100

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Contents

I. INTRODUCTION

Project Hindsight[1] was a 1969 U.S. Department of Defense (DOD) report that was an in-depth study sponsored by the Director of Defense Research & Engineering (DDR&E) and provided insights into the development of approximately 20 weapons systems across the defense spectrum. *Hindsight* was used as a model for a series of papers, including this one, in the analysis of research projects in DOD. Since the publication of *Hindsight*, DOD has continued to pursue research and development (R&D) and develop weapon systems to address new military threats to the United States. The Army Science & Technology (S&T) Executive sponsored a series of three reports that provided a retrospective look at the development of four major Army weapons platforms since *Hindsight*: the Abrams tank,[2] the Apache helicopter,[3] and the Stinger and Javelin[4] missiles. These three Defense & Technology Papers were focused on the Critical Technology Events (CTEs) that occurred in U.S. Army, industry, and academic laboratories that enabled these weapons platforms to have the necessary capability to accomplish their assigned missions. CTEs are ideas, concepts, models, and analyses, including key technical and managerial decisions, which have had a major impact on the development of a specific weapons system. CTEs can occur at any point in the system's life cycle, from basic research, to advanced development, to testing and evaluation, and to product improvements. CTEs can even relate to concepts that were developed but ultimately not incorporated into the weapons system. Also, CTEs can originate anywhere, from in-house laboratories, to private industry, and to academia. CTEs are not exactly the same as the *Hindsight's* Research and Exploratory Development (RXD) Events. Unlike CTEs, RXD events have the predominant meaning of an event that "defines a scientific or engineering activity during a relatively brief time that includes the conception of a new idea and the initial demonstration of its feasibility."[5] The purpose of this paper is to initiate a look at some current CTEs that are new or ongoing in the Army S&T community.

Section II of this paper will begin by analyzing *Project Hindsight*, as well as the previous efforts on the Abrams, Apache, and Stinger and Javelin. Section III describes the CTEs for the programs selected for this paper, while Section IV describes the efforts in databases, models, and simulations that support the selected programs. The last section, Section V, provides a set of findings of this report, bids discussion on a variety of topics, and offers concluding remarks.

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[1] Office of the Director of Defense and Engineering, *Project Hindsight: Final Report* (Washington, DC: Department of Defense, 1969).

[2] Richard Chait, John Lyons, and Duncan Long, *Critical Technology Events in the Development of the Abrams Tank-Project Hindsight Revisited*, Defense & Technology Paper 22 (Washington, DC: Center for Technology and National Security Policy, December 2005).

[3] Richard Chait, John Lyons, and Duncan Long, *Critical Technology Events in the Development of the Apache Helicopter-Project Hindsight Revisited*, Defense & Technology Paper 26 (Washington, DC: Center for Technology and National Security Policy, February 2006).

[4] John Lyons, Duncan Long, and Richard Chait, *Critical Technology Events in the Development of the Stinger and Javelin Missile Systems-Project Hindsight Revisited*, Defense & Technology Paper 33 (Washington, DC: Center for Technology and National Security Policy, July 2006).

[5] Office of the Director of Defense and Engineering, *Project Hindsight: Final Report* (Washington, DC: Department of Defense, 1969), xiv.

II. ADDITIONAL BACKGROUND

Project Hindsight

This study is modeled in part on a 1969 report, *Project Hindsight.* In 1965, DOD DDR&E, Dr. Harold Brown, established a project to take a retrospective look at DOD investment in R&D, to evaluate the results, and to take stock of lessons learned. Brown's overarching objectives for the study were to identify management factors that were associated with the utilization of the results produced by the DOD S&T program and to devise a methodology to measure the return on investment. He was motivated in part by the U.S. House of Representatives Committee on Defense Appropriations, which had questioned the efficiency of management and overall payoff for the part of the Research, Development, Testing and Evaluation program that pertained to S&T.[6]

In addition to sharing a broad goal with the original *Hindsight* report, this paper also takes from it a similar unit of analysis, the CTE. *Hindsight* evaluations were based on a concept called an RXD Event. In that report, an RXD event has the predominant meaning of an event that "defines a scientific or engineering activity during a relatively brief period of time that includes the conception of a new idea and the initial demonstration of its feasibility."[7] There may be one or two such events in the development of a component or system, or a whole string of such events. In the case of basic research RXD events, the report distinguishes between undirected (i.e., curiosity-driven) and directed (i.e., problem-driven) work. Lastly, the final fabrication of the system component or device "may or may not involve an Event depending on the state of the technological art at the time of fabrication."[8] Please note that our signal events, CTEs, differ from *Hindsight's* RXD events in that CTEs can occur at any point in the life cycle. We leave open the possibility that CTEs might result from efforts that have utilized funds other than R&D. For more background on the *Project Hindsight*, see Appendix D.

The importance of the three previous Defense & Technology Papers is the documentation of the Army S&T laboratories' contributions to the enabling of the weapons platforms. The CTEs noted in those reports influenced the Abrams main gun, including gun accuracy, penetrating rounds, armor and crew protection, engine and drive chain, command, control, communications, computers, intelligence, surveillance and reconnaissance (C4ISR) and fire control; the Apache helicopter engine and transmission, as well as survivability and structural advances, avionics, fire control, weapons; and the Stinger and Javelin missiles seekers, guidance and control, and propulsion. For all these platforms, extensive modeling, simulations, and databasing were contributed to the platforms.

Approach

This report was generated based on interviews and correspondence with people closely associated with the R&D and program management. Since these selected topics are near-term achievements, it is still unknown what their ultimate significance and impact will be. We have

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[6] Secretary Brown's letter in, Office of the Director of Defense and Engineering, *Project Hindsight: Final Report* (Washington, DC: Department of Defense, 1969), 135.
[7] Office of the Director of Defense and Engineering, *Project Hindsight: Final Report* (Washington, DC: Department of Defense, 1969), xiv.
[8] Office of the Director of Defense and Engineering, *Project Hindsight: Final Report* (Washington, DC: Department of Defense, 1969), xiv.

chosen those contributory CTEs that appear to be the most probable success stories in the more distant future. We iteratively interviewed the participants of these programs and generated a final product. Even though the subject is near-term products, some have a rather lengthy past and are to some extent described. In appropriate cases, we had to contact technical people that were already retired, or otherwise had left government service. We attempted to contact all relevant contributors to these topics. Although we believe that each topic documented in the report is complete, we do suspect that there are other parts that we did not select or uncover. Follow-on reports will occur as necessary.

III. SENSOR RELATED CRITICAL TECHNOLOGY EVENTS (CTE) FOR ENHANCED WARFIGHTING CAPABILITIES

Selected Projects

Five on-going projects within the Army S&T portfolio selected for inclusion in this report are the Global Positioning System (GPS)-guided munition, Excalibur; the persistent surveillance platform, Constant Hawk; Unattended Transient Acoustic/Artillery MASINT System (UTAMS); the thermal imaging night sight technology; and 5V Li-ion batteries for battlefield power sources.

The U.S. military has fielded the Excalibur GPS-guided munitions (XM982) for 155mm artillery and was used in Operation *Iraq Freedom* and is currently in use in Operation *Enduring Freedom*. Unprecedented accuracy for cannon fired artillery projectiles has been realized due to a collaborative S&T effort between Army Research Laboratory (ARL) and the Armaments Research and Development Center (ARDEC) in developing gun hardening GPS and micro-electromechanical systems (MEMS) Inertial Sensor Technology. This technology is not only used in the Excalibur, but is applied in the Army's Precision Guidance Kit (PGK) for use on existing conventional projectiles and the Mortar Guidance Kit (MGK) for use on conventional mortars to provide guidance and improved accuracy. The approach has been implemented as "screw on" devices for the existing stockpile of artillery and mortar rounds. This innovative approach came out of a strong S&T effort in the Army tech base and has resulted in upgrading the existing stockpile of Army munitions. To initialize GPS-guided munitions, the target, platform location, and GPS-specific data are entered into the projectile's mission computer through the Enhanced Portable Inductive Artillery Fuze Setter (M1155A1). Similar GPS-guided capabilities have been fielded by the U.S. Navy, such as the Joint Direct Attack Munition (JDAM); and the U.S. Air Force, such as the Guided Bomb Unit (GBU-36 and -37). Precision Urban Mortar Attack (PUMA) is a U.S. Marine GPS-guided or laser-designated munitions for 81mm mortar.

Constant Hawk is an airborne platform that addresses persistent surveillance over large fields of regard. In the conflicts that the U.S. Army is involved in today, it is critical to observe insurgent activities over large expanses of terrain in a persistent fashion to develop the Army's techniques, tactics, and procedures. High urban clutter demands high resolution that confounds the large area coverage requirement. It was due to the involvement of the Army S&T community that the Constant Hawk forensic capability was demonstrated as the first deployed wide field of view (WFOV) persistent surveillance system.[9] Scientists from ARL identified how the large field of view imaging system could be used as a forensics system. ARL was lead system integrator for the first five deployed systems, as well as training the analysts and developing the concept of operations for employment of this novel system. Subsequently, the Night Vision & Electronic Sensor Directorate (NVESD) of the Communications and Electronics Research, Development and Engineering Center developed a night capability.

UTAMS was developed as an acoustics sensor for force protection. Innovative Army S&T efforts applied the technology to the detection of rockets, artillery, mortars, and mine explosions over large expanses of terrain from sensor arrays of the ground. When deployed on an aerostat,

[9] Mr. William Ruff, Subject matter expert (SME) and project engineer, Army Research Laboratory, interviewed by authors, September 10, 2012.

the acoustic sensors could cover longer range due to higher signal-to-noise ratio when elevated. When integrated with an imager on an aerostat, it can cue the imager and get many image pixels on target for target verification and identification.

Thermal imaging or infrared is a widely deployed technology for day/night operations. However, infrared imaging has inherently less resolution than visible systems and image intensifier (I2) systems, the other night capability technology, due to the physics of diffraction limitations. Additionally, sensitivity is always an issue when longer ranges under degraded battlefield environments are needed to support the mission. S&T investigations have continued to enhance thermal imaging technology and enable coverage of more military applications over more combat missions. This technology continues to be proliferated in the Army sensor inventory.

R&D of the 5V Li-ion battery has the promise of making a significant impact on the amount and weight that a Soldier must carry on missions. This breakthrough will have its maximum impact, not just by transitioning to an Army program of record, but by transitioning to the commercial battery industry through licensing of the technology and an Army patent. This will result both in lightening a Soldier's load and reducing the cost to the Army by leveraging commercial sales.

Detailed Discussion of Sensor-Oriented CTEs

As stated above, the scope of this report is on near-term, ongoing or recently transitioned capabilities that can be associated with CTEs in the Army laboratory tech base in collaboration with the industrial tech base and academia. They are not associated primarily with one platform. Although Constant Hawk is one platform, it is representative of a whole class of potential platforms and the battery work is an enabler for many sensors. Further, the focus will be on Army sensor S&T, and that is why the already mentioned topics have been chosen.

a. GPS-Guided Munitions

The mission of the field artillery is to destroy, neutralize, or suppress the enemy by cannon, rocket, and missile fires and to help integrate all fire support assets into combined arms operations.[10] Artillery and mortars are indirect fire weapons for effect and destruction. Historically, there has been no guidance mechanism for the munitions other than laying fire. The lack of accuracy for the individual rounds implies a large number of rounds need to be expended to hit and destroy the target(s) of interest. This has major logistics implications since many more rounds need to be carried by the force in order to do the damage on the enemy that is needed. In addition, the use of unguided artillery munitions is limited in urban areas due to the concern regarding collateral damage. Therefore, any increase in accuracy that enables hitting and destroying targets with fewer rounds is extremely important and enables field artillery commanders an expanded capability to engage targets in highly concentrated urban areas while diminishing the threat of collateral damage.

Prior to GPS-guided munitions, such as Excalibur in the Army, there were smart submunitions such as Brilliant Anti-Tank (BAT), Sense and Destroy Armor (SADARM) and the semi-active laser guided Copperhead 155mm projectile. These were developed in the 1990s to increase accuracy by terminal guidance. BAT was delivered by the Army Tactical Missile System and had an acoustic sensor to detect tanks and an infrared (IR) terminal homing sensor. Intended for Multiple Launch Rocket System, SADARM is fired in a 155mm shell and parachutes into the

[10] Field Manual FM 6-50/MCWP 3-16.3, *Tactics, Techniques, and Procedures for the Field Artillery Cannon Battery* (Washington, DC: Department of the Army, December 23, 1996), 1-1.

target with millimeter wave radar, passive millimeter wave radiometer, and an IR telescope sensor. It also has a magnetometer for aiming and arming. The M712 Copperhead was a laser-guided projectile and was used in Operation *Desert Storm* and Operation *Iraqi Freedom*. BAT and SADARM demonstrated higher target accuracy, but with increased cost, and SADARM could not meet its reliability requirement. Both projects were subsequently shut down.

The major laboratories in the development of GPS systems were the Naval Research Laboratory (NRL) and the Air Force Research Laboratory (AFRL), along with the Applied Physics Laboratory at Johns Hopkins University and some serendipitous research interest by some far-thinking individual researchers, such as Rabi (molecular beam techniques), Townes (maser, the microwave forerunner of the laser), Ramsey (atomic clocks) and Getting (navigation systems at Aerospace).[11] Even though the Army S&T did not play an important role here, the main point of this paper is reinforced in that major contributions and leadership were provided by Service laboratories. The demonstration and development of GPS navigation would not have been facilitated and focused without them. The role of Service laboratories S&T to act as initiators, visionaries, leaders, enablers, and team contributors must not be overlooked.

Early testing by ARL and ARDEC with GPS-enhanced munitions looked at the value of knowing where a round landed when not on the target. This would create the critical mass for a variety of CTEs. A "screw on" GPS transponder was added to the munitions and continuous GPS location and the impact point were sent back to the launcher for launch adjustment **(CTE1)**. In this way, the major error in forward observer target coordinates could be overcome. Moving targets could also be engaged by this innovation, as well as mine-laying operations.[12]

The first use of GPS technology in a cannon-launched system was the use of GPS translators (auto-registration), which take the signal from the satellites, convert it into coordinates for the position of the round, and transmit it to a ground station **(CTE2)**. This provides registration of the position. The rotation of the round is addressed by using a conical antenna that surrounds the fuze such that it is always in view of the satellite and the ground station **(CTE3)**. Some material research was needed for the antenna. A monopole antenna was first tried but it took too much space in the fuze. The GPS round replaced the need for the forward observer but it made no change in the standard operating procedures for the ground crew of the howitzer. The concept was to be able to retrofit fuzes on the existing stockpiles of artillery rounds, as opposed to having to manufacture new rounds **(CTE4)**. Miniaturization of the electronics was evidently not very difficult and grew progressively easier. Test firing was conducted at Yuma Proving Grounds.

Prior to the start of the Army's Excalibur GPS-guided munitions development, ARL and ARDEC put together and led the Low Cost Competitive Munitions (LCCM) program. This program matured GPS and MEMS Inertial Sensor technology sufficiently for current Precision Guided Munitions, such as Excalibur, the only autonomous guided artillery projectile in the world. ARL was the first to demonstrate the feasibility of using GPS to track projectiles in flight. The GPS Auto-Registration fuze module translated GPS coordinates to the ground-based fire control unit in 1992 and this was the first demonstration of tracking in flight projectile trajectories using GPS technology **(CTE5)**.

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[11] Timothy Coffey, Jill Dahlburg, and Eli Zimet, *The S&T Innovation Conundrum*, Defense & Technology Paper 17 (Washington, DC: Center for Technology and National Security Policy, August 2005).
[12] Dr. Gary Horley, former SME, ARL-HRED, interviewed with authors, July 25, 2012.

The three parts to the LCCM program were the following: 1) Auto-registration with a GPS transponder in the projectile to track in-flight projectile trajectories; 2) One Dimensional Corrector that had target information provided prior to firing. The projectile would be fired beyond target position and an on-board GPS receiver would determine the projectile trajectory and provide appropriate time for a drag-inducing trajectory control device to be employed resulting in a correction to the flight path and subsequent improvement in accuracy or circular error probability (CEP) (**CTE6**). This part of the program was executed jointly by the United Kingdom and ARDEC; 3) 2D Corrector that employed a GPS receiver and MEMS Inertial Sensor technology to measure and calculate in flight trajectories and deploy canards to provide a more robust correction resulting in CEPs of less than one-half of previous CEPs (**CTE7**).[13] This effort was executed jointly with the U.S. Naval Surface Warfare Center Guns and Munitions Division.

Following the successful deployment of the Excalibur projectile, which was fielded and used in combat in Iraq and Afghanistan, the Project Manager Combat Ammunition Systems continued the development of these technologies and has fielded an MGK for Accelerated Mortar Initiative (APMI) and Precision Guidance Kit (PGK for 155mm conventional ammunition based on this technology. Excalibur APMI and PGK are currently being deployed in Afghanistan.

There are cannon-launched, mortar, and missile GPS-guided munitions. The XM982 Excalibur is a 155mm, GPS-guided, fire-and-forget projectile, debuted May 2007 in Iraq and became the Army's first all-weather precision guided artillery round. It debuted in Afghanistan February 2008 as the Army's next generation cannon artillery precision munitions.[14] The gun launched Excalibur (M982 Block 1a-2) was type classified in 2010. It can be fired from the M102Ab Paladin and the M777A2 Howitzer. In Afghanistan, it demonstrated exceptional accuracy out to significant tactical ranges, had an extremely high success rate, and "brought artillery back into the close urban fight."[15] ARDEC received an Army's Top 10 Greatest Inventions of the Year Award for 2007 for its development of Excalibur.[16]

As Excalibur was being fielded by Raytheon as the prime contractor, the cost growth became a concern. So the Program Manager asked the Army S&T community to develop a low cost version.[17] The result is the Very Affordable Projectile (VAP) program. ARL and ARDEC put together a new team including the company L3 for GPS technology. The VAP round has less ambitious control technology and, in test at the Yuma Proving Grounds, has achieved somewhat greater CEPs than for the Excalibur. The price for the VAP is estimated to be less **(CTE8)**.[18] However, VAP will probably have somewhat less capability and reliability than Excalibur, which will be greater than 90 percent, meaning that some capability will be lost for reduced cost. VAP has also not gone through the engineering and manufacturing development phase. In addition, with the planned Excalibur Increment 1b, which would field a lower cost and higher reliability system, funding for continued efforts on the VAP are unlikely.

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[13] Mr. Ray Sicignano, SME, ARDEC, interviewed by authors, July 23, 2012.
[14] Excalibur (XM982), *US Army 2010 Weapon Systems*, prepared by OASA (ALT), 92.
[15] Audra Colloway, "Picatinney's GPS-guided Excalibur artillery round deemed amazingly accurate by troop," *www.Army.mil*¸ September 11, 2008, available at <www.army.mil/article/12329>.
[16] "Soldiers select four Picatinney inventions as best of 2007," *Picatinney Arsenal*, June 6, 2008, available at <www.pica.army.mil/picatinnypublic/highlights/archive/2008/06-06-08.asp>.
[17] Mr. Peter Plostins, Associate Director of S&T, ARL-WMRD, and Dr. Dave Lyon, Branch Chief, ARL-WMRD, interviewed by authors, July 12, 2012.
[18] Mr. Ray Sicignano, SME, ARDEC, interviewed by authors, July 23, 2012.

There are two other Army programs for GPS-guided munitions mentioned above. One is the PGK for a screw-on fuze with some guidance for adding to legacy rounds currently in the stockpile.[19] (This is guided versus the earlier fuzed round that was fire-and-forget, so that the Army knew where the round hit and then could calculate the trajectory for the second round). The PGK is spin stabilized and also delivers a reasonable CEP. This system is based on commercially available hardware. As previously mentioned, the Navy and Marines are working on this technology for 81mm mortars. They have just demonstrated the mortar at Yuma Proving Grounds. This technology is at Technology Readiness Level (TRL)-6 with a planned date for first fielding at the end of FY2014.

The second program is the accelerated precision mortar initiative (APMI) which uses the MGK. The not-for-record program was fielded in limited quantities in Afghanistan, through a rapid fielding effort at the Project Manager Office. The kit contains the same technology as the PGK round. The services would like to convert the effort to a program of record.

The Army Research Office has funded basic research in another technology called Scorpion.[20] Scorpion is an entirely different munitions guidance technique that relates the munitions' orientation state to the Earth's magnetic field **(CTE9)**. It does not appear in any hardware at this time, but it is mentioned here for completeness as another potential guidance technique that has had basic research funding by the Army.

The community consensus is that there are six scientific innovations that enabled this Excalibur capability[21] that were contributions across several Army S&T organizations.

First was the Selective Availability Anti-spoofing Module (SAASM) **(CTE10),** which is the latest in military GPS technology developed jointly by the Services and industry. The module allows satellite authentication, over-the-air rekeying, and contingency recovery.

The creation of microelectronics to fit in the fuzes—MEMS for example—from service labs and industry is the second innovation. **(CTE11)**. Microelectronics for the three Services' military applications has many contributors and represents a unique function for Service specific applications. Whereas there is a large commercial microelectronics industry, the military-unique applications require in-house investment since there would be little incentive for commercial industry to pursue development of those devices that enable the military application. Fuzes are a prime example of a military-unique capability.

The third innovation is the high performance computer modeling of the non-linear responses of the airframe of the round under guidance changes **(CTE12)**. In other words, how the round itself responds to guidance changes in mid-air. Many different scenarios can be explored using computer models that cannot be addressed with real hardware in the field. ARL has pursued copious computer simulations to address all aspects of GPS-guided munitions for Excalibur and the VAP, as has been the case in the past for BAT, the Army Tactical Missile System (ATACMS), and the SADARM.

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[19] Note that Excalibur has an integrated fuze in the round.
[20] Scorpion is one of a series of very small guided munitions, such as grenades and large bullets, funded by DARPA. Dr. Tom Doligalski, Program Manager, ARO, interviewed by authors, September 6, 2012.
[21] Mr. Peter Plostins, Associate Director of S&T, ARL-WMRD, and Dr. Dave Lyon, Branch Chief, ARL-WMRD, interviewed by authors, July 12, 2012.

Fourth was the addition of micro-electromechanical system sensors and actuators **(CTE13)**. ARL-Sensors and Electron Devices Directorate (ARL-SEDD) is a world leader in these devices for actuators and worked with ARL Weapons and Materiel Directorate (ARL-WMRD) for implementation in Excalibur. ARL in-house investment in these sensors and actuators has been in collaboration with academia under the Micro-Autonomous Systems Technology (MAST) Collaborative Technology Alliance which was initiated with the identification of the potential importance of micro-systems on the modern urban battlefield.

Reduced state guidance was the fifth innovation, and uses intrinsic physics and aerodynamics for the system to reduce the burden on the guidance and actuation systems that reduce the hardware and software for maneuver **(CTE14)**.[22] Only seven out of twelve state vectors are used[23] and were found by ARL to be sufficient. This innovation reduces the system complexity of sensor systems.

The final innovation was the targeting technology used by Unmanned Aerial Vehicles (UAVs), aerostats, or Forward Observers **(CTE15)**.[24] This technology is referred to as Extended Area Protection Systems (EAPS). While it is not part of GPS-guided munitions per se, it completes the whole weapon system. EAPS is the counter incoming threat munitions with the goal to develop technologies for 360-degree mobile air defense against rockets, artillery, and mortars (RAM). ARDEC has the gun component and the Army Missile Research, Development and Engineering Center (AMRDEC) has the missile component.

b. Constant Hawk

Both Iraq and Afghanistan are defined by their large open areas and dense urban terrains. The scope of operations requires ubiquitous sensors for persistent wide-area surveillance, intelligence gathering, and precision targeting. Constant Hawk, which was originally named Mohawk Stare in 2005, was the first large area surveillance system fielded. Initially deployed as a 90-day demonstration, quick-reaction program to counter the threat from improvised explosive devices (IED), Constant Hawk used a fixed-wing Shorts 360-300 aircraft as a sensor platform and two analyst sites outside of the continental United States. Constant Hawk is a manned tactical aircraft platform containing sensor operators and sensors, whose acronym is sometimes confused with Global Hawk, which is unmanned. The RQ-4 Global Hawk is a high-altitude, long-endurance unmanned aircraft system with an integrated sensor suite that provides intelligence, surveillance, and reconnaissance capability worldwide. The large areas that Constant Hawk needed to cover for its mission implied not only a robust sensor, but also the acquisition, processing, and storage of large-image databases and intelligent computer processing to acquire events of interest. The Constant Hawk challenges were not only in integrating and maintaining the sensor, but also in processing, managing, and exploiting the database to drive intelligence products.

The original program Mohawk Stare envisioned a system that could be tasked to do surveillance and reconnaissance above a city. This initial program became Constant Hawk.[25] The Lawrence Livermore National Laboratory (LLNL) had the original idea for combining six independent

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[22] Mr. Peter Plostins, Associate Director of S&T, ARL-WMRD, participated in this research.
[23] VAP only, not Excalibur. Mr. Peter Plostins, Associate Director of S&T, ARL-WMRD, and Dr. Dave Lyon, Branch Chief, ARL-WMRD, private communication to authors, July 12, 2012.
[24] Concept is Part of Army ATO. See Manfredi Luciano, *Extended Area Protection and Survivability (EAPS) ATO*, PowerPoint, Presented at the 46th Annual Guns and Missiles Systems Conference, April 12, 2011, available at <www.dtic.mil/ndia/2011gunmissile/Tuesday11641_Luciano.pdf>.
[25] Mr. Andrew Ladas, Branch Chief, ARL-SEDD, interviewed by authors, July 9, 2012.

imaging sensors together to form larger fields of view (FOV) (66 megapixels flat focal plane) for greater ground coverage, called the "Sonoma Configuration" **(CTE16)**. This WFOV configuration of the six cameras combined the sensors using an off-the-optical-axis approach which produced degraded imagery over approximately one-third of the total field of view. The platform flight profile and collection geometry produced imagery, which covered approximately a 6-km diameter circle on the ground, however, only a 4-km diameter was exploitable due to image distortion and intensity fall off using the Somona configuration. ARL improved the camera configuration in a later Constant Hawk sensor design by orienting the six cameras on the optical axis and pointing them to cover the WFOV and by using improved commercial off-the-shelf (COTS) lenses that alleviated the distortion problems of the original configuration. The ARL sensor configuration provided exploitable imagery over the entire FOV. By 2009, all Constant Hawk platforms were upgraded to the ARL configuration along with six 16 megapixel cameras to give a 96 megapixel WFOV composite stitched image (**CTE17**).[26] Interface issues within the focal plane array (FPA) were a major problem that needed to be addressed. ARL worked with the sensor operators on a weekly basis to operate and optically filter the imagers to generate optimum imagery for exploitation throughout the entire deployment. The U.S. Air Force Angel Fire and follow-on Blue Devil program aimed to do the same thing for the U.S. Marines.

A second color version of the 16 megapixel camera, called the Auxiliary Persistent Sensor (APS), with an attached lens was added to two Constant Hawk platforms as a secondary auxiliary persistent camera that gave higher resolution imagery on the ground near the center of the Constant Hawk orbit. This camera was integrated into a separate gimbal and was pointed independently of the WFOV camera by the sensor operator. This camera had three applications: First, it spots pictures that replaced a previously deployed handheld camera; second, it uses step-stare photo mosaics to create large panorama high resolution images covering up to 4,000 square meters; third, it has persistent image of a fixed location within the larger WFOV footprint. This last mode allowed Constant Hawk to create hybrid products that contained high resolution color imagery of targets of interest overlaid on the standard Constant Hawk WFOV intelligence product, which covered the larger FOV at lower resolution (**CTE18**). This last mode allowed the deployed Constant Hawk platform to provide intelligence products to the warfighter at a similar resolution to the new >1Gigapixel systems currently under development.

Constant Hawk generated 1 Terabyte of data per hour. The MIT Lincoln Lab (MITLL) APIX viewer was used for real-time exploitation onboard the aircraft and at the operation centers through the tactical command data link (TCDL). The WFOV sensor imagery was collected in parallel onto two separate redundant hard drive arrays. One set of data that was on a hard drive went to the analysts on the ground for immediate exploitation in raw form. The second set went to a processing computer cluster on the ground at the bed down site. MIT developed and implemented algorithms that operated on the processing cluster for stitching the images together; image processing to sharpen the images, do histogram normalization, and data reduction; and JPEG compression. The MITLL APIX viewer was used for all forensic analysis, using raw and processed data, with any human processing done on the ground. The National Geospatial Agency was responsible for the data archiving, which was transferred to bases in the continental U.S. on hard drives or via satellite links.

[26] Mr. Bill Ruff, SME, ARL-SEDD, interviewed by authors, August 7-8, 2012.

The Constant Hawk platform was not designed for registering the airborne imagery with digital maps of the terrain. Typically, there was error in the location where the sensor was looking and where the actual location was on the ground. This was not acceptable for "publishing" the data as an intelligence product. Constant Hawk products, and thus the information derived from the analytical products and published to the customer, actually consisted of human analyst annotations using ArcGIS, a commercial geospatial product, as the base geo-spatial layer.[27]

ARL developed the approach to better register the data and give a three-dimensional perspective situational awareness view of the area using the Army Geospatial Center (AGC) Buckeye data **(CTE19)**.[28] The Buckeye data is a database that is based on Light Detection and Ranging (LIDAR) data and gives intensity and range to any point on the earth. The intensity data gives shadows in the scene, which can be used to register the objects like buildings that give large shadows for the otherwise contrast-less desert/urban scenes. An existing ARL algorithm was applied to the Constant Hawk imagery with the three-dimensional Buckeye imagery and reduced the Constant Hawk imagery geo-location error significantly. The tool also allowed the analyst to view the data in three-dimensions, generate line of sight from any location, illustrate sun shadow locations, and import Constant Hawk and other track and shape file data. This tool was deployed to Iraq as an analyst aid to streamline the analytical process and reduce the time to generate a Constant Hawk product.

The ARL hybrid approach to the registration was to drape a smooth simulated surface over any smooth ground surface and if the ground surface is not smooth, then use a discrete point cloud. This hybrid approach was not used by the time the war ended in Iraq. However, the three-dimensional visualization developed by ARL has been applied to all Buckeye data and any imagery available on the AGC website today is three-dimensional as a result of this ARL S&T effort.[29] The three-dimensional capability is now available for any user or image-gathering platform.

The Constant Hawk imagery was transferred to the ground stations where analysts then conducted manual exploitation of the imagery. Processing in terms of image understanding and context in the images needed to be developed. ARL scientists and engineers with MIT Lincoln Lab were able to successfully support the image analysis community with algorithms to enable this capability (**CTE20**).

The Constant Hawk forensics approach was deployed first in Iraq in August 2006. The Project Manager Airborne Reconnaissance and Exploitation Systems (PM ARES) became the Program Manager for the Iraq deployment and then for an Afghanistan deployment. The demonstrable success of ARL's Constant Hawk deployment to Iraq was underscored when U.S. forces in Afghanistan requested a clone system. NVESD took over the program execution from ARL for the Afghanistan system, while ARL continued to provide all analytical training for deploying analysts. The Constant Hawk collaborative effort represented a classic example of government, industry, and university efforts combining to solve a significant technical problem. ARL trained the analysts and developed the concept of operations for system employment while continuing to provide technical oversight to the deployed Iraq systems. ARL developed the software to register the Constant Hawk imagery to a geo-registered map that gave the real ground coordinates of the

[27] Ms. Susan Toth, SME, ARL-SEDD, interviewed by authors, September 5, 2012.
[28] Dr. Jeff Dammann, ARL-SEDD, interviewed by authors, August 17, 2012.
[29] Esri, Homepage, available at <www.esri.com/software/arcgis>.

imagery of interest by the analysts. They also developed the software to display the imagery in three dimensions. While LLNL developed the original concept behind the visible electro-optical (EO) camera, MIT Lincoln Lab developed the concept behind the data processing for recording, moving, and processing the 1Tb/hour imagery and implementing the registration technique. Under NVESD direction, BAE Systems developed the EO/IR MWIR camera (MWAPS). The two cameras gathered near infrared (NIR) and midwave infrared (MWIR) imagery simultaneously. NGA became the repository of data. This is the first time such a large data repository came into being.

c. Unattended Transient Acoustic/Artillery MASINT System (UTAMS)

Acoustic, seismic, and infrasonic sensors have the ability to monitor hostile territory, international borders, or detect firing of indirect fire weapons covertly. Small unattended ground acoustic, seismic, or infrasonic sensors can perform 24-hour surveillance and alert the onset of hostile military activity. Small, inexpensive non-imaging sensors such as these require little power and do not require dedicated human interaction.[30] Arrays of sensors can monitor large areas with relatively little investment in power sources and manpower.

Developed by ARL, UTAMS is a four microphone configuration that can locate the x, y, and z directions from an acoustic signal and is sensitive in the 20-500 Hz frequency range. It was deployed to Iraq in 2004 and 2005 for mortar detection **(CTE 21)**. Development was based on experience with an infrasonic surveillance system (<20 Hz). ARL developed the sensor arrays and signal processing. Noise reduction/cancellation algorithms, also developed at ARL, adapt to the surrounding ambient noises. These noises, such as that created by a generator, produce a continuous resonance that can be separated out via adaptive filtering. Processing developed for infrasound was combined with acoustic microphones and deployed in Iraq with smaller sensors arrays to detect rockets, small arms and mortars. UTAMS was specifically requested by the S&T field assistance team in Iraq to detect mortars and was funded by the U.S. Army Intelligence and Security Command. UTAMS acoustic sensors were also found to be able to detect IED explosions.

ARL infrasonic sensors were first deployed to Korea in 2001. The U.S. Army in Korea had a requirement for non-emitting surveillance systems on the Demilitarized Zone. Infrasonic sensors (< 20 Hz) are available for artillery detection (8-10 Hz) but mortars create a frequency spectrum in the 100 Hz region. Thus, they had a need for acoustic sensors (20-200 KHz) as well. In 2004 the request came from operations in Iraq for sensors to detect mortars since in theater radars were not able to perform this function.

The Rapid Equipping Force funded UTAMS in 2005 and 2006 for use in Iraq for Forward Operating Base protection. UTAMS arrays triangulate/localize acoustic signals. Networking of multiple UTAMS arrays is the next major development and will provide wider area coverage, less time delay and better location accuracy. The fielding of networked UTAMS will provide the opportunity for signal processing from the various sensors to provide more precise and accurate localization of events.

UTAMS sensor arrays have been mounted on an aerostat in Afghanistan. Aero-mounted UTAMS System (AMUS) was UTAMS mounted on aerostats at 3000 feet (915 m) with 8 microphones providing three-dimensional location. The Persistent Threat Detection System

[30] Mr. Steve Tenney, SME, ARL-SEDD, interviewed by authors, July 9, 2012.

(PTDS) employed UTAMS with an EO imager mounted on an aerostat that received UTAMS cues for the direction in which to slew the camera **(CTE22)**. Persistent Ground Surveillance Systems (PGSS) is a smaller aerostat much like PTDS. New signal processing is being developed for event identification. Further research is needed for more complete suite of detection, recognition, and identification of acoustic events. ARL has already developed the detection algorithm. ARL noise cancellation algorithms have been shown to reduce that false alarm rate and they include signal quality measures **(CTE 23)** for improved performance. ARL fabricated the first systems, which are now produced by vendors. The Project Manager Remote Unattended Systems took over procurement and fielding in 2007; the Program Manager Ground Sensors is taking over in 2012.

In 2006 UTAMS II was designed, based on lessons learned from previous fielding, and automatic alignment with two GPS sensors for pointing direction has been implemented. Pointing to within less than one degree in several hours has been demonstrated. Solar panels with batteries can be used as power sources to reduce power requirements. The Miniature Acoustic Warning System (MAWS) is a mobile UTAMS in a smaller package. Based on the successful performance of UTAMS, acoustic, seismic, and infrasonic sensors are now considered as viable sensors for any mission that requires multi-sensor capability.

d. Thermal Imaging

There are four ways to see at night: First, a source of visible light can illuminate the scene and the combatants, for example, by lighting a fire or with a searchlight. Second, invisible artificial illumination can be used with an image tube that converts the invisible radiation to visible. However, in both these cases the enemy can use the illumination (since very inexpensive image converters are widely available) as well as friends, negating any advantage due to the light.

A third night vision technology is image intensification (I2). This technology is a light amplification device that amplifies NIR ambient radiation from the moon, stars and night sky. This radiation at 0.7-0.9 microns is invisible to the human eye. Using NIR gathering optics, the images are focused on a photocathode that transduces the NIR light to electrons. The electrons can then be processed by a gain mechanism, such as a microchannel plate and focused on a phosphor display to the human. Assuming the opposing side does not have this technology, there is a night vision advantage to the user for target acquisition and terrain navigation.

I2 was initially fielded by the U.S. Army for night operations in the 1960s and 1970s in Vietnam. For the first time in history, an army could fight at night. Although image intensifiers enable night capability there are limitations. The devices use reflected ambient lighting for operation; thus, when there is no moon, performance is degraded.[31] Bright sources on the battlefield degrade imagery due to the halo and glare that surrounds them, as does naturally occurring hazes and fogs due to atmospheric propagation. Finally, the range limitations of the devices limit operations to primarily man portable applications. Larger weapons, such as tank main guns and helicopter gunships still had no night targeting capability with I2, although it was and is used for driving or as a piloting aid for flight.[32]

[31] Daniel Hoesk, SME, CERDEC NVESD, email to authors, December 13, 2012.
[32] This paper is describing CTEs for only the thermal imaging night vision technology. An entirely separate section of this paper could be dedicated to image intensification and the set of associated CTEs with I2, including image tubes, optics and photocathodes. However, the authors have chosen to limit the scope of this paper to only thermal imaging night vision technology.

Finally, the fourth way to see at night has been with the introduction of thermal imaging, known as Forward Looking Infrared (FLIR). Thermal imaging uses naturally emitted infrared energy from objects that are at a temperature above ambient. Room temperature infrared radiation at 300K peaks in the longwave infrared (LWIR), typical of body temperature and vehicle temperatures. Thermal imagers focus the ambient infrared radiation with infrared optics onto an infrared transducer, the detector array, that converts it to electronic signals that can be processed and then drive a display for viewing by a Soldier. It is light level independent and there are better transmission characteristics in the longwave infrared than the visible/near infrared radiation, especially under fog and smoke conditions. Of course, there are degradations due to object temperatures that are much lower than 300K and when the emissivity in the longwave infrared is very low.

Thermal imaging in the 8-12 micrometer longwave infrared spectral region is a natural complement to the I2 technology by covering more environmental conditions and enabling night sights for the larger weapons platforms. Thermal imaging technology along with I2 has been deployed to the extent that every combat Soldier in the U.S. Army has night vision capability. The tactical advantage of the night vision capability is evidenced by the fact that the American Soldier prefers to fight at night rather than during the day. Whereas I2 works only during the darkness of night, thermal imaging is a day/night technology that has proliferated across all Army platforms: helicopters, combat and transport vehicles, and the individual Soldier. It is even a prime candidate for the sensor for robot vision. In addition, thermal imaging has been applied to all sensor applications: reconnaissance, intelligence, surveillance and target acquisition, navigation, pilotage, seekers, munitions guidance, and countermine. There is a price to pay for these technology improvements: thermal imaging is significantly more expensive, heavier, and more power hungry than I2; high-performance infrared detectors must be cooled to, typically liquid nitrogen (77K). Both these technologies have significant missions on the modern battlefield.

The First Generation thermal imagers were developed and fielded in the 1970s and 1980s based on a set of infrared modules that could be configured in any package unique to a particular weapons platform and that were based on scanning a one-dimensional linear array of infrared detectors that scanned the infrared scene to generate a two-dimensional scene. This set of Army-patented Common Modules **(CTE 24)** in collaboration with US industry is composed of mercury cadmium telluride (MCT) detector arrays (60, 120 or 180 detectors long for man-portable, combat vehicle or helicopter systems, respectively), coolers, processing electronics, collimators, scanners, and LED displays that could be interfaced to any weapons platform for example, the TOW missile system, the M60 and Abrams tanks, the Apache helicopter, among others. This was the technology of *Operation Desert Storm* which caused the commander of the 24th Infantry Division Major General Barry McCaffrey to say, “Our night vision capability provided the single greatest mismatch of the war.”[33]

The Army Night Vision Laboratory (NVL)[34] working with its industry partners realized early on that resolution and sensitivity were the bottom-line parameters for all sensors. Therefore, techniques were explored with government-developed and owned performance bench tests (**CTE25**) and models **(CTE 26)** to discover and pursue methods to improve sensitivity and

[33] “NVESD Legacy-Changing the Way We Fight Wars,” Publicly released chart U.S. Army, CERDEC of CERDEC NVESD, circa 1992.
[34] This laboratory became the Night Vision & Electronic Sensors Directorate (NVESD) of CERDEC.

resolution of the Common Module-based imagers. The bench tests defined for thermal imagers are the techniques for measuring Minimum Resolvable Temperature Difference (MRT or MRTD).[35] Based on validated performance models that used the minimum measurement as the system figure of merit, and validating experimental data from existing thermal imagers, approaches to increase signal-to-noise ratio and pixels on target were proposed and pursued by Army scientists and engineers. The concept for a second generation was formalized and focused on a linear-scanned FPA with time-delay-and-integrate **(CTE 27)** to increase signal-to-noise at each pixel by having a series of detectors scanned at each pixel.

Given the overwhelming success of thermal imaging sensors, it became clear that the cost of the infrared systems technology needed to be addressed and significant cost reductions enabled through further S&T.[36] NVESD put together a candidate producibility program for MCT detectors, with funding from the Defense Advanced Research Projects Agency (DARPA) and involving the U.S. Army, Navy, and Air Force. The Infrared Focal Plane Array (IRFPA) program started in 1988 and the goal was to reduce the costs of the array by a factor of 100 times. The focus of the Army part of the program was on MCT growth processes; epitaxy, liquid phase epitaxy (LPE) and molecular-organo-chemical vapor deposition (MOCVD). There was also an effort in platinum silicide (PtSi) infrared material staring arrays. The IRFPA was followed by the DARPA flexible manufacturing program addressing the complete sealed cooler, or dewar, package in 1991 to 1994. Each of the service labs involved—NVESD, the Wright Patterson Air Force Laboratory, and the Naval Research Laboratory—ran a part of the program with each of the major infrared array manufacturers at that time. These manufacturing and producibility programs resulted in significant leaps forward in development of thermal imaging systems and major cost reductions for the proliferation of thermal imaging systems throughout the Services **(CTE28)**. The availability of staring arrays developed under the DARPA programs enabled the development of the fire-and-forget Javelin missile, which would not have been otherwise available, and would have resulted in the stopping of the Javelin development.[37] This whole infrared detector development is an example of the Service S&T laboratory community identifying a critical S&T objective and opportunity to give a leap-ahead military operational capability that would otherwise not be realized. This is a key leadership function of the Service in-house S&T community led by the laboratories.

Second Generation FLIR has been fielded to the Abrams tank, the Long Range Advanced Sensor Suite (LRASS), the Bradley Fighting Vehicle, and the Apache Helicopter.[38] This generation has a linear array scanned 480x4 format, like First Generation Common Modules, but each pixel has four detectors in series instead of one. The signal from each of the detectors is time-delayed and integrated, as the detector is scanned across the image, with the signal-to-noise ratio at each point in the scene increased by the square root of the number of detectors in series. Hence, use of four

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[35] J. Wood, "Laboratory Bench Analysis of Thermal Imaging Systems," *Optical Engineering* 13, no. 5 (1974), 93-197.

[36] Dr. John Pollard was invited to give the Dowd Lecture to the meeting of the National Military Sensing Symposium, 2006. Dr. Pollard documented the concerns that DOD Defense Product Engineering Services Office (DPESO) expressed on the producibility of IR FPAs. Funding was obtained and the program transitioned to DARPA with Tri-service participation. The Producibility program ran from June 1988 to 1991.

[37] John Lyons, Duncan Long, and Richard Chait, *Critical Technology Events in the Development of the Stinger and Javelin Missile Systems-Project Hindsight Revisited*, Defense & Technology Paper 33 (Washington, DC: Center for Technology and National Security Policy, July 2006).

[38] Dr. Don Reago, Associate Director, NVESD, interviewed by authors, July 17, 2012.

detectors results in a factor of two increase in signal-to-noise ratio at each point compared to first-generation scanned devices. The increased signal-to-noise results in greater performance in degraded atmospheric environments and can help with inherently low signature targets or ones that have been degraded due to environmental effects, such as rainfall on targets. Both first and second generation devices have to be cryogenically cooled to 77K.

Third Generation Dual Band (MW/LWIR) FLIR based on the MCT at 77K, the workhorse of IR imaging, and with a 1048x720 staring two dimensional array format is ready for transition to fielded platforms. The dual band permits higher resolution for target identification due to the shorter midwave infrared wavelength and greater atmospheric penetration in the longwave infrared, as well as some detection enhancement due to the multi-spectral sensing **(CTE 29)**. However, affordability of the more sophisticated FPA has been an issue. Collaboration between the Army laboratories such as NVESD and ARL, together with academic institutes like the State University of New York at Stony Brook for lifetime measurements of new kinds of detector structures, such as type II superlattices (T2SL), which are periodic structures of layers of two or more detector materials, and private industry companies like Raytheon and Teledyne are pursuing alternative, more affordable materials and FPA structures. The main thrust is growing MCT on silicon **(CTE 30)**, as opposed to the presently expensive cadmium zinc telluride substrates, but which has significantly different material mismatch characteristics. Another alternative is going to T2SL mentioned above. Superlattices **(CTE 31)** are an entirely different device structure. Whereas midwave infrared indium antiminide (InSb) is an available crystal growth technology that is inherently expensive in commercial foundries, epitaxially grown Type II superlattice structures of indium arsenide on gallium indium arsenide (InAs/GaInAs) is an attractive approach being pursued. Additionally, the radically different new nBn devices of InAs/GaSb heterostructure, superlattice detector design with extremely low surface currents **(CTE32)**[39] are being pursued with the potential benefits of large format MWIR cooled to only 150K for the Constant Hawk platform. This cooling temperature difference from 77K to 150K has enormous systems power impact.

Research and engineering on a longwave infrared thermal imaging technology that does not require cryogenic cooling has been pursued by NVESD and industry with uncooled bolometers fabricated, typically in commercial sensors with amorphous silicon or vanadium oxide(VOx)[40] material **(CTE 33)**. Present sizes for uncooled FPAs are 640x480 bolometer elements. This research and development is being aimed at large megapixel arrays (720x1280) for the Tactical UAV surveillance application and ultimately to 1080x1920 elements. Twelve micron pixels with extremely low noise equivalent temperature are the enablers for this application where power and size are critical. Although uncooled thermal imaging is inherently a lower power, weight, size, and cost technology than the cryogenically cooled technology, innovations are needed to configure the uncooled technology for different platforms. Helmet-mounted uncooled sensors with image intensifiers for multispectral applications are of great interest for individual Soldier applications. NVESD is pursuing new optical and display configurations to enhance uncooled longwave infrared imaging on such highly constrained platforms. A commercial market for uncooled infrared for firefighters helps support this technology since longwave infrared thermal

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[39] G. Bishop, E. Plis, J.B. Rodriguez, Y.D. Sharma, H.S. Kim, L.R. Dawson, and S. Krishna, "nBn detectors based on InAs/GaSb type-II strain layer superlattice," *Journal of Vacuum Science and Technology B* 26, no. 3 (2008), 1145-1148**.**

[40] x is variable but typically ~2.

imaging has smoke penetration capabilities. Firefighters with such devices can see people in smoke-filled rooms that otherwise could not be seen.

There are special niche thermal imaging technologies that have been and continue to be developed by the Army S&T community, particularly at ARL-SEDD. A prime example is the quantum well infrared photodiode (QWIP) detector technology. This is a gallium arsenide on aluminum gallium arsenide (GaAs/AlGaAs) material system composed of multi-layers of epitaxial grown layers from which diodes are formed sensitive in either the midwave or longwave infrared spectral regions, depending on material composition. Corrugated QWIP (C-QWIP) has been a recently developed new detector structure that through a photolithographic process fabricates a resonant superstructure on top of the detector. This structure orients more of the incident E-field of the infrared radiation on the detector to be parallel to the detector surface, which is the only orientation that the QWIP can absorb (**CTE34**).

QWIPs are an inherently less expensive and more available material system based on GaAs, than, for example, MCT, and can be fabricated in 640x480 or 512 formats with larger FPAs being addressed.[41] However, it does require cryogenic cooling from 77K to 85K. QWIPs are ideal for large field of view for persistent surveillance operating in the longwave infrared due to the high material uniformity and low cost. Designer applications where waveband tailoring is important can be pursued. The infrared technology company L3 has transitioned the technology from the Army to a commercial production line. At this time there has been no transition to an Army tech base program or platform. There has been a transition to NASA for satellite sensor applications.

e. 5V Li-Ion Batteries

The present average load for Soldier power for a 72-hour mission is 18 pounds (8.2 kg) for 70 batteries of 7 different types. These batteries are used for night sights, head sets, radios, laser range finders, beacons, handheld lights, among others. Standard rechargeable batteries used today are typically 3.8 volts. Energy density is proportional to the voltage of a battery. A recent breakthrough by ARL in 5 volt Li-ion batteries **(CTE 35)** has resulted in a potential 30 percent increase in energy density due to the increase to 5 volt. This increase in energy density can result in a number of potential advantages for the Soldier. For example, it could realize a 30 percent longer battery life or a 30 percent reduction in battery weight.[42]

This breakthrough was the result of research at ARL on the solid electrolyte interface (SEI) of graphite anodes and several high-voltage cathodes. A fundamental understanding (**CTE 36**) was gained for the reaction products between electrodes and electrolyte that gave rise to the identification of fluorinated phosphate ester structure being able to stabilize carbonate-based electrolytes on 5 volts class cathode surfaces. The additives participate in forming a protective interphasial chemistry not only on transition metal oxide cathodes at high voltage, but also on graphitic graphite at low voltage making formulation of an electrolyte that could support reversible Li+-intercalation chemistry at 5V. Several patents have been applied for this discovery. A strong modeling effort supported this research with the modeling of the 5V cathode

[41] C-QWIP infrared FPAs of 2K x 2K elements are being fabricated for NASA.
[42] Dr. Cindy Lundgren, Branch Chief, ARL-SEDD, interview with authors, August 6, 2012.

structure. The modeling gave a new understanding to why the electronic structure of LiCoPO4 decayed and changed.[43]

Various approaches, including design and synthesis of new solvents and additives, were formulated for electrolyte composition that support 5 volt Li-ion intercalation cathode with a low potential graphite anode. Unique ARL dry room facilities with extremely low dew points, with moisture less than five parts per million, were critical to this research. The research identified and focused on hexafluoro-iso-propanol (HFiP), a member of the phosphate ester family, as an important electrolyte component to be pursued that enabled attainment of 5 volt potentials **(CTE37)**. HFiP is a sacrificial dopant in the electrolyte which, on charging, passivates the cathode surface, thereby prolonging the life of the cell.

Ninety percent of the entire research effort on the 5 volt Li-ion battery was done at ARL. However, there were some significant contributions from other government laboratories making this effort a truly multi-laboratory collaboration. There was U.S. Department of Energy interest and funding, NRL did some modeling, and The Lawrence Livermore National Laboratory did characterization. In addition, others are using the new understanding of the additives and are conducting research with other cathodes. The research conducted by ARL in this area is having, and will continue to have significant long-term influence on the rechargeable battery technology community as a whole.

The significant 30 percent increase in energy density, due to the breakthrough of designing the right catalyst and cathode configuration, already has commercial industry interest. One license agreement is already in hand by the Army and ten material transfer agreements have been signed. The potential importance of this accomplishment is already acknowledged by the Army, which chose the industrial scale-up of the Li-ion battery additives and cathode as part of their Congressional Add request on “Alternative Energy.” While this battery technology will be transitioned to commercial industry, the result will have major impact for the Army. The new Li-ion battery technology will now be transferable to all Army platforms that use rechargeable batteries at commercially competitive prices.

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[43] Arthur Von Cresce and Kand Xu, “Electrolyte Additive in Support of 5V Li Ion Chemistry,” *Journal of the Electrochemical Society* 158, no. 3 (2011), A337-A342.

IV. DATABASES, MODELING, AND SIMULATIONS

The five systems discussed in the previous paragraphs have their success rooted in significant investments in modeling, simulations, and databases. Army unique investments and technical achievements in these supporting technologies are keys to the successes described previously.

a. GPS-Guided Munitions

The data required in order to completely cover the multitudinous engagement scenarios with all the possible parameters could not be obtained by any series of field experiments. The parameter space for the flight and target variables would require unobtainable R&D dollars to explore the entire range of variables, as well as unobtainable hardware. However, the availability of high performance computing (HPC) resources and engagement models permitted exploration of the many dimensions of the parameter space. More and more Army battlefield scenarios are being explored in this and other weapons areas by ARL with the use of HPC hardware and software resources available to Army laboratories and their industry and academic partners **(CTE38)**. ARL has a long history in using these resources to analyze new lethality concepts. Before Excalibur there were extensive HPC analyses on BAT, ATACMS and SADARM.

b. Constant Hawk

Constant Hawk generates an enormous and extremely complex image database. The complexity of urban terrain makes intelligent monitoring and forensics in large format imaging FPAs an insurmountable problem without appropriate off-focal- plane software to highlight targets and identify them in this enormous database. Megapixel images at standard frame rates of urban clutter are arguably the most difficult scenario of target acquisition, recognition, and tracking—even with human aids. Processing of such images needs more research investment for transfer to the field to augment the success of human intelligence analysts on the ground. The transition of any technique—such as adding a three dimensional perspective **(CTE39)**, as was done with Constant Hawk data—is a step in right direction. As the image databases continue to grow from Constant Hawk and similar imaging assets, more and more sophisticated algorithms are required to derive tactically relevant information in a timely manner. This technical challenge is the first step in the Data to Decisions[44] priority investment area for the Office of the Secretary of Defense for the FY13-17 to develop science and applications to reduce the cycle time and manpower requirements for analysis and use of large data sets that transcend the individual sensor data to commanders' decisions. ARL continues to address these areas.

c. UTAMS

The UTAMS database issues are similar to that of Constant Hawk except instead of locating targets in two dimensional images, the triangulation of acoustic/infrasonic signals in a cacophony of sounds is desired. The database of non-target to real targets is also routinely augmented. ARL continues to gather and store the requisite signal databases for this particular task depending on the operational scenario. Training on the surrounding noise sources is critical to maintaining an acceptable false alarm rate.

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[44] Robert Gates, memo, "Science and Technology (S&T) Priorities for Fiscal Years 2013-17 Planning," April 19, 2011, available at <www.acq.osd.mil/chieftechnologist/publications/docs/OSD%2002073-11.pdf>.

d. Thermal Imaging

Thermal imaging continues to be applied to more and more scenarios and systems. NVESD has a long history of development and system level models and simulations of infrared scenes viewed with infrared sensors. The validated models enable trade off studies of sensor concepts to satisfy various scenarios of interest. The FLIR model was based on the early television concept of the resolution of 3-bar test patterns to determine TV performance.[45] The NVESD modeling basic concept was to relate the ability to resolve bar patterns when viewing through an infrared imager to the ability of an ensemble of observers to detect, recognize, and identify tactical targets and was first suggested and validated in 1958 by John Johnson of NVESD.[46] The system level model[47] that was validated with realistic field data and released to the general community was adopted by the other Services, NATO, and the infrared industry as the standard yardstick against which any thermal imager performance could be determined before any hardware fabrication. Substantiated performance against the NVESD model with a proposed thermal imager design became a prerequisite for any Army procurement, such as the Apache helicopter and Abrams tank. The model is also used to represent target acquisition performance in large Army wargame simulations.

First, second and third generation thermal imaging sensors were all designed and optimized for the various Army scenarios via these models. The improvements predicted with the model have all been validated with real systems. As new scenarios arise or new innovations in system designs evolve, the models evolve and are calibrated and modified by NVESD. These models were not adopted by the entire international community because they were better than any other, but because they had the validation database to support their validity. Many extensive and small field tests were performed with thermal imagers to supply scientifically valid experimental data in order to substantiate the model's predictive capability.

The electromagnetic field level modeling for C-QWIPs done at ARL is leading to new innovative design parameters and specifications for QWIP detectors and FPAs. This modeling work is supported by extensive in-house experiments to validate the modeling and discover new physics for this unique infrared material and device configurations. This is an example of new research performed in an Army laboratory leading to new Army system possibilities that would not be pursued by private industry because of the lack of a commercial market. Moreover, this particular research is leading to a civilian space application by NASA before the military and will, ultimately, lead to the affordability for the military sector.

NVESD also pursued simulations of infrared scenes as viewed through thermal imagers. A capability for realistic battlefield scene generation was developed and used to transmit real time imagery to the U.S. Army's Training and Doctrine Command Battle Labs in support of experiments. The simulation called "Paint the Night" was used to generate canonical sets of

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[45] *Military Standard Photographic Lenses,* MIL-STD-150A (Washington, DC: Department of Defense, May 12, 1959), 20-21, available at <www.dtic.mil/dtic/tr/fulltext/u2/a345623.pdf>.

[46] J. Johnson, "Analysis of image forming systems," *Proceedings of Image Intensifier Symposium, US Army Engineering and Development Lab,* Ft. Belvoir, Virginia, 1958, 249-273, in R. B. Johnson and W.L. Wolfe, *Infrared System Design* 513, SPIE Milestone Series (1985).

[47] J.A. Ratches, W.R. Lawson, L.P. Obert, R.J. Bergemann, T.W. Cassidy, J.M. Swenson, "Night Vision Laboratory Static Performance Model for Thermal Viewing Systems," USA Electronics Command Report ECOM-7043, April 1973, AD-A011212; also, J.A. Ratches, "Static performance model for thermal imaging systems," *Optical Engineering* 15, no. 6 (December 1976), 525-530.

infrared scenes for human observers. It also became a scene generator for imagery to test automatic target recognition (ATR) algorithms against probability of detection and false alarm rate. This capability was transitioned to the training community in the form of training simulators for night sights on various weapons platforms such as the Abrams gunner's sight **(CTE40)**.[48] This program was named Recognition of Combat Vehicles (ROCV). In cooperation with the Program Executive Officer for Simulation, Training and Instrumentation, the ROCV simulators became training aids for thermal signatures of combat vehicles. The present version uses real IR images of vehicles taken at short range, which are then "wire wrapped" to display at different ranges. The backgrounds for the vehicles at these different ranges are simulated from Paint the Night Image Generator, which is an NVESD development from Paint the Night. Many threat combat vehicles under many environmental conditions were assembled in a booth that projected the variations in infrared signatures to a display for the Soldier to train. Cues on the signature were highlighted to help identification of the target.

ARL had a similar simulation called "Creation."[49] It was used as a scene generator for automatic target recognition (ATR) before being phased out. It is interesting to note that, whereas the synthetic target and scene generation techniques provided a reliable representation of scenes to the human observers, these techniques could not generate realistic scenes for ATR testing due to a wide discrepancy in false alarm rates. False alarm rate by ATR was always widely different between real and computer-generated scenes.[50] This finding is another example of the unique perspective that a Service laboratory can bring as a neutral adjudicator for technologies. This discrepancy between synthetic scene generators with respect to false alarms would probably not be investigated by industry or academic scientists due to lack of a broader vision of validation of candidate synthetic scene generation techniques.

e. 5V Li-ion Batteries

The breakthrough 5 volt Li-ion batteries were first discovered through electrochemical models of the SEI interfaces **(CTE41)**. New improvements in battery chemistry, energy density, lifetime, power, among others, are being addressed by model improvements with empirical validation generated from laboratory data conducted by ARL. ARL has this past year initiated a new Multi-scale Modeling of Materials effort, which is a collaborative modeling activity that has become a key initiative in ARL's Enterprise for Multi-scale Research of Materials, to investigate the transition of material modeling from the atomistic to continuum levels. Successful research from this activity will provide foundations for the White House's Office of Science & Technology Policy Materials Genome Initiative. This new initiative is a unique opportunity to leverage academic theoretical modeling and government in-house experimental expertise and laboratories for expanding the scientific frontier in sensors and power and energy.

This enterprise includes two Cooperative Research Agreements with academic research teams from several universities. One agreement on Multiscale/Multidisciplinary Modeling of Electronic Materials (MSME) involves a focus on electrochemical models that address the physics that were part of the Li-ion SEI success and will enhance the opportunities for further successes in

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[48] Recognition of Combat Vehicles, Homepage, available at <https://rocv.army.mil/>.
[49] Bruce A. Weber and Joseph A. Penn, "Synthetic FLIR Signatures for Training and Testing Target Identification Classifiers," *Optical Engineering* 43, no. 6 (June 1, 2004), 1414-1423.
[50] C.P. Walters, C.W. Hoover Jr., and J.A. Ratches, "Performance of An ATR Algorithm against Real and Two Versions of Synthetic Imagery," *Optical Engineering* 39, no. 8 (August 2000), 2279-2284.

similar battery architectures **(CTE42)**. The MSME agreement is led by the University of Utah, in cooperation with Boston University, and Rensselaer Polytechnic Institute. The research projects will be in interfacial physics and chemistry, nano-structures and solid-liquid interfaces. These are clear opportunities for batteries, capacitors, and fuel cells. A major identified goal is an increase in energy density by a factor of two.

The MSME modeling effort is a prime example of the research leadership role that the Service laboratories can and do play. They can track, influence trends, and identify critical research areas that lack significant understanding and require a broad based academic investment to address them. The Service labs, such as ARL in the Army, maintain an in-depth and broad base of knowledge of where a modeling initiative is required in order to ignite a new or renewed thrust that could move a technology forward. The MSME investment by the Army S&T through the ARL is a prime example of such a recent and ongoing initiative that will enable unprecedented new materials to become available for Army capabilities.

Activities of this sort are an example of a prime mechanism available to government laboratories that integrates academic expertise into the military S&T portfolio. An enormous technical asset resident in universities is the cadre of theoretical and experimental scientists that can be brought to bear to address major voids in scientific understanding that could enable new critical capabilities in military platforms. Collaborations, such as MSME, can add to a community with a different tool set into the partnership for addressing military problems. Also, the distribution of assets between theoretical and experimental disciplines can be redressed with judicious coalitions of service and academic organizations.

V. FINDINGS, DISCUSSION AND CONCLUDING REMARKS

Findings

We have identified 42 Critical Technology Events (CTE) in the development of these Army sensors. Appendix B shows the complete list of CTEs identified in this report. Also shown in this appendix is the origin or major player associated with the individual CTE: for example, *Government Laboratory* or *Combined* (government lab, industry and/or university). The distribution of CTEs for the sensor examples chosen are:

- *GPS-Guided Munitions — 16*
- *Constant Hawk — 6*
- *UTAMS — 3*
- *Thermal Imaging — 12*
- *5V Li-ion Batteries — 5*

24 of the 42 CTEs reported were uniquely contributed by the in-house Army laboratories. 57 percent of all the CTEs originated in the Army S&T laboratories.

It follows that Army laboratories make significant technical and enabling contributions to Army platforms and capabilities. The performance of Army laboratories can be measured by the contributions to material developments that enable required platform characteristics, which are set by Program Executive Officers and Program Managers to meet established warfighting requirements. The laboratories define, generate, and demonstrate CTEs, which are the building blocks for the desired characteristics and capabilities. The evaluation of Army S&T in the laboratories must focus on the multidisciplinary subject matter expertise of staff and management that are known of and highly visible in the larger scientific community, a research environment conducive to research excellence, and a corporate gestalt that creates the environment which nourishes scientific élan.

The Army S&T community of laboratories is uniquely suited to represent, defend, and guide the satisfaction of Army requirements. Academia and industry can never be entirely free of self interests. The Army laboratories owe and demonstrate total and complete allegiance to Army needs.

Army laboratories have the people, infrastructure, and determination to satisfy evolving and established needs.

The Army S&T community is the singular force in collaboration with industry and academia that ensures Army needs are optimally met in an effective, efficient, and affordable manner.

Discussion

Reviewing the previous reports mentioned as *Project Hindsight* inspired, along with this present one, there are actions, attitudes, awareness, and understanding gained during S&T phases of development that can enable or enhance and inspire the occurrence of CTEs. If Army S&T laboratories continue to be sensitive to these enabling characteristics, their successes will continue and will be maximized. Such characteristics that can cultivate CTEs during S&T are:

1. Foresight, and the incorporation of technical advances as they emerge during the S&T cycle.

2. Awareness of what others are doing, developing, or have in-hand for another problem that could help your system.
3. New understanding gained from new experimental data or validated modeling results.
4. Utilization of unique or national facilities and the intellectual talent outside of the performing laboratory, Service, or the United States.
5. Design modifications that can occur during R&D programs that address particular identified shortcomings or vulnerabilities.
6. Effective/efficient/enhanced transitions along the process of R&D and the system development cycle.
7. Awareness and integration of the lessons learned from others.
8. Pursuit of competing approaches.

In comparing this report to the previous reports, this report is unique in that it discovered that CTEs resulted in two entirely new platforms: Constant Hawk and GPS-Guided Munitions. Both were significant investments in technologies that have enabled surveillance and forensics and fire control capabilities that heretofore were not envisioned. Thermal imaging sensors are not in themselves platforms but are critically important and ubiquitous to many Army platforms. The same is true of the 5V Li-ion battery technology, having significant impact on the individual soldier. UTAMS is a platform based on an older acoustic technology that was improved and applied to a new mission of remote fire detection and localization.

This above discussion on the actions, attitudes, awareness, and understanding that are required of an S&T organization naturally leads to a discussion of how an S&T portfolio is evaluated to ensure ongoing and future relevance to Army needs. There are typically four characteristics of a research portfolio that need to be assessed in order to evaluate it: quality of the staff and the managers; relevance of the program; integration to/with the relevant technical community; and the ability to forecast technology developments. More details on these characteristics are discussed in the following paragraphs.

Quality of Staff and Managers: The technical staff must have a normalized distribution of disciplines, advanced degrees and age, with a reasonable turnover rate. Quality people should be recruited. There should be some staff that are members of the National Academies, fellows of various scientific or engineering societies, recipients of outside awards and prizes, and invited/keynote speakers at prestigious technical conferences and symposia. There should be copious peer-reviewed papers with emphasis on peer-review competition for basic research funding in the organization. Patents and breakthroughs for the last 10 years should be assessed. The managers should have well-known technical reputations outside of the organization. There should be a corporate vision with commonality of goals across the whole organization and a relevance to the enterprise. The opinion of superiors should be high and funding levels should be sufficient and consistent. An ability to influence sponsors and funding is essential. There should be an in-place process for selection of investment in sub-fields, as well as an external review process. Administrative burden on the researchers should be minimal. Besides people, state-of-the-art facilities and infrastructure are important.

Relevance of Program: Programs must prove their relevancy by showing their impact on the warfighter over time, which needs to be substantiated by funding level and consistency.

Relevance to the enterprise is shown by alignment with Army mission and vision and transitions made to programs of record and/or Program Executive Offices. The program should be balanced between enhancements to technology versus extension, new challenges in existing areas, and new emerging areas. Programs with crosscutting technologies that could be relevant to other programs should be highlighted. There should be regular meetings with customers and stakeholders.

Integration to/with Community: A Service laboratory needs to be aware of industrial Independent R&D. In-house Army STs should influence the technical program investment. Leveraging outside laboratory activities, including international, is necessary. A collaborative international technology alliance between the United States and the United Kingdom was recently cited as an example of such a productive leveraging of military laboratories, "Since 2006, an International Technology Alliance of industrial and academic organization from the US and UK, led by the U.S. Army Research laboratory and the U.K. Defense Science and Technology Laboratory, have been jointly conducting collaborative research to enhance information-sharing and distributed, secure, and flexible decision-making to improve networked coalition operations."[51] Peer review is essential, as is visibility by, and of, others.

Tech Forecasting: Astute technical forecasting is essential to determine if the S&T assets are on the "right horse" for maximum impact. This should be a criterion and assessment process for researchers and their career advancement. The ability to adjust and avoid technical surprise is critical to survival and success on the battlefield. Specifications of research and process score cards are required.

A more in-depth report on these factors, fundamentals, and metrics for S&T portfolio evaluation has been published. The Center for Technology and National Security Policy (CTNSP) at the National Defense University has prepared a report on how to evaluate the quality of S&T and what the appropriate metrics are. This was done at the request of the Army S&T Executive.[52]

Concluding Remarks

Our previous technical reports on Abrams, Apache, and Stinger and Javelin, showed how the Army S&T community developed Critical Technology Events to support and enable the development of these critical weapons platforms. This report attempts to show that the S&T resources and processes are still in place and functioning in generating continued CTEs in the sensor and power area for the next generation of Army systems. It is critical to the Army's mission to foster and nurture the Army's in-house S&T tech base.

Although, the Army tech base continues to contribute critical R&D to the next generation of Army systems, it is incumbent on the Army technical leadership to continually evaluate, nurture, and direct this tech base. The quality of the scientists and managers must be constantly appraised and cultivated with new professionals and laboratory infrastructure. Otherwise, eventually this enabling Army asset will wither and expire. Should that be allowed to happen, either the U.S.

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[51] "Joint Fact Sheet: U.S.-UK Higher Education, Science, and Innovation Collaboration," Press Release, The White House, March 14, 2012, available at <www.whitehouse.gov/the-press-office/2012/03/14/joint-fact-sheet-us-uk-higher-education-science-and-innovation-collabora>.
[52] John Lyons, Richard Chait and James Ratches, *Suggestions for Evaluating the Quality of the Army's Science and Technology program: The Portfolio and Its Execution.* Defense and Technology Paper 99 (Washington, DC: Center for Technology and National Security Policy, January 2013).

Army will lose its battlefield advantages, be at the mercy of profit-motivated commercial industry, or foreign sources. An initial attempt has been made in this report to indicate what characteristics are required of an Army S&T portfolio and organization in order to optimize S&T success.

APPENDIX A. ACRONYMS

AFRL – Air Force Research Laboratory

AGC – Army Geospatial Center

AMRDEC – Army Missile Research, Development and Engineering Center

AMUS – Aero-Mounted UTAMS System

APIX – MITLL viewer

APMI – Accelerated Precision Mortar Initiative

APS – Auxiliary Persistent Sensor

ARL – Army Research Laboratory

ARL-SEDD – ARL Sensors and Electron Devices Directorate

ARL-WMRD – ARL Weapons and Materials Research Directorate

ARDEC – Armaments Research and Development Center

ATACMS - Army Tactical Missile System

ATO – Advanced Technology Objective

ATR – aided/automatic target recognition

B&W – black & white (for example, a camera)

BAT – Brilliant Anti-Tank munition

C4ISR – Command, Control, Communications, Computers, Intelligence, Surveillance & Reconnaissance

CEP – Circular Error Probability

CERDEC – Communications & Electronics Research, Development and Engineering Center

CH – Constant Hawk

CONOPS – Concept of Operations

CONUS – continental United States

COTS – Commercial Off-the-Shelf

C-QWIP – Corrugated Quantum Well Infrared Photodiode

CRA – Cooperative Research Agreement

CTA – Collaborative Technology Alliance

CTE – Critical Technology Event

CTNSP – Center for Technology and National Security Policy

DDR&E – Director of Defense Research & Development

DARPA – Defense Advanced Research Projects Agency

DMZ – Demilitarized Zone

DOD – Department of Defense

DTP – Defense & Technology Paper (products from CTNSP)

E&M – electro-magnetic

EAPS – Extended Area Protection Systems

EO – Electro-optics (covers infrared portion of spectrum)

FA – Field Artillery

FAR – false alarm rate

FAST – Field Assistance for S&T

FLIR – forward looking infrared

FOB – forward operating base

FOV – field of view (of a sensor)

FPA – focal plane array (NxM array of pixels)

GBU – Guided Bomb Unit

GIS – Geospatial Information System

GPS – Global Positioning System

HPC – high performance computing

I2 – image intensification

IED – Improvised Explosive Device

IRFPA – Infrared Focal Plane Array (DARPA producibility program)

IMU – inertial mass unit

INS – Inertial Navigation System

INSCOM – U.S. Army Intelligence and Security Command

IR – infrared (~ 0.4 to ~ 100 micrometers wavelength of E&M spectrum)

ISR – intelligence, surveillance and reconnaissance

JDAM – Joint Direct Attack Munition

LCCM – Low Cost Competitive Munitions

LIDAR – Light Detection & Ranging (also LADAR)

LLNL – Lawrence Livermore National Laboratory

LPE - Liquid Phase Epitaxy (IR material growth)

LWIR – longwave infrared (8-14 micrometers spectral region)

LRASS – Long Range Advanced Sensor Suite

MASINT – Measurement and Signals Intelligence

MAST – Micro-Autonomous Systems Technology

MCT – mercury cadmium telluride (IR detector material)

MAWS – Miniature Acoustic Warning System

MBE – Molecular Beam Epitaxy (material growth process)

MEMS – micro-electromechanical systems

MGK – Mortar Guidance Kit

MITLL – MIT Lincoln Lab

MLRS – multiple launch rocket system

MOCVD – molecular-organo-chemical vapor deposition (IR detector growth technique)

MMW – millimeter wave

MRT/MRTD – Minimum Resolvable Temperature (Difference)

MSME – Multiscale/Multidisciplinary Modeling of Electronic Materials

MWAPS – MWIR Auxiliary Persistent Sensor

MWIR – midwave infrared (3-5 micrometers spectral region)

NDU – National Defense University

NET – noise equivalent temperature

NGA – National Geospatial Agency

NGIC – National Geospatial Intelligence Center

NIR – near infrared (~ 1 micrometer spectral region)

NRL – Naval Research Laboratory

NVESD – Night Vision & Electronic Sensors Directorate

OCONUS – outside continental United States

OEF – Operation Enduring Freedom

OIF – Operation Iraqi Freedom

OSTP – Office of Science & Technology Policy (White House)

PEO – Program Executive Officer

PEO-STRI – Program Executive Officer for Simulation, Training and Instrumentation

PGK – Precision Guided Kit

PGSS – Persistent Ground Surveillance System

PM – Program Manager (for a system)

PM ARES – Project Manager Airborne Reconnaissance and Exploitation Systems

PM CAS – Project Manager Combat Ammunition Systems

PM RUS – Project Manager, Remote Unattended Systems

POR – program of record

PTDS – Persistent Threat Detection System

PUMA – Precision Urban Mortar Attack

QWIP – quantum well infrared photodiode

R&D – Research and Development

RAM – Rockets, Artillery & Mortars

RDECOM – Research, Development and Engineering Command (under Army Material Command)

RXD – Research and Exploratory Development (from *Project Hindsight*)

REF – Rapid Equipping Force

RISTA – Reconnaissance, Intelligence, Surveillance and Target Acquisition

ROCV – Recognition of Combat Vehicles

S&T – Science & Technology

SAASM – Selective Availability Anti-spoofing Module

SADARM – Sense and Destroy Armor (submunitions)

SEDD – Sensors and Electron Devices Directorate (ARL)

SEI – Surface Electrolyte-Interface

SME – subject matter expert

SOP – standard operating procedures

TCDL – Tactical Command Data Link

T2SL – Type 2 superlattice detector structure

TDI – Time-Delay and Integrate (for a signal-to-noise)

TRL – Technology Readiness Level

TTP – Tactics, Techniques and Processes

UAVs – Unmanned Air Vehicles

UTAMS – Unattended Transient Acoustic/Artillery MASINT System

VAP – Very Affordable Projectile

VBIED – Vehicle Borne Improvised Explosive Device

WFOV – wide field of view

WMRD – Weapons and Materials Research Directorate (ARL)

WPAFL – Wright Patterson Air Force Laboratory Dayton, Ohio

YPG – Yuma Proving Ground Arizona

APPENDIX B. CTE SOURCES

CTE	Government Lab	Combined University/ Industry/Lab
1. “Screw on” GPS transponder	X	
2. Use GPS translators for position of round at ground station		X
3. Conical GPS antenna	X	
4. Retrofit stockpile rounds w/fuses	X	
5. 1st in-flight projectile tracking	X	
6. Drag to correct for trajectory		X
7. GPS/MEMS inertial sensor w/lower CEP		X
8. VAP	X	
9. Guidance by earth’s magnetic field	X	
10. SAASM		X
11. MEMS fuzes	X	
12. HPC modeling	X	
13. MEMS sensors and Actuators	X	
14. Reduced state guidance		X
15. Targeting technology	X	
16. Ganging 6 sensors together		X
17. Composite stitched image		X
18. Camera with hybrid products	X	
19. Registered 3D data	X	
20. Image analysis algorithms		X
21. Mortar detection	X	
22. Acoustics to cue imagers	X	
23. Noise cancellation algorithms	X	
24. Common Modules		X
25. MRT lab measurement	X	
26. FLIR performance model	X	
27. 2nd Gen FLIR		X
28. IRFPA		X
29. 3rd Gen FLIR		X
30. MCT on Si		X
31. T2SL		X
32. nBn detector structure		X
33. Uncooled IR		X
34. C-QWIPs	X	
35. 5V Li-ion battery	X	
36. SEI	X	
37. HFiP	X	
38. HPC GPS simulations	X	

CTE	Government Lab	Combined University/ Industry/Lab
39. Processing algorithms for TB/hr.	X	
40. Gunner sight simulator	X	
41. SEI model		X
42. MSME CRA modeling initiative		X

APPENDIX C. INDIVIDUALS CONTACTED

Last Name	First Name	Organization	Status
Choi	K.K.	ARL-SEDD	CSE
Doligalski	Tom	ARO	CSE
Dammann	Jeff	ARL-SEDD	CSE
Eicke	John	ARL-SEDD	CSE
Horley	Gary	ARL-HRED	GR
Ladas	Andrew	ARL-SEDD	CSE
Lundgren*	Cynthia	ARL-SEDD	CSE
Lyon	Dave	ARL-WMRD	CSE
Penn	Joseph	ARL-SEDD	CSE
Plostins*	Peter	ARL-WMRD	CSE
Pollard*	John	CERDEC NVESD	GR
Sicignano*	Ray	ARDEC	CSE
Reago	Don	CERDEC NVESD	CSE
Ruff*	William	ARL-SEDD	CSE
Tenney*	Stephen	ARL-SEDD	CSE
Toth*	Susan	ARL-SEDD	CSE

Government Retired GR
Civil Service Employee CSE
* Reviewed contributed relevant sections of report

APPENDIX D. *PROJECT HINDSIGHT*

This study is modeled in part on a 1969 report, *Project Hindsight.* In 1965, the Director of Defense Research and Engineering (DDR&E), Dr. Harold Brown, established a project to take a retrospective look at U.S. Department of Defense (DOD) investment in research and development (R&D), to evaluate the results, and to take stock of lessons learned. Brown's overarching objectives for the study were to identify management factors that were associated with the utilization of the results produced by the Defense Department science and technology (S&T) program and to devise a methodology to measure the return on investment.[53] He was motivated in part by the House of Representatives Committee on Defense Appropriations, which had questioned the efficiency of management and overall payoff for the part of Research, Development, Testing and Evaluation program that pertained to S&T.[54]

The study was conducted by ad hoc teams of military and civilian in-house personnel. Some 20 weapons systems were selected for review and a set of subcommittees was arranged, one for each system. The systems selected for review included air-to-surface, ballistic, and tactical missiles; a strategic transport aircraft; a howitzer; and an antitank projectile. Data were gathered by questionnaire and evaluated according to four criteria:[55]

1. The extent of dependence on recent advances in science or technology.
2. The proportion of any new technology that resulted from DOD financing of science or technology.
3. The management or environmental factors that appear to correlate with high utilization of S&T results.
4. A quantitative measure of the return on investment.

The project teams make the following finding with respect to these four criteria:[56]

1. Markedly improved weapons systems result from skillfully combining a considerable number of scientific and technological advances (Criterion 1).
2. More than 85 percent of the new science or technology utilized was the result of DOD-financed programs (Criterion 2).
3. The utilization factor appears insensitive to environmental or management science and technology centers (Criterion 3).
4. Most utilized new technological information was generated in the process of solving problems identified in advanced or engineering development (Criterion 3).
5. Most utilized new fundamental scientific information came from organized research programs undertaken in response to recognized problems (Criterion 3).

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[53] Harold Brown, *Letter to the Assistant Secretary of the Army (R&D), the Assistant Secretary of the Navy (R&D), and the Assistant Secretary of the Air Force (R&D)*, July 6, 1965, in, *Project "Hindsight: Final Report"* (Washington, DC: Department of Defense, 1969), 135.
[54] Brown, *Letter to the Assistant* Secretary, in *Project "Hindsight: Final Report,"*135.
[55] *Project "Hindsight: Final Report,"* xiii.
[56] *Project "Hindsight: Final Report,"* xxi.

6. Technological inventiveness and the utilization rate are dependent on the recognition of a need, an educated talent pool, capital resources, and an adequate communication path to potential users (Criterion 3).
7. Any crude approximation in measuring cost-performance will tend to be delusory (Criterion 4).

With regard to finding number seven, the study failed to find a satisfactory method for assessing cost benefit or cost performance from S&T work. To illustrate the difficulty that the study encountered, the report cited the example of the silicon-based integrated circuit. The circuit, invented during the period under review, revolutionized electronics and information technology and became a crucial part of virtually every system in the arsenal; there was no effective way to subdivide the effects on individual S&T programs.

This paper did not attempt to redress this or any other shortcoming of *Project Hindsight*; Dr. Brown's goal of quantifying the payoff of DOD investment in research and technology is if anything a loftier target today than it was in 1965. The fundamental purpose of this report, however, closely mirrors that of its predecessors: by examining the development of select Army systems, and in particular those signal technology events that propel systems to success, we hope to shed light on the factors that lead defense S&T research to fruition.

In addition to sharing a broad goal with the original *Hindsight* report, this paper also takes from it a similar unit of analysis, the CTE. *Hindsight* evaluations were based on a concept called a Research and Exploratory Development (RXD) Event. In that report, a RXD event has the predominant meaning of an event that "defines a scientific or engineering activity during a relatively brief period of time that includes the conception of a new idea and the initial demonstration of its feasibility."[57] There may be one or two such events in the development of a component or system, or a whole string of such events. In the case of basic research RXD events, the report distinguishes between undirected (i.e., curiosity-driven) and directed (i.e., problem-driven) work. Lastly, the final fabrication of the system component or device "may or may not involve an Event depending on the state of the technological art at the time of fabrication."[58] Please note that our signal events, CTEs, differ from *Hindsight's* RXD events. Most significantly, CTEs can occur at any point in the life cycle. We leave open the possibility that CTEs might result from efforts that have utilized funds other than R&D.

[57] *Project "Hindsight: Final Report,"* xiv.
[58] *Project "Hindsight: Final Report,"* xiv.