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Telemetry Systems and Electric Gun Projectiles

by William P. D'Amico

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William P. D'Amico
Weapons and Materials Research Directorate, ARL

Abstract

Using telemetry in gun-launched projectiles is not as common as it is in missile and aircraft systems. A primary reason is the launch environment of guns. Conventional solid propellant guns often produce launch accelerations approaching 100,000 g's. Additionally, if the bore is rifled, large lateral accelerations are also produced. Recently, the Hardened Subminiature Telemetry and Sensor System (HSTSS) program developed and demonstrated a series of telemetry products and technologies specifically designed to make gun-launched, in-bore, and flight measurements more routine and affordable. This report reviews the products and flight experiences from the HSTSS program and addresses the potential use of the HSTSS products and techniques on projectiles launched from electromagnetic rail guns.

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Table of Contents

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List of Figures

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1. Background and Status of the HSTSS Program

The Hardened Subminature Telemetry and Sensor System (HSTSS) program is under the direction of the program manager for instrumentation, targets, and threats simulation (PM-ITTS). A large number of HSTSS-based papers were recently presented at the 1999 International Telemetry Conference [1–12]. The goal of the HSTSS program is to provide a family of commercial off-the-shelf (COTS) products and assembly techniques (mechanical and electrical) that can be used to instrument gun-launched projectiles and munitions. The products include 3–5 V chip sets for telemetry and data acquisition that are compatible with emerging lithium battery technologies. Significant attention has been paid to establish affordable and configurable instrumentation-type miniature batteries [2]. The telemetry and data acquisition products will be available as packaged modules or as unpackaged electronic die. The HSTSS program has also been instrumental in the demonstration and use of microelectromechanical systems (MEMS) inertial sensors. Another program of interest is the multiple band antennas for telemetry (MUBAT) effort sponsored by the Central Test and Evaluation Investment Program (CTEIP). This program provides experience and technologies to design dual band antennas for telemetry and the global positioning system (GPS). The CTEIP and a U.S. Army instrumentation development line jointly sponsor the HSTSS program.

Major contracts have been led by the HSTSS to develop the telemetry and data acquisition devices. The telemetry products are being developed by M/A-COM, and initial deliveries and tests are just under way at the U.S. Army Research Laboratory (ARL). The telemeter will be selectively tunable across the L- and S-band frequencies according to International Range Instrumentation (IRIG) practices. A typical transmitter configuration is shown in Figure 1 [4]. The data acquisition devices are under development by the Systems and Process Engineering Company (SPEC). An expandable and programmable set of chips will meet a large variety of instrumentation needs. Several of the application-specific integrated circuits (ASIC) being developed by SPEC include: (1) a four-channel pulse code modulation (PCM), (2) an input signal conditioner (ISC), (3) a delay/repeater for in-bore measurements, and (4) a digitally implemented six-channel frequency division multiplexer [9–11]. The PCM ASIC is

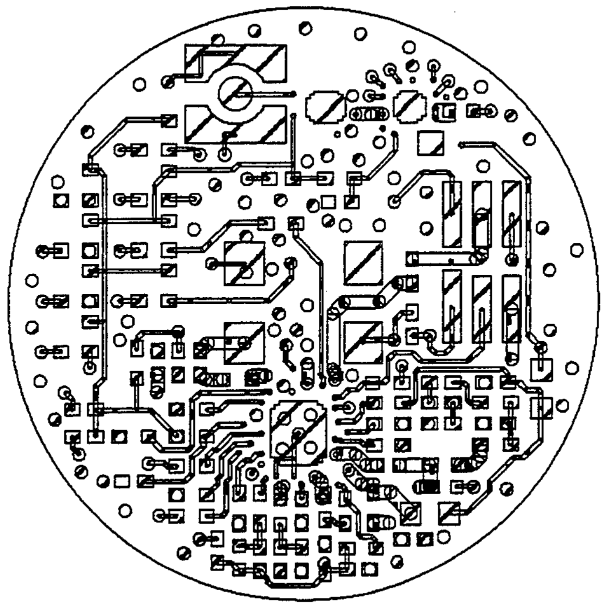

Figure 1. HSTSS Mixed Prototype Multichip-Module Transmitter (100 mW Output, 1-in Diameter × 0.2 Height, 3 V/500 mW Supply).

expandable to 64 channels with a maximum throughput of 10 Mb/s, which is the maximum bandwidth of the M/A-COM transmitter. PCM and ISC devices will be delivered to ARL in the near future for testing. Other products and technologies have been flight tested and will be reviewed in section 2.

2. Summary of HSTSS Flight Test Experiences

A substantial number of flight tests have been conducted on various types of conventional munitions. The strength of the HSTSS philosophy (qualified components rather than a single configuration) is shown by the broad variety of applications. Even though all of the HSTSS products are not completed (notably the transmitter and data acquisition chips), many demonstrations have been accomplished.

2.1 Kinetic Energy (KE) Projectile Flight Tests. Flight diagnostics via telemetry for KE projectiles are essentially not undertaken. A monolithic rod has no payload cavity for the location of sensors and telemetry components. Additionally, the launch environment is very severe, with axial accelerations of 75,000 g and transverse (commonly called balloting) accelerations of nearly 20% of the axial value. All direct-fire ammunition uses a tracer to aid the gunner in tracking the round. On a KE projectile, the tracer is located at the rear of the fin hub. The original HSTSS concept was to replace the standard tracer element of a KE projectile with a complete telemetry system. In fact, many of the most difficult specifications for the telemetry and data acquisition chips are driven by this requirement. Locating a telemetry system in a tracer cavity provides an even higher challenge since the rear face of the plug (to include a telemetry antenna and environmental cover) would be directly subjected to the propellant pressure and temperature.

This is exactly what has been accomplished, however. Figure 2 shows a telemetry plug that was successfully tested on a 105-mm KE training round. The system included a mechanical housing, an antenna with an environmental cover, a battery, a g-switch, an ARL-built S-band transmitter, signal/power conditioning, and a giant magnetoresistive radio (GMR) sensor for spin measurement [13]. Figure 3 shows spin data from the GMR.

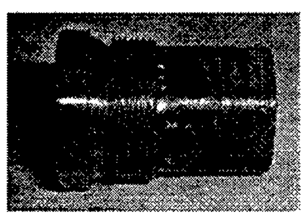

Figure 2. HSTSS Telemetry Tracer Well Plug (20-mm Diameter × 35-mm Height).

2.2 Artillery Projectile Flight Tests. Telemetry systems are often used for diagnostics in artillery systems where unused space can be found in the ogive or payload compartments, or by simply replacing a nose-located fuse. Several programs have been conducted using 155-mm and 105-mm projectiles [5]. These tests were primarily conducted to qualify HSTSS-modified lithium batteries and MEMS accelerometers. A seminal experience involved measuring axial force by an air bag accelerometer from analog devices. An ADXL05 was located along the spin axis (to avoid large off-sets due to centrifugal force). When combined with a

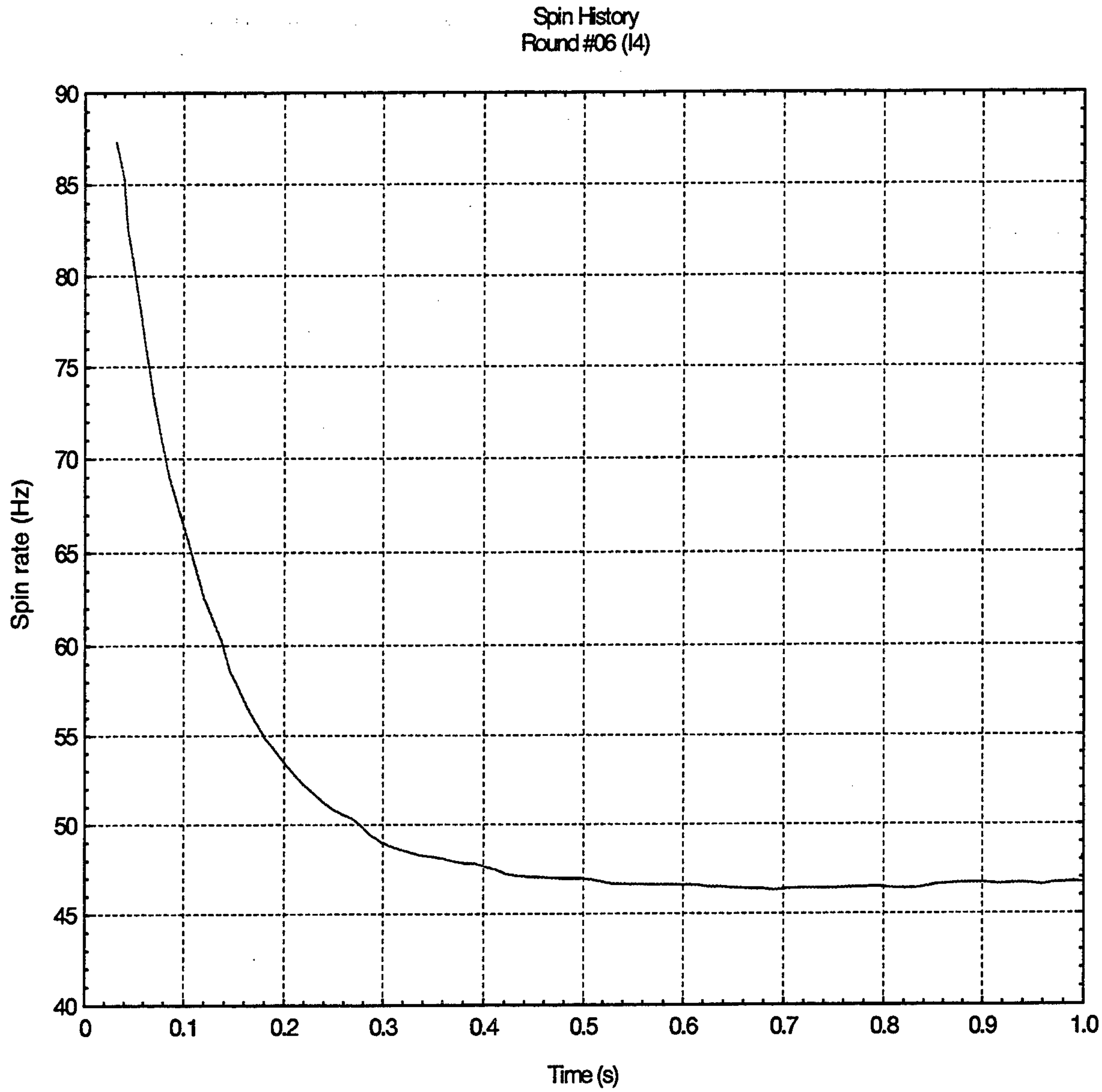

Figure 3. Spin Data From the Tracer Well Plug (105-mm KE Training Round With Rifled Tube).

GMR-measured spin history, these data yielded a drag history. These two sensors comprise a very simple one-dimensional (1-D) inertial measurement unit (IMU) that could be used for range-only corrections. Data are shown in Figure 4. A second generation of MEMS accelerometers (ADXL202, 105, 150, 250, 190) are now available; some have a frequency response approaching 20 KHz. As such, a MEMS accelerometer was used to characterize the in-flight radial vibration environment of a spin-stabilized artillery projectile.

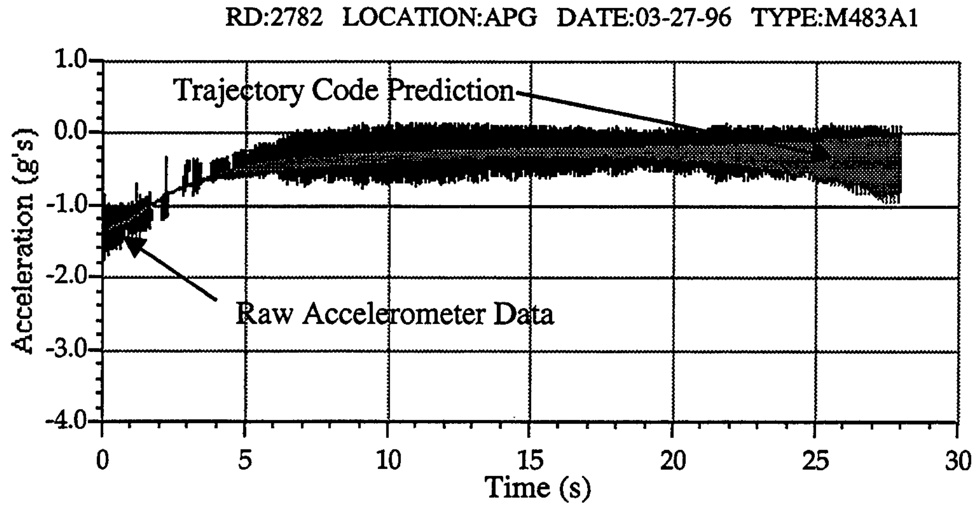

Figure 4. Comparison of MEMS Axial Force History and Trajectory Code Prediction for a 155-mm Artillery Projectile.

2.3 2.75-in Missile/Rocket Flight Tests. Although the launch environment of a 2.75-in missile/rocket is not as severe as a gun-launched projectile, the vibration environment for the solid propellant motors is not trivial. In addition, continuous and variable roll rates are common. The HYDRA-70 ballistic rocket system has very broad use, and it can be used as an "unclassified" surrogate to terminally guided air defense missiles. Axial force histories (similar methods used in the artillery example) were also gathered using MEMS accelerometers. With this as a background, ARL designed a three-axis IMU to use in operational tests of terminally guided 2.75-in missiles. The "soda can" size warhead is replaced by a telemetry kit (Figure 5) that monitors internal missile functions during jamming environments. For the first time a MEMS-based IMU could be used due to cost and space savings [14]. Nontraditional navigation sensors were used for angular rate measurements in the pitch and yaw axes. These sensors (from ATA Sensors) are magnetohydrodynamic in nature, using a loop of magnetic fluid and a permanent magnet to generate a signal in the presence of oscillatory motion and continuous roll. Because this sensor was originally designed and packaged for in-bore measurements of rifled artillery guns, it is miniature and rugged.

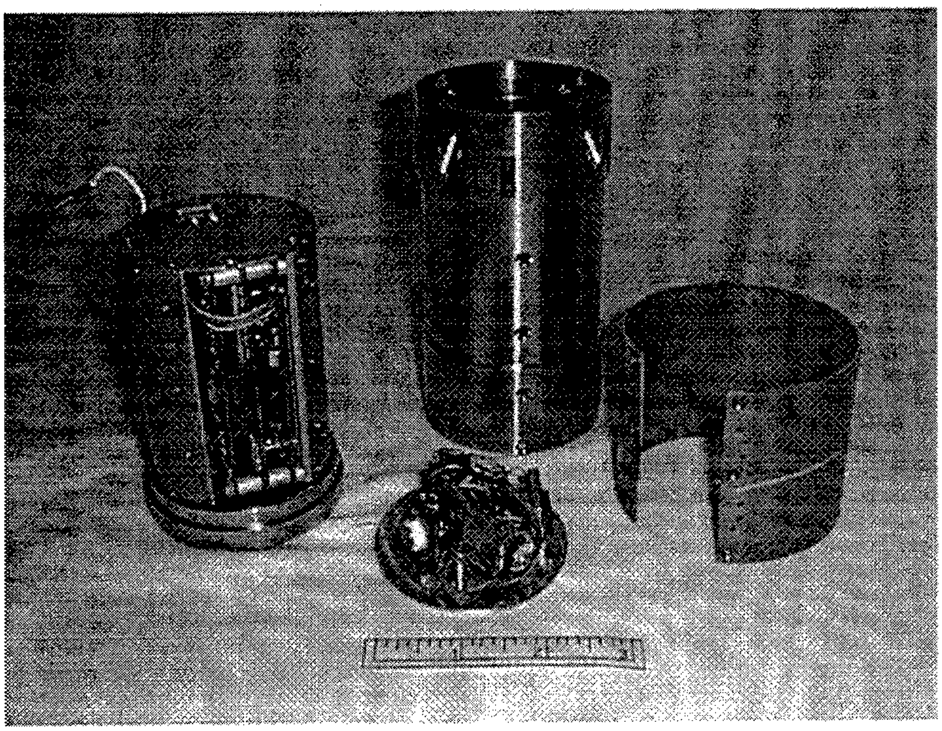

Figure 5. MEMS-Based Inertial Measurement Unit With Warhead Replacement Kit.

2.4 Modified 120-mm High Explosive Antitank (HEAT) Projectile Flight Tests. Given that the HSTSS telemetry and data acquisition products are available at the die level, high density electronic packaging techniques must be investigated and qualified for high shock levels. A recent set of flight tests has taken important initial steps for multichip module (MCM) packaging techniques [3]. Clearly, the key to survival in high shock environments is to reduce mass. Packaged ASIC's may simply have a mass and/or surface area that is too large to (even given ample mechanical support) survive large shocks. Designs must also consider reverse loading once shot exit has occurred. The difficulty with most MCM techniques is that large development costs and times can only be amortized when very high numbers of devices are produced. But this seems unrealistic for the munitions industry. HSTSS engineers identified an MCM substrate technology that is commercially available and programmable via a laser system. The design and first prototype turn-around times are only a few weeks rather than several months.

A three-channel sample and hold circuit was designed and implemented onto such a substrate and successfully fired from a modified 120-mm M831 HEAT training round. In-bore data repeated in free flight are shown in Figure 6, where a tri-axial accelerometer was recorded at 200-K samples/s, and subsequent to launch, retransmitted at a slower rate. The "repeated" data were ensemble averaged, providing high quality data at the muzzle exit. Such a diagnostic system would be beneficial in understanding the launch cycle of an armature/projectile system. In addition, as an interim and alternative solution to the HSTSS data acquisition devices, a COTS die level, field programmable gate array (FPGA) was used as an encoder data from an ADXL150 accelerometer. Both of these projectiles were launched in excess of 30,000 g.

Raw Data

Averaged Data

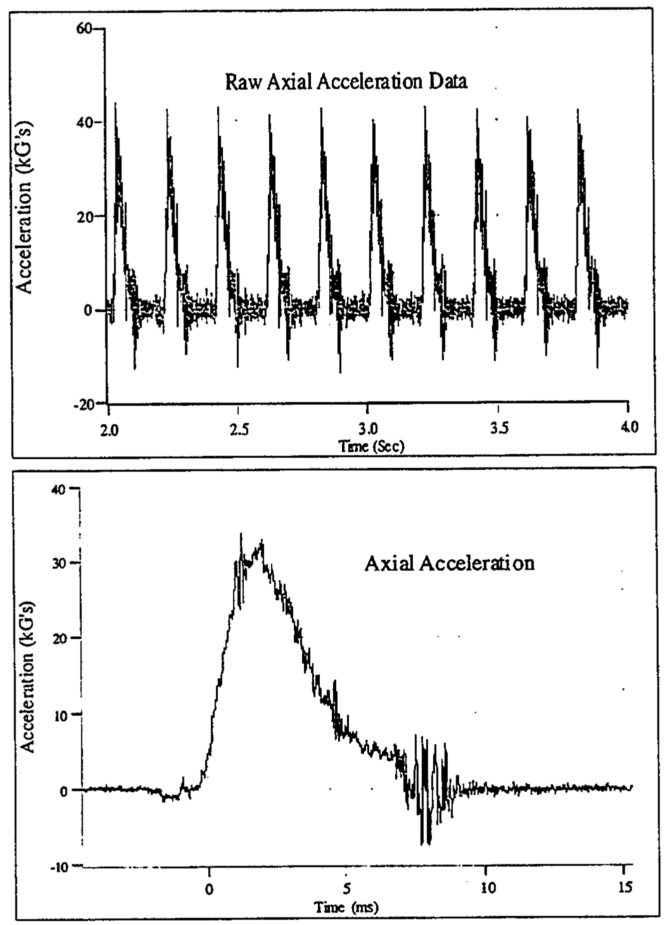

Figure 6. In-Bore Axial Acceleration Data Delayed and Repeated During Free Flight (Acceleration Data Shown in kG).

3. In-Bore and Magnetic Field Environment

A potential concern with using HSTSS products on an electromagnetic (EM) projectile are the in-bore electric and magnetic (EM) fields. The effect of the EM fields depends on whether projectile electronics and sensors are powered or unpowered during the launch cycle. Using HSTSS components for diagnostic measurements during the in-bore cycle is quite different from using a down range measurement system or a guidance, navigation, and control (GNC) system for a tactical projectile. Conformal telemetry and GPS antennae must also be considered.

The HSTSS program has not made railgun-related field measurements, but these types of data have been gathered by other researchers [15]. Measurements of EM field strength for simple rail gun were made. For large currents (hundreds of kA in a 50-mm square bore), the peak magnetic field in the bore direction ahead of the armature (dropping off rapidly with distance from the armature) is only a few tenths of a Tesla. Direct measurement of the E-field is not possible, and it is often complicated by spurious effects from other elements of the propulsion hardware (switched power supplies being a large conributor). The transverse E-field component also decays rapidly as distance down the bore ($<1\times10^6$ V/cm at 1000 mm of travel).* The spectral content of the axial magnetic field, the transverse electric field, and the muzzle voltage were not significant for frequencies above 1 MHz. These observations could be modified for different types of armatures and larger caliber guns. Zielinski suggests "greater concern in the case where the armature motion is not restrained" [16]. Time derivatives of field quantities should be considered, especially at the muzzle exit.

Zielinski [16] also tested the following components from a multi-option fuze for mortar (MOFM) in a 50-mm square railgun: (1) a microprocessor, (2) an antenna, and (3) a turbine/alternator. All components survived and were essentially operable. Coupling the EM fields into an antenna is possible if exact tuning occurs. The MOFM proximity sensor/antenna operate well above that boundary, which is much closer to the standard telemetry and GPS bands

* Breakdown and field strength voltages of silicon and silicon carbide are 0.3×10^8 V/cm and 2.4×10^8 V/cm, respectively [17].

(2.2 and 1.5 GHz). It would be very important if these experiments and results were expanded to experiments with larger caliber rail guns and for other electrical and antenna components. It is highly likely that GNC/fuse components, located in the forward portion of the projectile, would survive and operate if properly "engineered."

These data and observations cannot be directly related to the HSTSS products and their operation. The EM environments were performed under static conditions (i.e., the projectile was not launched). Some practical experiences were gained under the D2 projectile program [18]. An X-band data link was demonstrated in free flight after a launch from a solid propellant electrothermal-chemical gun [19]. Thruster and inertial guidance systems were supposed to be an integral part of the D2 projectile.

For a future smart projectile, it is logical to assume that MEMS inertial sensors would be used. Consider a typical MEMS device, where the material structure is often a piezoelectric material with a capacitive measurement principle. Under the simultaneous actions of acceleration and EM fields, problems could occur. Stiction (the nonrelease of MEMS structures subsequent to large over shocks) could be a problem. Davis has shown that powered and unpowered low-g accelerometers (of the type that could be used for GNC) have different thresholds for maximum shock survival (approximately 30,000 g powered and 60,000 g unpowered). The highly sensitive capacitive measurement circuits could be subject to small but electrical gradients. Given the inherent small size of typical MEMS devices and their packages, shielding (as considered by Zielinski) should be considered. Care must also be taken regarding the nature of the device operation. A MEMS magnetometer is under development where a xylophone-like bar is excited by a small AC current. As the bar is swept past a magnetic field, the Lorentz force causes a deflection that is capacitively measured. The current in the xylophone must be held very constant. As in the case of the MOFM experiments, various MEMS devices should only be tested [20]. If high density MCM packaging is used, then those packaging techniques must also be qualified.

4. Summary and Conclusions

The HSTSS program has developed and demonstrated a new generation of telemetry and measurement techniques particularly suited to the high-g launch environment of conventional solid propellant guns. These techniques and products should usher in new measurement capabilities [21]. Based on the work and experiences of other investigators in the rail gun community, the HSTSS products and technologies (telemetry, data acquisition, batteries, inertial sensors, and die-level electronic packaging) have a high probability of application and use compared to electrically launched projectiles. A series of diagnostic tests should be planned and conducted using the types of sensors and advanced packaging techniques that would most likely be used in the future.

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