A Research Program to Study Airborne Launch to Space

I. R. McNab, *IEEE Fellow*

Abstract—Researchers supported by a multi-university research initiative award from the Air Force Office of Scientific Research are studying the technical issues involved in an airborne electromagnetic launch to space of small payload masses. The payload mass under consideration (1–10 kg) is much smaller than in earlier studies of launch to space, where payloads of ≥ 1000 kg required a substantial and expensive ground-based launch facility. The lower mass now being evaluated allows all components—launcher and power supplies—to be scaled down, so that power and energy ratings and component masses are considerably reduced. To offset the aerothermal heating of the small projectile as it transits the atmosphere at > 7 km/s, the entire launch system may be mounted on a large cargo aircraft and airlifted to a high altitude, where lower air density reduces the aerothermal loads to a feasible level. Such an electromagnetic launcher and pulsed power supply system could fit in a large aircraft, such as a C-5B or A-380F.

Keywords—railgun, electromagnetic launch to space, micro-satellite

I. INTRODUCTION

The objective of this multi-university research initiative award from the Air Force Office of Scientific Research (AFOSR) is to identify and study the technical issues involved in the launch to space of microsatellite payloads using an electromagnetic (EM) launcher. Although launch to space using EM techniques has been discussed in scientific literature for over 20 years, three features distinguish this AFOSR-sponsored research from earlier work. First, the mass of the proposed microsatellite launch payload is much smaller than in earlier studies, where payloads ≥1000 kg were shown to require a substantial and expensive ground-based launch facility [1]. The smaller launch package has a major impact on the technical approaches that can be followed. Most importantly, it has allowed consideration of launch from an airborne platform (see Fig. 1).

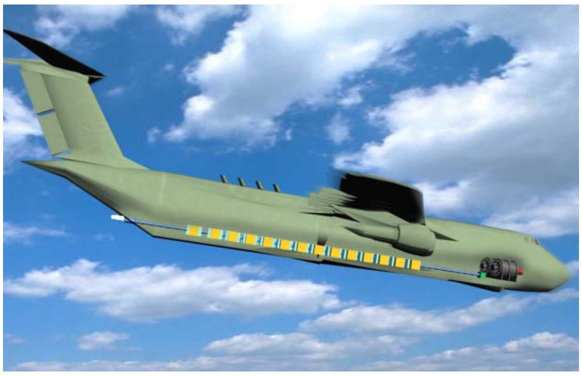

Fig. 1. Airborne launch platform showing a distributed EM launcher for launch to space.

This is possible because the smaller launch mass should require relatively small power supplies and an EM launcher of a modest length—both of which should be air-liftable. Both the launcher and the power supplies have yet to be invented that will do this job—and that is a major portion of this research effort—but railgun and power supply systems of a few tons are presently the goal of other developments. Present evaluations show that only by a high-altitude launch can the aerothermal loads on the projectile be reduced to a level that will permit a successful launch to orbit.

Second, significant progress in EM launcher research has taken place in the last two decades as a result of the development of tactical EM guns to launch payloads of 1–10 kg to > 2 km/s. This advance has resulted in approaches that, with further research, are likely to allow reductions in power supply size and weight, better rail and insulator materials, and improved launcher concepts for other applications. High-efficiency, multistage EM launcher concepts have been invented [2] that seem well suited to launch to space, but more research is needed to assure feasibility. Concepts for zero-ablation operation in EM launcher bores have been invented that show promise for overcoming the velocity limits observed in earlier experiments, but further research is needed to achieve successful operation of railguns at these velocities with useful (i.e., acceleration-limited) launch packages.

Third, recent years have seen the development of miniaturized and G-hardened electronics for gun-launched projectiles at accelerations up to ~ 250 km/s^2 (25 kG). This technology could form the basis for a robust and capable payload package or microsatellite where, to keep launcher length down to an acceptable level, acceleration hardening to ~ 65 kG may be necessary. Detailed research on the electronic components and their mechanical structure is required to assess the feasibility of this approach and limits on practical launch packages.

The four critical technical issues that will determine the feasibility of this concept are to:

- determine whether launch velocities of ~ 7 km/s can be achieved in an EM launcher with acceptable acceleration;
- determine which pulsed power approach can provide the required megamperes of current and gigawatts of power pulses to the EM launcher within an acceptable mass and volume budget;
- determine the aerothermal loads involved in launch and flight and develop approaches that will allow successful atmospheric transit from launch to space; and
- determine whether the microsatellite launch packages and components can withstand the acceleration levels required to make a launcher of practical length.

This study will be conducted by a consortium of research teams at four universities—The University of Texas at Austin, Texas Tech University, the University of Minnesota, and the University of New Orleans. These investigations into the basic physics and techniques to achieve railgun operation at up to 7 km/s go far beyond anything that has yet been achieved. The concept of a system that could be carried on a large aircraft and launched from high altitude is also more ambitious than anything previously envisioned but, we believe, ultimately feasible—subject to successful outcomes to the research studies described here. The launcher concept being considered

(Fig. 2) uses a multistage railgun powered by pulsed alternators at the low-velocity end and by distributed high-current, high-voltage power supplies for the high-velocity sections.

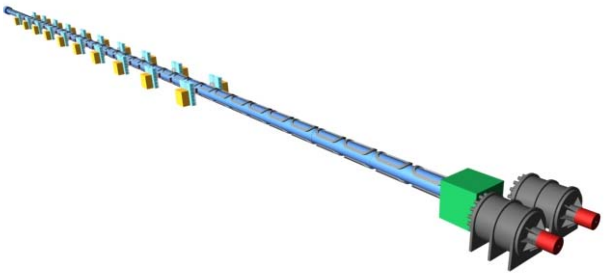

Fig. 2. Concept for a multistage EM launcher.

II. MULTISTAGE ELECTROMAGNETIC LAUNCHER CONCEPTS FOR > 7 KM/S

EM launch to space has been an appealing concept since the first demonstration of hypervelocity launch in the late 1970s [3]. That achievement, of 6.2 km/s with a small-bore, plasma-armature railgun, seemed at the time attractively close to the 7–8 km/s required for launch to space. However, the subsequent development of larger-caliber railguns by the Strategic Defense Initiative Organization (SDIO) produced disappointing results, and it is now clear that muzzle velocities of ~ 7 km/s cannot be achieved with a simple breech-fed EM launcher having rails a few meters long, as suggested for tactical railguns. By the mid-1980s, it was apparent that the velocity attainable with plasma-armature railguns was limited and, importantly, that the limit was a function of the launch package acceleration. Velocities of 4–5 km/s were demonstrated for medium-bore (25–50 mm) railguns operating at a typical acceleration of 400–600 kG [4], [5], increasing to 6–7 km/s for smaller-bore guns with accelerations of 1 MG or greater [6], [7]. The principal mechanism responsible for limiting the velocity was identified in the mid-1980s as viscous drag on plasma and neutral gas ablated from the bore walls by intense radiation from the plasma [8]. Several approaches were suggested for eliminating the effects of viscous drag [9]. These approaches were analyzed and tested in the early 1990s and were beginning to yield results when funding decreased and programs were discontinued.

Our initial approaches in these studies will be based on the promising techniques of ablation reduction begun in the 1980s [10]. The fundamental cause of performance loss in plasma-armature launchers is mass ablated into the bore by radiation from the plasma. This added mass has several deleterious effects. A portion of the mass is immediately ionized and added to the armature plasma; there is a loss of propulsive force required to accelerate this mass up to the armature velocity and a continuing loss due to the viscous drag of this mass against the bore walls. In addition, a substantial amount of neutral gas is ablated into the bore, particularly when the bore walls contain easily vaporized plastic. While it remains neutral, this mass has no effect on performance, but as the armature velocity increases, the electric field in the bore increases, until eventually, a breakdown occurs in the neutral gas. This is termed a *secondary arc*, and it usually occurs well behind the plasma armature. Not only are the ionized gas losses described above experienced by the secondary arc, it must also push against the mass and viscous losses of the dense cloud of neutral gas between it and the plasma armature. Once a secondary arc forms, the current rapidly transfers to it, and acceleration of the payload ceases. Until ablation of mass into the bore is eliminated, the goal of efficient launch to hypervelocity will not be achieved.

The approach we will study to achieve operation of a railgun without ablation combines four features: (1) pre-acceleration to prevent ablation of the metal rails at low velocity, (2) metal armature operation up to velocities ~ 2 km/s to eliminate plasma formation, (3) use of ceramic insulators to raise the ablation resistance of the bore, and (4) magnetic augmentation and distributed power feeds to reduce the power dissipation in the plasma. Experiments conducted in the early 1990s demonstrated that it was possible using some elements of this approach (ceramic insulators and augmentation) to operate a railgun without ablation, and that the non-ablating armatures appeared to be inherently stable, with no signs of incipient formation of secondary arcs or re-strike up to 4 km/s [11]. Building on this understanding, we will investigate techniques to achieve 7 km/s in a distributed-fed launcher at acceleration levels low enough for electronic package survival.

The funding provided for this research is not adequate to build all the new equipment required to determine the full feasibility of this approach. However, with minor modifications, an existing Institute for Advanced Technology (IAT) pulsed power system (see Fig. 3) can be used and an existing launcher modified.

Fig. 3. The existing IAT power supply has 13 independent 1 MJ capacitor modules.

The launcher research will be accomplished by modifying the existing IAT medium-caliber launcher (MCL). The MCL is a 7 m long launcher with a 40 mm square bore and will be reconfigured to operate as an 18 mm, square-bore, augmented launcher, as shown in Fig. 4. The new core will require new primary rails and new G-10 insulators, while ceramic tiles will be used in the plasma-facing region of the bore.

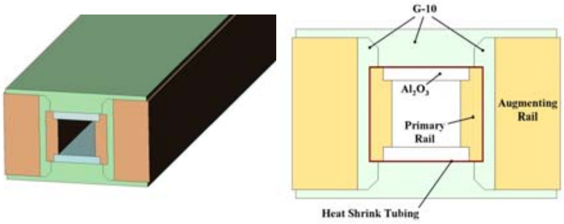

Fig. 4. Augmented hypervelocity test launcher configuration with ceramic alumina insulators.

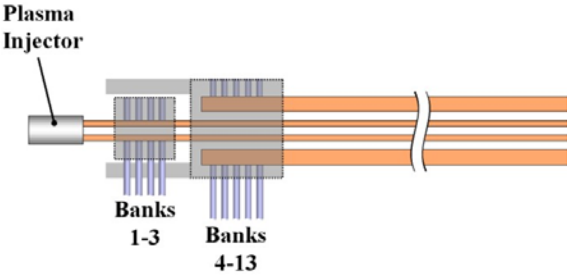

Fig. 5. Power feed arrangement for the augmented launcher.

Fig. 5 shows the electrical pulsed power connections to the augmented launcher. The existing power supply will be configured so that three 1 MJ capacitor modules will feed a small breech behind the MCL, while the remaining ten modules will feed the main breech. The ten modules will be connected to the augmenting turns to produce a peak current of 500–700 kA, and three banks to the primary rails to produce a peak current of ~ 200 kA. Each capacitor module will be energized independently, so that the desired current waveform can be achieved via timing adjustments. Calculations indicate that this augmented launcher configuration should accelerate a 7 g launch package to 7 km/s in about 2 ms with a peak acceleration of 50 kG.

A departure from prior work will be the use of a plasma injector to pre-accelerate the projectile into the launcher breech. Pre-acceleration is necessary in plasma-armature launchers because the effects of slow-moving arcs are quite damaging to bore components. In fact, operating without ablation is not possible below a certain threshold speed, which is a function of the materials used. The light-gas gun used in previous experiments produced the unintended consequence of introducing a substantial amount of cold gas from the injector into the plasma armature [12]. To avoid this, we will use a plasma injector rather than a light-gas gun. The plasma injector can impart the same energy to the projectile as a light-gas gun, while introducing significantly less gas into the bore of the launcher. Our first objective will be to demonstrate that it is possible to maintain stable plasma armatures to 7 km/s in a single-stage, augmented launcher using a pre-accelerated and pre-formed plasma armature, as described above. Subsequent technical issues will be to develop a hybrid armature to eliminate the need for pre-acceleration and to examine issues associated with distributed, multistage railguns.

III. ENERGY DELIVERY SYSTEM IN A MULTISTAGE RAILGUN

An airborne-based segmented, or distributed, railgun for launch to space will place high demands on the energy delivery system, which is expected to consist of rotating machines and high-energy-density capacitors. Such a system has to be lightweight, compact, and efficient while providing MA currents at supply voltages that are determined by the back-emf of the launcher, which—in the latter stages of the energy delivery system—will be up to ~ 20 kV.

It is estimated that a launcher for placing small payloads into earth orbit will require a barrel length of tens of meters. It is impractical and inefficient to power a barrel of this length only from the breech since, in addition to the substantial resistive losses in the rails, an amount of inductive magnetic energy remains stored and unused in the bore equal to the payload kinetic energy. Most of this stored energy is eventually dissipated as resistive heating, resulting in overall launcher efficiencies of 15% or less. By distributing the power input to the railgun in multiple, small power stages along the barrel, current flow can be localized in a short region near the armature. This increases efficiency and reduces the probability of secondary arc formation.

Although the final high-velocity railgun stages require high voltages, the first few stages can be driven at lower voltages than the latter stages, as long as constant current is maintained. This allows a compact, high-current, low-voltage supply, such as a pair of pulsed alternators, to be used on the early stages, while the later stages would be driven with high-voltage capacitor banks (see Fig. 2). The onboard aircraft power needed to replenish the dedicated pulsed power systems could, in the future, be provided by lightweight high-temperature, superconducting (HTSC) generators being developed by the Air Force.

Coupling between stages of the segmented railgun will improve the overall efficiency of the system. Calculations for a highly distributed launcher predict that electrical to kinetic energy efficiencies of 70% to 80% can be achieved [13]. Energy stored in the magnetic field as the projectile leaves each railgun stage can be recovered and delivered to downstream stages for re-use. Since the later stages are charged to higher voltages, redistributing energy from downstream to upstream stages will require voltage multiplication. Several techniques to boost voltage between stages, including transformers, resonant circuits, and diode multipliers are currently under consideration. Desirable features include high-energy-efficiency transfer between stages, minimal number of switches and other components, and the use of compact pulsed alternator energy storage and power delivery in early stages and capacitive storage in later stages.

IV. THERMAL PROTECTION SYSTEM REQUIREMENTS

The major challenge facing direct EM launch to space is aerodynamic heating of the launch vehicle at very high launch Mach numbers (M > 25). Such heating can have a major effect on the nosetip of the aerobody, as illustrated in Fig. 6, where the original dimension of a graphite nosetip is compared with its final shape after testing in an arc jet wind tunnel at 2–2.5 km/s [14].

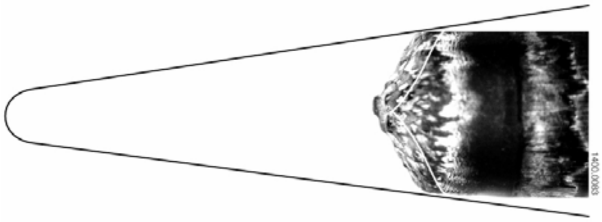

Fig. 6. Original (thin black line) and final profile for a conical graphitic aerobody nosecone at velocities of ~ 2.5 km/s.

Earlier studies suggested that EM launch from a high mountain could alleviate this problem. Although this is true for a large aerobody (a 1000 kg aeroshell was proposed in [1]), it is more problematic for a small aerobody. Standard launch equations [15] show that, for a slender, spherically blunted conical aerobody of 10 kg mass with a ballistic coefficient $\beta = 26{,}000\ m^2/kg$, a launch velocity of 9.1 km/s is required to achieve orbital velocity from a 4 km mountain for a launch angle of 45 degrees. Using a simple convective heating correlation [16] gives a stagnation-point heat flux of 28.6 kW/cm^2 as the aerobody leaves the launcher. This initial heating rate is significantly higher than that experienced by any other hypervelocity vehicle. For comparison, the most aggressive planetary entry ever performed was the Galileo spacecraft, which entered the atmosphere of Jupiter at a speed of 47.4 km/s and experienced a maximum heat transfer flux of 17 kW/cm^2. The Galileo vehicle thermal protection system was over 50% of the total mass—a level that would be unacceptable for this application. Thus, there is a serious concern that direct launch to low-earth orbit (LEO) is not feasible from the surface of the earth (even a high mountain) with a passive ablative carbon phenolic thermal protection system.

Because the heat transfer rate is inversely proportional to the square root of the nose radius, the conventional approach to reduce convective heating is to increase the nose radius until the heat flux is manageable. However, increasing the nose radius also increases the drag in the atmosphere, resulting in an increased launch velocity and yet higher heating.

This problem will be considerably eased—indeed, may only be feasible for a small projectile—if the launch takes place from a high-altitude aircraft. As an example, we have calculated launch conditions from an altitude of 16 km (50,000 ft) for a 1000 kg aerobody. These calculations show that the aerothermal loads, while high, appear manageable. Fig. 7 shows how the launch velocity and peak heat transfer rate vary with nose radius for the direct launch of this larger aerobody. A similar evaluation for smaller aerobodies will shortly be undertaken to optimize the flight characteristics and launch parameters.

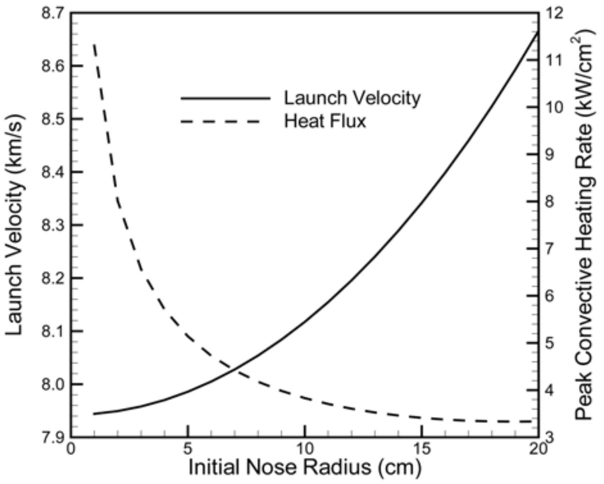

Fig. 7. Required launch velocity and peak heat flux variation with nose radius for EM launch to LEO for a 1000 kg aerobody.

A gun launch concept usually requires a rocket motor onboard the projectile for orbital insertion and maneuver. This rocket could also be used to assist the launch—resulting in a larger launch mass for a given payload but reducing the required muzzle velocity. Initial evaluations indicate that the benefit accrued by the extra thrust provided by the rocket exhaust at high altitude will reduce the required launch velocity, so that existing thermal protection system materials and designs might be used.

V. COMPUTATIONAL TECHNIQUES FOR PAYLOAD LAUNCH ASSESSMENT

The EM launch and flight concepts to be studied will require careful analysis and numerical modeling. The structural integrity of armatures, payloads, and gun structures under the severe EM fields and forces required to attain hypervelocity launch must be established. The design of a distributed, multistage EM gun with a hybrid armature requires computational tools that are not conventionally available, since multiple interrelated physical effects occur. The transient EM diffusion process that is integral to these studies is tightly coupled to the thermal and stress fields; therefore, all the field variables need to be solved simultaneously and spatially at all time steps during the launch duration. In addition, the computation must be performed for a full-scale launcher while retaining enough fineness to examine small-scale events. These requirements impose the severe computational burden of solving for many field quantities simultaneously in a transient manner at an unusually large number of discrete nodes.

The IAT has developed a unique transient code, EMAP3D, to address coupled EM, mechanical (elastic and plastic), and thermal problems in 3D. The code is parallelized and currently runs on a 32-parallel, dual-processor-node Beowulf cluster, which allows practical problems to be modeled in a reasonable period of time. The IAT has also coupled a 3D transient explicit stress code, DYNA3D, with EMAP3D to study coupled mechanical transient effects.

An important portion of this study is to investigate the launch of projectiles that contain electronic components and structures capable of withstanding the axial and lateral accelerations and decelerations encountered during launch and flight. G-hardened electronic components will be required to determine body attitude, initiate control correction, and provide global positioning system and data telemetry of position information. Recent years have seen the development of miniaturized and G-hardened electronics that can form the basis for a robust and capable payload package of the type needed for a guided, electronics-carrying projectile. The UK has conducted experiments with electronics packages that were launched from smooth-bore 120 mm guns at velocities of 1550 m/s and peak accelerations of 42 kG. The packages were retrieved using over-water recovery, and it was found that all 16-channel data-loggers and accelerometers survived the launch, along with a number of displacement transducers. Displacement transducers have been tested to 50 kG, while the 16-channel data recorders were tested to 80 kG [17]. These developments provide optimism that the required acceleration tolerances can be achieved within a few years.

VI. CONCLUSIONS

Launch to space from an airborne platform is a technically challenging concept that is being addressed in this program under funding from AFOSR. Multiple challenges exist, including the launcher concept for > 7 km/s operation with acceptable acceleration levels for launch package survival, the development of a high-efficiency, multistage pulsed power system, the aerothermal heating of the launch body during transit through the atmosphere, and the modeling required to ensure that all components in the launcher and launch package survive intact.

Acknowledgment

This material is based upon work supported by the Air Force Office of Scientific Research (AFOSR) under Award No. FA9550-05-1-0341 with guidance from the AFOSR Project Manager, Dr. Mitat Birkan. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the AFOSR. The overview provided here is based on inputs from key investigators at the participating universities, including Drs. J. V. Parker, S. Satapathy, and K. T. Hsieh and Mr. F. Stefani of IAT; Dr. J. Mankowski and Prof. M. Giesselman of Texas Tech University, Prof. G. Candler of the University of Minnesota; and Dr. M. Guillott of the University of New Orleans, to whom grateful thanks are due.

References

[1] I. R. McNab. “Launch to space with an EM railgun,” *IEEE Trans. Mag.*, vol. 39, pp. 295-304, 2003.

[2] I. R. McNab. “The STAR railgun concept,” *IEEE Trans. Mag.*, vol. 35, pp. 432-436, 1999.

[3] S. C. Rashleigh and R. A. Marshall, “EM acceleration of macroparticles to high velocity,” *J. Appl. Phys*., vol 49, pp. 2540-2542, 1978.

[4] J. J. Scanlon et al., “Analysis of experimental data form a 50-mm railgun driven by a 5-MJ capacitor power supply,” *IEEE Trans. Mag*., vol. 29, no. 1, pp. 859-864, 1993.

[5] K. A. Jamison and D. M. Littrell, “Performance characteristics of a high velocity, 25 mm railgun,” *IEEE Trans. Mag*., vol. 31, no. 1, pp. 168-173, 1995.

[6] N. Kawashima et al., “Stable and reproducible production of high velocity projectile in ISAS railgun [HVPAC],” *IEEE Trans. Mag*., vol. 29, no. 1, pp. 431-434, 1993.

[7] E. Drobyshevski et al. “Experiment on simple railgun with the compacted plasma armature,” *IEEE Trans. Mag*., vol. 31, no. 1, pp. 295-298, 1995.

[8] J. V. Parker, W. Parsons, C. Cummings, and W. Fox, “Performance loss due to wall ablation in a plasma armature railgun,” AIAA 18th Fluid Dynamics and Plasmadynamics and Laser Conference, 1985.

[9] J. V. Parker, “Why plasma armature railguns don’t work (and what can be done about it),” *IEEE Trans. Mag*., vol. 25, no. 1, pp. 418-424, 1989.

[10] M. Schulman et al., “HART hypervelocity augmented railgun test facility,” *IEEE Trans. Mag*., vol. 29, no. 1, pp. 505-510, 1993.

[11] F. Stefani, M. B. Schulman, R. E. Wootton, and J. V. Parker, “Zero-ablation tests on the HART augmented launcher,” *IEEE Trans. Mag*., vol. 29, no. 1, 1993.

[12] J. V. Parker, “Performance loss due to electrical breakdown of pre-accelerator gas,” *IEEE Trans. Mag*., vol. 29, no. 1, 1993.

[13] J. V. Parker, “EM projectile acceleration utilizing distributed energy sources,” *J. Appl. Phys.*, vol. 53, no. 10, pp. 6710-6723, 1982.

[14] W. Reinecke and M. Guillot, “Full scale ablation testing of candidate hypervelocity nose tip materials,” Proceedings of the 15th International Symposium on Ballistics, Jerusalem, Israel, May 1995.

[15] I. R. McNab, G. V. Candler, and C. S. Barbee, “Projectile nosetip thermal management for railgun launch to space,” to be presented at the 13th Electromagnetic Launch Symposium, Potsdam, Germany, May 22–25, 2006.

[16] M. E. Tauber and K. Sutton, “Stagnation-point heating relations for Earth and Mars entries,” *Journal of Spacecraft and Rockets*, vol. 28, no. 1, pp. 40-42, 1991.

[17] D. W. Lodge and A. M. Dilkes, “Use of an instrumented 120-mm projectile for obtaining in-bore gun dynamics data.” Proceeding of the 10th U.S. Army Gun Dynamics Symposium, pp. 433–443, Austin, TX, April 23–26, 2001.