

Critical Technology Events in the Development of the Stinger and Javelin Missile Systems

Project *Hindsight* Revisited

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The views expressed in this report are those of the authors and do not reflect the official policy or position of the National Defense University, the Department of Defense, or the U.S. Government. All information and sources for this paper were drawn from unclassified materials.

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I. Introduction

This paper seeks to identify the Critical Technology Events (CTEs) in the development of the Stinger and the Javelin missiles. It is the third paper in a series that, driven by the importance of understanding past military technological successes to today's defense science and technology (S&T) investment and management, examines some of the key factors that have led to meaningful technology generation and ultimate incorporation into current U.S. Army weapons systems. The first paper in the series focused on the Abrams tank.¹ The second focused on the Apache helicopter.² With studies of a complex ground system and a complex air system complete, this paper turns to two technologically advanced infantry weapons, the Stinger and the Javelin. These armaments have different roles in the arsenal, but they are both man-portable, fire-and-forget missiles whose development posed some unique challenges. A fourth and final paper in the series will summarize findings of this report, and the reports on the Abrams and the Apache, and offer recommendations for managing the Army's S&T portfolio.

We begin our study of the development of these two missile systems by briefly reviewing a project that served as a source of inspiration for this effort: Project *Hindsight*, a 1969 Defense Department (DOD) report.³ *Hindsight* was an in-depth study sponsored by the Director of Defense Research and Engineering that provided some insights into the development of approximately 20 weapons systems. This review of *Hindsight* is followed by a description of the methodology that we used to gather key data on the development of the Stinger and the Javelin. We then address each missile individually. For each missile, we first present a brief description of the system and history of the program. The information that we have gathered is then broken out by topic area (e.g., seeker; warhead and propulsion) and presented in terms of CTEs. CTEs are ideas, concepts, models, and analyses, including key technical and managerial decisions, that have had major impacts 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, to product improvements. CTEs can even relate to concepts that were developed but not incorporated into the weapons system. Also, they can originate anywhere, from in-house laboratories, to private industry, to academia. The final portion of the paper presents findings and concluding remarks that draw on the CTEs in the development of both missiles.

¹ Richard Chait, John Lyons, and Duncan Long, "Critical Technology Events in the Development of the Abrams Tank—Project Hindsight Revisited," *Defense and Technology Paper 22* (Washington, DC: Center for Technology and National Security Policy, December 2005).

² Richard Chait, John Lyons, and Duncan Long, "Critical Technology Events in the Development of the Apache Helicopter—Project Hindsight Revisited," *Defense and Technology Paper 26* (Washington, DC: Center for Technology and National Security Policy, February 2006).

³ Office of the Director of Defense Research and Engineering, *Project Hindsight: Final Report* (Washington, DC: Office of the DDRE, 1969).

The CTEs are noted in the left margin throughout the report. They are summarized in Appendix B. CTEs are numbered only for ease of reference; there is no hierarchical or chronological significance to their order.

While the link between high-tech weapons systems and battlefield success is often readily apparent, the geneses of CTEs often are not. CTEs depend on several important factors, including providing adequate funding, establishing clear priorities, fostering proper technical competencies, and leveraging the resources of the private sector and academia. It is our hope that this retrospective look at the Stinger and the Javelin can highlight the importance of such factors, and thus can be of value to current S&T leadership within the Army and DOD as they wrestle with tight budgets, a changing workforce, and new acquisition strategies.

II. Background and Study Methodology

Project Hindsight

The study undertaken here is modeled in part on a 1969 report, *Project Hindsight*.⁴ In 1965, the Director of Defense Research and Engineering (DDR&E), Dr. Harold Brown, established a project to take a retrospective look at 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 DOD S&T program and to devise a methodology to measure the return on investment.⁵ He was motivated in part by the House Committee on Defense Appropriations, which had questioned the efficiency of management and the overall payoff for the part of the Research, Development, Testing and Evaluation (RDT&E) program that pertained to S&T.⁶

The study was conducted by ad hoc teams of military and civilian in-house personnel. Some twenty 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.⁷ These criteria were:

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 made the following findings with respect to these four criteria:⁸

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).

⁴ Ibid.

⁵ 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), 6 July 1965 in *Project Hindsight: Final Report* (Washington, DC: Office of the DDRE, 1969), 135.

⁶ Ibid.

⁷ Office of the Director of Defense Research and Engineering, *Project Hindsight: Final Report* (Washington, DC: Office of the DDRE, 1969), xiii.

⁸ Ibid, xxi.

3. The utilization factor appears insensitive to environmental or management differences between industry, in-house laboratories, and university-associated S&T 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).
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 will 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 predecessor: by examining the development of select Army systems, and in particular those signal technology events that propelled these 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."⁹ 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 (curiosity driven) and directed (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."¹⁰ Please note that we use a definition for CTEs that differs from *Hindsight*'s RXD event. Most significantly, as noted previously, 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.

⁹ Ibid., xiv.

¹⁰ Ibid.

Scope

We have chosen to focus this report on those things we deemed to be major technical developments. Though the Stinger and the Javelin both have many complex components that required innovation, we have concentrated only on those features that are vital to the missiles' performance and set the missiles apart from their predecessor systems. Further, this study does not intend to provide exhaustive technical detail on the CTEs, but rather to identify them and highlight key aspects of their origin.

We have divided the discussions of each missile's development into specific topic areas. This separation of topics comes at the acknowledged price of diminished discussion of integration, systems engineering achievements, and the teaming of in-house laboratories, contractors, and the Program Manager (PM). The important integration work performed by the contractor, working closely with the PM shop and in-house laboratories, was vital to the final product.

Approach

This report is based primarily on interviews and correspondence with people who were directly involved in the development of the Stinger and the Javelin missiles, as well as information available in open source literature. Given the technical emphasis of the report, we interviewed and corresponded mostly with technical professionals. We also sought out personnel who had been at the PM office and with the contractors. The objective of these communications was to obtain a picture of how important critical technology events unfolded.

The interviews covered a broad range of pertinent topics, including the historical background of the developments in question. The focus of discussion, though, was the CTEs. We asked interviewees to identify those technology events that they considered critical to the development of the missiles; to detail the impact of the CTEs; to indicate where the work in question was done, who contributed to it, and who funded it.

Often, we first interviewed a project scientist, engineer, or manager and then obtained further information through follow-on conversations and correspondence with others identified by that person. Almost all of the discussions began with the interviewees providing highlights of the relevant experiences, after which we asked focused questions on topics not initially covered.

It must be noted that the interviewees and correspondents were asked to relate events that took place as many as forty years ago. Detailed information was sometimes unavailable. Data on funding levels, for instance, were obtainable only intermittently. Wherever possible, we consulted multiple individuals on the same subject and checked their accounts against written sources. When interviewees and correspondents differed on what constituted a critical technology or who had made essential contributions, we revisited the issue until we established the most accurate possible picture of events. As a result, we

are confident that we have captured the most pertinent information related to the major technical events in the development of the Stinger and the Javelin.

III. The Stinger

The Stinger is a heat-seeking, man-portable, air defense (MANPAD) missile.¹¹ The system consists of a reusable grip stock and a sealed launch tube with a five-foot-long missile. The grip stock and missile tube together weigh about 35 pounds. The weapon has a maximum altitude of about 10,000 feet, and a range of about five miles. Over 44,000 Stingers have been built. It is used by the U.S. Army (which plans to keep it in the inventory until at least 2018), the Marine Corps, and the Navy.¹² It is also used by numerous foreign nations.¹³



Figure 1. Stinger launch tube assembly (left) and Stinger missile round.¹⁴

¹¹ Since its initial development, the Stinger has been configured to be mounted on a range of systems, including the Apache helicopter and the Bradley Fighting Vehicle. This report addresses only the manportable configuration.

¹² “Stinger Missile,” Raytheon Missile Systems brochure, 2004.

¹³ The Stinger is perhaps best known for a role it played in the Cold War. Starting in 1986, the CIA provided roughly a thousand Stingers to the Mujahideen in Afghanistan to aid them in their struggle against the invading Soviet Army. The Stinger’s introduction to the battlefield provided the Afghans with a way to counter Soviet airpower. The missile is credited with bringing down about 250 Soviet planes and helicopters.

¹⁴ “Stinger/MANPADS Briefing,” PowerPoint presentation, Raytheon Missile Systems Cruise Missile Defense Systems Project Office, 2001-2005.



Figure 2. Stinger missile round.¹⁵

Background

The Stinger was developed to answer the Army’s need for an effective MANPAD to protect ground personnel from low-flying aircraft. The weapon then in the arsenal to accomplish this mission was a missile called Redeye, which was manufactured by General Dynamics. The most significant problem with Redeye was that it was effective only in specific engagement circumstances: the soldiers on the ground had to fire the missile directly at the exhaust of the target aircraft in order to allow the weapon’s infrared (IR) seeker to establish a lock. This meant that the missile could only be fired at the target after it had passed over and, presumably, had already delivered its munitions in the area. Redeye was referred to as a “revenge” weapon for this reason.

Advances in technology, many of which are detailed in the subsequent sections, made it possible to improve on the Redeye and build a longer-range missile that could acquire targets quickly and engage an incoming enemy aircraft before it could release its ordnance. The Army began advanced development on a replacement for Redeye, dubbed Redeye II and later renamed the Stinger, in 1967. The contract to develop Stinger (officially designated FIM–92) was awarded to General Dynamics in 1972. The Stinger achieved initial operating capability in 1981.¹⁶

The Army has procured four successive versions of the Stinger: Stinger Basic, Stinger–Passive Optical Seeker Technique (POST), Stinger–Reprogrammable Microprocessor (RMP), and Stinger Block I. All have the same fundamental attributes and dimensions. Stinger Basic was produced between 1978 and 1987 and Stinger–Post between 1985 and 1987. Stinger RMP entered production in 1985 and is still being manufactured. Stinger Block I entered production in 1996 and is also still being manufactured. Raytheon Missile Systems is the current prime contractor for the Stinger.¹⁷

¹⁵ Ibid.

¹⁶ Notably, the Stinger was fielded as an Air Defense Artillery (ADA) asset. The Redeye was an all-arms weapon, meaning that any personnel were capable of using it without significant training. Tests conducted in 1972 determined that the Stinger’s increased range and all-aspect engagement capability greatly increased the chances of fratricide. This, in addition the Stinger’s increased complexity, necessitated specific air defense training. Don Peterson, email to authors, 2 April 2005.

¹⁷ General Dynamics sold its missile division to Hughes in 1992. Raytheon bought Hughes’s missile division in 1997.

To operate the missile, the gunner mates the launch tube with the grip stock and uses the sight on the launch tube to track the target aircraft. A belt pack Identification, Friend or Foe (IFF) transceiver tells the gunner if the incoming aircraft is friendly. If he determines that the aircraft is hostile, the gunner activates the battery/coolant unit (BCU) and with it the missile's IR seeker. The system gives the gunner an audio cue when the seeker has established a lock on the target. After the gunner fires, the missile is ejected from the tube by a launch motor and then carried to the target at speeds in excess of Mach 2 by a two-phase flight motor. It destroys the target using a hit-to-kill high explosive (HE) warhead.

The following discussion of the Stinger will address the CTEs behind this system's key components. We will examine the development of the seeker, the guidance and control system, and the propulsion and warhead. The section concludes with a discussion of the modeling and simulation used to develop the missile.

Seeker

The Stinger is a fire-and-forget missile, meaning that its onboard systems must be able to engage the target without further assistance from the gunner or any other external source. The tracking process begins with the IR detectors in the seeker, which pick up the heat from the target. The detector signals go to a microprocessor that creates an image frame. This action is repeated constantly while the missile is in flight. The multiple frames are sent to the tracker microelectronics. The tracker interprets the sequence of such frames and decides how the missile should maneuver to intercept the target. The signal is then sent to the guidance circuits, which instruct the control surfaces to steer the missile. Starting with the seeker, the technologies involved in this process are those that are most critical to the Stinger's performance.

The Stinger has employed two basic kinds of IR seekers. Stinger Basic had a reticle scan seeker, the same general type found in Redeye. This type of seeker was developed by General Dynamics and Navy laboratories at China Lake, CA, in the late 1950s.¹⁸ The Redeye reticle scan seeker had a single detector element. The target "hot spot" (it is not a resolved image) was viewed through a reticle, with alternating opaque and transparent vanes.¹⁹ The spinning reticle captured the target pattern as a circle, the radius of which represented the magnitude of the deviation from true alignment with the target. The trouble with this design, with the center of the reticle representing the null position of true alignment, was that the radius was expressed as amplitude. As the missile homed in on the target and the deviation decreased, the signal-to-noise ratio became less favorable, producing lower accuracies.

CTE 1

This kind of reticle design was improved upon in Stinger Basic, which used a technique called conical scanning developed by General Dynamics.²⁰ In this type of seeker, the

¹⁸ David Hardesty, interview with authors, Tucson, AZ, 13 December 2005.

¹⁹ J.J. May, Jr. and M.E. Van Zee, "Electro-optics and Infrared Sensors," *Microwave Journal*, September 1983, 121-31.

²⁰ Tony Thomas, email to authors, 31 January 2006.

reticle was fixed in place and the spot image picked up by the IR detectors was scanned in a circle by spinning mirrors. If the target was on the optical axis the circle would be centered on the reticle; if it was off-axis, the circle would be off the reticle center. The on-center pattern produced a symmetrical square wave signal because the amount of time spent on the reticle's transparent vanes was the same as that on the opaque vanes. If the circle was off-center there was varying time spent on the two types of vanes, producing a modulation of the frequency of the signal. Unlike the sort of spinning reticle used by Redeye, errors do not increase as the deviation from true alignment decreases.

CTE 2

The next version of Stinger, Stinger-POST, made three major improvements to the seeker. First, the reticle seeker was replaced with a rosette scan seeker. The rosette scan was an improvement because it used a very narrow instantaneous field of view (IFOV) vis-à-vis the simpler spinning reticles, which had a wider IFOV. This provides much more accurate target discrimination.²¹ The rosette scan was patented by General Dynamics in 1977 based on work done in the late 1960s.²² Refinement and development of the concept (there was significant trouble designing the new seeker so that it could be efficiently produced)²³ and the eventual incorporation into Stinger Post and, later, Stinger RMP, was a collaborative effort between General Dynamics and engineers from the U.S. Army Missile Research Development and Engineering Center (MRDEC)²⁴ at Redstone Arsenal in Huntsville, AL.

CTE 3

The second major improvement in Stinger-POST's seeker was a change in the capabilities of the IR detectors. The Redeye used a lead sulfide (PbS) detector that operated in the near infrared.²⁵ Stinger Basic had an indium antimonide (InSb) mid-wave infrared detector. Stinger-POST was equipped with a dual wave length detector assembly made in a stack—one detector that operated at the mid-infrared made of InSb and another detector that operated at the near ultraviolet (UV) made of cadmium sulphide.²⁶ The IR detector was for sensing the hot exhaust gases from the aircraft engines; the UV detector allowed the Stinger to track radiation emitted by the aircraft skin. This improved Stinger's all-aspect engagement capability—the missile was no longer as dependent on picking up engine heat, which would always be strongest at the rear of an aircraft. Stinger-POST seeker heads were also designed to be modularly fitted to Stinger Basic airframes.²⁷

CTE 4

The third major improvement in Stinger-POST was the incorporation of integrated digital circuits to perform the seeker signal processing functions. This was a significant

²¹ Thomas, telephone interview with authors, 10 January 2006.

²² The patent was issued to Glen W. Ashley, Jr., Ernest O. Buenting, Charles A Leonard, and Gerhard Lessman, of General Dynamics, Pomona, California.

²³ Peterson, email to authors, 29 March 2006.

²⁴ MRDEC is now called the U.S. Army Aviation Missile Research, Development and Engineering Center (AMRDEC). AMRDEC is part of Research, Development and Engineering Command (RDECOM).

²⁵ Frank Hayes and David Light, interview with authors, Huntsville, AL, 14 September 2006.

²⁶ The General Dynamics patent on the Rosette scan seeker cited above includes the dual wave detector.

²⁷ "Raytheon Electronic Systems FIM-92 Stinger Low-Altitude Surface-to-Air Missile System Family," Jane's Land Based Air Defence, available online at <http://www.janes.com/defence/air_forces/news/jlad/jlad001013_2_n.shtml>, accessed 15 March 2005.

electronic packaging and performance improvement over the analog circuitry found in Basic Stinger or even discrete digital circuitry. Conceived, developed, and demonstrated by MRDEC, the concept was embraced and incorporated (albeit with different devices) by the prime contractor, General Dynamics.²⁸

CTE 5

Stinger RMP introduced another major improvement. This design (as the name Reprogrammable Microprocessor indicates) enabled the onboard microprocessor to be updated with new software as new information on threats and countermeasures became available. Properly programmed, the processor can recognize countermeasures (like flares) and filter them out from the information it sends to the guidance system. The reprogrammable circuitry, conceived and developed by General Dynamics, made it possible to add capability to the missile without fully redesigning it.²⁹ Stinger Block I also has this capability.

The Stinger's seeker technology continues to improve. The technology for using staring two-dimensional arrays for the Stinger was developed in the mid 1990s but has not yet gone into production.

The seeker depends on a comparatively less complex but nevertheless essential element: the BCU, an expendable, one-use-only unit that plugs into the grip stock. Once the target is determined as unfriendly, the gunner pushes the impulse generator switch on the grip stock. This releases pressurized argon gas from the BCU to cool the IR detector; the process takes 3–5 seconds.³⁰ Most IR detectors, those on the Stinger included, must be kept at a very low temperature to improve the signal to noise ratio. The cooling occurs from the sudden expansion of the gas, a phenomenon known as the Joule-Thompson effect. A very similar approach was used to cool the detector on the Redeye missile.³¹ Once the missile's seeker is cooled, the gunner can use it to lock onto the target. The BCU also provides all the pre-launch electrical power, not only for the seeker coolant system but for gyro spin-up, guidance electronics, ignition of the ejection motor, and activation of the missile's onboard thermal battery.³² Once turned on, the BCU's battery has power for at least 45 seconds.³³ The missile's battery has enough energy to power the missile's systems for about 19 seconds.³⁴

CTE 6

The missile also has an onboard battery to power the systems after launch. This was initially a chromate battery. Based on PM-funded work at Sandia National Laboratory, a lithium-based battery was developed in the mid-1990s for use in Stinger Block I as a

²⁸ Light, email to authors, 15 February 2006.

²⁹ Ibid.

³⁰ "Raytheon Electronic Systems FIM-92 Stinger Low-Altitude Surface-to-Air Missile System Family," Jane's Land Based Air Defence.

³¹ Mary Cagle, *History of the Redeye Weapon System* (Huntsville, AL: Historical Division, U.S. Army Missile Command, Redstone Arsenal, 1974), 127.

³² "Raytheon Electronic Systems FIM-92 Stinger Low-Altitude Surface-to-Air Missile System Family," Jane's Land Based Air Defence.

³³ Ibid.

³⁴ Ibid.

replacement for the chromate battery. The lithium battery is lighter, smaller, and provides faster ignition and greater energy capacity.³⁵

Guidance and Control

Once the seeker has acquired the target, the rules of proportional navigation are used to guide the missile until impact. The principle of proportional navigation is relatively simple, and has been used to guide homing missiles since the 1950s. The missile's seeker locks on to the target and establishes a line of sight at all times. The Stinger's tracker computes, in Cartesian coordinates, a primary and a secondary vector related to the center point, and uses simple trigonometry to find the deviation and plot a course to intercept.³⁶ The tracker then gives signals to the guidance circuits, which manage the control surfaces. Control is effected by adjusting the position of the two moveable canards at the front of the airframe. For the Stinger, this guidance process is what is known as "open loop." Once the guidance system has adjusted the canards, there is no attempt to verify their positions and feed this information back into the system. Rather, the process begins again based on seeker data from the next IR frame.

Though the computation necessary to track a target in this manner is straightforward, the instrumentation necessary to make it possible is complex. To start with, the missile's seeker has to be capable of pointing at the target throughout the flight, even if the airframe of the missile is on a different axis. This task is further complicated by the fact that the Stinger is a rolling airframe missile; roll is deliberately induced to help with flight stability.³⁷ Though this concept had already been introduced with the Redeye, its importance is not to be underrated; it is a fundamental feature of the Stinger's design.

The direction of the Stinger's flight is determined by the phase of the wing movements with respect to the missile roll position.³⁸ To guide the missile effectively, the guidance system needs to know where in its roll the missile is. The guidance system may want to steer the missile 'up,' but, given the rapid roll, the way that it must angle the canards to accomplish this changes many times a second. The principle rolling airframe-related improvement over Redeye introduced with Stinger Basic was a better servomechanism to drive these canards.³⁹ The servomechanism was developed by General Dynamics.⁴⁰

While the missile rolls, the seeker platform is maintained in a fixed relation to the ground by spinning mass gyroscopes on gimbals. These are coupled electrically to the rest of the missile body through a set of induction coils. The electrical induction signals from these

CTE 7

³⁵ Robert Little, interview with authors, Huntsville, AL, 14 September 2005.

³⁶ R.G. Lee et al, *Guided Weapons* (New York: Brassey's Defence Publishers, 1988), 97-98.

³⁷ The thrust of launch imparts a stabilizing 10-20 Hz roll to the airframe. The rolling airframe has the advantage needing fewer moveable control surfaces. The idea of a stabilizing roll came from industry, where General Dynamics obtained a patent. David Curry, interview with authors, Huntsville, AL, 14 September 2005.

³⁸ Raytheon Stinger/MANPADS Briefing.

³⁹ Hardesty, telephone interview with authors, 7 March 2006.

⁴⁰ Hardesty, email to authors, 26 April 2006.

CTE 8

coils depend on the geometric overlap. The signals are then used to calculate the instructions to the mechanical motors controlling the orientation of the missile's components. For earlier versions of the Stinger, the coil signals were also used to determine the rate of roll, a necessary piece of information to control the position of the canards to steer the missile. The latest version of the Stinger—Block I—has a roll frequency sensor that uses laser ring gyros to measure the roll rate. The missile's orientation to true vertical is set before firing and is then used to compute the relative position of the missile body at every instant in time. This information is used to synchronize control instructions from the guidance unit. The roll frequency sensor was developed in a collaborative effort between the PM, Raytheon, and Honeywell. The effort began around 1990 and cost a total of about \$8 million.⁴¹

CTE 9

One further guidance wrinkle is introduced at the final stage of the missile's flight. The missile makes an adjustment in the last moments before it impacts the target, turning from the focus on the high-temperature plume of the target aircraft to the airframe itself. This is done using a Target Adaptive Guidance (TAG) circuit. The TAG introduces bias to the signal sent from the seeker to the guidance system, causing it to steer the missile towards the vulnerable part of the aircraft a few feet forward of the exhaust plume.⁴² This concept was perfected for the Stinger by a collaborative effort between the contractor and MRDEC.⁴³

Propulsion and Warhead

Once the Stinger's operator has located a target, identified it as a threat, and established lock with the missile, he pulls a trigger on the grip stock. The trigger activates the missile's battery. Within one half second, the launch motor is ignited. To protect the gunner from the rocket blast, the launch motor finishes its burn before the missile completely clears the end of the tube. Once the missile clears the tube, the two moveable canards and the tail fins open out and the launch motor is jettisoned. After the missile coasts to a predetermined safe distance from the gunner, the fuze timer ignites the 2-stage boost/sustainer solid propellant flight motor and the missile is propelled at speeds of over Mach 2 toward the target. Once the missile passes Mach 1, two fixed wings deploy to stabilize the airframe.

The Stinger's propulsion system is called a launch-boost-sustain system. This type of three-phase propulsion is a key technology for shoulder-launched guided missiles, enabling the flight performance characteristics needed for adequate guidance to hit moving targets. The Stinger's propulsion system was based in part on Redeye's, which had a similar launch motor.⁴⁴ Stinger propulsion performance was enhanced over Redeye by advances in propellant technology. These were achieved principally through improvements to the propellant binder, one of the three basic ingredients in composite

⁴¹ Hardesty telephone interview.

⁴² Hardesty Tucson interview.

⁴³ Thomas, email to authors, 31 January 2006.

⁴⁴ Little interview.

CTE 10

solid propellants (the other two being ammonium perchlorate and aluminum in particulate form). When Atlantic Research Corporation (ARC) tailored the specific propellant formulations (one each for the boost and sustain phases) for Stinger, it drew on work done by the Propulsion Directorate of at Redstone Arsenal in the 1960s and early 1970s.⁴⁵ Researchers there developed a binder polymer system based on liquid hydroxyl-terminated polybutadiene (HTPB). After the propellant is mixed and cast in slurry form, the HTPB is converted by chemical reaction with diisocyanates to an elastomeric form that imparts the structural properties required by the missile design. The HTPB binder, which is used in several missiles besides Stinger, enables a wider range of burn characteristics and structural capabilities than earlier binders for composite propellants. These enhanced capabilities allow the design, development and production of a missile with the speed, maneuverability and environmental survivability of Stinger.

CTE 11

The capabilities of HTPB propellant allowed ARC to design a flight motor for Stinger in which both the boost and sustain propellant grains are bonded to the motor case. This design superseded one in which the sustain grain was cartridge loaded. Case-bonding, by eliminating much of the case insulation associated with cartridge loading, allows a greater volume of propellant to be loaded into the motor, which increases its total propulsive energy.⁴⁶ The case-bonded grain is also lower-cost and more reliable than the cartridge-loaded grain.

The seeker, guidance, and propulsion systems exist for one purpose: to deliver the Stinger's 0.8 lb High Explosive (HE) warhead to the target. The warhead is armed by the acceleration of the missile from the launch tube, with the proper acceleration rate achieved after about one second of flight. (If the missile does not strike the target after about 17 seconds it will detonate automatically.) The force of impact of the missile traveling at supersonic speed can be enough on its own to destroy the target,⁴⁷ but the HE charge amplifies the effect many-fold. Engineers at Picatinny Arsenal have perfected a smooth fragmentation titanium casing, a material with an optimal strength-to-weight ratio.⁴⁸ Current Stinger warhead efforts focus on developing fragmentation casings for improved lethality against a wider range of targets, including ground vehicles.⁴⁹

Modeling and Simulation

CTE 12

The Stinger program was the first missile development program to utilize computer-based simulation from design through production.⁵⁰ For Stinger, full-up simulations were developed by a community consisting of MRDEC, the prime contractor, the Army Materiel Systems Analysis Activity (AMSAA), the user community, and the PM office. They simulated the results of live-fire shots—flight and overall performance—and performed sensitivity experiments on the seeker on the computer. The models were tied

⁴⁵ Henry Allen, telephone interview with authors, 27 January 2006.

⁴⁶ John Schaeffel, interview with authors, Huntsville, AL, 14 September 2005.

⁴⁷ Kim Christianson, interview with authors, Tucson, AZ, 13 December 2005.

⁴⁸ Christianson, email to authors, 3 April 2006, and "Raytheon Electronic Systems FIM-92 Stinger Low-Altitude Surface-to-Air Missile System Family," Jane's Land Based Air Defence.

⁴⁹ Christianson interview.

⁵⁰ Curry interview. Some analogue simulation was done on the design of the Redeye.

to the development of a set of specified production parameters. Sufficient real experiments were performed to validate the models. Use of the computer models saved an estimated \$100M for the Stinger program.⁵¹ As an illustration, the Hawk missile, developed with no simulation, required about 120 launch tests before approval; the Stinger required only about 20.

CTE 13

Between the prime contractor and MRDEC, two hardware-in-the-loop simulators were used in the Stinger's development.⁵² Basic Stinger was the first Army missile system to use a validated hardware-in-the-loop (HWIL) simulation to perform many of the system evaluation tasks previously done by extensive (and expensive) hardware testing.⁵³ In these simulations, the performance of the seeker/guidance and control systems are evaluated against real time simulated target and environment scenes while they are integrated with the missile. The seeker and associated electronics send control signals to keep the seeker on target and the missile body aligned with the seeker. Missile control is simulated by creating aerodynamic conditions on the moveable fins such the response of the fins is measured and the corrected course is charted. that they can measure the response and chart the corrected course. They simulate the movements of the missile on a six-degree-of-freedom test station. During pre-engineering development, the HWIL simulation was used to help design the system and its production test equipment and to perform trade-off studies on missile sub-components. During engineering development, the simulation was used to determine the tolerance limits for production test parameters, conduct pre-flight and post-flight analyses, and analyze test flight failures. At the completion of development, the HWIL simulation was used to conduct a system Performance Assessment (PA), consisting of several thousand simulated missile flights, as part of the contractual obligations of the prime contractor.

⁵¹ Ibid.

⁵² Thomas interview.

⁵³ Thomas, email to authors, 4 April 2006.

IV. The Javelin

The Javelin is a shoulder-launched, man-portable, antiarmor missile. The Javelin system is composed of a missile round and a separate, reusable Command Launch Unit (CLU). The missile round consists of a launch tube, a BCU, and a missile. The CLU includes a day/night sight for surveillance, target identification, and acquisition. The missile has a range of about 2,000 meters and can be used against buildings and bunkers as well as armored vehicles.

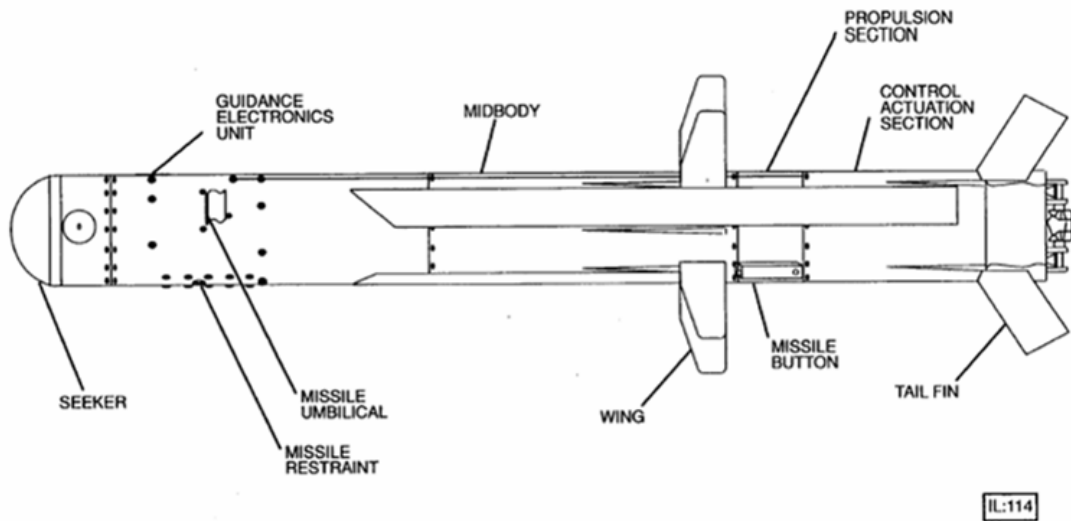


Figure 3. The Javelin missile.⁵⁴



Figure 4. The Javelin gunner looks through the CLU.⁵⁵

⁵⁴ Technical Data Document for the Javelin Anti-Tank Weapons System, Document Number DT-0023 Revision K, 15 November 2000, p.4.

Background

Man-portable antitank weapons were an important capability for U.S. infantry to have as they faced Soviet armored forces in Central Europe. The weapon that served this role for much of the Cold War was the Dragon missile.⁵⁶ This wire-guided antitank weapon was developed in the 1960s and early 1970s and first deployed in 1975. It was in the force through the 1990–91 Gulf War.

Dragon had significant shortcomings. Its limited range (around 1,000 meters in its original design) meant that the gunner had to get uncomfortably close to the target to fire, and the wire guidance system meant that the gunner had to stay exposed and keep his sight reticle on the target throughout the missile's flight (as long as 11 seconds).⁵⁷ It was also inaccurate. The Infantry School at Fort Benning was an adamant supporter of a new system. In 1979, the Army embarked on its first attempt to replace Dragon, called Rattler, but canceled the effort after just a few months because the prototype was rejected as too heavy.

In 1981 the Defense Advanced Research Projects Agency (DARPA) undertook a research program to develop an antitank missile that would make use of an imaging IR guidance system and employ a top-attack strategy, that is, the round had to be able to strike the top of a tank, where its armor is thinnest. This program was known as "Tankbreaker." The technology for Tankbreaker showed promise, and as a result the U.S. Army's PM office at Redstone Arsenal was assigned to manage the effort.

CTE 14

The DARPA Tankbreaker program had a demanding set of requirements. Among them, the missile had to be a fire-and-forget weapon, it had to have a range of 2,000 meters, it had to weigh less than 35 lbs, and it had to have top-attack capability. After a design competition, proposals from Hughes Aircraft and Texas Instruments (TI) were selected for further development. Both proposals were based on imaging IR seekers. As the name indicates, this sort of seeker resolves IR signals into an image, in contrast to the simpler seeker in the Stinger, which discerns only hot spots. The Tankbreaker program consisted primarily of development work on these IR seekers, culminating in a series of captive flight tests; the funding was not sufficient to conduct "system level" missile work.⁵⁸

Throughout 1985–86, the Infantry School at Fort Benning continued to articulate their need to replace the Dragon system and began writing a Required Operational Capability

⁵⁵ "Army Fact File: Javelin," *U.S. Army*, available online at <http://www.army.mil/fact_files_site/javelin/index.html>, accessed 15 March 2006.

⁵⁶ The light man portable system was the Light Antitank Weapon (LAW).

⁵⁷ William Bishop, interview with authors, Huntsville, AL, 14 September 2005, and "M-47 Dragon Anti-Tank Guided Missile," available online at <<http://www.globalsecurity.org/military/systems/munitions/m47-dragon.htm>>, accessed 15 March 2006.

⁵⁸ Bishop, email to authors, 24 March 2006.

(ROC) document. This ROC was eventually combined with a US Marine Corps requirement for a replacement for Dragon to create a Joint ROC (JROC).

In 1986, the Army issued a request for proposals addressing a two-year, Proof of Principle (POP) phase for an Advanced Antitank Weapons System—Medium (AAWS–M), thus launching a second acquisition effort to replace Dragon. Development contracts worth \$30 million each were given to Texas Instruments (imaging infrared technology) and Hughes (fiber optic guidance technology) and Ford Aerospace (laser beam-rider technology). Approximately 18 months into the POP phase, the Army/USMC issued an RFP for the Full Scale Development phase. A Source Selection Board eventually chose a Joint Venture (JV) composed of TI (whose missile business was later purchased by Raytheon) and Martin Marietta (now Lockheed Martin). The JV won the AAWS–M competition using a proposed missile design very similar to what TI had developed for Tankbreaker: an imaging IR seeker-based system that could attack a target either from the top or directly and was fire-and-forget. This missile was later dubbed the Javelin. The first Army unit was equipped with the Javelin in 1996.

CTE 15

The Army decision to use a JV approach for the Javelin was an important part of the program's success.⁵⁹ The government's intent in requiring a JV was to carry two major contractors through the development phase in some sort of a teaming arrangement chosen by the contractors. The government would then be in a position in the production phase to split the teammates and obtain competitive production proposals from each of them.⁶⁰ The government later decided, for a number of reasons, not to execute that opportunity and continued with the Javelin JV into the production phase.

This JV entity manages the Javelin program, but the technical work and much of the manufacturing is done by the two participating companies on the basis of a workshare agreement. Raytheon is now responsible for the command launch unit, missile guidance electronics unit, system software, and system engineering management. Lockheed Martin is responsible for final missile assembly and for producing the missile seeker (though, as noted below, TI had responsibility for developing the missile seeker).

To operate the Javelin, the gunner uses the IR system in the CLU, which projects a TV-like image for him to locate the target. He then switches to the IR system in the missile, which allows him to set track gates around the target, establish a lock, and fire. As with Stinger, the Javelin system uses a soft launch to eject the missile from the launch tube, which is essential for firing from enclosures (a requirement of the Javelin JROC). Once the missile has cleared the launch tube, the main rocket motor ignites and 6 small wings and 4 tail fins flip out as the missile is propelled toward the target at high speed, flying at altitudes of up to about 150 feet for direct attack and about 500 feet for the top attack mode. The missile's warhead, a shaped charge, attacks the target with a jet of solid metal particles.

⁵⁹ John Holly, telephone interview with authors, 29 September 2005.

⁶⁰ Bishop email.

The Javelin has proven successful on the battlefield. Over 1,000 missiles were fired in the 2003 Iraq war, and the CLU, used independently of the missile round, continues to be popular with U.S. troops as a night vision device.⁶¹

The following discussion of the Javelin will address the CTEs associated with the system's key components. We will first examine the development of the CLU, then the seeker, the guidance and control system, and the propulsion system and warhead. The section concludes with a discussion of the use of modeling and simulation in the development of the missile.

Command Launch Unit

The firing process starts with the CLU. Unlike the comparatively simple grip stock to which the Stinger round is mated, the Javelin's CLU is a complex component of the system. The CLU has a 4x telescope and a long wave IR night sight with two fields of view: 4x magnification and 9x magnification. Both visible and IR images are viewed through a monocular sight. The CLU operates from a standard Army battery, which provides power to operate the CLU electronics and the cooler that keeps the detector array at operating temperatures.

CTE 16

The imaging IR is the most vital part of the CLU. Unlike earlier systems that identify a heat source as a simple spot, an imaging IR system produces a detailed picture of the target. The CLU's scanning IR array is where the target recognition capability resides. It is a higher-resolution system than the missile seeker because the gunner needs a high resolution image to identify a target as friend or foe. The missile seeker's IR detector (discussed below) just has to detect the target after the gunner has recognized it and set his track box around it.

CTE 17

The CLU developed by TI outperformed alternative designs in competition, seeing at longer ranges and demonstrating superior performance through smoke and other hindrances.⁶² It had a 240x1—later 240x2 and 240x4—focal plane array (FPA) of mercury cadmium telluride (MCT) detectors, operating in the long-wave IR region of 8–12 microns. The detectors were scanned at 30Hz in a bi-directional, interleaved fashion. Moving from right to left the odd pixels (1, 3, 5, etc.) are sampled, then moving from left to right the even pixels are sampled. A resolver allowed the CLU's circuitry to know the angular position of the scanning mirror so that it can align the forward scan and the reverse scan to yield a coherent picture. The bi-directional scan developed for the Javelin was unique and allowed a significant power savings. This scanner motor approach was later transitioned to several other TI programs.⁶³

The CLU's IR capability also benefited from a new method to normalize the detector chips. Earlier IR systems used a black body kept at a stable temperature to keep the chips

⁶¹ John Dillon, interview with authors, Huntsville, AL, 15 September 2005.

⁶² William Deckert, interview with authors, Tucson, AZ, 14 December 2005.

⁶³ Deckert, email to authors, 12 February 2006.

CTE 18

calibrated. TI developed a Thermal Reference Assembly (TRA),⁶⁴ a passive optical assembly that provides two temperature points against which each detector pixel is calibrated. The first point is a single off-axis reference scene, and the second point comes from a “reflection” generated by a cold element. Every time the array scans, the pixels are recalibrated in this manner based on their reading of the two temperature points. Importantly, the TRA was passive, requiring no additional power or control circuitry. That allowed the system designers to calibrate using existing imaging circuitry as well reduce power and save space.⁶⁵

CTE 19

As with Stinger, the Javelin CLU’s IR detectors require cooling to a very low temperature to increase the signal-to-noise ratio. The CLU makes use of a Dewar flask, a container that uses vacuum between double walls to provide thermal insulation. Cooling is provided by a closed-cycle Stirling engine with a cold finger projecting into the Dewar and up against the back of the detector. The cooler, developed by TI, was designed to reduce power—it consumes only 1/5 watt—and meet weight requirements and yet deliver the cooling capacity required to cool the FPA in a two-and-a-half-minute period.⁶⁶ The cooler was difficult to manufacture at first but, with DARPA and internal TI IRAD support, the process was improved to obtain acceptable costs.⁶⁷

TI’s development of the CLU’s IR system drew in part on work done by the Army’s Night Vision Laboratory (NVL). NVL provided critical expertise in IR system modeling, particularly involving Minimum Resolvable Temperature (MRT) measurements and focal plane array engineering expertise, throughout the AAWS–M acquisition process.⁶⁸ A joint Army/USMC countermeasures requirements determination team was assembled and led by ARL; NVL, the users, and MICOM were key participants. The team developed the countermeasures requirements for the JROC and for the system performance specification. NVL’s models and simulations are still a standard for measuring the performance of IR FPAs. NVL also helped incorporate a measurement technique called 3D Noise that further refined thermal modeling fidelity to better account for dynamic noise within the sensors under test. Further IR modeling refinements by MRDEC and NVL led to the development of newer, more user friendly, and higher fidelity models that approximated the system’s IR performance and converted it to detection, recognition, and identification ranges.⁶⁹

CTE 20

Since the original design of the CLU’s IR imager, progress has been made on improving the system’s performance. A DARPA-funded program in the early 1990s helped to make detectors more producible.⁷⁰ The result was the so-called Dash 6 detector, which was quieter to cool and scan, thus reducing the audible noise-signature of the Javelin operator in the field. The Dash 6 detector was added to production CLUs in 1998–1999. TI also moved from four separate “through hole” circuit boards to two surface mounted boards.

⁶⁴ Deckert interview.

⁶⁵ Deckert email.

⁶⁶ Ibid. and Dillon, email to authors, 24 February 2006.

⁶⁷ Deckert email and Bishop email.

⁶⁸ Bishop email.

⁶⁹ Deckert email.

⁷⁰ Deckert interview.

The original CLU (the one that was qualified and built during the LRIP phase of the program) was developed using “through hole” circuit board technology, but this initial unit exceeded all weight budgets.⁷¹ These circuit cards used surface mounted components. In a cost-reduction program, advantage was taken of advances in semiconductor device integration, particularly in the density of gates that could be put in digital application specific integrated circuits to reduce the circuitry to two double-sided card assemblies.

CTE 21

Saving weight was a persistent concern, one that influenced all aspects of the Javelin system’s development, from beyond the CLU’s IR imager to the rest of the unit to the missile round itself. The CLU’s housing was originally made of aluminum. The designers dipped the housing in acid in an effort to etch away as much wall thickness as possible. This did take weight off, but it was expensive and led to a less robust unit.⁷² In 1999, the aluminum was replaced with a 17-layer carbon resin fiber composite. This saved some weight but mostly made the housing stronger. Also, production results were more consistent than with the acid etching. The current Javelin CLU now achieves greater than 300 hours mean time between hardware mission failures, well over the 150 originally required of the system.⁷³

Plans for a new generation of the Javelin, Block I, include an improved CLU. The CLU will feature 4x and 12x magnification instead of 4x and 9x. The CLU will also incorporate a color organic light emitting diode-based flat panel display. The goal is to increase the imager’s range by 50 percent, but weight considerations impose a serious constraint on how much the optics can be upgraded.

Seeker

CTE 22

As with the Stinger, the Javelin is a fire-and-forget missile. After launch, it has to be able to track and destroy its target without any further input from the gunner or other external source. This fire-and-forget capability came from the Joint Army/USMC Source Selection Board’s decision to select the JV AAWS–M design, which coupled an imaging IR system with a state-of-the-art onboard tracking system.

As described above, the gunner uses the CLU’s IR system to find and identify the target. He then switches to the missile’s independent IR system to set a track box around the target and establish a lock. The gunner places track gates around the image of the target, closing them until as much of the target fills up the space between the gates as possible. The seeker’s job, in effect, is to stay focused on the target’s image, continuing to recognize it even as the target moves and as the missile’s flight path alters the seeker’s point of view at over 150 meters/second, as attack angles change, and as the target’s apparent size changes as the missile approaches the target.⁷⁴ All of the seeker’s many parts must function in order for the system to work, but the importance of three

⁷¹ Deckert email.

⁷² Dillon email.

⁷³ Deckert interview and Deckert email.

⁷⁴ Dillon email.

components stands out: the focal plane array, the cooling and calibration system, and the stabilization system.

CTE 23

The seeker assembly is encased in a hemispherical dome made of zinc sulfide, which is transparent to the long-wave infrared radiation of interest to the FPA. The IR radiation passes through the dome and then through transparent lenses, made of germanium and zinc sulfide, that focus the energy. The IR energy is reflected specularly by mirrors of polished aluminum on to the FPA.⁷⁵ The missile seeker for the Javelin is a two-dimensional (2D) staring FPA of 64x64 detector elements. The detectors are made of an alloy of cadmium-tellurium and mercury-tellurium (termed mercury cadmium telluride or HgCdTe). Note the contrast with the CLU's IR system,⁷⁶ which is a scanning linear array. The FPA processes the signals from the detectors and relays a signal to the missile's tracker.

Development of the 2D staring array turned out to be very difficult. TI's design for both the CLU's scanning array and the missile's staring array used a photo-capacitive device wherein incident photons stimulate electrons, which are initially stored in the detector as an accumulated charge.⁷⁷ The electrons are discharged, pixel by pixel, as currents to a read-out integrated circuit (IC) attached at the rear of the detector. Whereas this approach worked for the array in the CLU, it proved very hard to build working 2D staring arrays for the missile seeker this way. TI could not get the quality of HgCdTe necessary for the photo-capacitive process to work and there was not enough electron storage capacity on the seeker pixels in the 2D array.⁷⁸ TI had been able to build enough 2D arrays to assemble the missiles to win the AAWS-M competition but was unable to use its process to meet manufacturing quality standards and yields. Only .5% to 2% of the FPAs it was producing met the full performance criteria.⁷⁹ The manufacturing problem risked doubling the development cost of the program and causing its cancellation.⁸⁰

CTE 24

The pressing nature of this problem became clear in 1991-92. The Office of the Secretary of Defense (OSD), the Department of the Army (DA), and MICOM assembled teams to try to resolve the issue. Drawing on in-house technical expertise, the teams concluded that TI was simply not going to be able to manufacture its design in sufficient quantity for it to be viable. Though the Army had recognized that the success of the program hinged on the seeker technology and had established a second source for FPAs with LORAL Corp. as part of the original acquisition strategy, LORAL also had difficulty producing arrays.⁸¹ Fortunately, a solution was at hand: Hughes' Santa Barbara Research Center (SBRC), working under a DARPA contract, had developed another design for a focal plane array that could be manufactured more efficiently. The Hughes design utilized a

⁷⁵ The materials for the dome, lenses, and mirrors were selected by Texas Instruments and reflected standard technology at the time of development. Jerome Schaefer, email to authors, 21 March 2006.

⁷⁶ The CLU's system also has higher resolution suitable for identification of the target. This is primarily a function of the higher sampling rate generated by a scanning array.

⁷⁷ Fenner Milton, interview with authors, Fort Belvoir, VA, 28 September 2005.

⁷⁸ Bishop email.

⁷⁹ Bishop interview.

⁸⁰ Ibid.

⁸¹ Bishop email.

photovoltaic mechanism in which a voltage signal was developed directly from the impact of the photons and charge storage was done in the readout IC rather than in the detector material.⁸² The AAWS–M Program dropped TI as the prime producer of seeker FPAs, dropped the still-struggling LORAL as a second source, and decided to go with SBRC as the seeker FPA vendor. As the program evolved, SBRC met FPA performance, delivery quantity, and production yield expectations.⁸³ TI continued to manufacture the CLU’s scanning array.

In order for the seeker to function optimally, the FPA must be cooled and calibrated. The CLU’s IR detectors are cooled using a Dewar flask and a closed-cycle Stirling engine. There is not sufficient space in the missile for this approach. Prior to launch, a BCU mounted on the outside of the launch tube activates the electrical systems in the missile and supplies cold gas from a Joule-Thompson (J–T) expander to the missile detector assembly while the missile is still in the launch tube. When the missile is fired, this external connection is broken and coolant gas is supplied internally by an onboard argon gas bottle.⁸⁴ The gas is held in a small bottle at around 6000 psi; there is enough coolant for the duration of the flight—approximately 19 seconds. The external BCU must be replaced if seeker is activated and missile is not fired within the four-minute operational specification of the BCU.

This cooling assembly also envelops the IC. Initially the IC was outside the cold section and therefore, for large arrays, many wires had to be routed out of the cold section. The manufacturer had learned how to place the microprocessor in the cold section in electrical contact with the back of the detector. Only from the microprocessor must wires run to the outside of the cooler; the number of wires is thus greatly reduced, from 200 to about 25.⁸⁵

CTE 25

The Javelin’s seeker is calibrated using a “chopper” wheel. This device, which is essentially a fan, has 6 blades: 5 black blades with very low IR emissivity, and one semi-reflective blade. These blades spin in front of the seeker’s optics in a synchronized fashion, such that the FPA is continually provided with points of reference in addition to viewing the scene. These reference points allow the FPA to reduce fixed pattern noise—noise introduced by response variations in the detector elements.

In addition to being continuously cooled and calibrated, the platform on which the seeker rests must be stabilized with respect to the motion of the missile body and the seeker must be moved to stay aligned with the target. Though, unlike the Stinger, the Javelin’s airframe does not roll, the stabilization system still must cope with rapid acceleration, up/down and lateral movements, and other exigencies demanded by a flight path that may include swift altitude gain and a steep dive. This is done by a two-axis gimbal system, accelerometers, spinning mass gyros, and motors to drive changes in position of the

⁸² Schaefer email.

⁸³ Bishop email.

⁸⁴ Javelin Technical Data Document, 137-160.

⁸⁵ Dillon Huntsville interview.

platform.⁸⁶ Information from the gyros is fed to the guidance electronics, which drive a torque motor attached to the seeker platform to keep the seeker aligned with the target. Those wires that connect the seeker section with the rest of the missile were specially developed to cause no friction, so that the seeker platform could remain precisely balanced.⁸⁷ The Javelin's seeker deviates only 10–20 microradians per G, an excellent rate of isolation.⁸⁸

Guidance and Control

CTE 26

The Javelin's tracker is the essential element of the missile's guidance and control capability. The signals from each of the seeker's over 4,000 detector elements are passed to the FPA's readout IC, which reads them and creates a single channel video output that it sends to the tracker system for further processing.⁸⁹ By comparing the individual frames, the tracker determines the needed corrections to keep the missile on target. To do this, this tracker must be able to determine which portion of the image represents the target. The target is initially identified by the gunner, who places the track gates around it. After that, the tracker uses algorithms to compare that region of the frame, based on image, geometric, and movement data, to the new image frames being sent from the seeker. At the end of each frame, the reference is updated. The tracker is able to keep track of the target even though the seeker's point of view can change radically in the course of flight.

To guide the missile, the tracker locates the target in the current frame and compares this position with the aim point. If this position is off center the tracker computes a correction and passes it to the guidance system, which makes the appropriate adjustments to the control surfaces (the Javelin has four moveable tail fins, as well as six fixed wings at mid-body).⁹⁰ This portion of the system is termed the autopilot. It uses closed loop control to guide the missile; that is, the system has sensors that check that the control surfaces are positioned as requested. If not, the deviation is sent back to the controller for further adjustment.

There are three stages in the flight managed by the guidance unit: an initial phase just after launch, a mid-flight phase that lasts for most of the flight, and a terminal phase in which the tracker selects the "sweet spot" for the point of impact.⁹¹ With guidance algorithms, the autopilot uses data from the seeker and tracker to determine when to transition the missile from one phase of flight to another. Depending on whether the missile is in top attack (the default mode) or direct attack mode, the profile of the flight can change significantly. The top attack mode requires the missile to climb sharply after launch, cruise at an altitude of roughly 500 feet, and then dive on the top of the target. In

⁸⁶ Dan Rice, interview with authors, Tucson, AZ, 13 December 2005 and Javelin Technical Data Document, 153-154.

⁸⁷ Rice interview.

⁸⁸ Rice interview.

⁸⁹ Javelin Technical Data Document, 151.

⁹⁰ The Javelin also makes use of thrust vector control early in its flight: the motor that drives the four tail fins also drives four thrust vector control vanes that sit in the exhaust nozzle.

⁹¹ Sam Wood, telephone interview with authors, 20 October 2005.

direct attack mode, the missile cruises at about 150 feet. The exact flight path, which takes into account the range to the target, is calculated by the guidance unit.

CTE 27

Development of the Javelin's tracker was done by both industry and Redstone Arsenal. Texas Instruments designed and built prototypes, and Redstone provided both upgrades and an independent assessment of the tracker's capabilities.⁹² Extensive Captive Flight Testing (CFT) of the AAWS-M seekers and trackers enabled the tracker teams to test, refine, and update algorithms prior to missile firings. These CFT programs also provided invaluable data for the Integrated Flight Simulation developers (discussed below). The tracker development program is still active.

Propulsion and Warhead

As with Stinger, the Javelin system uses a soft launch to eject the missile from the launch tube. That is, a launch motor fires within the launch tube, but ceases to burn before the missile clears the tube so that the gunner is not harmed by hot gases. The soft launch permits a low-recoil shoulder launch and enables firing from inside buildings or covered platforms. When the missile has cleared the launch tube and traveled a safe distance, the main rocket motor ignites and the wings and fins flip out. The missile is propelled toward the target at subsonic speeds. The Javelin's unique propulsion unit design required advances in the state of the art due to the requirements for soft launch, gunner safety, and weight. Significant technology advances were made by propulsion engineers from the Javelin PM office, the Joint Venture, and MRDEC, which operated as a team.⁹³ Coupled with industry advances, the Javelin program was able to develop a propulsion system that met the challenging requirements.

CTE 28

The Javelin's motor was developed by the Atlantic Research Company (ARC), now Aerojet.⁹⁴ ARC had adapted the design from one developed by Alliant Technology.⁹⁵ Like the Stinger, the Javelin has an integrated launch and flight rocket motor. Among other advantages, this integrated design kept system weight as low as possible.

The motor operates as follows.⁹⁶ The launch motor initiator ignites the launch motor igniter, which in turn ignites the launch motor propellant grain. The launch motor propellant grain burns on the inside and the outside, as well as on the ends.⁹⁷ Gases vent through the launch motor nozzle. After a delay, a signal is sent to the flight motor initiator, which ignites the flight motor igniter, which in turn ignites the flight motor propellant. When enough gas pressure builds up in the flight motor chamber, a burst disk

⁹² Dillon email.

⁹³ Bishop email.

⁹⁴ The ARC motor design was not in the missile with which TI won the AAWS-M competition. The ARC design was in Hughes's missile and was later picked up by TI. Susan Burroughs, telephone interview with authors, 24 January 2006.

⁹⁵ Ibid.

⁹⁶ Burroughs, email to authors, 24 February 2006.

⁹⁷ Ibid.

that separates the launch motor and the flight motor ruptures, and flight motor gases flow down the launch motor chamber and out the launch motor nozzle.

CTE 29

Gunner safety was a key consideration. The Javelin is equipped with a pressure release system to ensure that a malfunctioning launch motor does not cause an explosion. The launch motor has shear pins, developed jointly by government and industry, that fracture in the event of launch motor overpressure and allow the motor to be pushed out the back of the launch tube.⁹⁸

ARC also developed an annular igniter for the launch motor. This circular ring design was key to integrating the launch motor and the flight motor.⁹⁹ The launch motor igniter had to be placed in the nozzle, but it could not be blown out the nozzle because the debris would be an unacceptable hazard to the gunner. The annular igniter allowed exhaust gases to be vented past it. The ring design also provides 360 degrees of hot gases onto the propellant grain, giving a more robust ignition of the grain.¹⁰⁰

CTE 30

Another important propulsion design element is the burst disc that separates the launch motor and the flight motor. This feature, developed by ARC, has a higher tolerance for pressure on the launch motor side, and lower tolerance on the flight motor side.¹⁰¹ This allows the disc to protect the flight motor from the ignition of the launch motor, yet, when sufficient pressure develops, still let the flight motor rupture the disc and send flight motor gases past it and down through the launch motor chamber.

The Javelin's propulsion system draws on propellant technology developed for earlier missiles. The launch motor propellant is the same as that used in other missiles. The flight motor propellant is derived from the propellant used in the Tube launched, Optically tracked, Wire guided (TOW) and Hellfire missiles, which was altered for Javelin in a combined government/industry effort.

As with the propulsion system, a teaming effort was crucial to developing a successful warhead for the Javelin. The PM office, the U.S. Naval Surface Warfare Center, and MRDEC, working with industry, were particularly successful in optimizing tandem warhead performance.¹⁰² The Javelin missile's tandem warhead is a high explosive antitank (HEAT) round. This round utilizes an explosive shaped charge to create a jet of superplastically deformed metal formed from trumpet-shaped metallic liners. The result is a high velocity jet (10 km/s at the tip and 2–5 km/s at the tail) that can dynamically penetrate through solid armor.

The basic concept of a shaped charge has existed since the 1880s, but U.S. Army laboratories did significant work to improve the technology and apply it to weapons systems. BRL contributed basic research, especially on modeling, while Picatinny

⁹⁸ Burroughs interview.

⁹⁹ Burroughs email.

¹⁰⁰ Ibid.

¹⁰¹ Burroughs interview.

¹⁰² Bishop email.

Arsenal played a design and performance demonstration role.¹⁰³ Picatinny's work was important to developing the trumpet shaped charge warhead, so-called because it was squatter than earlier charges and was shaped like the bell of a trumpet.¹⁰⁴ Physics International, working on contract from Redstone, used this concept to design a trumpet shaped charge for the Javelin's main warhead.¹⁰⁵

CTE 31

Advances in the lethality of shaped charge rounds were made to counter the advent of explosive reactive armor (ERA). ERA lays panels over a vehicle's main armor that explode when impacted by a warhead. This explosion does not harm the vehicle's main armor, but causes the steel panels to fly in the path of the HEAT round's jet so that the jet expends its most potent energy cutting through the panels rather than the main armor. To defeat this, the Javelin uses two shaped charge warheads in tandem. The precursor charge sets off the ERA and clears it from the path of the main charge; the main charge penetrates the target's primary armor. This concept, first applied in the TOW missile, was based on work done at BRL and Picatinny Arsenal.

CTE 32

The Javelin's designers initially struggled to make the tandem warhead work. Though Physics International's main charge, which used a copper liner to form the penetrating jet, performed well, its copper-lined precursor charge design had trouble clearing ERA. A competitor for the warhead contract, Conventional Munitions Systems Inc. (CMS), purchased a company called Orlando Technology Inc., that, using its own computer models, had developed a successful precursor design using a two-layered molybdenum liner.¹⁰⁶ The CMS design was ultimately used for the precursor, while Physics International's design was used for the main charge.

CTE 33

Another challenge for the Javelin's tandem warhead development was to protect the main charge as much as possible from the explosive blast, shock, and debris caused by the impact of the front of the missile and the detonation of the precursor charge. Fragments and explosive force could interfere with the formation of the main charge's jet. To limit interference, a blast shield was developed at Redstone Arsenal and placed between the main charge and the precursor charge. This was the first composite blast shield, and the first that had a hole through the middle of it; the hole provides a less disturbed jet.¹⁰⁷

The next block of improvements for the Javelin's warhead design include changes in the main charge liner to produce a higher velocity jet. These changes will make the warhead more effective as a penetrator and make it smaller, thus leaving more room to add propellant and increase the missile's range. Technical development work on this has been done at Picatinny Arsenal and at General Dynamics Ordnance and Tactical Systems, which took over part of Physics International.¹⁰⁸

¹⁰³ Ernie Baker, telephone interview with authors, 25 January 2006.

¹⁰⁴ Ibid.

¹⁰⁵ Ibid.

¹⁰⁶ Ibid.

¹⁰⁷ Ibid. and Baker, email to authors, 2 March 2006.

¹⁰⁸ Baker interview and Christianson email.

During the Javelin's development major improvements were made in the fusing and arming of the warhead. Prior to the Javelin, fusing was mostly mechanical, consisting of gears, rotors, pins, etc. With the multiple warheads, variable time delay requirements, and weight and volume constraints of the Javelin and other missiles, and with safety requirements becoming more stringent, mechanical fusing was inadequate. As a result, an electronic arming and fusing effort was initiated for missile systems. This concept, based on work done for nuclear warheads at Sandia and Los Alamos, came from engineers at Redstone Arsenal in the mid 1980s.¹⁰⁹ It was given the acronym ESAF,¹¹⁰ for Electronic Safe Arming and Fire. Early ESAF packages proved too large, but the application of micro-electronics made it applicable not only to the Javelin but to the fuze assemblies of other missile systems such as the Hellfire.

The ESAF system enables the firing and arming process while imposing a series of safety checks on the missile. ESAF cues the launch motor after the trigger is pulled. When the missile reaches a certain rate of acceleration (indicating to the system that it has cleared the launch tube and moved down range a safe distance from the gunner), in conjunction with other missile functions, the ESAF initiates a "second arming" to fire the flight motor. After another check on missile conditions (such as checking to make sure it still has target lock), ESAF initiates "final arming," which enables the warheads to be detonated at target impact. When the missile strikes the target, ESAF enables the tandem warhead function described above: it ensures that there is an appropriate time lapse between the detonation of the precursor charge and the detonation of the main charge.

Modeling and Simulation

Many of the technical achievements associated with the Javelin's development were enabled by modeling and simulation. A mechanical accelerator, for instance, was used to develop and test the seeker stabilization system.¹¹¹ Perhaps most importantly, though, the Javelin team developed an all-software simulation called the Integrated Flight Simulation (IFS). IFS, created by Texas Instruments before the establishment of the Javelin Joint Venture, models all the physics of missile performance "down to the number of photons involved."¹¹² The model does sensitivity analyses, simulates behavior of the focal plane arrays and the tracker, shows the voltages sent to the guidance unit, etc. While developed for the Javelin, the model is now also used on other missile systems. The Army at Redstone Arsenal validated, through actual flights, the performance of the IFS, relating the tests to the models through the probabilities of hit and kill. Collaboration was such that on flight tests from helicopters representatives from industry and MICOM would be aboard.¹¹³ The program is accredited by AMSAA. MRDEC has a version of the IFS with simulated infrared scenes developed there.

¹⁰⁹ Paul Turner, interview with authors, Huntsville, AL, 15 September 2005, and Christianson interview.

¹¹⁰ Such devices are also known as Electronic Safe and Arm Devices (ESADs).

¹¹¹ Rice interview.

¹¹² Ibid.

¹¹³ Dillon, telephone interview with authors, 10 January 2006.

Redstone Arsenal has a comprehensive modeling and simulation capability at both MRDEC and the Redstone Technical Test Center. Captive flight testing was discussed earlier. Redstone also has extensive HWIL capability. The facilities are used for verification and performance testing, for evaluating component performance, and reliability testing. Among other things, they were crucial to developing the Javelin's autopilot.¹¹⁴

¹¹⁴ Rice interview.

V. Findings and Conclusions

1. We identified 35 CTEs for the two missile systems—13 for the Stinger and 22 for the Javelin. They are grouped as follows:

| | <u>Stinger</u> | <u>Javelin</u> |
|-------------------------|----------------|----------------|
| Background | 0 | 2 |
| Seeker | 6 | 4 |
| Command Launch Unit | N/A | 6 |
| Guidance and Control | 3 | 2 |
| Warhead and Propulsion | 2 | 7 |
| Modeling and Simulation | 2 | 1 |

2. Both missile systems’ developments relied heavily on the strong missile technology base that existed in industry. This was particularly true in seeker design and guidance and control systems. The Army took advantage of this capability when it formed the Javelin Joint Venture, a successful acquisition strategy that today involves Raytheon and Lockheed Martin.

3. The Army laboratories played several key roles. MRDEC had accumulated a great deal of experience in missile technologies and it was involved throughout these programs, working closely with the contractors, proposing new approaches to problems, and evaluating and critiquing concepts from industry. MRDEC provided technical support to the PM office both by doing sponsored work and by transferring staff either by permanent reassignment or by rotations. Other laboratories also made important contributions, including Picatinny Arsenal and the Night Vision Laboratory.

4. Modeling and simulation (M&S) played an important role. Because a large number of experiments can be run using M&S, the number of actual experiments is greatly reduced and fewer dead ends are explored. M&S thus leads to significant cost savings. In the Stinger’s development, MRDEC, the contractor, AAMSA, the user, and the PM office all were involved in M&S. MRDEC made significant contributions to M&S, including developing hardware-in-the-loop and man-in-the-loop simulations. M&S technology had advanced further by the time of the Javelin’s development. Both the contractor and MRDEC had simulations, including hardware-in-the-loop, that encompassed all of the physics and useful sensitivity analyses, and which could be used to evaluate new concepts.

5. Both missile systems were developed with significant user input. The user drove the need for fire-and-forget, man-portable, shoulder-fired weaponry. The Infantry School at Fort Benning was especially instrumental in driving the Javelin’s development. The strict weight restrictions imposed by the user’s needs affected every aspect of both missiles, and safety considerations were also an important design element.

6. DARPA played a significant role in the development of the concepts for the Javelin. In particular, DARPA, in its project Tankbreaker, pushed hard for the use of imaging IR arrays, notably the two-dimensional array for the seeker. DARPA also funded an alternate source for FPAs that proved crucial to the Javelin program's success.

7. The Program Manager's office encouraged and assisted collaboration between MRDEC and the contractors. There was regular consultation between working engineers; the contractor would send a prototype of a component to the in-house laboratories and obtain their reaction and critique. This back-and-forth communication in real time often provided early detection of potential dead ends and thus saved time and money. It seems clear that success was achieved through the effective work of all three players—the contractors, the in-house experts, and the PM office.

Appendix A: Individuals Contacted

Individuals Contacted for the Stinger and the Javelin Project

Key

| | | | | | |
|------------------------|-----|-------------------------|-----|------------------|-----|
| Civil Service Employee | CSE | Academia | ACD | Active Military | AM |
| Government Retired | GR | Military Retired | MR | Industry Retired | IR |
| Consultant | CST | Private Sector Employee | PSE | Contractor | CTR |

* denotes that the individual reviewed some or all of the draft document for completeness and accuracy.

| Last Name | First Name | Javelin or Stinger Development-era Organization | Current Status |
|----------------|------------|---|----------------|
| * Allen | Henry | Missile Research, Development, and Engineering Center (CSE) | GR |
| Baker | Ernest | Picatinny Arsenal (CSE) | CSE |
| * Bishop | William | PM office (CSE) | CTR |
| Burroughs | Susan | Missile Research, Development, and Engineering Center (CSE) | CSE |
| * Christianson | Kim | Honeywell/Alliant/Raytheon (PSE) | PSE |
| Curry | David | Missile Research, Development, and Engineering Center (CSE) | CSE |
| * Deckert | William | Texas Instruments/Raytheon (PSE) | PSE |
| * Dillon | John | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Ducotte | Marjorie | Missile Research, Development, and Engineering Center (CSE) | GR |
| Fong | Richard | Picatinny Arsenal (CSE) | CSE |
| * Fowler | Bruce | MRDEC (CSE) | |
| * Hardesty | David | General Dynamics/Hughes/Raytheon (PSE) | PSE |
| Hayes | Frank | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Holly | John | PM office (AM) | MR, CST |
| Johnson | Greg | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Kelley | Michael | General Dynamics/Raytheon | PSE |

| | | | |
|------------|----------|--|-----|
| | | (PSE) | |
| Lannon | Joseph | Picatinny Arsenal (CSE) | CSE |
| Light | David | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Little | Robert | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Milton | Fenner | Headquarters, Department of the Army (CSE) | CSE |
| * Peterson | Don | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Phillips | Margaret | Missile Research, Development, and Engineering Center (CSE) | CSE |
| Reed | Jean | DARPA (AM) | CSE |
| * Rice | Dan | Texas Instruments/Raytheon (PSE) | PSE |
| * Schaefer | Jerome | Texas Instruments/Raytheon (PSE) | PSE |
| Schaeffel | John | Missile Research, Development, and Engineering Center (CSE) | CSE |
| * Thomas | Tony | Missile Research, Development, and Engineering Center (CSE) | CSE |
| * Turner | Paul | PM office (CSE) | CSE |
| Wood | Sam | Missile Research, Development, and Engineering Center (CSE) | CSE |

Appendix B: Critical Technology Event List

| Number | CTE | Report Section |
|--------|------------------------------------|---------------------------------|
| 1 | Conical scanning | Stinger Seeker |
| 2 | Rosette scan seeker | Stinger Seeker |
| 3 | IR/UV detector | Stinger Seeker |
| 4 | Seeker microprocessors | Stinger Seeker |
| 5 | Reprogrammable microprocessors | Stinger Seeker |
| 6 | Lithium battery | Stinger Seeker |
| 7 | Canard servomechanism | Stinger Guidance and Control |
| 8 | Roll frequency sensor | Stinger Guidance and Control |
| 9 | Target adaptive guidance | Stinger Guidance and Control |
| 10 | HTPB propellant binder | Stinger Propulsion and Warhead |
| 11 | Propellant case bonding | Stinger Propulsion and Warhead |
| 12 | Computer simulation | Stinger Modeling and Simulation |
| 13 | Hardware-in-the-loop simulators | Stinger Modeling and Simulation |
| 14 | Tankbreaker decision | Javelin Background |
| 15 | Javelin Joint Venture decision | Javelin Background |
| 16 | CLU long-wave imaging IR | Javelin CLU |
| 17 | CLU bi-directional scanner | Javelin CLU |
| 18 | Thermal reference assembly | Javelin CLU |
| 19 | CLU cooling system design | Javelin CLU |
| 20 | CLU system improvements | Javelin CLU |
| 21 | Composite housing | Javelin CLU |
| 22 | Army fire-and-forget requirement | Javelin Seeker |
| 23 | Seeker focal plane array | Javelin Seeker |
| 24 | Hughes FPA design | Javelin Seeker |
| 25 | Seeker calibration "chopper wheel" | Javelin Seeker |
| 26 | Javelin tracker | Javelin Guidance and Control |
| 27 | Captive flight testing | Javelin Guidance and Control |
| 28 | Integrated propulsion design | Javelin Propulsion and Warhead |
| 29 | Launch motor shear pins | Javelin Propulsion and Warhead |
| 30 | Burst disc | Javelin Propulsion and |

| | | |
|----|------------------------------|---------------------------------|
| | | Warhead |
| 31 | Tandem shaped charge warhead | Javelin Propulsion and Warhead |
| 32 | Precursor charge design | Javelin Propulsion and Warhead |
| 33 | Blast shield | Javelin Propulsion and Warhead |
| 34 | ESAF | Javelin Propulsion and Warhead |
| 35 | Integrated flight simulation | Javelin Modeling and Simulation |