STARING DOWN THE BARREL OF A RAILGUN...

The railgun is quickly hurtling toward inclusion on future Navy platforms, thus revolutionizing the design and use of those platforms and, in turn, Navy strategies and tactics. This hypervelocity, multimegajoule, hypersonic electric launcher has been demonstrated in more than a thousand successful launches, promising new capabilities for the Navy, including long-range fire support, antiship warfare, and ship self-defense against air threats.

Great power does not come easily. Launching projectiles at extreme velocities and energies is difficult. In-bore failure of the projectile due to barrel wear or material fatigue can have catastrophic consequences. Therefore, attention is now aimed at studying, measuring, analyzing, and simulating rail and barrel wear-and-tear on the micro level. The Naval Research Laboratory's Materials Testing Facility (MTF) is concentrating on the microscopic nitty-gritty of railgun barrel science and technology in quantifying rail wear and damage. Using their expertise in armature design, profilometry, metallography, and modeling and simulation, MTF laboratory personnel are helping to develop an operational railgun that will perform in real-world Navy-relevant conditions. With the ability to rapidly modify the barrel to test designs and materials, MTF staff have continuously modified and upgraded the railgun system and transferred their results to NSWC Dahlgren, Virginia, the Navy's lead lab for railgun research, for full implementation.

Electromagnetic Railgun Barrel Damage Experiments

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The Navy has invested considerable resources over the last decade in the development of hypervelocity electric launcher technology. The program has been highly successful, demonstrating a multimegajoule hypersonic railgun launch. A prototype weapon system is expected to be on a naval platform within the next decade. The Navy railgun, when fully developed and coupled with guided projectile technology, will provide new capabilities for multiple Navy missions. These include long-range fire support for littoral missions, naval antiship or small craft surface warfare, and ship self-defense against air threats. High-performance electric launch weapons will thus have a significant effect on Navy strategies and tactics.

The Naval Research Laboratory is a partner with the Office of Naval Research in this development effort. NRL's focus is the science and technology behind high-power railguns. To fully exploit the potential of this technology, the reproducibility of the launch and the lifetime of the barrel are important metrics. Single-shot failure or gradual wear of the barrel materials on a shot-to-shot basis can lead to unacceptable barrel lifetime. Damage or wear can lead to lateral acceleration or loss of low-voltage sliding contact, which can affect launch characteristics or rapidly increase wear. Avoiding wear relies on designing armatures and barrels that can withstand the immense forces and high temperatures generated during launch. This requires understanding the wear processes and selecting appropriate designs and materials. The conditions inside a high-power railgun greatly exceed normal engineering constraints. Currents are measured in million amperes (MA), pressures reach hundreds of megapascals (MPa), accelerations exceed 10,000 gravities (10 kilogees), and local temperatures reach the melt temperature of most metals. The NRL program focuses on understanding the launch processes, measuring the conditions during launch, modeling the system, and developing techniques or designs that resolve or mitigate damage mechanisms in the barrel.

The NRL railgun program is centered around the Materials Testing Facility (MTF) located on the NRL campus. This facility houses a 6 m long railgun with a 5 cm diameter bore. An 11 megajoule (MJ) capacitive energy store is housed in the laboratory. The railgun is designed to permit rapid modification of the barrel and access for diagnostics to monitor launch performance. Experiments with different rail and armature designs and materials are performed. Over 1000 high-power shots have been fired on the system, which has undergone continuous modification and upgrade over the last 5 years of operation. Results from the experiments are analyzed and compared with state-of-the-art computer modeling, and materials are analyzed using detailed metallographic analysis techniques.[1] Materials properties are measured and specific bits of physics relevant to the operation are tested using small test stands. This article discusses electromagnetic (EM) launch technology in general and presents examples of barrel damage experiments performed by the NRL program.

EM LAUNCH TECHNOLOGY

Railgun technology is based on using electrical rather than chemical energy to accelerate a projectile to high velocity. There are several advantages to using electrical acceleration. Railguns use magnetic pressure rather than gas pressure to accelerate the projectile. Electrical current is driven through a set of conductors (rails) and the resultant magnetic field accelerates the short circuit (armature) by Lorentz force down the

rails. This mechanism removes the gas expansion limits of propellant guns and allows higher launch velocity. The velocity limits of expanding gases are replaced by the limits of maintaining a low-resistance, high-velocity sliding contact during launch. Electromagnetic acceleration offers the added benefit of allowing the launch parameters to be controlled through the current waveform, which enables optimization or modification of the launch dynamics. The high launch velocity decreases delivery time, and the high terminal velocity allows one to use kinetic energy rather than explosives for target interaction. The removal of the propellants and explosives simplifies the handling and storage requirements for shipboard applications, and greatly increases onboard safety.

MTF LABORATORY

Figure 1 shows the MTF laboratory including the capacitive energy store and the 6 m railgun. The switch arrays and series inductors can be seen on the individual banks. The figure includes pictures of the target chamber, dual-axis flash X-ray imager, muzzle arc containment, and the breech. The railgun is divided into six 1 m long Type 304 stainless steel containment segments that are clamped together with vertical thread rods and auxiliary steel supports. The entire structure is mounted on an epoxy laminate base. Current from the different banks is combined and fed into the rails in the breech. The rails are terminated by tungsten copper electrodes at the muzzle, which are designed to arc to electrodes after the armature leaves the gun. Current still flowing in the system is dissipated by the resistance of the muzzle arc and the rails themselves. The muzzle blast is contained by a cylindrical steel structure. Magnetic field probes are located along the length of the gun to measure the location of the armature as it is accelerated down the barrel. Probes are located at the breech and muzzle ends of the gun to monitor the voltage between the rails.

Figure 2 shows a cross section of the railgun. In this example, 0.25 in. thick rectangular steel liners are used for the rail surface. The rails are mounted vertically and backed with 1 in. thick copper rails. The rail spacing is set by "T" insulators located on the top and bottom of the core. The figure shows a nominally 1.8 in. × 1.75 in. flat rail core. Epoxy–glass fiber laminated material is used for the "T" insulator and for the insulators surrounding the rails. The stainless steel containments clamp the core in place. Wedges located inside of the

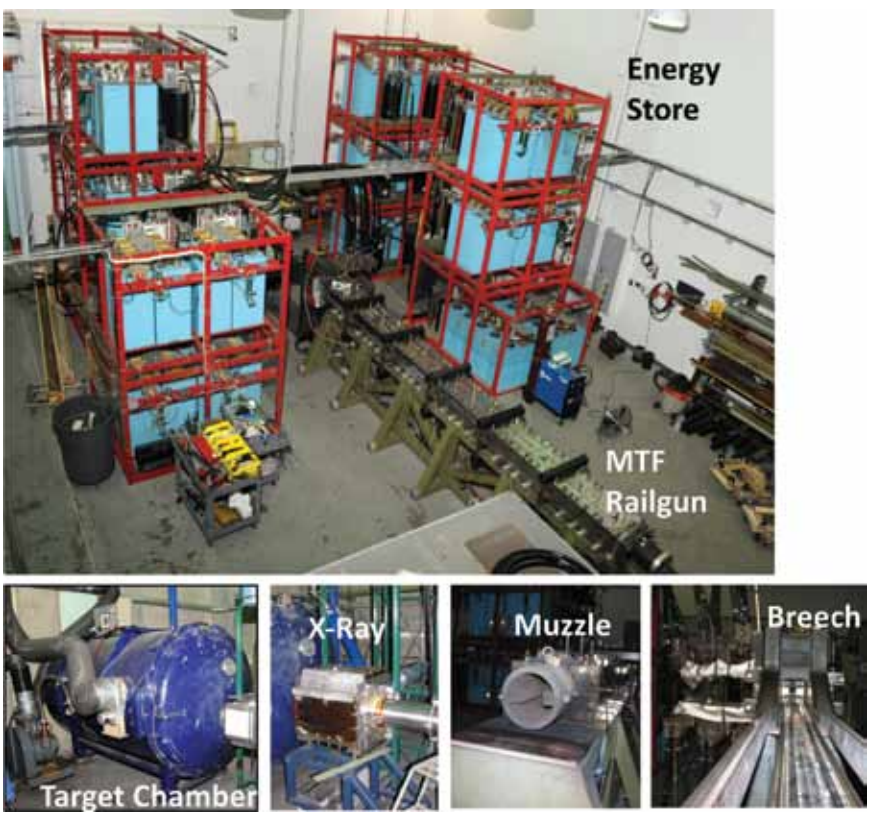

FIGURE 1
The top image shows a view of the NRL Materials Testing Facility with the capacitor bank energy store and the railgun. Bottom images show the target chamber, X-ray imager, and muzzle and breech views of the railgun.

containment are adjusted to provide preload to the rails. Different core designs can be substituted for the square bore design shown in the figure by altering the insulators.

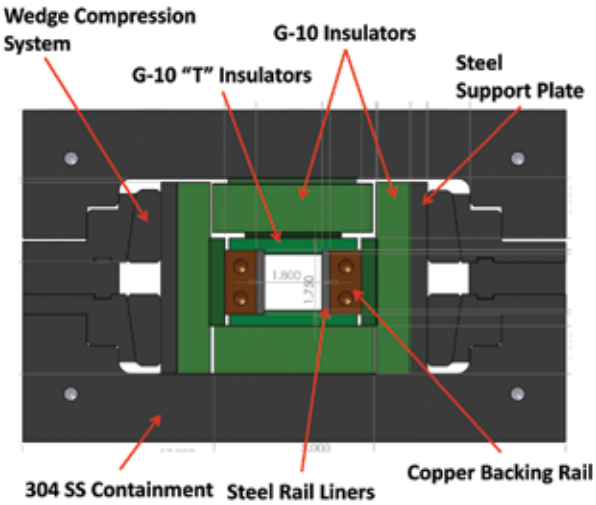

FIGURE 2
A cross section of the MTF railgun is shown. The rails are mounted vertically with a wedge system to provide uniform compression to the rails. The clamshell design containment holds the system together during launch.

CAPACITOR BANK DESIGN

Figure 1 shows the capacitor banks stacked close to the breech of the railgun. Twenty-two 500 kJ solid-state switched capacitor banks are connected to the railgun.[2] The banks are charged in parallel over several minutes from several independent power supplies. A solid-state switch (thyristor stack) is triggered to connect the banks to a series 80 microhenry inductor and the railgun. After peak current, a second switch (diode stack) shorts out each bank, isolating the capacitors from the railgun and trapping the energy in the inductor and rail system. A resistor located in the diode leg of the circuit provides a series resistance for the individual bank modules, allowing the decay time of the current from a particular bank to be modified. The different banks can be independently triggered, allowing one to modify the current waveform delivered to the railgun. The use of the resistors and the different bank timings allow one to program the waveform. The goal is to generate a relatively flat-topped current waveform but decrease the muzzle current to minimize muzzle arc damage.

ARMATURE DESIGN

A critical component of a railgun is the armature that serves as the current path between the two rails. Magnetic fields generated by this current then drive the armature along the rails due to the Lorentz force. A typical armature design has a "C" shape with the sliding contacts following the body of the armature (see Fig. 3). A projectile would be coupled to the armature and pushed down the bore by the current in the armature. The "C" shape utilizes the magnetic pressure generated by the current to push the legs onto the rail surface. The acceleration on the projectile can be measured in tens of kilogees. At these accelerations, the stress on the armature body itself can exceed elastic yield levels. Complicating this is the resistive heating of the armature. This can soften the metal, which lowers the stress that the armature can withstand before it fails. The legs can literally fall off, resulting in loss of the sliding contact, arc generation, and damage to the rails. Armatures are designed using detailed 3D design codes. An example of a model predicting stress in a simple rectangular leg armature is shown in Fig. 3, where a triangular mesh and von Mises stress values in the armature are generated for a simulated launch. Here, the highest stress is in the throat of the armature, which also coincides with the maximum heating region. Thus, one would expect failure of the armature to start in the throat of this armature where the stress is highest.

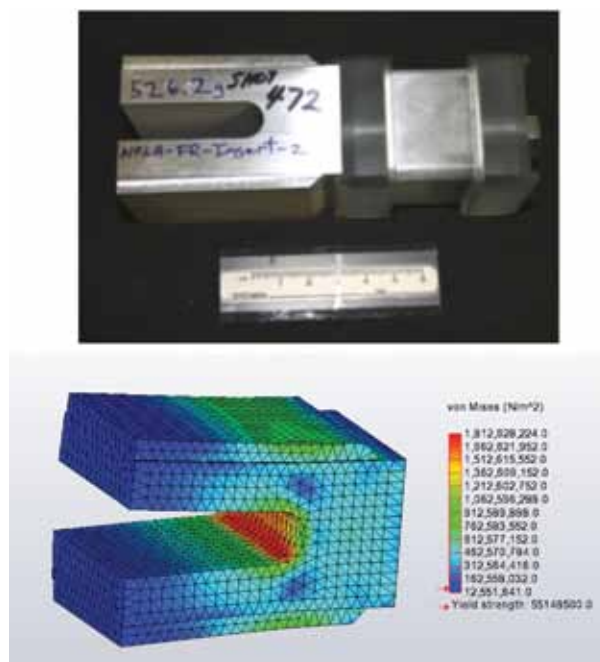

FIGURE 3
Top: An armature used in high-power launch experiments is shown. The aluminum "C" shaped armature provides a short circuit between the rails as it is accelerated down the rails. The acrylic bore riders keep the armature centered in the gun. The ballast allows the mass of the armature to be adjusted. Bottom: An example of a simulation of the armature response to high pressure loading experienced during launch.

NRL EXPERIMENTS

A wide range of experiments have been performed on the MTF railgun. Figure 4 shows data recorded during several launches using the armature type shown in Fig. 3. The armature was loaded to 27 cm from the breech end of the 6 m long containment. A current monitor on the breech shows 1.5 MA peak current driven in the rails. Voltages between the rails at the breech and muzzle ends of the railgun are also shown. The breech voltage measures the inductive voltage across the rails as the armature moves down the bore added to the voltage across the rails, armature, and sliding contact. The muzzle voltage measures the voltage across the front of the armature. A set of magnetic field pick-up loops spaced along the containment monitor the armature position during launch, resulting in the velocity vs location curve. The increase in muzzle voltage starting around 4 m indicates that the sliding contact is degrading at the high-velocity end of the gun. This behavior usually indicates the contact has started to transition into a plasma contact rather than a low-resistance metal-to-metal sliding contact. After each shot, the rails and insulators are inspected using a small-diameter camera inserted from the breech to observe any macroscopic damage from the previous shot.

The images on the right side of Fig. 4 are from the dual-axis flash X-ray imager located 5 m downstream of the muzzle end of the gun. The imager provides horizontal and vertical snapshots of the armature before it hits a steel target plate. The high-voltage X-ray pulse is triggered using a magnetic field sensor just upstream of the imager. The images show some wear and plastic deformation of the armature legs. In some cases, the legs break off, resulting in images of armatures tilted at an angle and pieces of leg flying beside the body.

Just downstream of the X-ray imager is the target chamber. Inside the chamber is a stack of six half-inch-thick steel plates separated by half-inch spacers. The armature usually penetrates the first three or four plates before stopping. Some information about the energy at impact and the orientation of the armature can be obtained from these witness plates.

PROFILOMETRY

Much useful information is obtained by analyzing the exterior rail topography, a technique referred to as profilometry. For instance, the launches deposit aluminum from the armature on the surface down nearly the entire length of the gun. Rail surfaces also erode due to the high-pressure metal-on-metal sliding and the large currents at the rail-armature interface. Quantifying the location and amount of deposition or erosion can offer clues to the conditions at this sliding interface during launch. To do this, the surface profiles are mapped using a laser profilometer. Individual profiles are generated every few centimeters along the length of the rails and compiled into complete, 3D representations of the rails, as seen in Fig. 5.

METALLOGRAPHY

After profiling, further materials analysis is performed. Small samples of the rails are cut out, mounted in a dielectric material, polished, and analyzed using metallographic techniques. A high-resolution camera

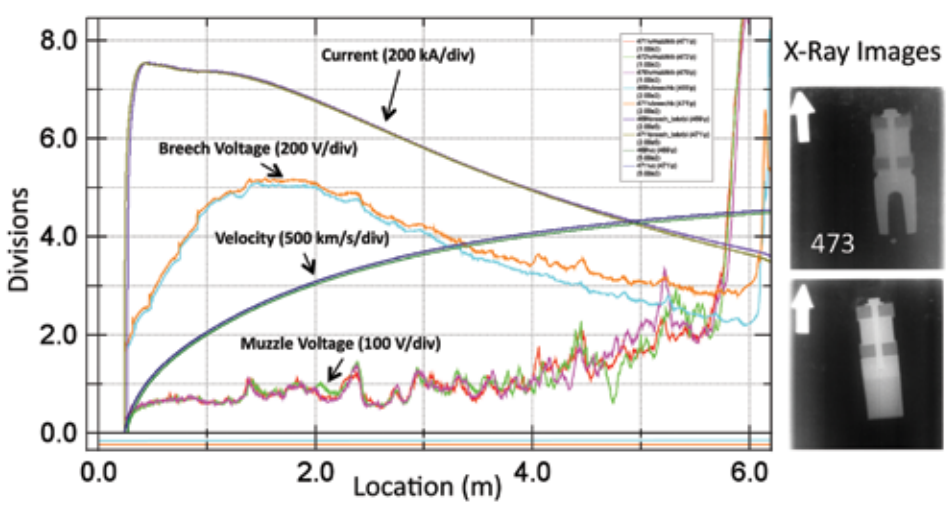

FIGURE 4
Data from several launches is shown as a function of location in the bore. Peak current is 1.5 MA and launch velocity is 2.25 km/s. Breech voltage peaks at 1 kV and muzzle voltage runs at 100 V until 4 m, where it starts to ramp up before muzzle exit. On the right are two X-ray images of the armature 5 m downstream from the muzzle.

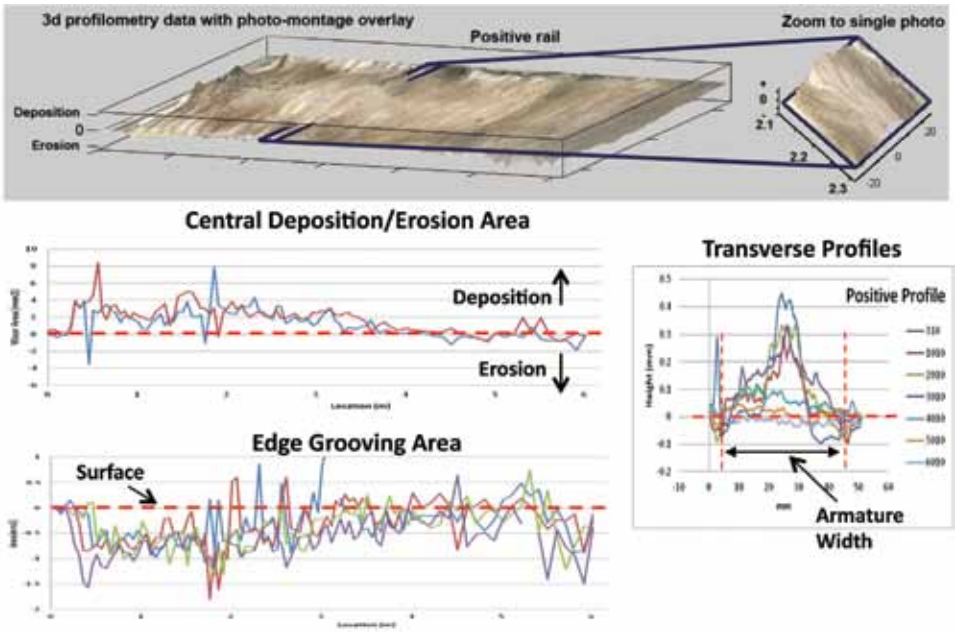

FIGURE 5
Data generated by the laser profilometer is shown. The scanner can resolve ~15 μm changes in the rail surface in a 30 μm spot size. The right graph shows selected transverse profiles along the length of the rails from 310 to 6010 mm. The top panel shows an overlay of the profile and optical imagery. The left graphs show various integrals of the change in the surface profiles.

and a scanning electron microscope (SEM) are used to observe the regions near the rail surface. Energy dispersive X-ray spectroscopy (EDS) is used to identify the composition of small spots on the rails. Different stains and polishing techniques can be applied to bring out the structure of the metals. Micro-hardness measurements can be made to measure changes in the material near the surfaces. Some steels are particularly interesting because they change their hardness or crystal structure depending on temperature and heating or cooling rates of the material. This provides information on the heating and cooling rates of the surface.

Figure 6 shows results of a metallographic analysis of the rail shown in Fig. 5. A detailed surface profile is shown from the 93 cm location. An SEM image from a spot 4 mm from the edge of the negative rail is shown. This location is in an edge groove eroded by the ten launches on the rail. There is a 14 μm thick deposit on the rail surface at this location. Different layers of aluminum and iron aluminide can be seen in the deposit. The EDS analysis from the indicated spot shows peaks associated with the Al and Fe atoms. The signals indicate roughly equal amounts of aluminum and iron in the layer. After passage of the armature, a molten mix of aluminum and iron is left on the rail surface. All of these layers likely formed during the cool-down phase of the surface. The presence of the iron-aluminide suggests that the surface temperature exceeded the 660 °C melt temperature of the aluminum, possibly approaching the melt temperature of the steel.

MODELING AND SIMULATION

The ultimate goal of the NRL program is to understand the processes involved in high-power railgun launches. This understanding can then be used to improve the design and lifetime of the barrel and to scale the results. A significant fraction of this relies on developing computational codes that contain the appropriate physics. The multiple and coupled physical fields and the multiple size scales and materials involved along with the geometric complexity present make this a difficult problem. Finite element analysis (FEA) codes have made great strides over the last decade. The complete railgun problem, however, is still beyond the state of the art. To model a railgun with an FEA code, one breaks the device into a large number of smaller areas or volumes. A mesh defining the different elements is established, similar to the simplified mesh shown in Fig. 3. The size and shape of the different elements are determined by geometry or other considerations. The interactions of the different elements of the mesh are governed by a set of equations representing the conservation laws relevant to the physics of the problem. The problem is reduced to solving a very large number of coupled algebraic equations and keeping track of how they move or change during a single time step. The process is then repeated over and over again. This rapidly becomes a very large problem depending on the number of elements and the number of fields participating in the interaction of the different elements

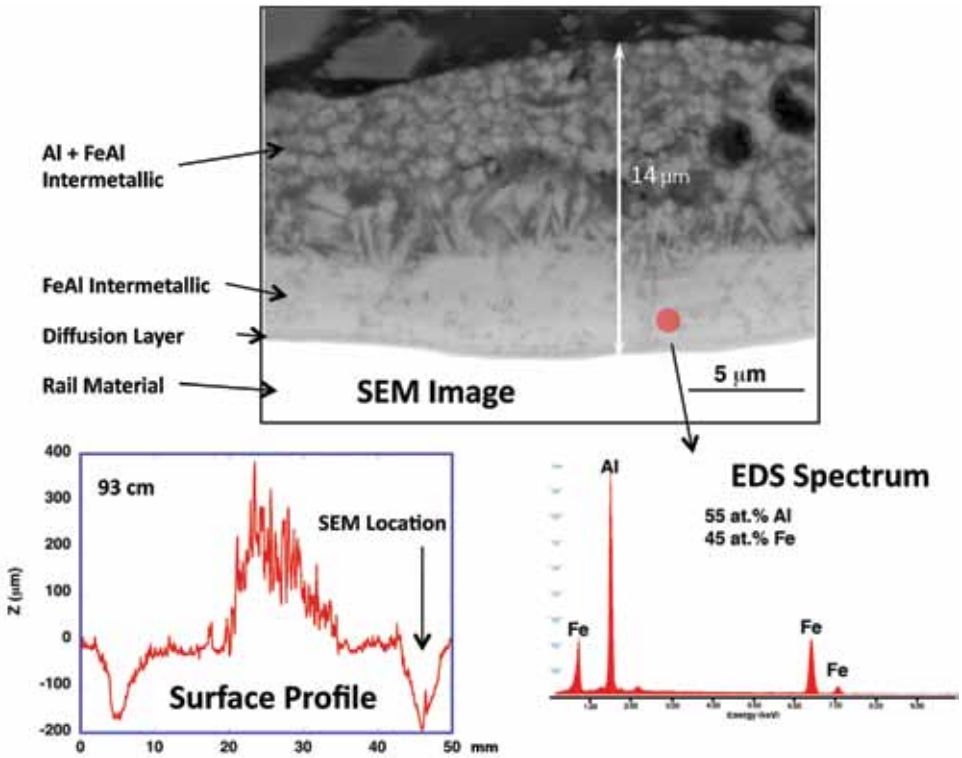

FIGURE 6
Microstructure and deposit composition approximately 1 m down-bore and in the region of maximum edge-groove erosion. The thin deposit here appears to have resulted from the deposit of hot liquid following the passage of the armature on the last shot. The deposit near the rail interface contained more Fe than that observed at 43 cm down-bore, implying a higher interface temperature, at least 1200 °C.

and the length of each time step required to resolve the changes.

NRL is at the forefront of FEA modeling. Figure 7 shows the results from a simulation using COMSOL Multiphysics, a state-of-the-art 3D FEA code.[3] This figure shows the magnetic flux density on the surfaces of an armature similar to that in Fig. 3. The aluminum armature is moving at ~1 km/s on a copper rail with ~700 kA current passing through the armature. The local high field regions appear on the edges of the armature and behind the armature on the corners of the rail. The high speed of the sliding armature forces the current and the flux to the edges of the rail. This flux concentration is consistent with the edge grooving damage patterns shown in Fig. 5.

TEST STAND EXPERIMENTS

The experiments performed on the MTF railgun provide clues on the physics behind high-power railgun launch. In general, railguns operate at what would be considered extreme levels of pressure, current density, acceleration, temperature, etc. to most scientists and engineers. In many cases, the conditions present in the railgun do not fall in regions where materials properties are well known. To provide needed information, NRL researchers have developed a series of relatively small test stands. These systems allow one to test materials or processes under conditions approaching those in a rail-

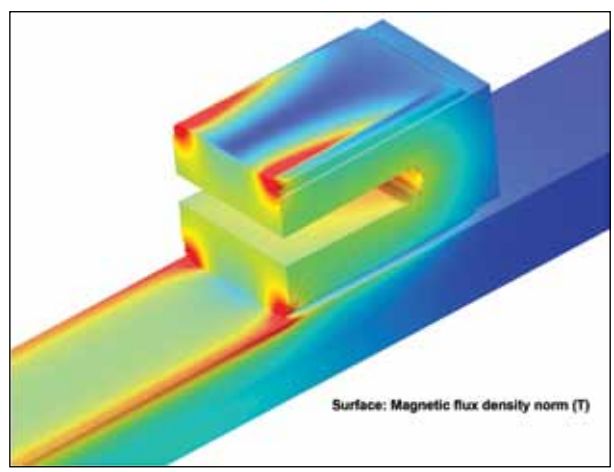

FIGURE 7
Image shows the results from an FEA simulation of a moving armature on a flat rail. The fully electromagnetic simulation shows the high magnetic flux concentration on the edges of the rail. The effect of field penetration into the rail material is shown by the low flux in the center of the contact region.

gun. An example is shown in Fig. 8. This test apparatus consists of a load frame capable of pushing contacts together with contact pressures comparable to those found in a railgun. The force is applied to a series of small-diameter electrodes made from materials used in railguns. A capacitor bank is attached to drive current through the contact. Voltage probes and high-speed cameras are used to observe the history of the contact. The experiment illustrates how high currents driven in static contacts can result in arcs at the metal-to-metal interfaces depending on the level of force and amount of current at the contact.

has done numerous experiments on the basic physics of railguns. The MTF railgun has routinely launched projectiles at relevant velocities for Navy mission requirements. The pressures and current densities generated by the system are similar to mission requirements. The damage observed on the rails is the primary hurdle to a viable weapon system. The key to avoiding or mitigating the damage is developing the understanding of the processes involved. Experiments coupled with modeling and detailed materials science are the keys to developing this understanding.

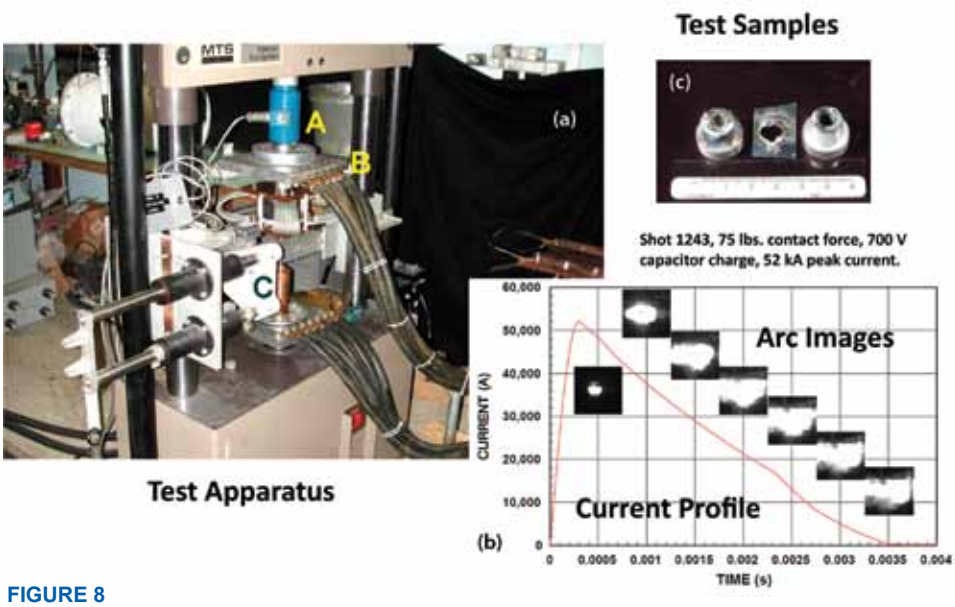

FIGURE 8
(a) The system used to investigate surface contact arcing. A load frame is used to provide contact pressure similar to that found at the sliding interface in a railgun (A = load cell; B = current connection; C = diagnostic mount). (b) The current waveform driven in the contact is shown along with optical images of the contact during the current pulse. (c) The photo shows damage done to the conductors after the pulse.

SUMMARY AND CONCLUSIONS

The development of a railgun electric launcher has made great strides over the last decade. If brought to its full potential, the technology will significantly change the design of future Navy platforms and alter how these platforms are used. The NRL program is a part of a large Navy program led by the Office of Naval Research and involving multiple Navy, Department of Defense, and private corporations in the United States. The work described in this article is a sample of the type of research going on to understand and advance the technology. The results generated by the NRL program are transferred to the Navy's lead lab for railgun research, the Naval Surface Warfare Center at Dahlgren, Virginia.

The NRL railgun facility has been operational for over 5 years and has fired over 1000 shots thus far. It

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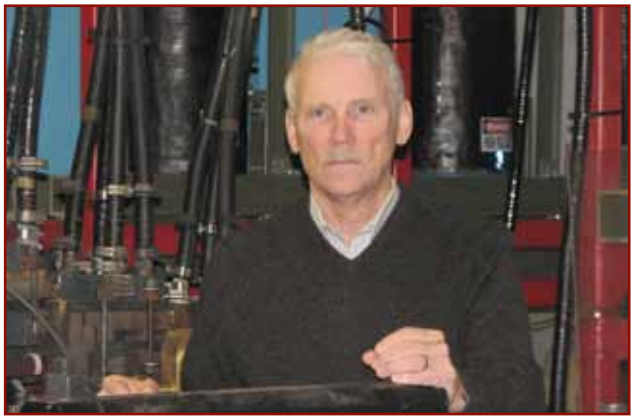
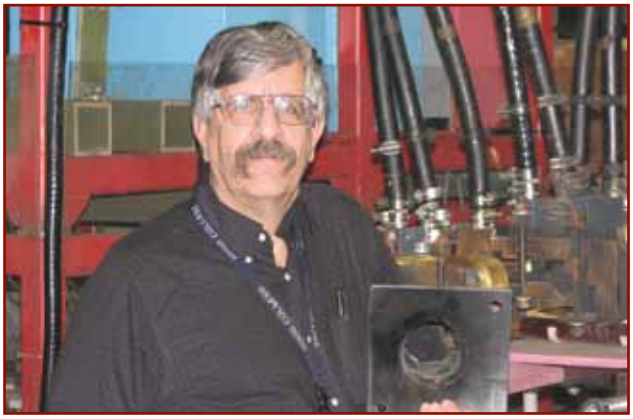


ROBERT A. MEGER heads the Charged Particle Physics Branch at the Naval Research Laboratory. Dr. Meger received his Ph.D. from Cornell University in 1977 in pulsed power and beam-plasma interaction physics. After two years as a postdoctoral researcher at the University of Maryland, he joined NRL's Plasma Physics Division, where he has served as a section head and branch head. His research has focused on applications of pulsed power to plasma physics. During his tenure he has originated, managed, and participated in multiple research projects, including high current plasma switches for inductive pulsed power, high energy electron beam propagation for directed energy weapons, beam-produced plasmas for radar beam directors and large area plasma processing, and electric launchers for hypersonic projectile launch. His branch currently performs experimental and theoretical research on electric launchers, plasma processing, and ground- and space-based plasma phenomena. He has authored over 75 research publications and holds over 10 patents on different technologies. Dr. Meger received the 2008 Delores M. Etter Top Scientists and Engineers Award, the 2011 Navy Meritorious Civilian Service Award, and the 2011 NRL Award of Merit for Group Achievement for his work on railguns. Dr. Meger is a fellow of the American Physical Society.

BRETT M. HUHMAN was born in Kansas City, MO. He received B.S. and M.S. degrees from the University of Missouri, Columbia (MU), in 2003 and 2006, respectively, both in electrical engineering. At MU, he developed a method for decontamination of an office environment using cold fog dispersal with electrostatic and UV enhancement. From 2005 to 2007, he was with L3-Titan Pulsed Sciences Division working at NRL on the development of compact pulsed power radiography devices and electromagnetic launchers. In 2007, he joined the Pulsed Power Physics Branch of the Plasma Physics Division at NRL, in the Electromagnetic Launcher and Advanced Systems Section. He is currently the operations manager and pulsed power engineer for the NEMESYS EM launcher at the NRL Materials Testing Facility. His research interests include electromagnetic launchers, pulsed power engineering for radiography, and rep-rate pulsed power design. He has published over 30 conference papers and refereed journal articles on a variety of topics as first and secondary author. He received his professional engineering license in January 2011, and is a registered engineer in Washington, DC, in electrical and electronics engineering. He received the 2011 NRL Award of Merit for Group Achievement for his work on the railgun program.



JESSE M. NERI received a B.S. in physics and mathematics from the University of Denver in 1976 and a Ph.D. in applied physics from Cornell University in 1982. He worked with JAYCOR, Inc. at the Naval Research Laboratory and then joined the Pulsed Power Physics Branch in the Plasma Physics Division as a research physicist in 1983. His research has included plasma opening switch experiments and simulations, production and transport of intense ion beams, applied magnetic field ion diodes, data acquisition and analysis software for pulsed power facilities, and pulsed power engineering. He is the section head of the Electromagnetic Launch and Advanced Systems Section. His current research is on high- and low-velocity electromagnetic launchers for Navy applications and rep-rated pulsed power systems.

TODD BRINTLINGER joined the Nanoscale Materials Section of the Materials and Sensors Branch as a staff member in 2008. This followed a postdoctoral appointment in the Materials Science and Engineering Department at the University of Maryland, College Park, where he also received his Ph.D. in physics. His graduate work included the fabrication, imaging, and electrical transport of carbon nanotubes, while his postdoctoral work focused on a variety of in situ transmission electron microscopy (TEM) experiments, including novel electron-diffraction-based thermal mapping, frustration in artificial spin ice, and real-time imaging of electrically driven magnetic domain motion. At NRL, he is contributing to the railgun project by developing new profilometry measurements, as well as through coordinated materials analysis of armatures and rail materials. His work with in situ TEM also continues, including the study of plasmonic nanostructues and multiexciton generation in solution-processed nanowires.

HARRY N. JONES received a B.S. degree in metallurgical engineering from Virginia Polytechnic Institute in 1971, and an M.S. degree in solid mechanics and materials engineering from the George Washington University in 1976. Before coming to NRL in 1984, he was employed as the senior metallurgical engineer for Norfolk Southern Corporation. At NRL his research initially addressed high-energy laser and particle beam effects on structural materials for the Strategic Defense Initiative. His fundamental research has focused on the mechanical behavior of rapidly heated metals and composites. He has published extensively on the thermal activation of flow stress transients in metallic alloys. Mr. Jones has authored 31 scientific publications, holds two U.S. patents, and is a professional engineer licensed in the Commonwealth of Virginia.

As a research scientist/engineer and head of the Computational Multiphysics Systems Lab (CMSL) of the Center for Computational Materials Science at NRL, **JOHN G. MICHOPOULOS** oversees multiphysics modeling and simulation efforts and computational sciences research and development, operations, and initiatives at CMSL. Some of his current major initiatives include research and development to link performance to material through data- and specification-driven methodologies; electromagnetic launcher dissipative damage modeling and simulation; mechatronic/robotic data-driven characterization of continua; and multiphysics design optimization. Dr. Michopoulos also currently serves as the chair of the Computers and Information in Engineering Division of the American Society of Mechanical Engineers. He is a member of the editorial board of the *Journal of Computing and Information Science in Engineering* and the *Journal of Computational Science*, and he is the founding chair of the International Science and Technology Outreach Society. He has authored and co-authored more than 240 publications and has been honored with numerous awards. Dr. Michopoulos holds an M.Sc. in civil engineering and a Ph.D. in applied mathematics and mechanics from the National Technical University of Athens, and has pursued postdoctoral studies at Lehigh University on computational multifield modeling of continua and fracture mechanics. He received the 2011 NRL Award of Merit for Group Achievement for his work on the railgun program.

Growing up in a small manufacturing town in rural Wisconsin, **RICHARD CAIRNS** has been a "tinkerer" his entire life. At age 13, he successfully rebuilt his first dirt bike and by age 15 he had built his first drum set. During the September 11, 2001 incident, Rich designed processes for building fire trucks at FWD Seagrave, New York City's primary fire truck supplier. In 2005, he graduated from the University of Wisconsin-Platteville with a B.S. in engineering physics. After college, Rich started his own company, designing specialized optics, robotics, photovoltaic systems, instruments, and custom electronics (with patents applied for). Also a professional musician, Rich has toured across the United States and Canada. In early 2008, he became a project engineer with the U-Line Corporation, an industry leader in under-the-counter refrigeration and a subsidiary of Maytag and Subzero. Several of Rich's designs have been patented. Since late 2008, when he came to NRL, he has been the lead designer for the Materials Test Facility railgun in the Charged Particle Physics Branch of the Plasma Physics Division.

SCOTT DOUGLASS, Ph.D., currently a Sotera Defense Solutions research scientist at the Naval Research Laboratory, is working to develop an understanding of the physics of rail wear in rail guns. He has worked at BAE Systems, Energetics Division on projects such as hypervelocity, electrochemical combustion light gas guns. Most of his work involved developing underwater acoustic shock prototype sources and source arrays for Navy applications. Before BAE Systems he worked at FM Technologies, a small business working in research in beam physics and microwave processing of materials. Dr. Douglass worked on a two-beam accelerator concept. He built a compact induction re-accelerator for a high-current, relativistic bunched beam that would serve as an RF power source for an adjacent RF linac beam line. Dr. Douglass received a B.S. in physics from University of Maryland, and M.S. and Ph.D. degrees from the University of California, Davis, in applied science. His graduate career was based at the Lawrence Livermore National Laboratory, where he concentrated on controlled fusion and plasma-based particle accelerator concepts. His postdoctoral work was at NRL, characterizing electron cyclotron plasmas used for plasma processing applications.