Critical Technology Events in the Development of the Apache Helicopter

Project *Hindsight* Revisited

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I. Introduction

Understanding past military technological successes is crucial to defense science and technology investment and management. This study is the second in a series that examines some of the key factors that have led to meaningful technology generation and ultimate incorporation into the U.S. Army weapons systems we see in the field today. The first report covered the development of the Abrams tank.[1] Analysis of the development of the Javelin and Stinger missiles will follow. The results of all studies will be compiled in a wrap-up report that will include a look at the implications of the findings for today's science and technology environment.

We begin this paper by briefly reviewing a project that served as a source of inspiration for this study: Project *Hindsight*, a 1969 Defense Department (DOD) report.[2] *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 across the DOD spectrum. Following the review of *Hindsight*, we present a short history of the events that led to the start of the Apache program. This is followed by a description of the methodology that we used to gather key data on the development of the Apache. The information that we have gathered is then broken out by topic area (Power System; Survivability and Structural Advances; Avionics, Fire Control, and Weapons; and Modeling and Simulation and other Enabling Methodologies) and presented in terms of Critical Technology Events (CTEs). CTEs are ideas, concepts, models, and analyses, including key technical and managerial decisions, that 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, to product improvements. CTEs can even relate to concepts that were developed but that ultimately were 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 the concluding remarks and findings based on the CTEs that characterize the Apache helicopter's development.

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 and processes associated with CTEs often are not. CTEs depend on several important factors, including effective management, adequate funding, clear priorities, technical competence, and the leveraging of the resources of the private sector and academia. It is our hope that this retrospective look at the Apache helicopter can

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[1] This study, *Critical Technology Events in the Development of the Abrams Tank, Defense and Technology Paper #22*, was published in February 2006 by the Center for Technology and National Security Policy at National Defense University. It is available online at <http://www.ndu.edu/ctnsp/publications.html>.

[2] Office of the Director of Defense Research and Engineering, *Project Hindsight: Final Report* (Washington, D.C.: Office of the DDRE, 1969).

highlight the importance of these factors, and thus can be of value to current science and technology leadership within the Army and DOD as they wrestle with tight budgets, a changing workforce, and new acquisition strategies.

II. Background

In this chapter we highlight some of the objectives and findings of the first *Hindsight* report of 1969. We also present a brief review of the circumstances that led to the creation of the Apache program.

Project Hindsight

This study is modeled in part on a 1969 report, Project *Hindsight*.[3] 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 science and technology (S&T) program and to devise a methodology to measure the return on investment.[4] 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.[5]

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.[6] 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: [7]

1. Markedly improved weapons systems result from skillfully combining a considerable number of scientific and technological advances (Criterion 1).

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[3] Ibid.
[4] 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, D.C.: Office of the DDRE, 1969), 135.
[5] Ibid.
[6] Office of the Director of Defense Research and Engineering, *Project Hindsight: Final Report* (Washington, D.C.: Office of the DDRE, 1969), xiii.
[7] Ibid, xxi.

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 differences between industry, in-house laboratories, and university-associated 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).
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 science and technology 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 science and technology 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."[8] 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."[9] Please note that our signal events, CTEs, differ from *Hindsight*'s RXD events. Most significantly,

[8] Ibid., xiv.
[9] Ibid.

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.

The Need for the Apache

The conflict in Vietnam conclusively demonstrated the importance of helicopter-provided close air support. Armed helicopters could move readily within a theater of operations and bring significant firepower to bear to, among other things, support beleaguered ground units, hold enemy combatants in place for a ground attack, and secure a landing zone as part of a vertical envelopment operation. The attack helicopter function was initially performed by transport and scout helicopters, most notably the Bell UH-1 Huey and the OH-6A Cayuse, retrofitted with additional armament. The Army's first purpose-built attack helicopter, the Bell AH-1G Cobra, was deployed to Vietnam in 1967.

While the Cobra, based on the UH-1, was a step forward in helicopter technology, the experience in Vietnam revealed some key deficiencies. The Cobra's engine often could not provide the power to carry a full load of fuel or ammunition to the fight, and the aircraft proved vulnerable to ground fire.[10] The latter issue was of particular importance to the Army because the anticipated future combat environment, on the plains of central Europe against an adversary with modern air defenses, promised to be even more hazardous to helicopters than Vietnam.

The first attempt to build an improved, more survivable attack helicopter was unsuccessful. The Advanced Aerial Fire Support System program, begun in the mid-1960s, produced Lockheed's AH-56A Cheyenne. The Army tested prototypes of the aircraft, but ultimately rejected it. The Cheyenne was an improvement in some areas, but it suffered from assorted technical shortcomings. In addition, the Army had reassessed the threat environment and its aviation needs. The Cheyenne had been designed to engage ground targets while making swift passes. This was the way in which the Cobra was employed, but this type of operation was made significantly more dangerous by the proliferation of effective, man-portable, antiaircraft missiles. The North Vietnamese forces had some success against U.S. helicopters with the SA-7 shoulder-fired anti-aircraft missile, a type of weapon the Soviet bloc would have in great supply.[11] These losses, and subsequent experience that showed that helicopter gunships could adjust and sustain low-level operations,[12] prompted the Army to rethink helicopter tactics and the capabilities that the next aircraft would need.[13]

In the wake of the cancellation of the Cheyenne program, the Army refined the role that the Cobra's replacement would play. Looking toward a confrontation with the Soviets, and measuring the increasing threat posed air defense systems and increased lethality of small arms weapons, it called for a stand-off tank killer, an aircraft that could be effective

[10] Doug Richardson, *Modern Fighting Aircraft: AH-64 Apache* (New York: Prentice Hall Books, 1987), 4.
[11] Ibid.
[12] Curt Herrick, email to authors, 5 July 2005.
[13] Richardson, 4.

against Warsaw Pact armor while keeping its distance from a majority of ground-fire threats. The basic tactical concept was for the helicopter to remain below the tree line as much as possible, rising only to fire antitank missiles. The Advanced Attack Helicopter (AAH) program requirements were defined for this mission. The new helicopter had to be able to operate day or night in poor weather, sustain ground fire and continue to operate, protect its crew in the event of a crash landing, and carry a complete complement of antitank weaponry. Establishing these directives necessitated close interaction between the developers and the user as technical capabilities were weighed against operational concepts to determine the limits of possible requirements.

The AAH program issued a request for proposals to industry in late 1972. DOD picked two of the initial five bidders—Bell Helicopter Company and Hughes Helicopter Incorporated—to enter a competitive development phase in 1973. In the end, the Hughes[14] design, designated YAH-64, won the competition. In December, 1976, Hughes was awarded the contract to build the new AAH. The first Apaches[15] were delivered to the Army in 1985.

Before describing the capabilities of the AH-64 and the most recent version, the AH-64D "Longbow," a brief comparison to the AH-1G Cobra is worthwhile. The AH-64, dubbed the Apache, was a significant step forward from the AH-1G Cobra in every area. It was more survivable. The fuel tank and hydraulics were given ballistic protection. Each of the twin GE T700-GE701 turboshaft engines had enough power to take the aircraft home if the other was knocked out, a huge advantage over the single-engine Cobra.[16] The Apache's transmission was required to run dry for thirty minutes. Structural components, including the rotors, were built to sustain direct hits by small arms fire. Advanced armor protected the two-man crew. A lower acoustic signature and lower heat signature made the Apache a more elusive target than the Cobra.

The AH-64 was also a more lethal aircraft than its predecessor. The target acquisition and weapon systems represented significant breakthroughs. As befitted a tank-killer, the AH-64's primary weapon was the anti-armor Hellfire missile. The laser-seeking Hellfire was a major upgrade over the wire-guided TOW missiles carried by later Cobra models. Another version of the Hellfire's guidance system, fielded around 1997, gave the Apache autonomous fire-and-forget capability. This missile was guided by the Longbow millimeter wave radar that was introduced on the AH-64D Longbow Apache. The AH-64 was also equipped with an innovative chain gun and could carry a range of other munitions, including 2.75 inch rockets.

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[14] Hughes Helicopter was purchased by McDonnell Douglas Corporation in 1984. McDonnell Douglas merged with Boeing in 1997 to create the Boeing Company.

[15] The helicopter was not formally named the Apache until 1981. Its first designation was AAH for Advanced Attack Helicopter. The Hughes design that was funded after the Army selected Hughes and Bell as the final two competitors for the AAH contract was called the YAH-64. To improve readability, this report sometimes anachronistically refers to the "Apache" and the "Apache program" in the context of pre-1981 events.

[16] The Marine Corps still operates a much-updated version of the Cobra. The AH-1W SuperCobra has, among other improvements, a second engine.

The Apache’s crew controlled these weapons and piloted the aircraft with the aid of the Target Acquisition/Designation System (TADS) and Pilot Night Vision Sensor (PNVS). The sensors for these systems are mounted in a turret on the nose of the aircraft, and include thermal imagers, direct view optics, a television camera, a laser spot tracker, and a laser rangefinder. The sensor turret is slaved to the crew’s helmets, turning as they turn.

After a review of study methodology, we describe the CTEs that led to these battlefield capabilities.

III. Study Methodology

Scope

We have chosen to focus this report on those things we deemed to be major technical developments. The Apache has hundreds of components that undoubtedly required some innovation. This study intends neither to cover every CTE in the course of developing the helicopter nor to provide exhaustive technical detail on those CTEs that it does address. The intent is to concentrate on major technical developments that relate to the Apache's core capabilities.

We have divided this report into four major topic areas: power system; survivability and structural advances; avionics, fire control, and weapons; and modeling and simulation and other enabling methodologies. This separation of topics comes at the acknowledged price of diminished discussion of integration, systems engineering achievements, and the teaming of in-house laboratoriess, 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. This fact is highlighted again in chapter VIII of this paper and will be the subject of additional discussion in a summary paper after the other reports in this series have been completed.

Approach

This report is based primarily on interviews and correspondence with people who were directly involved in the development of the Apache, 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 the 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 Apache; to detail the impact of the CTEs; to indicate where the work in question was done; who contributed to it; who funded it; the nature of the funding (e.g., 6.1, 6.2, 6.3, etc.);[17] the number of staff involved; and the management factors that contributed to success.

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[17] DOD divides Research, Development, Test and Evaluation (RDT&E) spending into seven different activity categories. Category 6.1 refers to the budget line item for Basic Research; 6.2 is for Applied Research; 6.3 is for Advanced Technology Development. These three categories are referred to collectively as Science and Technology.

Often, we first interviewed a source and then obtained further information through follow-on conversations and correspondence. 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 in some cases took place decades ago. A few of these individuals are still in government service but most are retired or active in the private sector. 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 Apache.

IV. Power System

The Apache is a substantially more powerful aircraft than the AH-1G Cobra it was designed to replace. We start this section with a discussion of CTEs associated with the Apache's T-700 turboshaft engine, then turn to the transmission.

T700 Engine

CTE 1

The conflict in Vietnam revealed substantial shortcomings in U.S. helicopter engine performance. The chief problems were insufficient power, poor reliability, high maintenance needs, and poor specific fuel consumption.[18] These deficiencies led the Army to develop a new engine for its next generation of helicopters. The staff at the Army Aviation Systems Command (AVSCOM), and especially at its Aviation Applied Technology Directorate (AATD) at Fort Eustis, managed the early development of the new engine. The AATD program, called the "1500 Demonstrator Engine Program" (DEMO), did work on a 1500 horsepower turboshaft engine in the late 1960s. The DEMO program drew on their earlier work on gas turbine engines of this size. Subsequently, AATD was tasked to set requirements for these engines, with special emphasis on maintainability.[19] Their approach was to estimate the outer limits of the existing technology and incorporate challenging goals in the request for proposals. In addition to addressing the problems noted above, AATD set the following specific requirements for the engine: [20]

- An inlet particle separator
- Low maintenance/ fast overhaul; easy access to components
- Performance targets in terms of horsepower-to-weight and specific fuel consumption
- Little performance deterioration over life
- Low acquisition cost
- A history recorder to track the health of each engine
- Controlled development cost

General Electric, which had provided the first-ever turboshaft engine for a rotorcraft, and Pratt & Whitney were the chief competitors for the contract. The work on the new engine was funded with 6.3 money from AATD.[21] Ultimately, General Electric's design for a 1500-1600 horsepower engine was selected to power the Army's new generation of helicopters. The Army first used the engine, dubbed the T700, in the Utility Tactical Transport System (UTTAS), requiring in 1971 that competitors for the UTTAS contract include the T700 in their designs.[22] The Army strongly encouraged the competitors for

[18] Gene Hower, email to authors, 7 April 2005.
[19] Sandra Hoff, telephone interview with authors, 28 February 2005, and Richardson, 24.
[20] Robert Turnbull, telephone interview with authors, 13 April 2005.
[21] Hoff interview.
[22] Richardson, 22.

the AAH contract to use the T700 as well.[23] The T700 family was consequently used in Sikorsky's UH-60 Black Hawk (the result of the UTTAS program) and Hughes's AH-64 Apache.

The Apache's twin T700s provided substantially more power than the single Lycoming T53 used in the AH-1G Cobra, and were 27 percent more fuel efficient.[24] This added efficiency meant a reduced fuel load, which enabled designers to lighten the airframe and choose either to realize a weight savings or carry more armaments and armor. This improvement in efficiency produced large savings in air frame costs.[25] Each engine is capable of carrying the aircraft home should the other be knocked out.

CTE 2

CTE 3

GE engineers incorporated several innovations in the T700. GE simplified the combustor by going to a machined-ring configuration that was made in one piece. Earlier combustors were made of several pieces and tended to move and slowly deteriorate, limiting performance and life.[26] Another important aspect of the engine design is the scheme for removing particles from the incoming air. (Recall the disastrous attempt to rescue the hostages in Iran in 1980, when the intake of sand degraded helicopter engine performance and compromised the mission). This technology uses cyclonic effects (swirl vanes) in the front of the compressor together with an air pump to eject the separated particles. The device has been continually improved by GE over the years.[27]

CTE 4

CTE 5

GE engineers also overcame several initial challenges. They encountered forced vibration of compressor blades when there was a resonant frequency common to both blades and housing. This problem required some redesign.[28] Also, the unusually high rotational speed of the compressor shaft (45,000 rpm) and the power shaft (20,900 rpm, turning freely and concentrically within the compressor shaft) called for improvements in the properties and design of the disks and blades. GE learned how to manufacture these assemblies in one piece that they termed "blisks," using powder metallurgy with a nickel-based alloy. This is said to be one of the first applications of powder metallurgy.[29] This blisk design was mandatory on the first compressor stage, because a conventional dovetail could not hold the blade at these high rotational speeds.[30] Blisks were also used on the rest of the compressor stages, because they improved performance and maintenance cost.

Additional important T700 design innovations include:[31]

- Minimum oil, fuel, or hydraulic lines on outside of engine
- Special "curvic" joining the high power rotor
- Tie rods holding the engine rotors together

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[23] Ibid., 6.
[24] Nick Kailos, email to authors, 20 May 2005.
[25] Ibid.
[26] Turnbull interview.
[27] Ibid.
[28] Ibid.
[29] Ibid.
[30] Turnbull, email to authors, 5 May 2005.
[31] Turnbull interview.

- Spall-resistant bearing materials
- Special compressor design for high rpm
- Run-dry oil reservoir at bearings (discussed below)
- Special cleanliness for oil sump (clean room spec)
- Redesign of air flows to avoid slow speed stalls
- No lockwires to secure bolts for reduced maintenance

While most of the work on the engine was done on contract, the Army engineers co-located at NASA Glenn in Cleveland conducted 6.1 and 6.2 work that supported the contractual effort and focused on the problems arising during the development of the Apache.[32] They worked on the shape of the air foils in the turbine, on the cooling system, on pitting in metals, and on lubrication. They ran in-house engine tests in which they mapped engine temperatures, measured heat distortions and overheating, and took heat transfer data. They also studied contingency power, i.e., the availability of power in the event of an emergency, particularly the loss of one engine. More recently, they have studied the possible extension of the operating life of the engine and the reuse of some components during major overhaul. They have devised inspection protocols, including methods and timing of crack detection in the metals. Army engineers made the fruits of all this labor, including data sets from tests and experiments, available to industry.[33] This important work laid the foundation for several engine-related technical innovations.

CTE 6

One especially successful piece of Army 6.1 work at NASA Glenn was related to the process, now standard in the industry, for applying ceramic coatings to line the combustor and the blades in the hot section of the engine**.** Ceramic coating allows higher operating temperatures and hence greater efficiencies.

This engine work at NASA Glenn required 4-5 full time technologists, of whom 1-2 were Army employees.[34] Some in-house contractor staff were also involved.[35]

CTE 7

The Army also funded 6.1 basic research at universities on rare-earth magnets that enabled significant weight and size reductions for starters and generators. The engineers at AATD realized the significance of university findings in this area and brought them to the attention of GE, which first utilized them in full-scale production of helicopter engines in 1978.[36]

CTE 8

Work continues today that will eventually lead to additional improvements to the T700 series.[37] A significant DOD program paralleling and reinforcing the Apache work is the

[32] Robert Bill, telephone interview with authors, 16 February 2005.
[33] Ibid.
[34] Ibid.
[35] On materials research it is estimated that they devoted about 5 man years. Ibid.
[36] Kailos, telephone interview with authors, 23 February 2005.
[37] The latest needs statement for helicopter engines of this class is for upgrading the Black Hawk. The JTAGG team's work on the development of the gas generation section for the new Black Hawk engine is complete. However, more S&T work is needed to address integration of the power turbine, controls, accessories and inlet technologies. The new engine will have on the order of 3000 hp. Hoff, email to authors, 28 February 2005.

Joint Turbine Advanced Gas Generator (JTAGG) program.[38] This joint program, managed by AATD, addresses the goals of the DOD program on Integrated High Performance Turbine Engine Technology. The work has been done on contract. It is a three-phase program with ambitious goals to produce a 120 percent increase in the ratio of shaft horsepower to engine weight and a decrease in specific fuel consumption of 40 percent.[39]

This new technology has already supported upgrades to the T700 leading to the T700 GE 701C and D. The D version applies new material technologies derived from the Commercial CT7-8 engine experience to the power turbine section and to select other parts of the engine to produce a power increase to ~2000 hp and significantly improve predicted reliability.[40] The 701D engine has completed engine airframe compatibility testing for retrofit to the Block I or II configuration AH-64D models as a replacement for the 701C engine (it maintains 701C power limits) and will be retrofitted to these aircraft by attrition. The 701D will be qualified in the AH-64D Block III configuration during the Block III System Development and Demonstration tests and will be installed on the production line for Block III and beyond.[41] The substantial increase in power achieved for the 701D over the original T700-700 configuration (see figure 1 below) has come at the cost of minor additional engine weight. The power increase is the result of incremental improvements in operating temperatures, greater air flow volumes, and higher compressor ratios.[42]

[38] Hoff, email to authors, 28 February 2005.
[39] Ibid.
[40] Larry Plaster, email to authors, 6 September 2005.
[41] Ibid.
[42] Kailos interview and Turnbull interview.

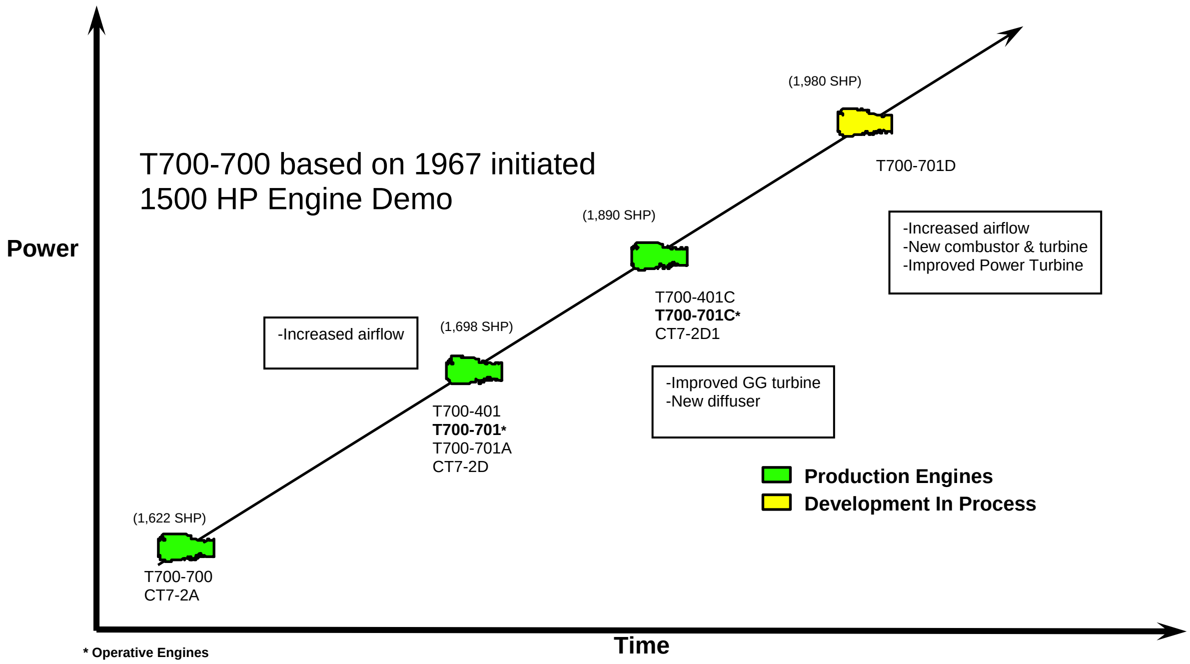

Figure 1. T-700 family growth path.[43]

Transmission

Work on the transmission was equally important to the Apache's power system development. The transmission, initially designed by Hughes,[44] takes input power from the two T700 engines, reduces the speed of rotation, and transfers the power to the main rotor shaft, accessory gearbox, and tail rotor assembly. Between each engine output shaft and the main transmission is an engine nose gearbox. Each gearbox is equipped with an over-running clutch. If the shaft from the transmission is running faster than the corresponding shaft from the turbine, the clutch disengages. When the opposite is true or the speeds of rotation are equal, the clutch is engaged. The turbine output shafts rotate at 20,900 rpm. This is reduced in the gear box at the front of the engine by reduction gears by a factor of 2.129; the transmission and subsequent gear boxes then further reduce the rotational speed such that the main rotor turns at about 200-400 rpm.[45] This is a total gear reduction of about 50:1 (compared to an automobile in which the gear reduction is only about 4:1).

[43] Figure from Hoff, email to authors, 28 February 2005.
[44] Plaster, email to authors, 6 September 2005.
[45] Hoff, email to authors, 18 May 2005.

Special emphasis in transmission development was placed on maintainability. The unit is highly reliable, but in the event of a breakdown the entire transmission was designed such that it could be replaced in two hours.[46] Among its other key features, the Army required that the transmission be protected against sudden loss of oil so that the Apache could sustain significant damage and still fly home. The resulting run-dry design enables the transmission to operate for up to 30 minutes after losing oil.[47] This is accomplished by use of anti-wear additives in the lubricant that have residual lubricating effects, even when the fluid is drained, and by surface treatment of the metals, use of premium materials, and close-tolerance machining.

CTE 9

The transmission also required considerable work on advanced gear technology by the Army/NASA Glenn staff. For gears and bearings, the Army/NASA work overcame barriers to higher performance in terms of speed, loading, and operating temperatures. Work on double-vacuum melted, high hot-hardness bearing steel and on gear alloys "doubled the power density compared to previous engines and vastly improved reliability" and removed a major barrier to progress in engine and transmission technology.[48] Results of this work are now used throughout industry.[49]

CTE 10

These transmission advances were achieved through considerable collaboration between the private sector, academia**,** and in-house laboratory engineers. The Army's in-house work on transmissions was done at NASA Glenn.[50] Money for work on the transmission came both from AATD and from mission funds from the Army Research Laboratory through the Army propulsion group co-located at NASA Glenn. The Defense Advanced Research Projects Agency (DARPA) has also supported some of this work. In the mission-funded area, they worked on gear-tooth profiles, spiral gears, and gear geometry. They also published data sets for use by industry.[51]

Recent work at Army/NASA Glenn and in industry on face-gear drives will be put in service in the latest Block III Apache upgrade. This technology, developed over 10 years of work at NASA Glenn and industry, splits the engine input torque evenly between upper and lower face gears (which are smaller and lighter than conventional main-drive sun gear designs), eliminating one planetary gear stage and allowing more power throughput with no increase in transmission size or weight.[52]

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[46] Herrick.
[47] Turnbull interview.
[48] Bill, email to authors, 22 February 2005. A comprehensive report on this work by Army/NASA Glenn engineers is: Erwin Zaretsky, ed., *Tribology for Aerospace Applications* (Park Ridge, Illinois: The Society of Tribologists and Lubrication Engineers, 1997).
[49] Bill email.
[50] Bill interview.
[51] Ibid.
[52] F.L.Litvin et al, "Face Gear Drives, Design, Analysis, and Testing for Helicopter Transmission Applications," Propulsion Directorate, U.S. Army Aviation Systems Command and NASA Lewis Research Center, NASA Glenn Technical Reports No. E-7743, 1992; Boeing News Release "New Apache Transmission Technology Offers More Power and Capability," February 22, 2005; D.G. Lewicki et al, "Evaluation of Carburized and Ground Face Gears," U.S. Army Research Laboratory and NASA Glenn Research Center, NASA Glenn Technical Research Report No. E-11700, 1999; F.L.Litvin et al, "Handbook

One of the key technology breakthroughs needed to successfully produce the split-torque face gear design was development of a grinding machine capable of economically producing the face gears with their complex gear-tooth profiles in production quantities.[53] The manufacturing technology was developed via a partnership between Boeing and Northstar Aerospace of Canada in which Northstar provided much of the gear manufacturing technical expertise and the funding required to develop the advanced-technology gear-grinding machine.[54]

In addition to development of the face-gear technology, the new Apache main transmission scheduled to be fielded with the AH-64D Block III upgrade includes several other significant rotorcraft transmission technology achievements developed by both government and industry research. The end result of the combined efforts of NASA Glenn, AATD, Boeing, Northstar Aerospace and Penn State University is a new Apache main transmission design that is the same size as the old design but is capable of 25% more power throughput and has more than twice the endurance life of the current design.[55]

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on Face Gear Drives With a Spur Involute Pinion," University of Illinois at Chicago and the Boeing Company, NASA Glenn Technical Report No. E-12127.

[53] Plaster, email to authors, 6 September 2005.

[54] Ibid.

[55] Ibid.

V. Survivability and Structural Advances

Some of the most important innovations on the Apache had to do with keeping the crew safe. Crew safety was a fundamental requirement of the AAH program. The helicopter had to be able to withstand hits from heavy machine guns, and its crew must have a 95 percent chance of surviving a crash at a vertical speed of 42 feet per second.[56] In this chapter we first present CTEs associated with two categories of survivability: vulnerability (reducing the likelihood of a kill if hit) and susceptibility (reducing the likelihood of being hit in the first place). This is followed by a discussion of important structural advances.

Vulnerability and Susceptibility Reduction

CTE 11

The Apache benefited from a range of noteworthy advances designed to protect the crew and the aircraft from hostile fire. Important strides were made in ballistic protection. In the mid-to-late 1970s, using about $200,000 per year of 6.2 funds, the Army Materials Laboratory at Watertown developed the concept of using a transparent laminate armor material to separate front and rear cockpits.[57] The material, a glass/polycarbonate laminate, was patented by Army researchers and used above the seat line. With this shielding system in place, the likelihood that both the Apache pilot and gunner would be injured by a single hit was significantly reduced.

CTE 12

The development of ceramic composite materials by industry[58] and the Army laboratory at Watertown[59] led to additional ballistic protection for Apache crew members. Seats that provided ballistic protection had their origin in the mid-1960s, when work at Watertown showed that ceramic materials, with their high hardness and stiffness, were effective against small arms ammunition of the type encountered in Vietnam. Boron carbide was demonstrated to be the most effective ceramic material; when coupled with glass-reinforced composite back-up material, it was able to defeat small arms threats. Following the Vietnam War, the use of Kevlar was proposed by Watertown as a material for the rear of the boron carbide armor.[60] This combination provided even better weight efficiency and was chosen for use in the Apache for the helicopter crew seats.[61]

Another flight-safety effort addressed the hazards presented by communication and power lines. These wires are a particular threat during nighttime or adverse-weather

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[56] Richardson, 5.
[57] Gordon Parsons, telephone interview with authors, 3 March 2005.
[58] William Perciballi, interview with authors, Phoenix, AZ, 11 December 2005.
[59] Deborah E. Gray, *The U.S. Army Laboratories at Watertown, Massachusetts Contributions to Science and Technology: A History* (Watertown, MA: Army Research Laboratory Materials Directorate, August 1995) 39.
[60] Ibid., 40.
[61] Ibid.

daytime operations, especially in confined areas and during nap-of-the-earth (NOE)[62] flying. Analysis of Army accidents showed that over 16 percent of Army aviation fatalities and over 8 percent of materiel losses in peacetime operation between January 1974 and January 1980 were due to in-flight wire strikes.[63] In the late 1970s, separate U.S. and Canadian programs addressed the issue and developed systems for wire strike protection. The U.S. design, developed by AATD, was very basic: a cutter/deflector system consisting of an upper and lower cutter that would sever steel, copper and aluminum wires. The Canadian design was similar and a cooperative effort ensued. To evaluate the design, a unique qualification test procedure was developed by AATD and full-scale qualification tests of Army helicopters were successfully conducted by AATD at NASA's Langley Research Center.[64] As a result, the system was retrofitted to the Apaches in the mid-1980s and built into all Army helicopters except the CH-47. Current research in avoiding wire strikes focuses on avoidance.[65]

CTE 13

Recognizing that despite the above advances, hostile fire, wires, or other factors would occasionally bring down the aircraft, the Army placed great emphasis on protecting the Apache's crew during a hard landing. This emphasis was especially prudent considering that the Army required the AAH to execute NOE operations; low-speed, ground-hugging flying, sometimes at night, increases the probability of having an accident or being hit by ground fire. The Apache benefited from work at AATD towards the goal of having a crashworthy rotary-wing aircraft. A helicopter crash research program involving subject matter experts from private-sector safety groups was initiated in the late 1950s and continued into the 1980s. The program was funded by 6.2 and 6.3 monies. The funding levels were modest at first but ramped to about $1 million per year.[66] Other Services also contributed to the effort as part of the Joint Logistics Commanders Aircraft Survivability Group's activities.[67]

CTE 14

In this pre-Apache effort, data were gathered from full-scale crash tests and actual helicopter crash investigations. These data showed the presence of several deficiencies.[68] Among them were loss of occupiable volume due to structural collapse, inward buckling of frames, seat tear-out due to floor breakup, and penetration into occupied areas by landing gear and the main rotor gearbox. The landing gear was designed in accordance with conventional practice at that time for hard landings with some reserve. Crash energy attenuation was not a consideration, thus excessively high acceleration forces were allowed to be transferred to the occupants.

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[62] Flight at varying airspeeds as close to the earth's surface as vegetation, obstacles and ambient light will permit, while generally following the contours of the earth.
[63] LeRoy T. Burrows, "Wire Strike Protection for Helicopters," *U.S. Army Aviation Digest*, September 1980, 36.
[64] Ibid., 38.
[65] Neale Bruchman, email to authors, 17 January 2006.
[66] LeRoy Burrows, telephone interview with authors, 2 March 2005.
[67] Herrick.
[68] C. Hudson Carper and LeRoy T. Burrows, "Evolving Crashworthiness Design Criteria," *Energy Absorption of Aircraft Structures as an Aspect of Crashworthiness Conference Proceedings* (Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development, May 1988), 2.

CTE 15

As the data were evaluated, the emphasis of the Army program shifted from crash prevention to improving occupant survival and reducing materiel losses. This emphasis led to the first ever crash-survival design guide for light fixed- and rotary-wing aircraft.[69] It was published in the late 1960s and revised in the 1970s and 1980s. The design guide was subsequently converted into a military standard, Mil-Std 1290, which governed the design of both the Apache and Black Hawk helicopters and created a systems approach to design for crashworthiness. It called for the following important areas to be addressed: a structure of sufficient strength and stiffness to prevent aircraft plowing in soft soil; proper retention strength for high mass items to preclude break-away and to maintain a survivable occupant volume; use of crushable structures and load-limiting designs for landing gear and aircrew seats to reduce occupant acceleration; restraint systems and padding to prevent injury from flailing; and post-crash hazard reduction—protection from flammable fluids and emergency egress provisions for the occupants under all conditions.[70] As a result of this significant step forward, the Apache crew has a 95 percent chance of surviving a crash with no spinal or thermal injury when the helicopter approaches the ground at rates of up to 42 feet per second.[71]

CTE 16

The Army's development of sound design criteria for crashworthy fuel systems has produced the largest payoff in the endeavor to improve rotorcraft crash safety.[72] Before this work, 41 percent of fatalities from otherwise survivable crashes were attributed to post-crash fuel fires.[73] This number has been reduced to zero percent for aircraft equipped with internal and external crashworthy fuel systems.[74] Changes were made in both fuel system materials and design. Self-sealing and tear-resistant polymers enhanced protection of the fuel tank. Changes were also made in the breakaway, self-sealing valves, fuel lines, filling system, and vents. The work was a contractual effort funded by AATD. In 1968 the Army Chief of Staff approved use of the fire-resistant system in the first helicopter—the UH-1—and the fleet in Vietnam was retrofitted. This level of fire safety was then specified in Mil Std 1290 and in the design guide and incorporated in the subsequent requests for proposals for the Apache and Blackhawk.[75]

CTE 17

In addition to these ballistics and crashworthiness improvements, the Apache incorporated several advances designed to prevent the aircraft from being targeted at all. There was a major effort through the Army's S&T program and Aircraft Survivability Equipment program to develop a suite of active and passive defenses. In-house laboratories such as AATD and CECOM, working closely with industry, provided

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[69] LeRoy T. Burrows and Kent F. Smith, "Crashworthy Helicopters Save Lives and Equipment," *Army Research, Development and Acquisition Bulletin*, July-August 1989, 6.
[70] Ibid.
[71] Burrows interview. This holds true only with the reasonable roll/yaw/pitch envelop that is cited in Mil-Std 1290.
[72] Burrows, email to authors, 6 May 2005.
[73] Burrows interview.
[74] Ibid.
[75] It is important to note that much of the fire safety technology specified in Mil Std 1290 and included in the Crash Safety Design Guide was derived from the automobile racing industry, which had been forced to incorporate crashworthy fire safety features into racing cars due to the extreme flammability of the high octane fuels used for Indy Car racing. Plaster, email to authors, 6 September 2005.

advances in the following areas: engine exhaust IR suppressor design; the ALQ-144 IR countermeasure system, a device designed to jam incoming heat-seeking missiles; low-signature paint and windshield concepts; and radar and laser warning systems.[76]

Structural Advances

CTE 18

During the Apache development, the idea of using integral armor for structural load-carrying purposes as well as for ballistic protection was advanced by Hughes Helicopter during discussions with Army materials scientists.[77] Hughes utilized this innovative approach to realize significant weight savings. For example, the company made extensive use of electro-slag, high-strength steel for integral armor application in such components as hydraulic actuators, rotor pitch links, bearing sleeves, and crank assemblies.[78] Fabrication from steel that exhibited high hardness and strength as well as high toughness enables the components to sustain ballistic impact and continue to function.

CTE 19

Among the next major structural challenges for ongoing Apache development work was the design of an all-composite rotor blade for the aircraft. Materials scientists and aircraft engineers have been working on incorporating composite materials, which have high strength to weight ratios, into helicopter rotors for many years. Fiberglass composite materials had been under consideration for rotor blade applications since the late 1940s, when fiberglass rotor-blade prototypes were tested in the private sector under Air Force contract.[79] In the late 1960s, AATD explored the use of fiber composite materials, and the processing methods thereof, for structural components, including the main rotor blade.[80] Also in the 1960s, Hughes fabricated a unidirectional fiberglass composite prototype blade for the Cobra helicopter.[81] The exceptionally low service life of metal rotor blades in Vietnam (as low as 25 flight hours) due to fatigue and ballistic and foreign object damage again spurred interest in composite materials in the early 1970s.[82] Continued interest led Kaman Aircraft in the mid-1970s to design and manufacture the world’s first production all-composite rotor blade for the AH-1G Cobra.[83]

CTE 20

These and other efforts in this area have paved the way for the eventual addition of an all-composite rotor blade to the Apache. When the Apache was first fielded, composite materials were not yet available that could meet the AAH program ballistic requirement at an acceptable weight: the rotor had to be ballistically tolerant to damage from a 23mm high explosive incendiary (HEI) round. To meet this requirement, the Apache main rotor blade initially was manufactured from metal using four, interlocked, metal spar

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[76] Raymond Wall, email to authors, 20 January 2006.
[77] Dino Papetti, telephone interview with authors, 23 February 2005.
[78] Gray, 67.
[79] Richard M. Carlson, “Composite Structures,” *American Helicopter Society Magazine*, May 1994, 32.
[80] Ward Figge, telephone interview with authors, 16 February 2005.
[81] Ibid.
[82] Figge, email to authors, 16 May 2005.
[83] Kaman Corporation, “Kaman History.” Available online at: <http://www.kaman.com/history/kamanhist_main.html>, accessed 9 August 2005.

structures.[84] This unique structural design provided a very lightweight blade structure that could meet the stringent ballistic requirement. Research done after initial fielding of the Apache by AATD, combined with experience gained by Boeing in developing composite blades for the CH-47, the commercial model MD-900, and the Comanche (the planned armed reconnaissance helicopter that the DOD canceled in 2004), resulted in new materials and analytical tools for blade spar sizing. This allowed the design of a new single spar, all-composite main rotor blade for the Apache, which is planned for fielding in 2008.[85] The design process for the composite spar was noteworthy. The design was generated and refined using a series of prototype blade sections subjected to 23mm HEI live-fire testing.[86] Refinements in the design after each test resulted in a final design that exceeded the capability of the original metal blade design to continue operations after damage from a 23mm HEI round.

CTE 21

It should be noted that the use of composites for rotor blades and other helicopter applications was supported by important research on the materials' failure modes. Since the 1970s, a group of Army researchers co-located at the NASA Langley Research Center has been among the leaders in quantifying the delamination process in composite materials. As a result of this effort, crack energy release rates at the delamination front have been documented. In the 1990s, this work led to accepted test methods and guidelines for determination of delamination, which is highly important to the ability to predict failure in composite materials.[87]

[84] Plaster, email to authors, 6 September 2005.
[85] Ibid.
[86] Ibid.
[87] T.K. O'Brien, email to authors, 2 March 2005.

VI. Avionics, Fire Control, and Weapons

In this section we cover the CTEs that have been instrumental in giving the Apache the capability to operate day or night under adverse weather conditions, to find, track, and destroy enemy targets. These capabilities, combined with those discussed above, make the Apache the world's most advanced attack helicopter.

TADS/PNVS

CTE 22

The Target Acquisition and Designation Sight and the Pilot Night Vision Sensor (TADS/PNVS) are key to the Apache's ability to operate at all times, especially in all conditions, to find, track, and fire upon targets. Designed by Martin Marietta, TADS/PNVS is an integrated system that pulled together for the first time thermal imaging devices, laser range finders and laser designators.[88] The TADS is used by the gunner/co-pilot for target search, detection, designation, and tracking. It has a Forward Looking Infra-Red (FLIR) sensor for night operations; a TV camera with both narrow and wide views for day operations; direct view optics; a laser spot tracker; and a laser rangefinder.[89] The PNVS has a FLIR sensor that gives the pilot the wide-angle view that is needed to fly and maneuver at night as well as to locate targets. The sensors for both units are located in a rotating turret mounted on the Apache's nose.

CTE 23

Critical to the TADS/PNVS is the FLIR sensor. The significant strides that the Army laboratories made in FLIR technology while working on the Abrams tank[90] and other weapons systems also benefited the Apache. Among these advances were a common module approach to FLIR production and a minimum resolvable temperature (MRT) determination as a way to measure FLIR performance. Also, it should be noted that for the Apache, with the work on the MRT as a foundation, the U.S. Army Night Vision Laboratory (NVL) produced a mathematical model that could be used to evaluate the performance of IR devices.[91] The model predicts the performance in terms of the probability of recognition and detection. As a result of the success of the model, the Army required that it be used to evaluate the performances of IR devices that were included in proposals submitted to the government during the Apache development, as well as subsequent Army weapons acquisitions that required thermal imaging.

[88] Richardson, 26.
[89] CTEs related to the laser rangefinder have already been detailed in our earlier paper on the Abrams tank. CTEs include the early work on the ruby laser rangefinder, the improvements that came with development of the Nd:YAG laser that provides the wave length required for target designation for semi-active seekers, and work to improve eye safety characteristics.
[90] Some CTEs associated with FLIR development that apply to the Apache have already been detailed in our earlier paper on the Abrams tank.
[91] James A. Ratches et al., *Night Vision Laboratory Static Performance Model for Thermal Viewing Systems* (Fort Belvoir, VA: U.S. Army Electronics Command, April 1975).

CTE 24

The Apache required significantly longer operational target engagement ranges than existing systems; it demanded a FLIR with more than twice the resolution of the one used by the Abrams.[92] The Apache initially had a non-standard high line rate imaging system that was enabled by significant improvements in detector and optics quality sponsored by NVL and Frankford Arsenal.[93]

CTE 25

In-house engineers at NVL also played a major role in the development of PNVS for night piloting and NOE flying.[94] Field exercises demonstrated the ability to fly below the tree tops at night with thermal imaging. The different trade-offs in FLIR system design compared to those for targeting systems were pursued to optimize sensor design for piloting parameters, such as field-of-view and sensitivity sufficient for background discrimination.

CTE 26

One of the most important features that contributes to the battlefield effectiveness of the Apache and enhances the capability of TADS/PNVS is the use of the Integrated Helmet and Display Sight System, better known as IHADSS, which slaves the helmet to the sensor turret so that the pilot views the terrain and target area through the PNVS. Similarly, TADS is slaved to the co-pilot/gunner's helmet, as is the chain gun. Both crew members' helmets are fitted with a monocle-like heads-up display that gives piloting and target information.

The initial head mounted sight, which evolved into the IHADDS, had its beginning at Frankford Arsenal in the mid-1960s.[95] The Cobra incorporated a mechanical linkage for the pilot and co-pilot gunner stations for directing fire with the 20MM turreted Gatling gun. It was realized, though, that this mechanical linkage could be improved upon with an infrared, acoustic, or magnetic-based sensor linkage system.[96] Industry noted the idea and began to provide internal funding to conduct needed R&D.[97] They worked closely with engineers at Frankford Arsenal, who had the necessary in-house talent to move the idea forward. At Frankford, a group of about 10 engineers with backgrounds in areas such as optical design, mechanical design, testing, and systems analysis supported the project over a period of approximately 5 years.[98] During this time period, the technology was continuously transitioned to industry. As a result, the Apache IHADSS makes use of infrared linkages.[99]

CTE 27

With IHADSS, symbols representing such important information as aircraft heading, air speed, altitude, and target cueing is superimposed on displays that fit in front of the pilot's and gunner's right eyes. The crew thus see the data in addition to the scene being viewed. This enables the crew to fly and fight without having to look at the panel-mounted displays in the cockpit. This capability is especially important with NOE flying.

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[92] Joseph Lehman, email to authors, 11 May 2005.
[93] Ibid.
[94] James Ratches, email to authors, 4 May 2005.
[95] Donald Furmanski and Lehman, telephone interview with authors, 1 April 2005.
[96] Lehman email.
[97] Furmanski and Lehman interview.
[98] Ibid.
[99] Ernest Burcher, email to authors, 18 May 2005.

CTE 28

The Army laboratory co-located with NASA Ames played a key role in optimizing symbology for the Apache.[100] Being co-located at the NASA Ames Research Center, where they had access to a flight simulator, engineers at the aerodynamics laboratory were able to define protocols that were used for the evaluation of the proposed symbols. Design standards were established and transitioned to industry to ensure that the proposed symbols and the pilot's feel for the motion of the helicopter were matched.[101] Additional enabling methodologies involving leveraged capabilities at NASA Research Centers are discussed in chapter VII.

Fire Control

CTE 29

The Apache's fire control system integrates the data needed to ensure that the aircraft's crew can accurately fire on the targets they identify using TADS/PNVS and other sensors. The heart of the fire control system is the helicopter's on-board fire control computer. Important work on fire control for Army rotorcraft was done at BRL during the 1970s and early 1980s. BRL research provided a general 6-degree of freedom (6-DOF) model for ballistic weapons, namely gun ammunition and rockets, which could compensate for helicopter downwash, projectile drag, aircraft motion, atmospheric conditions, etc.[102] This model was integrated with Apache's on-board fire control computer; combined with target motion data from the TADS, it provided significantly increased engagement accuracy.

CTE 30

Another challenge was the software control and integration of multiple complex target acquisition systems. This capability to manage these systems evolved from fundamental work done at Frankford Arsenal in the mid-1970s in software algorithms.[103] Keeping FLIRs, lasers, radars, rockets, missiles, and cannons precisely aimed with proper timing so that no firing errors occurred was a daunting task. The answer was fast computer programming using innovative algorithms coupled with equally innovative boresighting aids and procedures.[104] Exploiting Frankford Arsenal's experience developing the fire control system computers/microprocessors, engineers there were able to develop the first helicopter system controller.

CTE 31

In today's Apache, the multiple microprocessors and disciplined software management, together with a multiplexed digital databus (the standard for which was developed by IEEE and detailed in Mil-Std 1553), provide the interconnections for the avionics suite, including the TADS/PNVS system, IHADSS, and the navigation system. The Mil-Std 1553 databus concept was a key technology required to enable the high degree of integration used by the Apache's onboard processing and sensor systems to display relevant piloting and targeting information to the crew. The 1553 databus technology was

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[100] Andy Kerr, telephone interview with authors, 9 March 2005.
[101] Ibid.
[102] Burcher email.
[103] Lehman email.
[104] The Apache was the first Army system platform requiring millions of lines of computer code. Lehman email.

derived primarily from work done on the Air Force's B-1 bomber program, which was essentially the first practical application of the high-speed databus concept.[105]

CTE 32

The digital architecture also enabled integration of other key elements of the fire control system for the Apache Longbow: the mast mounted millimeter wave (MMW) fire control radar (discussed in the following section) and the integral radar frequency interferometer (RFI). Industry led development of the RFI.[106] The system, which is integrated with the Longbow MMW, passively detects and analyzes radar emissions from potential targets.[107] The fire control system combines information from the fire control radar and the RFI to rapidly provide a clear picture of the battlefield.

CTE 33

Another key improvement to the Apache's fire control relates to communication among aircraft. Initially known as the Automated Target Handover System, the Improved Data Modem (IDM) permits the Apache to digitally communicate crucial threat, targeting, and other operational information with other aircraft and with ground units so that the force has a unified picture of the battlefield. This could be considered one of the first elements of network-centric warfare for Army aviation.[108] Industry was heavily involved with development of the IDM, as was the Army's in-house avionics program.

AATD Aviation Weaponization Group: It should be noted that as many ideas, such as the mast mounted sight, millimeter wave radar, and ever more powerful microprocessors, began to emerge, the Army aviation leadership wanted to establish an organization that would be in position to waste little time in applying the technology to aviation-specific needs.[a] As a result, an Army aviation weaponization group was created at AATD in the late 1970s-early 1980s. This was a key management decision; the new organization played a major role in recognizing and bringing forward worthwhile ideas (CTEs), such as developing and integrating the Longbow MMW radar system, coordinating with other laboratories (both in-house and out-of-house), and managing the efforts with industry.

a. Kailos interview.

[105] Plaster, email to authors, 6 September 2005.
[106] Brad Rounding, telephone interview with authors, 3 August 2005.
[107] Plaster, email to authors, 23 January 2006.
[108] Burcher email.

Longbow Millimeter Wave Radar

The AH-64D version of the Apache incorporated upgrades in several areas, but the most notable of these was the Longbow MMW fire control radar.[109] The radar, mounted on the Apache's mast, supplemented the FLIR with a second, completely independent target acquisition sensor. The Longbow enabled the Apache to carry a second type of Hellfire (discussed below). This new missile was guided by radar rather than semi-active laser. This greatly enhanced the Apache's lethality in adverse atmospheric conditions, because infrared sensor and laser-guided weapons can have difficulty coping with smoke, dust, fog, and precipitation. This fire control radar is normally used independent of TADS for rapid automatic detection of targets within a 34-square mile area, and the classification and display of the 16 highest priority targets.[110] The Army is converting about 590 of more than 800 AH-64As to the D configuration.[111]

CTE 34

The use of MMW radar for military purposes has been the subject of research since the 1950s. Its application as an all-weather sensor for helicopter applications gained attention in mid-1960s. Two programs were important to advancing MMW radar applications to armed helicopters.[112] The first was the Frankford Arsenal/Emerson Electric Moving Target Radar System Program. The system, based on Ka-band radar technology, was first tested on a UH-1 Huey helicopter and demonstrated a capability to significantly enhance the ability of the crew to detect moving targets in vegetation as well as in the open. It was married to the FLIR system on the Cobra Helicopter and deployed to Vietnam, where it was evaluated by the Army Concept Team in 1970.[113] The radar increased the range at which the crew could detect targets by 1000 meters beyond what could be detected by the FLIR alone.[114]

The second helicopter radar system of note in the mid-60s was the Texas Instruments Rotor Blade Radar System.[115] The TI system used a transmitter in the leading edge of the UH-1 Huey rotor blades and a receiver on the nose of the helicopter to detect targets. This system never left the R&D stage, but served as exploratory technology that helped to lead to the successful Longbow radar discussed below.[116]

In the 1980s, Martin Marietta defined the advantages of using a higher frequency MMW radar to detect, classify, and recognize the target and transfer the information for use by a

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[109] The Longbow Fire Control Radar also has a Terrain Profiling Mode (TPM), which is supposed to provide obstacle detection and adverse weather piloting aids to the Longbow Apache crew; however, the pilots do not often use this feature. Burcher email.

[110] Jane's Avionics, "AN/APG-78 Longbow Radar." Available online at: <http://www4.janes.com>, accessed 4 August 2005.

[111] Jane's All the World's Aircraft, "Boeing AH-64 Apache." Available online at: <http://www4.janes.com>, accessed 4 August 2005.

[112] Lehman email.

[113] Ibid.

[114] Ibid.

[115] Ibid.

[116] Ibid.

radar seeker missile weapon system.[117] Briefings were given to the Army leadership on this concept. In the early 1980s, the effort gained high-level support within the Army, which instituted a program to field such a system. This program (which is classified, thus limiting information on the R&D effort) yielded the Longbow. The Longbow is produced by a joint venture between Lockheed Martin (which subsumed Martin Marietta) and Northrop Grumman (which bought Westinghouse Electric Corporation, a partner with Martin Marietta in Longbow development).

CTE 35

Important to the MMW radar was the very fast analog circuitry provided by gallium arsenide (GaAs) semiconductors. In the 1980s, a DOD program administered through DARPA established the industrial base to supply GaAs to the military.[118] This program, known as the MIMIC (microwave monolithic integrated circuits) program, provided the basis for product, process, and applications technologies. The program was funded at nearly $1 billion over 6 years from 1987 to 1993.[119] Program management was shared among the services, with the Army's Electronics Technology and Development Laboratory (ETDL) overseeing about one-third of the effort. The bulk of the funds went for contract studies ranging from basic research to technology demonstrations. Included here was funding (about $20 million) for work at the ETDL on qualification of GaAs material for integrated circuit chips, associated reliability testing, and technology demonstrations. The work included coordinated efforts in the private sector and universities. The work on technology demonstrations included the development of a power amplifier for the Longbow MMW radar.[120]

CTE 36

Further MIMIC benefits: It is interesting to note that another fielded result of the MIMIC program was a multiple option fuse for a chip programmable in the field.[b] Shortly after the MIMIC program was completed a small New Jersey company began to offer such chips for the direct (satellite) television business. Now the GaAs chips are used as amplifiers in cell phones—an enormous market facilitated by this DOD MIMIC program.[c]

b. Vladimir Gelnovatch, email to authors, 6 September 2005.
c. Ibid.

Another key innovation associated with the Longbow radar is its location on the mast. This idea had its origin in the late 1960s to late 1970s. The Army leadership was concerned with the low operational life of the light observation helicopters in Vietnam, which were projected to last only 17 flight-hours in a mid-intensity conflict environment.[121] It was obvious that the observation helicopters had to be hidden or masked from view to survive. The solution came from the Helicopter Fire Control Branch at Frankford Arsenal: a mast-mounted sight that would allow the helicopter to remain

CTE 37

117 Maurice Yeager, telephone interview with authors, 16 March 2005.
118 Vladimir Gelnovatch, email to authors, 6 September 2005.
119 Ibid.
120 Ibid.
121 Lehman email.

concealed.[122] In less than three months and with a small amount of in-house money, the concept of a mast mounted sensor was demonstrated. Results were briefed to the Army leadership and quickly led to a major program involving key players from industry, including Honeywell, Rockwell International, and Martin Marietta. The OH-58 Kiowa Warrior observation helicopter was one of the first systems to employ a mast-mounted FLIR sight. Eventually, as the Apache Longbow evolved, the mast was chosen as the site for the MMW radar. Besides reducing the helicopter's susceptibility to enemy detection by allowing the sensor to see over terrain while the airframe remained concealed, there were two additional benefits: the mast was located at the aircraft's center of gravity, and installing the sight on the mast conserved space that was in short supply elsewhere on the aircraft.[123]

CTE 38

Army-NASA tests: Important aerodynamic studies conducted at the Army-NASA site were also key to the location of the Longbow radar. Researchers were able to show the aerodynamic effect of the sight's location and configuration and ensure that its addition would not compromise the aircraft's airworthiness.[d] Similar research, including NASA wind-tunnel tests,[e] detailed the rotor-fuselage interaction and aided in designing the horizontal stabilizer (discussed also in "Co-Located Army-NASA Research Sites").[f]

d. T.A. Ghee and H.L. Kelley, "Flow Visualization of Mast-Mounted-Sight/Main Rotor Aerodynamic Interactions," AIAA-93-3517-CP.
e. J.C. Wilson and R.E. Mineck, "Wind-Tunnel Investigation of Helicopter rotor Wake Effects on Three Helicopter Fuselage Models," NASA TM X-3185, 1975.
f. R.W. Prouty "Development of the Empennage Configuration of the YAH-64 Advanced Attack Helicopter," USA AVRADCOM-TR, 82, D-22, February 1983.

Weapons Suite

Once the target has been identified, whether by the Longbow or by other means, the gunner has at his disposal several effective options. The Apache carries rockets and missiles on four articulated external pylons, two on each wing-like structure extending from the sides of the main fuselage. The aircraft can carry up to 16 Hellfire missiles or 76 2.75-Inch Folding Fin Aerial Rockets or a combination of missiles and rockets. It also has a turreted 30mm cannon under the nose linked to a load of 1200 rounds.

The Apache was designed primarily as an antitank weapon system, and its main armament for that mission is the Hellfire (HELicopter Launched FIRE-and-forget) missile.[124] The Hellfire is a 7-inch diameter guided missile carrying a large shaped-

[122] Ibid.
[123] Ibid.
[124] This discussion of Hellfire missiles is brief. We will release another report in this series that deals exclusively with the development of two other Army missile systems, the Javelin and the Stinger.

charge warhead for the penetration of tank armor. Each of the four weapons pylons can carry up to four Hellfire missiles.

The Hellfire, designed and initially built by Rockwell International Corporation, was the culmination of many years work to replace TOW (Tube-launched, Optically-tracked, Wire-guided) missiles as the main antitank weapon available for helicopter use. The major shortcoming of the TOW was that the helicopter needed to remain exposed while the missile homed in on its target. Further, its limited range brought the helicopter closer to the threat. The Hellfire flies faster and farther than its TOW predecessors, enabling greater standoff firing distances. The Hellfire with which the Apache was initially equipped was guided by a semi-active laser (SAL) seeker. The missile homes on a laser spot that can be projected either from the Apache or other aircraft or ground observers. It has lock-on-before-launch and lock-on-after-launch capability. If the target has been designated by another source, the Apache can return to cover immediately after the missile has left the launch rail. There have been three models of SAL-guided Hellfires.

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The Hellfire's SAL seeker was designed independently from the rest of the missile. The laser system had its origin in the mid- to late-1960s. At that time there was exploratory research interest at Redstone Arsenal in the development of a laser-based, semi-active system.[125] Also important was a systems study at Hughes Helicopter and Martin Marietta for a SAL missile. The study concluded that such a concept was within the state of the art.[126] In the early 1970s, Martin Marietta, with DARPA funds, carried the concept further and conducted a field demonstration that showed a successful hit of a ground target by a SAL-guided rocket.[127] Martin Marietta won a multi-service laser seeker design contract known as Low Cost Alternate Laser. It was initially an alternate seeker for the Hellfire, but Martin Marietta was eventually made an equal partner on the Hellfire contract, and its seeker was added to the Rockwell airframe.[128]

CTE 40

As described earlier in the chapter, the AH-64D Longbow Apache is equipped with a MMW radar. A new type of radar-guided Hellfire was designed for use with the Longbow. This missile (considered to be a second generation weapon, with the first generation encompassing the three SAL models) provided the Army with its first helicopter all weather attack system. It also provided a true autonomous fire-and-forget capability. The Longbow Hellfire can lock on to the target before launch or it can be inertially guided to the target area based on a position derived from the mast mounted acquisition radar and then acquire the target with its own radar.

Though less advanced and individually less lethal than the Hellfire, rockets add important capability to the Apache. The 2.75 inch rockets, for use primarily against personnel and

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[125] U.S. Missile Command, "Hellfire." Available online at: <http://www.redstone.army.mil/history/systems/HELLFIRE.html>, accessed 5 August 2005.

[126] Ibid.

[127] Kailos interview and Yeager interview.

[128] Rockwell has become part of Boeing and Martin Marietta is now part of Lockheed Martin. Today, SAL Hellfire missiles are manufactured by Hellfire Limited Liability Company, a Boeing/Lockheed Martin joint venture. The Longbow Hellfire is made by Longbow Limited Liability Company, a joint venture between Lockheed Martin and Northrop Grumman.

soft-skinned vehicles, are fired from re-usable pod launchers suspended from two wing-like extensions attached to the main helicopter body. The Apache can carry up to four pods of 7 or 19 rockets each for a maximum of 76. The unguided rockets are used primarily for area saturation.[129] Though the 2.75 inch rocket is a relatively simple weapon, engineers have made progressive improvements, equipping it with a more powerful motor and alternative payloads, including flechettes, multi-purpose submunitions, flares, and smoke.[130]

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Below the nose of the Apache is a rapid-fire, turreted 30mm chain gun. The chain gun gets its name from the electrically driven chain that feeds ammunition into the breach. This simple innovation, similar in principle to a basic drive belt, solved the difficult problem of machine-gun jamming. A conventional machine gun relies on energy from the exploding cartridge of the first round to advance the ammunition belt to the next round. If one round fails to fire, the gun jams, and there is no easy way to clear a jam from a gun mounted on the underbelly of an aircraft in flight. Engineers at Hughes Helicopter came up with a new single-barreled chain gun design for the Apache that could fire 11 rounds per second, was highly reliable, resistant to dirt and wear, and could continue to fire when rounds failed.[131] Hughes initially developed the design for a 20mm weapon, but adapted it for the Apache when the Army made a 30mm cannon a requirement for the AAH.

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[129] Richardson, 38.
[130] Ibid.
[131] Ibid., 40.

VII. Modeling and Simulation and Other Enabling Methodologies

In addition to the work on specific systems and components described above, the Army supported more broadly applicable research to improve helicopter technology that continues to benefit the Apache program. Much of this work was in computer modeling. The Army also conceived of new ways to collaborate with academia and industry in this and other important areas.

Co-Located Army-NASA Research Sites

The development of very powerful computers has transformed many branches of science and engineering. Computer models replace, to a considerable degree, expensive and time-consuming physical experimentation. A great many experiments can be conducted on the computer in less than the time it would take for one physical experiment. In many instances, experiments are carried out only to validate the computer models.

Much of the modeling work related to helicopter development has stemmed from co-location of Army engineers and scientists at NASA research facilities.[132] These sites are at NASA Langley, NASA Glenn, and NASA Ames. This 6.1 and early 6.2 work, which made use of NASA staff and experimental facilities, enabled verification of the predictions made by the computer-based models. The experimental work also provided data sets for use by industry. The use of NASA facilities was especially significant because the Army did not, and still does not, have its own, very expensive experimental facilities, such as special purpose, carefully calibrated wind tunnels.

Some computer-based models and techniques that resulted from this highly leveraged Army-NASA effort have been utilized throughout the aeronautical and space scientific community. Examples include:[133]

- Development of new computer modeling techniques in computational fluid dynamics (CFD) and finite element (FE) structural analysis
- Research into the physics and mechanics of helicopters, including computer modeling of the aerodynamics of airfoils for engine turbines and helicopter rotors
- Comprehensive structural mechanics using the NASTRAN FE computer program
- Studies of the vibrational behavior of the rotor-structure interactions, the loading on the rotors, and the flight behavior of the system
- Use of CFD to design the airfoils in the gas turbine engine
- Research to better understand dynamic stall effects
- Vibration analysis by FE analysis

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[132] Bill interview; Wolf Elber, telephone interview with authors, 17 February 2005; Kerr, telephone interview with authors, 23 February 2005.
[133] Ibid.

- Development and application of a comprehensive aircraft model for rotorcraft aeromechanics using CFD coupled with Computational Structural Mechanics

CTE 42

Many of the above technologies were relevant to the development of the Apache. For instance, interaction between the rotor and the airframe of the AH-64, particularly in the tail, caused serious, potentially catastrophic vibrations. Applying advanced structural dynamics analysis and comprehensive aeromechanics analysis, researchers worked with industry in a major configuration redesign of the tail, relocating the horizontal stabilizer and converting it to a movable stabilator.[134] They then verified the work in the wind tunnel. It is interesting to note that this particular issue received the close attention of the Apache PM, who made the necessary resources available and was involved with making the key decisions necessary to keep the program on track.[135]

In a related effort, researchers generated a "comprehensive and definitive" data set called Design Analysis Methods for Vibrations (DAMVIBS), which was generated through experimental work at NASA structural dynamics test labs and other experimental rigs.[136] The research included the design of special instrumentation to obtain information that was used to update structural dynamics modeling capability for dynamics and loads estimation and control.

CTE 43

Significant advances in rotorcraft computer codes used to simulate complex helicopter aerodynamics and helicopter flight control laws resulted in development of an Engineering Design Simulator (EDS) for Apache at Boeing Mesa. The EDS had operational fidelity that was accurate enough for it to be certified by the Army test community for use as an A-Model to D-Model transition trainer.[137] The EDS was also used by the Army to complete Limited User Test tasks required to obtain the full Airworthiness Release in lieu of expensive aircraft flight testing. This significantly reduced the time required to complete qualification and testing of the AH-64D model, and put this weapon system in the hands of the user much sooner than would have otherwise been possible.

Other Collaborative Efforts

In 1994, the Army established the National Rotorcraft Technology Center (NRTC) at the Army's unit at NASA Ames to enhance collaboration between the military, academia, and industry. Although the NRTC was established too late (1994) to impact the earlier development of the Apache, it represents an enhanced effort to produce technology for use in upgrades of the Apache and for future Army helicopters. It does this by formally involving both universities and industry. The NRTC facilitates communication and technology planning among the participants. It also funds and manages Rotorcraft Centers of Excellence (CoEs) at three universities: the University of Maryland, Penn State University, and Georgia Tech. The NRTC convenes the Rotorcraft Industry

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[134] Elber interview.
[135] Herrick.
[136] Kerr, telephone interview with authors, 4 March 2005.
[137] Plaster, email to authors, 6 September 2005.

Technology Association to provide industry input into the planning and prioritization of the research program at NRTC. The three university Rotorcraft CoEs receive $2.4 million annually, divided roughly equally.[138] This is Army 6.1 funding for basic research. In addition, the centers receive funding from NASA, other government agencies, industry, and the universities themselves that total about $12 million annually for all three CoEs.[139] This funding, combined with the 6.1 funding for the three Army units co-located at NASA facilities, supports most of the basic research done on helicopters in the Army.[140]

The funding for the Rotorcraft CoEs is largely for costs associated with engineering students and their projects—there are about 100 graduate students and three times as many undergraduates. The university programs at the CoEs emphasize aeroflight dynamics, computational modeling, power trains, smart composites, design optimization, and technology for unmanned aero vehicles. The centers produce well-trained graduate engineers at the BS, MS, and PhD levels, approximately 75 percent of whom go into industry.[141] Their presence in the helicopter industry strengthens the technology base and improves technology transfer.

It should be noted that the CoEs have developed experimental facilities, some of which are unique. More will become unique if NASA closes its facilities. (Additional commentary on this is provided in the findings and concluding remarks). These include test rigs for rotor blades and hubs, wind tunnels, blade whirl towers, and large-scale vacuum chambers.

In addition, the focused research at the CoEs has led to some significant accomplishments in a number of areas applicable to current as well as next generation helicopters:[142]

- Development of analytical and design tools—CFD and FE —and the application of these tools to rotorcraft problems
- Advanced composite rotor blade technology
- Viscoelastic dampers for the rotors
- Vibration prediction and active control
- Simulation of maneuvering wakes
- Modeling and simulation of steady and transient noise generation in terms of enemy detection

The CoE activities are important to the following characteristics that future aircraft may possess:[143]

- Heavy lift capability
- More powerful engines
- More fuel efficient engines[144]

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138 Inderjit Chopra, interview with authors, College Park, MD, 5 April 2005.
139 Ibid.
140 Ibid.
141 Ibid.
142 Ibid.
143 Ibid., except where noted.
144 Plaster, email to authors, 6 September 2005.

- No swashplates
- Wide application of advanced composite materials
- Fly-by-wire and integrated electro-optical systems
- Automatic rotor speed control via increased use of smart sensors, structures, and actuators (to increase both range and endurance)
- Compound helicopter capability

CTE 44

A more recent collaborative effort that will have a far-reaching impact on many future DOD systems is the effort known as the Rotorcraft Pilot Associate (RPA) program, developed and tested by Boeing and AATD.[145] The RPA program developed very robust Cognitive Decision Aiding System (CDAS) software intended to reduce the workload of the Apache's crew in the highly complex, low altitude combat environment. The RPA program demonstrated in both a high fidelity aircraft simulator and in a specially modified test Apache that models based on human behaviors could be used to make decisions for routine flight and navigation tasks on behalf of the crew, freeing them to concentrate on the battle at hand. RPA technology has also been applied to UAV control and to the Future Combat System Warfighter Machine Interface.[146] The Apache Block III configuration will incorporate eight of the approximately 20 cognitive decision aiding behaviors demonstrated during the RPA technology demonstration program.[147]

[145] Ibid.
[146] Ibid.
[147] Ibid.

VIII. Findings and Concluding Remarks

Findings

1. We have identified 44 Critical Technology Events in the development of the Apache helicopter.

- Power System CTEs
  - T700 Engine: 8
  - Transmission: 2
- Survivability and Structural Advances CTEs
  - Vulnerability and Susceptibility Reduction: 7
  - Structural Advances: 4
- Avionics, Fire Control and Weapons CTEs
  - TADS/PNVS: 7
  - Fire Control System: 5
  - Longbow Millimeter Wave Fire Control Radar: 4
  - [Sidebar:1]
  - Weapons Suite: 3
- Modeling and Simulation and Other Enabling Methodologies CTEs
  - Co-Located Army-NASA Research Sites: 2
  - Other Collaborative Efforts: 1

2. *Success in meeting user needs was due to many factors.* Among the most important was the expertise of the Army in-house scientists and engineers. In-house laboratories were deeply involved in CTEs that pertained to requirements that were vital to the development of the Apache. For example, the laboratories devoted a great deal of attention to crashworthiness, ballistic protection, thermal imaging, and the fire control system. The competence and dedication of the industrial partners was also crucial to the program's success. Industry's creative work on the T700 series of helicopter engines is an example.

3. *The Army experiences with helicopters in Vietnam had a strong influence on the Apache program*. Needs identified by the user included better crew protection and crash-worthiness, more payload, improved fuel economy, and more capable weapons systems. These needs drove specifications for a new, more powerful engine, many innovations in protecting the crew and reducing fatalities from crash, fire, and enemy munitions, and improved targeting and fire control systems.

4. *The Army funded most of the technical work on the Apache*. Before the Apache program was begun, the Army specified and funded a competition for the design of a new, more powerful helicopter engine and for targeting and fire control systems. However, industry originated and provided some financial support for early work on

some components, e.g., the Hellfire missile and the mast-mounted millimeter-wave radar concept.

5. *Integration of the many systems and components was critical for success.* The Apache is a complex weapons system containing many different subsystems and components. These were integrated under the supervision and strong leadership of the Program Manager's office, which championed the program throughout the development cycle and ensured effective teaming among all government and industry contributors.

6. *Basic and early applied research were done at co-located Army-NASA research sites.* Since 1968, the Army and NASA have collaborated at NASA Langley, NASA Glenn, and NASA Ames. This arrangement greatly facilitated work on structures, propulsion, and modeling and simulation. NASA's specialized experimental facilities were used to validate models and test out new concepts, e.g., in large, special purpose wind tunnels.

Concluding Remarks

These findings and conclusions apply to the Apache helicopter and may not apply to other Army weapons systems. While the analysis in this report has suggested to us some general recommendations that likely *would* apply to other Army weapons systems, we will reserve judgment until we have completed our series of papers. Also left until we complete the series of reports will be any comments related to current matters of interest, such as acquisition strategies and technical personnel skill mix.

We would like to re-emphasize that this study has not set out to capture every technical innovation in the development of the Apache. Nor have we striven to present the CTEs in exhaustive technical detail. We are confident, however, that we have captured most of the major technical events pertaining to the helicopter and that these events support the above conclusions.

Appendix A

Individuals Contacted for the Apache 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**	**Apache-era Organization**	**Current Status**
*Ballard	Richard	HQ, Department of the Army (CSE)	GR, CST
Bill	Robert	Army laboratory co-located at NASA Glenn (CSE)	GR
*Burcher	Ernest	Aviation Applied Technology Directorate (CSE)	CSE
*Burrows	LeRoy	Aviation Applied Technology Directorate (CSE)	GR
Buser	Rudy	Night Vision Laboratory (CSE)	GR
*Carmona	Waldo	Aviation Applied Technology Directorate (AM)	MR, PSE
Chopra	Inderjit	University of Maryland (ACD)	ACD
*Del Coco	Gene	Frankford Arsenal (CSE)	GR
*Elber	Wolf	Army laboratory co-located at NASA Langley (CSE)	CSE
*Figge	Ward	Aviation Applied Technology Directorate (CSE)	GR
*Furmanski	Donald	Frankford Arsenal (CSE)	GR
Gelnovatch	Vladimir	Electronic Technology and Device Laboratory (CSE)	CSE
Giordano	Robert	Communications-Electronics Command (CSE)	GR, CST
Good	Danny	Aviation Applied Technology Directorate (CSE)	GR, CTR
*Herrick	Curt	Apache PM Office (AM)	CST
*Hoff	Sandra	Aviation Applied Technology Directorate (CSE)	CSE
Hower	Gene	General Electric (PSE)	PSE

*Kailos	Nick	Aviation Applied Technology Directorate (CSE)	GR, CST
Keesee	Robin	Human Engineering Laboratory (CSE)	CSE
*Kerr	Andrew	Army laboratory co-located at NASA Ames (CSE)	CSE
*Lehman	Joseph	Frankford Arsenal (CSE)	GR
*Meitner	Peter	Army laboratory co-located at NASA Glenn (CSE)	CSE
*O'Brien	T.K.	Army laboratory co-located at NASA Ames (CSE)	CSE
*Papetti	Dino	Materials Technology Laboratory (CSE)	GR
Parsons	Gordon	Materials Technology Laboratory (CSE)	GR
Plaster	Larry	Bell Helicopter/McDonnell Douglas (PSE)	PSE
Perciballi	William	Materials Technology Laboratory (CSE)	PSE
*Ratches	James	Night Vision Laboratory (CSE)	CSE
Rounding	Bradley	Officer, US Army (AM)	PSE
*Sciarretta	Al	Officer, US Army (AM)	MR, CST
*Sibert	George	Officer, US Army (AM)	MR
Singley	George	Aviation Applied Technology Directorate/Army Aviation Systems Command HQ (CSE)	GR, PSE
*Turnbull	Robert	General Electric (PSE)	PSE
Wade	Jack	Survivability and Lethality Analysis Directorate (CSE)	GR
Wall	Raymond	Aviation Applied Technology Directorate (CSE)	CSE
*Yeager	Maurice	Martin Marietta (PSE)	CST

Appendix B

Critical Technology Event List

Number	***CTE***	***Report Section***
1	AATD sets engine requirements	*T700 Engine*
2	Simplified combustor design	*T700 Engine*
3	Particle separator design	*T700 Engine*
4	Re-design to reduce vibration of compressor blades	*T700 Engine*
5	Blisks	*T700 Engine*
6	Ceramic coating	*T700 Engine*
7	Rare earth magnets	*T700 Engine*
8	Incremental T700 improvements	*T700 Engine*
9	Run-dry transmission	*Transmission*
10	Gear technology advances	*Transmission*
11	Transparent armor to separate cockpits	*Vulnerability and Susceptibility Reduction*
12	Improved armor for seats	*Vulnerability and Susceptibility Reduction*
13	Wire-strike protection	*Vulnerability and Susceptibility Reduction*
14	Priority placed on crashworthiness	*Vulnerability and Susceptibility Reduction*
15	Crash survival design guide	*Vulnerability and Susceptibility Reduction*
16	Crashworthy fuel system	*Vulnerability and Susceptibility Reduction*
17	Active and passive susceptibility measures	*Vulnerability and Susceptibility Reduction*
18	Load-bearing armor	*Structural Advances*
19	Composite materials for the rotor	*Structural Advances*
20	Composite rotor blade for Apache	*Structural Advances*
21	Analysis of delamination process in composite materials	*Structural Advances*
22	TADS/PNVS	*TADS/PNVS*
23	FLIR performance model	*TADS/PNVS*
24	High-resolution FLIR for TADS	*TADS/PNVS*
25	Pilotage-optimized FLIR for PNVS	*TADS/PNVS*
26	Head mounted site for IHADSS	*TADS/PNVS*

27	Symbology for IHADSS	*TADS/PNVS*
28	Protocols and design standards for IHADSS symbology	*TADS/PNVS*
29	Model for rotorcraft ballistic fire control	*Fire Control*
30	Software integration	*Fire Control*
31	1553 databus	*Fire Control*
32	Radio frequency interferometer	*Fire Control*
33	Improved Data Modem	*Fire Control*
34	Early rotorcraft targeting radars	*Longbow Millimeter Wave Radar*
35	Longbow MMW radar	*Longbow Millimeter Wave Radar*
36	MIMIC	*Longbow Millimeter Wave Radar*
37	Mast-mount for Longbow	*Longbow Millimeter Wave Radar*
38	Aerodynamic studies for mast-mounted Longbow	*[Sidebar]*
39	SAL seeker for Hellfire	*Weapons Suite*
40	Longbow Hellfire	*Weapons Suite*
41	30mm chain gun	*Weapons Suite*
42	Modeling to prevent structural failure due vibration	*Co-Located Army-NASA Research Sites*
43	Engineering design simulator	*Co-Located Army-NASA Research Sites*
44	Rotorcraft Pilot Associate program	*Other Collaborative Efforts*