatherhead, UK (1962–65); taught physics and performed research in plasma spectroscopy at the University of Maryland (1965–70); and was a Research Scientist for Imperial Chemical Industries, Ltd., Slough, UK (1970–73). His work at NRL involved the interaction of high-energy lasers with both solids and gases, laser-guided electric discharges, lightning, the interaction of intense relativistic electron beams with the atmosphere, and the electrostatic charging of helicopters. Dr. Greig was a Section Leader and Acting Chief of the Experimental Plasma Physics Branch when he left NRL to join GT-Devices in 1986. At GT-Devices, Dr. Greig is Program Manager/ Principal Investigator for GT-Devices efforts in Electrothermal-Chemical (ETC) Gun Research. In this capacity, he has made significant contributions to the Solid Propellant ETC Gun effort in both the design of the capillary plasma generator and the solid propellant charge, and in simulation/modeling using IBHVG2 modified to allow ET power input and Deterred BALL POWDER® propellants. He has been responsible for firing over 600 ET/ETC gun shots at 20-mm and 30-mm bore diameter. Dr. Greig has published widely in all the above research areas including a series of nine papers from 1991 to 1993 that have helped to redefine Electrothermal-Chemical Gun Technology.

Dennis Keefer. Dr. Keefer is the B. H. Goethert Professor of Engineering Sciences at the University of Tennessee Space Institute (UTSI). He received a BS in Engineering Sciences and an MS and a PhD in Aerospace Engineering from the University of Florida. He served on the faculty of Aerospace Engineering at the University of Florida from 1967 to 1978, when he joined the faculty at UTSI. Dr. Keefer's research interests have covered a wide range of plasma applications, including laser propulsion, arc-jet and ion thrusters, and laser discharges. Since 1986, he has led a plasma armature railgun research program at UTSI that has encompassed diagnostic, experimental, and theoretical analysis.

Ian R. McNab. Dr. McNab was Vice President for Major Systems at Maxwell Laboratories (1990–1994). He received a BS in Physics from Leeds University in England in 1960 and a PhD in Applied Science in the area of magnetoplasmadynamics from Reading University in 1974. In England, he worked on magnetoplasmadynamic generators and current collection technologies for homopolar generators before moving to the United States in 1975. From 1975 to 1990, he was involved in research and development programs on electric guns, homopolar generators, and liquid metal pumps for the Westinghouse Research Center and Sunnyvale Division. Included in these efforts were the delivery of the 16-MJ homopolar-powered EMACK railgun system to an Army Laboratory in Picatinny in 1981, and the delivery of 11-MJ and 40-MW homopolar generator systems to the US Air Force, for which he was awarded letters of commendation by DARPA and ARDEC. In these areas he holds 15 US and UK patents. Since 1990, he has been responsible for electric guns and related pulsed power systems, including the 32-MJ Green Farm electric gun facility, at Maxwell Laboratories in San Diego. Present interests include the development of compact pulsed energy systems for defense and commercial applications, including areas such as rock breaking. He has published over 60 papers on these topics, has edited a book on current collection, and has contributed a chapter to a handbook on wear. He is a Fellow of the UK Institute of Physics and a Member of the UK Institution of Electrical Engineers and has served on several defense-related study panels and committees. He is a Senior Industrial Fellow at the Institute for Advanced Technology and a member of the Steering Committee for the annual Electromagnetic Launch Symposium. He was a founder member and past president of the Electromagnetic Launch Association. In 1990, he was awarded the Peter Mark Medal for outstanding contributions to electromagnetic launch technology.

Zivan Zabar. Dr. Zabar is Professor of Electrical Engineering at the Polytechnic University in Brooklyn, New York (Brooklyn Poly). He received his PhD from the Technion–Israel Institute of Technology in 1972. His areas of interest are linear propulsion, electrical power conversion systems, and power electronics. Since 1986, he has been the principal investigator of a US Army SDC contract to investigate and develop electromagnetic coil launcher systems. Dr. Zabar has four patents (two on magnetic propulsion), and has published more than 50 papers in technical journals. He is a senior member of the IEEE, and a member of Sigma Xi.

APPENDIX B

GLOSSARY OF ABBREVIATIONS AND ACRONYMS

A	ampere
ABB	Asea/Brown Bovery
AC	alternating current
Al	aluminum
AMD	ablation mass driver
AN	Akademiya nauk ([USSR/Russian]Academy of Sciences)
ANU	Australian National University
ARA	Aeroballistic Range Association
ARDEC	(US) Army Research, Engineering & Development Command
ARL	(US) Army Research Laboratory
As	arsenide
AS	avalanche shaper
ATBM	anti-tactical ballistic missile
AV	avalanche sharper
BAe	British Aerospace (United Kingdom)
cc	cubic centimeter
CEA	Commissariat à l'Energie Atomique (France)
CEM-UT	Center for Electromechanics, The University of Texas at Austin (United States)
CET	Centre d'Etudes de Gramat (France)
CFD	computational fluid dynamics
CGE	Compagnie Générale d'Electricité (France)
CIWS	Close-In Weapons System
CNET	National Telecommunications Research Center (Centre National d'Etudes des Télécommunications, France)
CNRS	National Center of Scientific Research (Centre National des Recherche Scientifique, France)
CFD	computational fluid dynamics
CIWS	close-in weapon system (US Navy)
CPA	current-plasma armature
CS	current sheath

DC	direct current
DES	distributed energy store
DRA	Defence Research Agency (United Kingdom, formerly the Royal Armament Research and Development Establishment)
DRET	Direction des Recherches Etudes et Techniques (French Ministry of Defense)
DSRD	drift step-recovery diode
EEF	electric enhancement factor
ELGG	electrothermal light gas gun
EM	electromagnetic
EMA	electromagnetic accelerator
EMG	explosive-driven magnetic generator
EML	electromagnetic launch
EMP	electromagnetic pulse
ENSM	Ecole Nationale Superieure de Mechanique (France)
EOARD	European Office of Aerospace Research & Development
ET	electrothermal
ETBS	Etablissement Technique de Bourges (France)
ETC	electrothermal-chemical
ETO	Earth to orbit
FE	finite element
FMC	Food Machinery Corporation (renamed United Defense)
FOD	foreign object damage
FSU	Former Soviet Union
g	gram
Ga	gallium
GDLS	General Dynamics Land Systems Div ision (United States)
GEC	General Electric Company (United Kingdom—no relation to General Electric in the United States)
GIAT	Groupement des Industriel des Armaments Terrestres (France)
GmbH	Gesellschaft mit beschränkter Haftung (limited ability company—Germany)
GV	gigavolt
GW	gigawatt

H	henry
HCT	high-current thyristor
HPG	homopolar generator
HTF	Hypervelocity Test Facility
Hz	hertz
IABG	Industrie Anlagen Betreibs Gesellschaft (Germany)
IAT	Institute for Advanced Technology
IEEE	Institute of Electronics and Electrical Engineers
IFP	Southwest Institute of Fluid Physics (Sichuan, PRC)
IOC	initial operational capability
IPP	Institute of Plasma Physics (Anhui, PRC)
IRD	International Research and Development Co., Ltd. (United Kingdom)
ISL	French-German Research Institute of Saint-Louis (Institute Franco-Allemand de Recherche de Saint-Louis, France)
J	joule
JDA	Japan Defence Agency
JSW	Japan Steel Works
K	[degrees] Kelvin
kA	kiloamp(ere)
kb	kilobar
kg	kilogram
kHz	kilohertz
kJ	kilojoule
km	kilometer
kV	kilovolt
kVA	kilovoltamp
kW	kilowatt
LANL	Los Alamos National Laboratory (United States)
LCR	L = inductance; C = capacitance; R = resistance
L/D	length-to-diameter ratio
LEMG	linear electromechanical generator
LIL	linear induction launcher
LP	liquid propellant

m	meter
MA	mega(a)mp(ere)
MBB	Messerschmitt Bolkow Bohm (Germany)
MBT	Main Battle Tank
MC	magnetic compressor
MCG	magnetocumulative generator
MDS	magnetic-dynamic storage
μF	microfarad
mF	millifarad
MFCG	magnetic field compression generator
mg	milligram
MG	megagauss
μH	microhenry
MHD	magnetohydrodynamic
MJ	megajoule
mm	millimeter
MOD	Ministry of Defense
mΩ	milliohm
Mo	molybdenum
MPa	megapascal
MRL	Materials Research Laboratories (Defense Science and Technology Organization, Australia)
μs	microsecond
ms	millisecond
MV	megavolt
MW	megawatt
Nb	niobium
NCL	Norfolk Capacitors, Ltd. (United Kingdom)
NCLI	National Chemical laboratory for Industry (now, National Institute of Materials and Chemical Research [NIMCR], Japan)
nH	nanohenry
NIMCR	National Institute of Materials and Chemical Research (formerly, National Chemical Laboratory for Industry [NCLI], Japan)
nm	nanometer
ns	nanosecond
OIC	ohmic ignition chemical
ONERA	National Office for Aerospace Studies and Research (France)

PCPS	photo-conductive power switch
PDD	plasma dynamic discharge
plc	publicly licensed company (United Kingdom)
PFN	pulse forming network
PFU	pulse forming unit
PI	Physics International (PI)
PISP	plasma initiation separated from the plasma
PML	Prins Maurits Laboratory (The Netherlands)
PPS	pulsed power system
PRC	People's Republic of China
ps	picosecond
psi	pounds per square inch
QPF	quasistationary plasma flow
RARDE	Royal Armament Research and Development Establishment (United Kingdom, currently the Defence Research Agency)
RCT	reverse controlled transistor
RLPG	conventional liquid propellant gun
RMCS	Royal Military College of Science (United Kingdom)
RO	Royal Ordnance (United Kingdom)
RSD	reverse switched dynistor
s	second
SCR	silicon-controlled rectifier
SDIO	(US) Strategic Defense Initiative Organization
SMES	superconducting magnetic energy storage
SP	solid propellant
SPETC	solid propellant electrothermal chemical
SPIE	International Society for Optical Engineering
T	tesla
Ti	titanium
TMD	Theater Missile Defense
TNO	The Netherlands Organization for Applied Scientific Research
TRDI	Technical Research and Development Institute, Japan Defense Agency (Tokyo)

TUM	Technical University of Munich (Technishe Universität München, Germany)
TW	terawatt
TZN	Technology Center North (Technisches Zentrum Nord, Germany)
UK	United Kingdom
US	United States
USAFOSR	United States Air Force Office of Scientific Research
V	volt
VISAR	laser velocity interferometer
VSE	velocity skin effect
VUZ	(Russian) higher educational institution (Vysshyeye uchebnoye zavedeniye)
W	tungsten; watt
WTD	Weapons Technology Directorate

APPENDIX C
RESEARCH FACILITIES CITED IN TEXT

(full information not available for all facilities)

Australia

Australian National University (ANU), Maribymong, Victoria

CSIRO Division of Manufacturing Technology, Preston, Victoria

Defence Science & Technology Organisation Materials Research Laboratory

China

East China Institute of Technology, Nanjing (PRC)

Electric Launch Laboratory (ELL), Plasma Physics Institute, Chinese Academy of Sciences, Hefei (PRC)

Nuclear Energy Research Institute, Lung-Tan (Taiwan)

Plasma Physics Institute, Chinese Academy of Sciences, Hefei, Anhui (PRC)

Southwest Institute of Fluid Physics, Chengdu, Sichuan (PRC)

France

Alcatel Alsthom Research, Marcoussis
(Alcatel-Alsthom Recherche)

Atomic Energy Commissariat, Vaujours-Moronvilliers Research Center, Courtry
(Commissariat à l'Energie Atomique [CEA], Centre d'Etudes de Vaujours-Moronvilliers)

CEDRAT Research, Meylan
(CEDRAT Recherche)

CGE, Marcoussis
(Compagnie de Guerre Electronique)

Electrotechnical Laboratory, University of Paris South, Orsay
(Laboratoire d'Electrotechnique, Université de Paris Sud)

Electrotechnical Laboratory, National Telecommunications Research Center, Grenoble
(Laboratoire d'Electrotechnique, Centre national d'Etudes des Télécommunications/CNRS)

ENSM, Nantes
(Ecole Nationale Superieure de Mechanique)

ETBS, Bourges
(Etablissement Technique de Bourges)

French-German Research Institute Saint-Louis, Saint-Louis
(Institut Franco-Allemand de Recherches de Saint-Louis/ISL])

GEC Alsthom, Belfort

Giat Research Center (CRET) and Giat Vecteur, Bourges
(GIAT = *Groupement des Industriel des Armaments Terrestres*)

Grenoble Electrotechnical Laboratory, Saint-Martin-d'Heres
(Laboratoire d'Electrotechnique de Grenoble)

Haefley

Matra

France (cont'd.)

Remy

Thomson-CSF

Thomson LCC, Saint-Apollinaire

University of Paris
(Université de Paris)

Germany

Braunschweig Technical University, Braunschweig
(Technische Universität Braunschweig)

BWB, Meppem Test Range

Diehl GmbH, Röthenbach

Ernst-Mach Institute (EMI), Ballistics Division, Weil-am-Rhein
(Ernst-Mach Institut, Abteilung für Ballistik/AFB)

French-German Research Institute Saint-Louis, Saint-Louis
(Institut Franco-Allemand de Recherches de Saint-Louis/ISL)

German Federal Office of Defense

Graz Technical University, Graz
(Technische Universität Graz)

Grundl und Hoffmann GmbH, Starnberg

High-Voltage Technology Institute, Braunschweig Technical University, Braunschweig
(Institut für Hochspannungstechnik, Technische Universität Braunschweig)

IABG, Ottobrunn
(Industrieanlagen-Betreibsgesellschaft mbH)

Karlesruhe University, Karlesruhe

Magnet Motor GmbH, Starnberg

Messerschmitt Bolkow Bohm (MBB)

Rhine Metal Works, Düsseldorf

Rheinmetall GmbH,

Space Technology Department, Technical University of Munich, Munich
(Lehrstuhl für Raumfahrttechnik, Technische Universität München/LRT-TUM, München)

Technical Center North, Research & Development Center, Unterlüss
(Technisches Zentrum Nord/TZN–Forschungs- und Entwicklungszentrum Unterlüss GmbH)

Technical Electrophysics Department, Technical University of Munich, Munich
(Lehrstuhl für Technische Elektrophysik, Technische Universität München/LTE-TUM, München)

Technical University of Braunschweig, Braunschweig
(Technische Universität Braunschweig)

Technical University of Munich, Munich
(Technische Universität München)

Weapons Test Center, Ministry of Defense, Meppen

Israel

Israeli Aircraft Industries (IAI)

Ministry of Defense, State of Israel, Tel Aviv

Propulsion Physics Laboratory, Soreq Nuclear Research Center, Yavne

Rafael

SOREQ Nuclear Research Center, Israel Atomic Energy Commission, Yavne

Tel Aviv University, School of Physics & Astronomy, Tel Aviv

Italy

Department of Electric Systems & Automation, University of Pisa, Pisa
(Dipartimento di Sistemi Elettrici e Automazione, Università di Pisa)

Electronics & Electric Systems Department, University of Cantania, Cantania
(Dip. Elettronico Elettrico e Sistemistico, Università di Catania)

Energy Institute, University of Perugia, Perugia
(Instituto di Energetica, Università di Perugia)

Polytechnic of Turin, Turin (Torino)
(Politecnico di Torino)

University of Catania, Catania
(Università di Cantania)

University of Pisa, Pisa
(Università di Pisa)

University of Perugia, Perugia
(Università di Perugia)

Japan

Ceramics Research Center, Engineering Materials Research Laboratory, Tokyo Institute of Technology, Yokohama

Engineering Materials Research Laboratory, Tokyo Institute of Technology, Yokohama

Fuji Electric Company

Hitachi Company

Ishikawa-Harima Heavy Industries (IHI)

Japan Atomic Energy Research Institute, Naka-gun

Japan Defence Agency, Meguro, Tokyo

Japan Steelworks, Ltd., (JSW), Tokyo and Yotukaido, Chiba

Kawasaki Heavy Industries

Kobe Steel, Ltd., Kobe

Kumamoto University, Kumomoto

Mitsubishi Electric Company

Mitsubishi Heavy Industries, Kobe

Mitsubishi Heavy Industries, Ltd., Sagamihara Machinery Works, Kanagawa

Mitsubishi Heavy Industries, Ltd., Takasago Research & Development Center, Takasago

Japan (cont'd.)

National Chemical Laboratory for Industry (NCLI), Ibaraki

National Institute for Fusion Science, Nagoya

National Institute of Materials & Chemical Research (NIMCR—formerly, NCLI)

Nichikon Company

Osaka City University, Osaka

Plasma Physics Institute, Nagoya University, Nagoya

Shonan Institute of Technology, Kanaga

Space & Astronautical Science Institute (ISAS), Kanagawa

Sumitomo Electric Company

Korea (South)

Electrical Engineering Department, Seoul University, Seoul

Electrical Engineering Department, Kangwon National University, Chucheon

Netherlands

Laboratory for Power Electronics & Electrical Machines, Delft University of Technology, Delft

TNO PML Pulse Physics, Rijswijk, Delft
(The Netherlands Organization for Applied Scientific Research, Prins Maurits Pulse Physics Laboratory)

Russia

Applied Mathematics Institute im. M. V. Keldysh, Russian Academy of Sciences, Moscow State University im. M. V. Lomonosov, Moscow
(Institut prikladnoy matematiki imeni M. V. Keldysha/IPM, Moskovskiy gosudarstvennyy universitet imeni M. V. Lomonosova),

Applied Mechanics & Electrodynamics Research Institute, Moscow Aviation Institute im. Sergo Ordzhonikidze, Moscow

(Nauchno-issledovatel'skiy institut prikladnoy mekhaniki i elektrodinamiki, Moskovskiy aviatsionnyy institut imeni Sergo Ordzhonikidze/MAI)

Applied Scientific Problems Institute, Russian & Ukrainian Academies of Sciences, Moscow
(Institut prikladnikh nauchnykh problem)

Astrofizika Corporation, Moscow

Atomic Energy Institute im. I. V. Kurchatov, Moscow
(Institut atomnoy energii imeni I. V. Kurchatova/IAE)

Chuvash State University im. I. N. Ul'yanov, Cheboksary
(Chuvashskiy gosudarstvennyy universitet imeni I. N. Ul'yanova)

Electrical Engineering All-Russian Institute im. V. I. Lenin, Istra, Moscow Region
(Vserossiskiy elektrotekhnicheskiy institut imeni V. I. Lenina)

Electrical Engineering Institute, Novosibirsk
(Novosibirskiy elektro-tekhnicheskiy institut/NETI)

Electrophysical Apparatus Scientific Research Institute im. D. V. Yefremov, St. Petersburg
(Nauchno-issledovatel'skiy institut elektro-fizicheskiy apparatury imeni D. V. Yefremova/ NIIEFA)

Russia (cont'd.)

Electrophysics Institute, Russian Academy of Sciences, Yekaterinberg
(Institut elektrofiziki, Rossiskaya akademiya nauk)

Electrophysics Problems Institute, Russian Academy of Sciences, St. Petersburg (formerly, the Electrical Machine Building All-Union Scientific Research Institute)
(Institut problem elektrofiziki, Rossiskaya akademiya nauk/IPE)

Experimental Physics Research & Development Institute, Sarov (formerly Arzamas-16)
(Vserossiskiy nauchno-issledovatel'skiy institut eksperimental'nogo fiziki/VNIIEF)

General Physics Institute, Russian Academy of Sciences, Moscow
(Institut obshchey fiziki, Rossiskaya akademiya nauk/IOFAN)

"Girikond" Scientific Research Institute, St. Petersburg
(Nauchno-issledovatel'skiy institute Girikond)

High-Energy Density Research Center, High Temperatures Institute, Moscow
(Institut vysokikh temperature, Rossiskaya akademiya nauk/IVTAN)

High-Voltage Scientific Research Institute, Siberian Branch, Russian Academy of Sciences, at Tomsk Polytechnic Institute im. S. M. Kirov, Tomsk
(Institut sil'notochnoy elektroniki, Tomskiy politekhnicheskiy institut imeni S. M. Kirova)

Hydrodynamics Institute im. M. A. Lavrent'yev, Siberian Division, Russian Academy of Sciences, Novosibirsk
(Institut gidrodinamiki imeni M. A. Lavrent'yeva, Sibirskoye otdeleniye, Rossiskaya akademiya nauk)

Krasnoyarsk State University, Krasnoyarsk
(Krasnoyarskiy gosudarstvennyy universitet)

Lyubertsy Scientific Production Association "Soyuz," Dzerzhinskiy, Moscow Region

Moscow Aviation Institute im. Sergo Ordzhonikidze, Moscow
(Moskovskiy aviatsionnyy institut imeni Sergo Ordzhonikidze)

Moscow Engineering Physics Institute, Moscow
(Moskovskiy inzhenerno-fizicheskiy institut/MIFI)

Moscow (State) Technical University im. N. Ye. Bauman, Moscow
(Moskovskiy gosudarstvennyy tekhnicheskiy universitet imeni N. Ye. Baumana)

NOVIK Research & Production Corporation, St. Petersburg State Technical University, St. Petersburg
(Sankt-Peterburgskiy tekhnicheskiy universitet)

Physical Technical Institute im. A. F. Ioffe, Russian Academy of Sciences, St. Petersburg
(Fiziko-tekhnicheskiy institut imeni A. F. Ioffe, Rossiskaya akademiya nauk/FTIAN)

Russian Research Center/Atomic Energy Institute im. I. V. Kurchatov, Moscow
(Institut atomnoy energii imeni I. V. Kurchatova/IAE)

St. Petersburg Mechanical Institute im. D. F. Ustinov, St. Petersburg
(Sankt-Peterburg mekhanicheskiy institut imeni D. F. Ustinova)

St. Petersburg State Technical University, St. Petersburg (formerly, Leningrad Polytechnic Institute im. M. I. Kalinin
(Sankt-Peterburgskiy tekhnicheskiy universitet; formerly, Polytechnic Institute imeni M. I. Kalinin)

Synthetic Rubber (All-Union) Scientific Research Institute

Technical & Applied Mathematics Institute (Siberia)

Russia (cont'd.)

Theoretical & Applied Mechanics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk
(Institut teoreticheskoy i prikladnoy mekhaniki, Sibirskoye otdeleniye, Rossiskaya akademiya nauk/ITiPM),

Thermal Physics Institute, Siberian Branch, Russian Academy of Sciences, Novosibirsk
(Institut teplofiziki, Sibirskoye otdeleniye, Rossiskaya akademiya nauk)

Tomsk Polytechnic Institute im. S. M. Kirov, Tomsk
(Tomskiy politekhnicheskiy institut imeni S. M. Kirova)

Troitsk Innovation & Fusion Research Institute (TRINITI), Troitsk

Sweden

National Defence Research Establishment (Research Institute of National Defense), Sundbyberg

Switzerland

Asea/Brown Bovery (ABB) Semiconductors AG, Lenzburg

Ukraine

Electrodynamics Institute, Ukrainian Academy of Sciences, Kiev
(Institut elektrodinamiki)

Electrohydraulics Design & Development Office
(Proyektno-konstruktorskoye byuro [PKB] elektrogidravliki, Akademiya nauk Ukrainy)

New Physical & Applied Problems Institute, Ukrainian Academy of Sciences, Kiev
(Institut novykh fizicheskikh i prikladnykh problem, Akademiya nauk Ukrainy)

Problems in Simulation in Power Engineering Institute, Ukrainian Academy of Sciences, Kiev

United Kingdom

AEA Industrial Technology, Culham Laboratory, Abingdon, Oxon, England

Aerobel Defence Technology, Ltd.

British Aerospace (BAe) Defence, Ltd., Nottingham, England

Cambridge University, Cambridge, England

Culham Laboratories

Defence Research Agency (DRA), Fort Halstead, Sevenoaks, Kent, England (major experimental facility at Kirkcudbright, Scotland)

English Electric Company, Lincoln

Fluid Gravity Engineering, Ltd., Surrey and Godalming, England

Frazer-Nash Consultancy, Ltd.., Leatherhead, Surrey, England

GEC–Marconi Radar & Control Systems

International Research & Development Co., Ltd. (IRDC), Newcastle-upon-Tyne, England

JEM Systems, Abingdon, Oxon, England

Loughborough University of Technology, Loughborough, Leicestershire, England

Norfolk Capacitors, Ltd. (NCL)

Rolls Royce, Ltd.

United Kingdom (cont'd.)

Royal Military College of Science (RMCS), Shrivenham, England
Royal Ordnance PLC, Guns & Vehicles Division, Nottingham, England
Sowerby Research Centre, British Aerospace PLC, Bristol, England
Straughn & Henshaw
University of Bath, Bath, England

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APPENDIX D
FASAC REPORT TITLES

(* asterisk before title indicates report is classified)

(in production)

FY-93		Non-US Advanced Signal Processing System Technology
		Non-US Pattern Recognition and Image Understanding Research and Development
		FASAC Special Study: Non-US Artificial Neural Network Research (III)
FY-90-92		FASAC Special Study: Non-US Artificial Neural Network Research (II)
		Foreign Research in and Applications of Heavy Transuranics

(completed)

FY-90-92		Soviet Chemical Propellant Research and Development
		Optoelectronics Research in the Former Soviet Union
		Parallel Processing Research in the Former Soviet Union
		Nonlinear Dynamics Research in the Former Soviet Union
		Penetration Mechanics Research in the Former Soviet Union
		Foreign Bandpass Radome Research and Development
	*	Foreign Research Relevant to Countering Stealth Vehicles
		Pulsed Power Research in the Former Soviet Union
		Climate Research in the Former Soviet Union
		Non-US Data Compression and Coding Research
		Non-US Electrodynamic Launchers Research and Development
FY-86/89		Soviet Magnetic Confinement Fusion Research
		Recent Soviet Microelectronics Research on III-V Compound Semiconductors
		Soviet Ionospheric Modification Research
		Soviet High-Power Radio Frequency Research
		Free-World Microelectronic Manufacturing Equipment
		FASAC Integration Report II: Soviet Science as Viewed by Western Scientists
		Chinese Microelectronics
		Japanese Structural Ceramics Research and Development
		System Software for Soviet Computers
		Soviet Image Pattern Recognition Research
		West European Magnetic Confinement Fusion Research
		Japanese Magnetic Confinement Fusion Research
	*	Soviet Research in Low-Observable Materials

(completed/cont'd.)

FY-86/89		FASAC Special Study: Comparative Assessment of World Research Efforts on Magnetic Confinement Fusion
		FASAC Special Study: Defense Dependence on Foreign High Technology
		Soviet and East European Research Related to Molecular Electronics
		Soviet Atmospheric Acoustics Research
		Soviet Phase-Conjugation Research
		FASAC Special Study: Soviet Low Observable/Counter Low Observable Efforts: People and Places
		Soviet Oceanographic Synthetic Aperture Radar Research
		Soviet Optical Processing Research
		FASAC Integration Report III: The Soviet Applied Information Sciences in a Time of Change
		Soviet Precision Timekeeping Research and Technology
		Soviet Satellite Communications Science and Technology
		West European Nuclear Power Generation Research and Development
		FASAC Special Study: Non-US Artificial Neural Network Research (I)
	*	Radiation Cone Research in the Former Soviet Union
FY-85		FASAC Integration Report: Selected Aspects of Soviet Applied Science
		Soviet Research on Robotics and Related Research on Artificial Intelligence
		Soviet Applied Mathematics Research: Electromagnetic Scattering
	*	Soviet Low-Energy (Tunable) Lasers Research
		Soviet Heterogeneous Catalysis Research
		Soviet Science and Technology Education
		Soviet Space Science Research
		FASAC Special Report: Effects of Soviet Education Reform on the Military
		Soviet Tribology Research
		Japanese Applied Mathematics Research: Electromagnetic Scattering
		Soviet Spacecraft Engineering Research
		Soviet Exoatmospheric Neutral Particle Beam Research
		Soviet Combustion Research
		Soviet Remote Sensing Research and Technology
		Soviet Dynamic Fracture Mechanics Research
FY-84		Soviet Physical Oceanography Research
		Soviet Computer Science Research
		Soviet Applied Mathematics Research: Mathematical Theory of Systems, Control, and Statistical Signal Processing
		Selected Soviet Microelectronics Research Topics
	*	Soviet Macroelectronics (Pulsed Power) Research

(completed/cont'd.)

FY-82/83 * Soviet High-Pressure Physics Research
Soviet High-Strength Structural Materials Research
Soviet Applied Discrete Mathematics Research
* Soviet Fast-Reaction Chemistry Research

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