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Westinghouse EMACK Railgun

Ian R. McNab, *Life Fellow, IEEE*

***Abstract*— Westinghouse Electric Corporation was the early leader in railgun technology in the 1980s and developed the 16 to 30 MJ stored energy homopolar-generator (HPG) powered system, EMACK, which provided the highest muzzle energy of any railgun from 1982 to 1988 during testing at Westinghouse Research and Development Center, Pittsburgh, PA, USA, and after installation at ARDEC, Picatinny, NJ, USA. Details of the design, components, and fabrication of EMACK are provided here, and results from the abbreviated initial testing are included. Many scientists, engineers and technical staff who worked on the project described here some 30 to 40+ years ago have by now mostly retired, moved on to other activities, or sadly, in several cases, are deceased. However, it would be remiss if their pioneering efforts were not recognized, and this article attempts to do that. Prospects for future energy storage and pulsed power developments using HPGs and more recent developments are also discussed.**

***Index Terms*— Electromagnetic (EM), generator, homopolar, launch, railgun.**

I. INTRODUCTION

FOLLOWING the pioneering work of Barber [1] and Marshall [2] in developing a homopolar generator (HPG) powered railgun at the Australian National University (ANU) in Canberra in the late 1960s and early 1970s, the Westinghouse Electric Corporation became the earliest U.S. developer of railguns in the 1970s and 1980s and their efforts spurred the national and international growth of interest in this technology. This article describes some aspects of the early part of that development.

In 1969, while on a sabbatical leave of absence from ANU, Richard Marshall spent a few months at the International Research and Development Company in Newcastle upon Tyne, England, where I was helping to develop current transfer technology for superconducting HPGs and motors [3]. After returning to Canberra, he kept me appraised of HPG and railgun developments at ANU, including sending me a copy of John Barber's interesting thesis [1]. After moving to the Westinghouse Research Center near Pittsburgh, PA, USA in 1975, I suggested to the management that he would be a good addition to the research team already in place there. After negotiations took place and an entry visa was obtained, he joined Westinghouse in 1976.

At that time, there was lingering corporate knowledge of railguns and pulsed power technology at Westinghouse because of its involvement in the evaluation of German railgun technology during World War II (see [4]) after the German equipment and documents were brought to the USA some 30 years earlier [5], Following internally-funded studies for over a year, a proposal was finalized in 1978 for a project to design and build a research railgun. The Westinghouse team was being funded by Defense Advanced Research Projects Agency (DARPA) through Office of Naval Research (ONR)[1] on the development of superconducting and normal temperature HPGs and generators for ship propulsion, so the proposal was sent to DARPA for review.

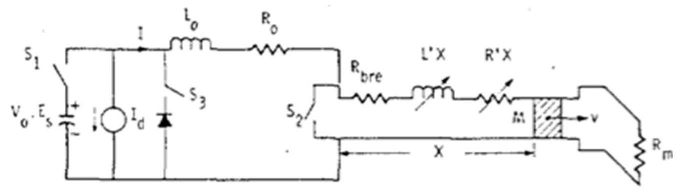

Fig. 1. EMACK equivalent circuit diagram.

Following presentations to DARPA, a study contract was awarded to Westinghouse in April 1979 and I acted as the Principal Investigator. At that time, Westinghouse Research and Development used a five-symbol system for identifying projects and I chose EMACK for this project on the basis that ACK-ACK was the British World War I (WWI) military terminology for Anti-Aircraft guns, and this would be an electromagnetic (EM) type of gun.

The detailed design study was conducted for six months and completed in September 1979 [6]. This led to a contract starting in January 1980 funded by DARPA, with Army Research and Development Command (ARRADCOM) participation, to build the railgun system [7].

II. SYSTEM CONCEPT

The EMACK concept was modeled on the approach used at ANU, with an HPG storing energy inertially but delivering it electrically as a high current to the breech of the railgun through an inductor that was used to compress the current pulse. The equivalent circuit diagram is shown in Fig. 1, where the HPG is shown on the left-hand side, with the inductor at the top, and the railgun and projectile on the right-hand side.

The main difference to the ANU system was that the HPG was much reduced in size, storing 16 MJ of rotational energy at 6735 revs/min, compared with the massive 550 MJ ANU HPG which had two 42-ton disk rotors spinning at up to 900 revs/min [8]. Also, the railgun itself was considerably

[1] At that time, DARPA did not have an in-house procurement capability.

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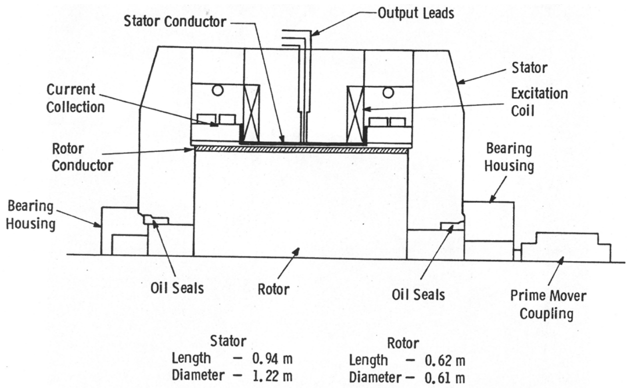

Fig. 2. HPG design details outline.

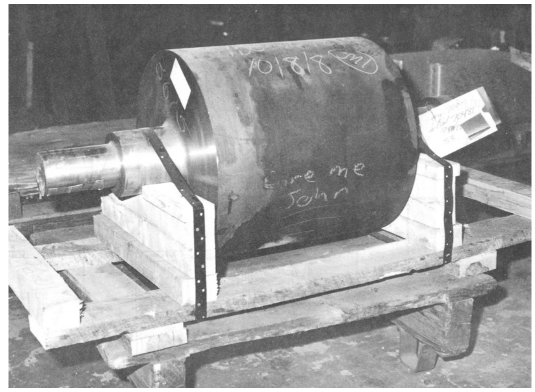

Fig. 3. Steel rotor forging.

Fig. 4. Aluminum sleeves.

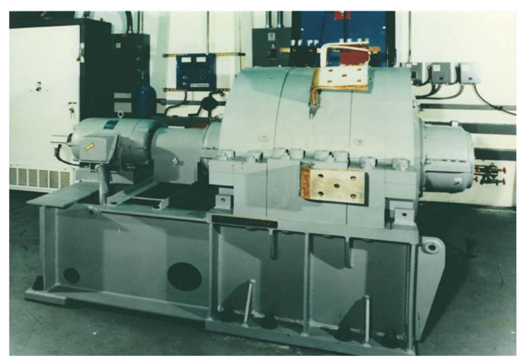

Fig. 5. 16 MJ, 1.5 MA HPG, and drive motor.

larger, with a 50 mm square bore compared with the 12.5 mm bore of the ANU railgun, and capable of launching a ∼0.3 kg projectile in place of the ∼3 g used at ANU. The HPG, pulse shaping inductor, and railgun were close-coupled to not only reduce bus bar losses but to start to approach a tactically feasible system. Befitting an indoor laboratory system, a diagnostic section and armored catch tank were installed beyond the muzzle of the 5-m long barrel. The goal was to accelerate a 0.3 kg mass to 3 km/s. At that time, the system was envisioned as essentially a single-shot research device, so no arrangements were made to cool any of the components, apart from the HPG field coils, and the designs for all components were based on adiabatic heating to a temperature within acceptable materials limits. The drive motor providing the power to store rotational energy in the HPG rotor was small (100 hp), so that spin up took about 20 min.

Assembly of the system was undertaken in a high bay at the Westinghouse Research and Development Laboratories during late 1981 and early 1982 under the supervision of Dr. Daniel W. Deis.

III. Homopolar Generator

The HPG parameters were determined during the design study while the detailed design and fabrication of the machine were undertaken by the Westinghouse Marine Division in Sunnyvale, CA, USA. The machine was designed to generate 108 V and deliver a current of 1.5 MA from the ∼1360 kg rotor at 6735 revs/min; its internal resistance was 5.5 $\mu\Omega$. The machine cross section is shown in Fig. 2. The rotor core was high strength steel forging with integral shafts (Fig. 3) and, with the selected radial and axial bearings, was sufficiently stiff to ensure that the first dynamic resonance was above the design operating speed. To prevent an adverse armature reaction caused by current flowing through—and magnetizing—the steel core, an aluminum sleeve (Fig. 4) was shrunk onto the outside of the core over a layer of insulation so that the load current would be confined in the sleeve. Fig. 5 shows the assembled machine and drive motor as delivered to the Westinghouse Research Laboratories on December 24, 1981.

Once the rotor was spun up to full speed by the 100 hp drive motor using the 120-kVA inverter power supply, the water-cooled field coils were energized from a 75-kVA dc power supply, and electrical contact was made to close the circuit comprising the HPG and inductor by pneumatically activating the brushes to contact the aluminum sleeve surface—this is the closing switch S_1 in Fig. 1. The two regions where the brushes contacted the aluminum sleeve were copper plated to ensure good electrical contact.

The brush design (Fig. 6) was based on an earlier Westinghouse design for the Homopolar Energy Transfer System (HETS) for a Los Alamos-Livermore-Electric Power Research Institute (EPRI) project on controlled thermonuclear fusion [9]. The brush design was extensively tested before installation in the fixture shown in Fig. 7 [10].

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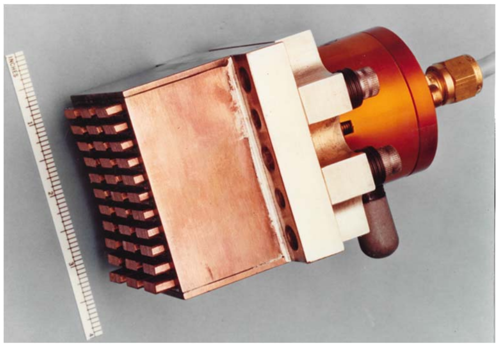

Fig. 6. HPG brush box.

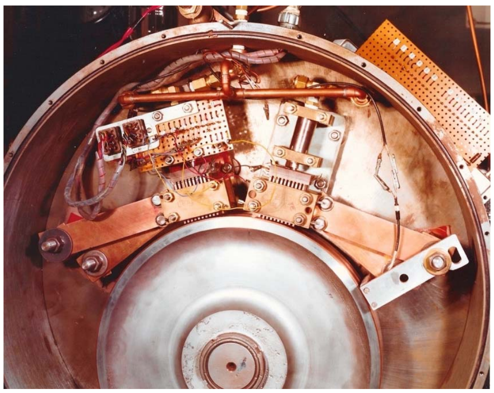

Fig. 7. High speed brush test fixture.

For the design current pulse length of 100 ms, the rotor speed dropped to about 50% and the current rose in a sinusoidal manner as it transferred approximately 75% of the rotor stored energy (less resistive losses) into the inductor, through eight sets of close-spaced insulated busbars arranged around the machine emanating from its midpoint.

As the rotor slowed down quickly, in about 0.1 s, during the discharge of the HPG, the stator experienced an equal and opposite torque. This was taken through the frame of the machine and transferred into the floor, where a 200-ton, 1.6 m deep reinforced concrete foundation containing 58 embedded anchor bolts had been previously installed to tie down the HPG and launcher recoil assembly.

IV. Inductor

In contrast with capacitor-based pulsed power supplies for railguns where inductors are used to extend the intrinsic current pulse delivered by capacitors, the inductor in this system (L_0 in Fig. 1) was used to shorten the 100 ms pulse delivered by the HPG down to a few milliseconds to match the transit time of the launch package through the launcher.

Since a 1.5-MA inductor was not an available "standard" item, a design was chosen based on experience at the National High Field Magnet Laboratory, which was based at Massachusetts Institute of Technology (MIT) at that time. The chosen design was the Bitter-type toroidal high field magnet, shown in Fig. 8. In this, each thick copper plate comprised one turn

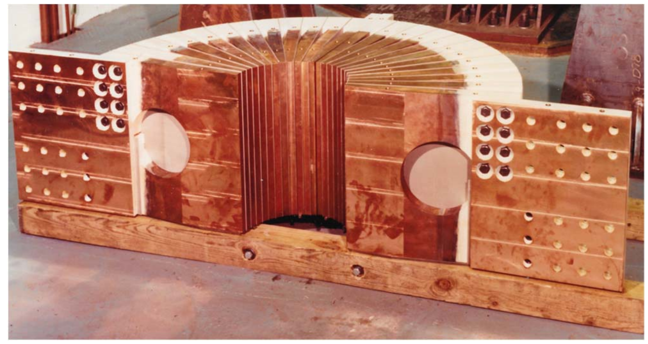

Fig. 8. Half-section of bitter-type inductor.

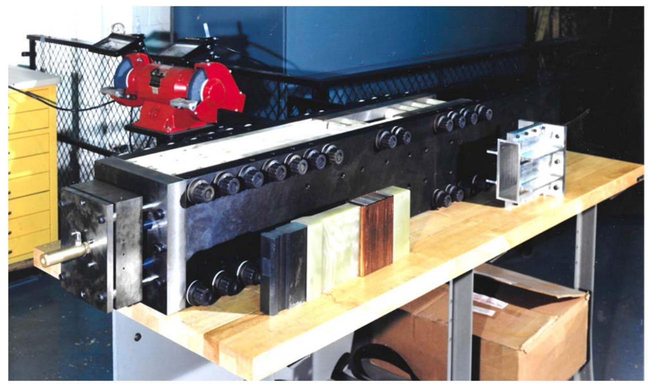

Fig. 9. 1.5 MA switch assembly.

that carried up to the maximum current of 1.5 MA. With an inductance of 4.5 μH, the total stored energy was 5 MJ.

V. Opening Switch

Perhaps the most significant issue for any HPG-inductive pulsed power system for this circuit is the need for an opening switch to divert current from the inductor and feed it into the breech of the railgun (S_2 in Fig. 1). As with other components, there was then, and still is now, no "standard" switch design capable of the current and coulomb rating needed. The solution adopted followed the ANU approach and used a relatively heavy and slow-moving "projectile" as the switch in another larger railgun arranged perpendicular to, and at the breech of, the main railgun. Fig. 9 shows the switch components before assembly onto the railgun breech. During the $\sim$100 ms current transfer from the HPG to the inductor, the switch projectile (Fig. 10) was held stationary against the forces trying to accelerate it by hydraulic clamps holding onto the detent on the left-hand side of the body in Fig. 10. The clamp fixture was tested to its design force of 220 kN without failure before installation. When the current reached the maximum value, the clamps were released, and the forces exerted by the 1.5-MA current propelled the 11 kg projectile down the switch rails, causing it to pass over an insulated section at 200–300 m/s and thereby diverting the current into the railgun breech, where the launch package had already been installed, and which was then launched. The switch armature was safely stopped in a catch box containing crushable

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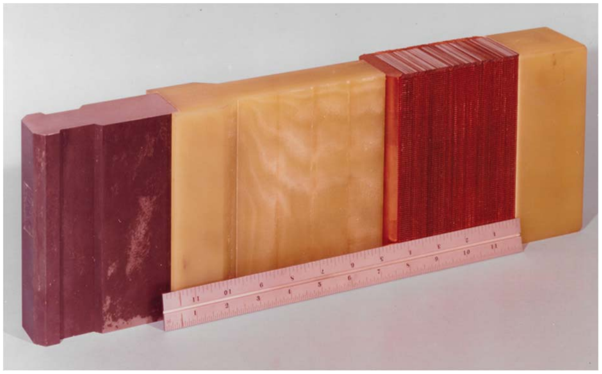

Fig. 10. Side view of the switch “projectile.”

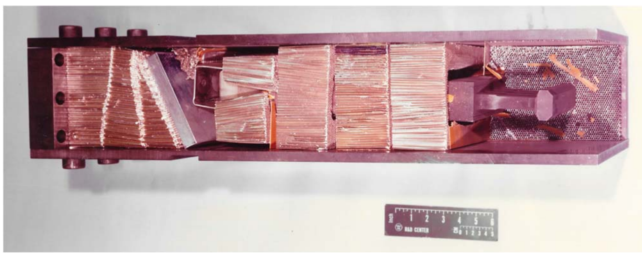

Fig. 11. Top view of the switch projectile stopped in the catch box.

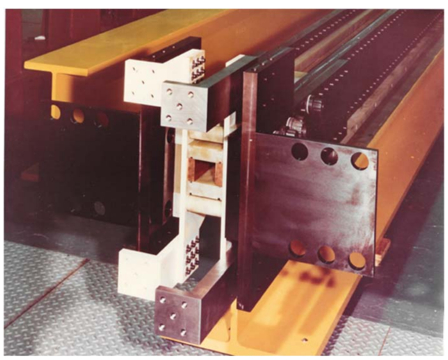

Fig. 12. Launcher breech.

aluminum honeycomb (Fig. 11). The current passed into the armature through stacked multiple thin copper sheets which used flexible “fingers” for their contacting surfaces.

VI. Launcher

The launcher was designed to match the other system components and with dimensions that were thought to be potentially representative of a future tactical gun system, being 5-m in length with a square bore cross section of 50 mm. Copper rails were used with G-10 epoxy-impregnated insulators and backing sections. The inner bore was retained in a bolted steel containment (Fig. 12). The breech section was solidly bolted to a steel reaction structure which, in turn, was bolted to the deep reinforced concrete foundation under the HPG.

Even though the muzzle led directly into a closed diagnostic and catch tank section, it was thought best to try to mitigate the expected muzzle arc to allow high-speed camera photography, so two slotted stainless-steel muzzle resistors were attached above and below the rails for this purpose (Fig. 13). As with other components, their expected adiabatic temperature rise per shot was within the material limits. The resistors were restrained against their launch forces with a bolted assembly.

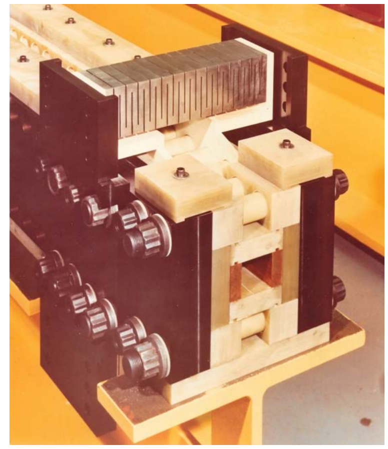

Fig. 13. Launcher muzzle and resistor.

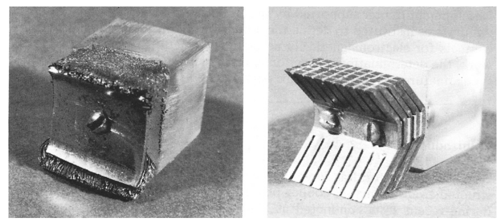

Fig. 14. Two armature concepts tested in the 12.7-mm bore ELF railgun. (Left) Multifiber concept. (Right) Trailing leaf chevron.

VII. Launch Package

Several armature designs were considered during the design phase, some of which were based on the ANU experience [11] and with advice from Dr. John Barber.[2] The trailing leaf chevron version used multiple copper foil slotted with many bent fingers to ensure flexible multipoint current-carrying contacts across the entire rail height. The design was one of two that was validated in the 12.5 mm bore of a small 50-kJ capacitively driven Westinghouse railgun, known as electromagnetic launcher facility (ELF), by taking flash X-rays of its performance during launch through the nonmetallic sidewalls [12], [13]. Fig. 14 shows the two candidates tested in ELF. The chevron design on the right was similar to the one used in ANU experiments but modified with a longer straight center section for the larger rail separation used in these tests.

The foils were designed to vaporize during the current pulse, yielding a plasma that would launch the projectile through a titanium pusher plate that supported a Phalanx-like projectile made of steel. Fig. 15 shows the components, with the armature on the right. A titanium pyramidal support plate for the small projectile was embedded in the Lexan containment (second from the right); its function was to spread

[2]Richard Marshall left Westinghouse in 1978.

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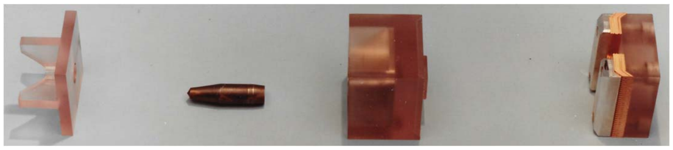

Fig. 15. Launch package with pseudo-phalanx projectile.

Fig. 16. Multifiber armature.

the acceleration forces experienced by the projectile which would have otherwise made it difficult to support.

An alternate armature design was also developed in 1981 during testing on ELF. This concept (on the left in Fig. 14) was based on earlier Westinghouse work on multifiber brushes for current transfer in high current homopolar machines [14]. The full-scale multifiber armature is shown in Fig. 16.

VIII. Diagnostic Section and Catch Tank

The design of the diagnostic section was largely handled by the University of Dayton Research Institute (UDRI), and International Applied Physics (IAP) Research. The diagnostics included flash X-rays and a Q-switched pulsed ruby laser-illuminated Hall camera station intended to take photographs of the launch package as it transited the section before the catch tank. The X-ray section, launch tube, and catch tank are visible in sequence from left to right in Fig. 17. Additional diagnostics included the inductor current, the barrel dI/dt, and the muzzle voltage.

IX. Completed System

Fig. 18 shows the system close to its final configuration, Fig. 19 shows the then state-of-the-art control panel, and Fig. 20 shows the final assembly as of January 1982.

X. Test Results

Once the total system was completed, tests were scheduled in conjunction with DARPA and ARDEC.[3] However, the planned testing period at Westinghouse was severely curtailed because of the Army's desire to transfer the equipment as soon

[3]At that time it was called ARRADCOM – Army Research and Development Command and, later, AMCOM, Army Materiel Command.

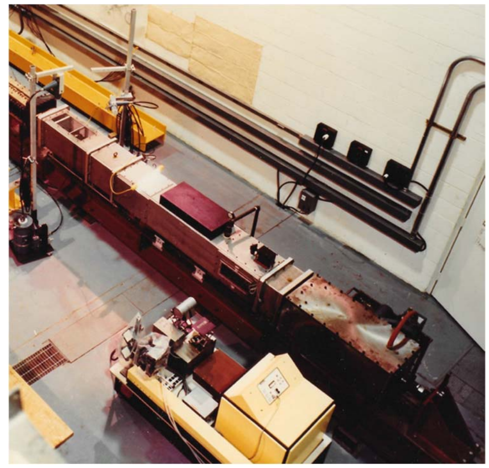

Fig. 17. Diagnostic section and catch tank.

Fig. 18. EMACK assembly crew.

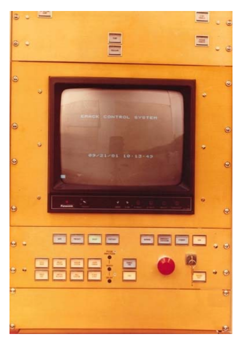

Fig. 19. EMACK control panel.

as possible to a new laboratory under construction at ARDEC, Picatinny, NJ, USA. Consequently, it was only possible to perform five tests during February 1982, before the activity was terminated. Since this was a new and uncharacterized system involving very high stored energy, high currents and voltages, and an expected very high muzzle velocity, the plan involved a cautious yet accelerated test schedule in which the HPG rotor speed was increased in steps from Test 1 on February 7th to Test 4 on February 19th with 2, 4, 8, and 16 MJ of stored energy. Test 5 on February 25th was a "show and tell" demonstration for visiting dignitaries from Washington,

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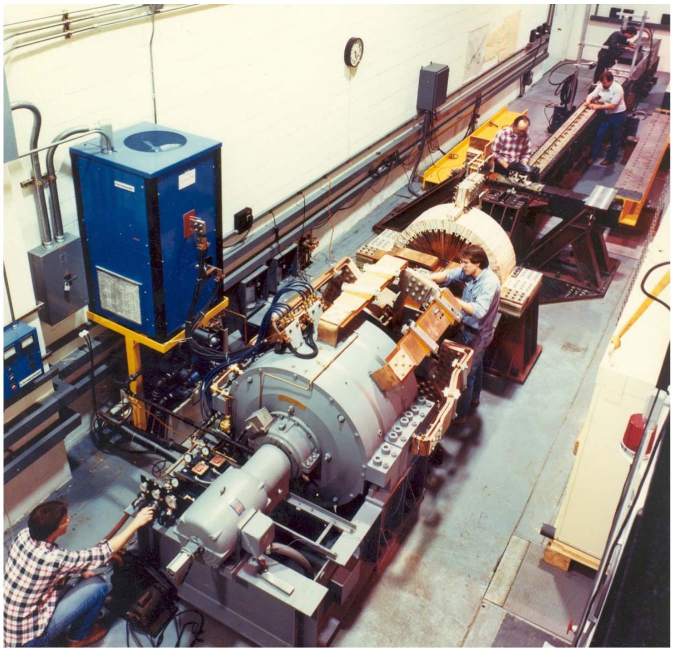

Fig. 20. EMACK final assembly.

TABLE I
SUMMARY OF EMACK COMMISSIONING TESTS

Test	1	2	3	4	5
Stored energy (MJ)	2	3.8	7.6	16.3	7.6
HPG voltage (V)	37	50	71	105	
Peak current (MA)	0.53	0.75	1.16	2.1	1.6
Current risetime (s)	0.120	0.120	0.063	0.095	
Peak voltage (kV)	1.5	3.0	2.5	8	
Commut. time (ms)	0.26	0.40	0.70	1.4	
Breech voltage (kV)	0.7	1.5	2.0	5.0	
Launch mass (kg)	0.195	0.225	0.275	0.317	0.318
Armature type	Plasma	Plasma	Plasma	Fiber	Fiber
Velocity (km/s)	0.49	*	1.5	4.2	3.0
KE (MJ)	0.02	*	0.3	2.8	1.4

• Not obtainable from data.

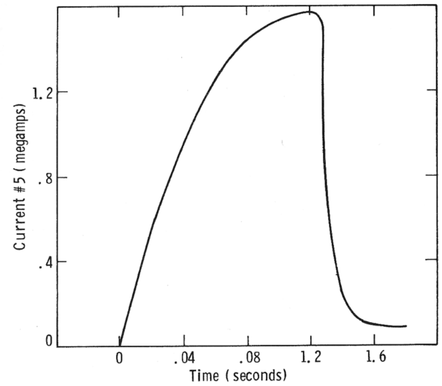

Fig. 21. Measured inductor charge current for Test 5.

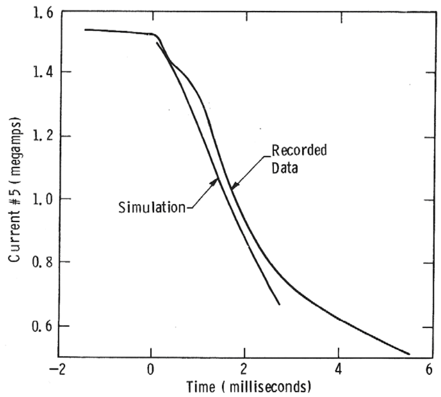

Fig. 22. Inductor discharge current versus prediction for Test 5.

Fig. 23. Recovered launch package fragments from Test 3.

DC, and the HPG energy was limited to 8 MJ to reduce unexpected risks.

A summary of the test results obtained at the time is given in Table I. Tests 1, 2, and 3 used the first type of launch package (Fig. 15) while Tests 4 and 5 used the fiber armature type (Fig. 16). Details are given in [15]. The barrel was completely disassembled between shots. It was found that rail damage was greater with the plasma armatures, with liquid metal splattered onto the rails and arc damage in the breech region, although after the first 0.5 m the rails were largely undamaged. With the fiber armature, the damage was less except for two small indentations about 2 mm deep at the initial location of the armature. In all cases, the bore interior was covered with a thin layer of soot.

Of all the data recorded during the tests, the measurements of dI/dt, HPG voltage, and barrel muzzle voltage were considered to be the most reliable based on internal consistency and redundancy tests. The Flash X-ray and Hall camera failed to provide definitive data on any of the tests. Test 5 provided the most reliable data as the team gained more experience and corrected problem areas during the accelerated testing schedule. Figs. 21 and 22 show the measured inductor charge and discharge currents for Test 5.

Test 3 used the Phalanx-like launch package as shown in Fig. 15. Post-test fragments were recovered from the catch tank (Fig. 23). The entry cone to the catch tank showed that the 0.12 kg steel projectile had impacted off-center but ricocheted to safely enter the tank (Fig. 24).

At the time of the tests, it was concluded from the available data that Test 4 had exceeded the design goals by reaching a muzzle velocity over 4 km/s. The measured peak inductor current was 2.1 MA, as shown in Fig. 25. However, subsequently, doubt was thrown onto this conclusion by the appearance of the witness plate in the catch tank. Fig. 26 shows the witness

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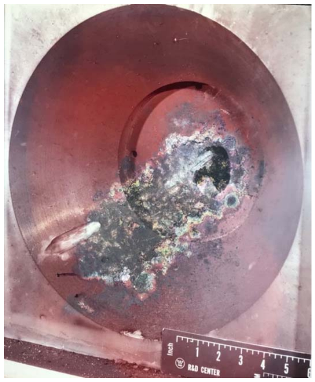

Fig. 24. Catch tank entry cone, Test 3.

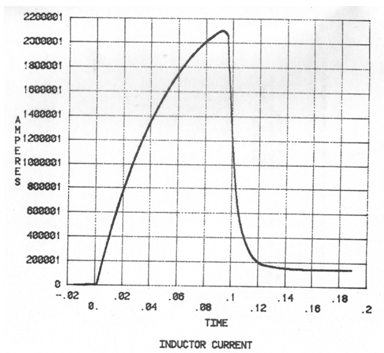

Fig. 25. Measured inductor current for Test 4.

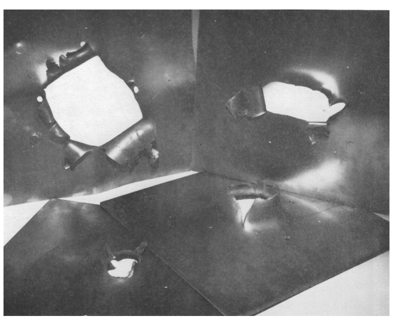

Fig. 26. Witness plates for Tests 1 to 4 in counterclockwise order from the upper right.

plates for the first four tests; these were located just inside the catch tank entrance.

For the first two tests, the witness plates were 1.6 mm thick while for Tests 3 and 4 they were 6.35 mm thick. A comment was made that a true hypervelocity impact would not cause a witness plate to petal, as all of these plates showed, but would create a circular "burn-through" hole. Since no independent measurements of velocity were obtained from the diagnostic section, it was never possible to resolve this discrepancy satisfactorily. It is also important to point out that it was not clear when the petaling of these witness plates occurred—it could have been "long" after the projectile had passed through them and caused by the muzzle arc or a large amount of ablated "after-launch" hot gas bore byproducts following the projectile exit—a feature that has been subsequently observed in most railgun launches.

Fig. 27. ARDEC building 329, 1983.

Fig. 28. ARDEC building 329, 1984.

XI. Transfer to ARDEC

When the capabilities of EMACK became apparent, two competing entities in the U.S. Army evinced interest. The Army Ballistic Research Laboratory (BRL[4]) in Aberdeen, MD, USA wished to have the equipment to conduct hypervelocity impact research, whereas ARDEC wished to have the equipment to conduct research on EM launch technology. In the event, ARDEC prevailed and although the laboratory was not ready to install the equipment, it was shipped there shortly after the five tests described above were completed. It remained in storage until late 1982 when Building 329 became available. Fig. 27 shows the ARDEC team during the process of installation in 1983 while Fig. 28 shows a smaller group of the ARDEC personnel in 1984 following completion of the installation in Building 329.

The EMACK system was used and developed in various ways at ARDEC and remained a useful facility there for many years.

In late 1984, following modifications to the opening switch release mechanism to replace it with shear pins to improve its reliability, a sequence of events caused the brushes to drop onto the rotor surface but not complete the electrical circuit or retract. The subsequent rapid frictional heating caused the aluminum sleeve to overheat and lose its shrink-fit onto the underlying steel rotor, with catastrophic results [16]. The rotor was subsequently replaced by Westinghouse but without a

[4]Now ARL, the Army Research Laboratory.

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replacement aluminum sleeve. This allowed a higher rotational speed, and therefore, up to 30 MJ stored energy, but because the load current diffused into the rotor core, an armature reaction was created in which the output current caused the generator voltage to decrease. For this reason, the HPG was derated to operate with a lower output current. Subsequently, additional improvements were made by installing a larger drive motor (320 hp.), which decreased the rotor spin-up time to a few minutes [17]. With the advantage of operating experience, several suggestions were made on system improvements [18] and many considerable diagnostic and other improvements were implemented by ARDEC.

Although the era of the 1980s and the 1990s were largely dominated by railgun research using single-shot facilities, it was appreciated that if railguns were to become useful weapons, they would need to be capable of repetitive operation. As a consequence, multishot switches were in development and were tested at Westinghouse, ARDEC, and elsewhere (See [16], [18], [19]).

One development that stemmed from the fiber armature used in Tests 4 and 5, was the involvement of the Dutch National Defense Prins Maurits Laboratorium (TNO), in adopting this technology. through the interest of a TNO senior scientist during his assignment to ARDEC on a scientific interchange program [20]. TNO continued the development of this technology and it was subsequently adopted by the French-German Research Institute Saint-Louis (ISL) and used there in modified form for many years. (See [21], for example.)

XII. Discussion and Conclusion

In retrospect, it seems clear that the Westinghouse EMACK system provided the major step forward in railgun technology to the MA current and MJ energy levels after many decades of earlier research at kJ levels. It provided the impetus for many U.S. and international organizations to become involved in the technology and the 1980s saw an explosion of interest, as documented in the proceedings of the Symposia on EM Launch Technology in the IEEE Transactions on Magnetics and, later, the IEEE Transactions on Plasma Sciences.

The efforts described here are but one part of the expansion of interest in railguns and related technologies in the U.S. and around the world in the 1980s. The Westinghouse Electric Corporation was an early pioneer in the field and invested considerable funding and manpower in supporting these advances. Although Westinghouse no longer exists, some of their operating divisions that were integral to the efforts described here continue under other names–for example, the Westinghouse Cheswick Electromechanical Division is now Curtiss Wright, and the Westinghouse Marine Division in Sunnyvale is now part of Northrop Grumman.

It was very unfortunate that the original testing schedule was so abbreviated (only 19 days including weekends) since it did not allow the many new high energy systems and diagnostics to be fully evaluated and brought to their full operational capability, which would have resolved some of the discrepancies that were observed. However, many of those issues were addressed during the subsequent ARDEC testing.

By comparison with today, relatively little was known when these efforts started in the late 1970s, and much of the 1980s and even later was largely devoted to single-shot laboratory research to identify and characterize the effects taking place in launchers, projectiles, and pulsed power systems. By the late 1980s and early 1990s, the state-of-the-art as measured by muzzle kinetic energy had progressed from the >1 MJ demonstrated by EMACK to close to 10 MJ—a remarkable increase on any results before 1980—but still much less than the >30 MJ that has been demonstrated today [22]. Another major change today is the capability to fire multishot salvos at multi-MJ levels, which was always understood to be necessary for future systems but was never demonstrated in the earlier high-energy programs. The third recent capability, which was close to unthinkable in the 1980s, is to be able to launch a projectile that has guidance capability. This has been made possible by advances in ruggedizing microelectronic components so they can withstand gun launch acceleration forces. Taken together, these advances have made railguns closer to implementation today.

XIII. Future Possibilities

Some challenges remain for the development of railgun systems, one of which is to improve the energy storage density of all electrical systems which, at kJ/kg, remains far below that of chemical gun propellants (MJ/kg). Following the example set at ANU and with knowledge of similar prior technology, this project and several subsequent programs used iron-cored HPGs as an inertial energy store and for pulsed high current delivery [23]–[25]. While these HPGs were rugged and capable machines, they generated longer pulses at much lower voltages than needed to drive railguns directly, and so required pulse compression and voltage enhancement with an inductor and an opening switch using the circuit shown in Fig. 1. Although improved versions of these machines designed after EMACK featured, for example, multiple stages and high magnetic fields for increased output voltage, superconducting field coils, and self-excitation, [26]–[31] all still suffered from the same basic issue that the voltage generated was well below that required to drive a railgun, thereby necessitating the inductor and opening switch.

Nevertheless, it is worth considering whether this approach should be revisited using modern technology and materials to determine if it could offer an alternative to the capacitor-based pulse forming networks that are presently the pulsed power approach of choice, despite their complexity, high parts count, and high cost.

The inductor in the circuit shown in Fig. 1 plays the important role of delivering the current to the railgun, having been electrically energized with a MA direct current by the HPG. One question is whether there is any other way in which the inductor could be supplied with energy–and an answer today for a transportable system is that modern Li-ion batteries may be able to do that job. The basic Li-ion cell voltage is low (typically $\sim$3.7 V) so about 30 cells would need to be connected in series to provide the same voltage as used by EMACK and, assuming a pulse current capability

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per cell of 1 kA, 1600 parallel series stacks of series chains would be needed to achieve a current of 1.6 MA. Managing the resulting 48.000 battery cells would not be a negligible issue and performance degradation has been observed in such situations [32].[5] An assessment of the relative merits of such batteries versus a modern high-technology HPG would need to take into account these issues and, in both cases, the need for auxiliaries and control systems. The most obvious difference between the two approaches may be the modularity of the battery storage system versus the more concentrated bulk of one or more pairs of contra-rotating generators, as preferred to eliminate external torque reactions on the platform. Battery storage may also offer the opportunity to service a wider range of loads.

Megampere opening switches of the type required in the circuit shown in Fig. 1 are a different matter. Switches of this type, which must carry current for (in this case) ∼0.1 s before opening to a current of a megampere or more, are not used in any other situation and must thus be developed specifically for this application. Apart from the use of an auxiliary railgun to perform the switching, as used with the ANU railgun and with EMACK, other approaches have used triggered explosive cutting of busbars (e.g., [33]) or a repetitive rotary variant of the ANU design developed by IAP in which alternate conductive and insulated rotor sections were rotated under conducting contacts at high speed [19]. This latter approach resulted in arcing damage and erosion of the conducting sections unless care was taken, but it was used successfully in a three-shot burst salvo test at United States Air Force (USAF), Eglin [34]. High current explosive opening switches have only been used in single-shot operation, so far as is known, although designs have been suggested for multiple shots [33].

Under these conditions, the preferred option of using solid-state switches is still not feasible for opening megampere currents. Sitzman solved this problem by subdividing the switching duty and using commercially available gate turn-offs (GTOs) rated at 2 KA opening capability on individual battery cells [35]. These provided current to the primary side of a pulse transformer and when the GTOs were simultaneously opened, the secondary side of the transformer delivered a high current to the railgun.

In conclusion, it may be worth considering if modern high-technology HPGs could be used in novel circuits using pulse transformers that could take advantage of recent advances in solid-state switch technology, but such an assessment should also consider the capabilities of modern batteries and supercapacitors for the same application. It is not clear that an HPG could advantageously replace batteries in this situation.

Acknowledgment

The many scientists, engineers, and technical staff who worked on the project described here some 30 to 40+ years ago have by now mostly retired, moved on to other activities, or sadly, in several cases, are deceased. However, it would be remiss if their pioneering efforts were not recognized, and this article attempts to do that. They were not, by any means, the only ones involved in EM launcher activities at that pivotal time, but they were a major driving force in the early years of the U.S. railgun program and their pioneering efforts enabled and supported major advances in the technology.

The Westinghouse Research Center team led by John Mole included Roy Stillwagon, George Kemeny, Donald Litz, Dr. Dan Deis, Doug Fikse, Dave Scherbarth, Dr. Gerry Ferrentino, Dave Marshak, Ray Wilkinson, and Tom Cronin. The Westinghouse Marine Division personnel included Dan McAllistair and Henry Miller. The DARPA personnel included Dr. Arden Bement, Dr. Ray Gogolewski, and Dr. Mike Buckley. The MIT efforts were supervised by Dr. Henry Kolm, the UDRI efforts by Dr. Stephan Bless, and the IAP efforts by Dr. John Barber and Dave Bauer. The ARDEC team initially led by Dr. Harry Fair, included: Dr. Peter Kemmey, Dr. Ted Gora, Curtis Dunham, John Bennett, Tom Coradeschi, Harry Moore, John Pappas, Doug Witkowsk, Dr. Willem Kolkurt (TNO), Brian Nagle, Bill Snow, Alex Zielinski, Greg Columbo, and Dr. Gerry Ferrentino, who joined ARDEC from Westinghouse. Many more people were involved than are named here and their contributions were essential to the success of this and subsequent railgun projects.

[5]For comparison, a Tesla Model S contains 7100 individual cells and reliable operation in the consumer market has been demonstrated, although the Tesla cells do not operate in a subsecond pulsed mode of the type required here.

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